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Remote sensing of vital sign of human body with radio frequency

Harikesh Dalal[1] · Ananjan Basu[1] · Mahesh P. Abegaonkar[1]

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Abstract Medical technology has improved remarkably in the field of health monitoring over the past few decades, becoming more sophisticated and less invasive as the years progress. Now, non-contact measurement of respiration and heartbeat with microwave Doppler radar phase modulation, offers an attractive alternative to commonly prescribed chest strap monitors. To monitor the vital signs an unmodulated radio frequency signal is transmitted toward the human body, where it is phase-modulated by the periodic physiological movement and reflected back to the receiver. The radar receiver captures the reflected signal and demodulates it to extract the vital sign signal components. The reflected signal from the body depends on the radar cross section (RCS) of body. In this paper the RCS of human body is measured in the X-band (8–12 GHz). There are several advantages to a noncontact measurement method: physically, it neither confines nor inhibits the subject and does not cause discomfort or skin irritation as electrodes and straps do. By measuring heartbeats, this technology can also be used to detect a person's presence, search-and-rescue for earthquake or fire victims and border patrol. It has also attracted the interest of organizations requiring high security, such as see-through- wall radar and airport security monitoring.

Keywords Heartbeat · Non-contact · Radar cross section · Respiration · Vital sign

1 Introduction

The microwave Doppler radar for sensing the vital sign of human body is known since 1970s. A microwave technique for measuring respiratory movements of man and animal is described [1]. The technique is non-invasive and is based on the scattering of continuous wave radiation by the radar. An X-band microwave life-detection system is discussed in [2] that can be used to detect the heartbeat and breathing of human subjects lying on the ground at a distance of 30 m. This system may be useful for locating persons trapped behind rubble or barriers or it may find medical applications such as the remote monitoring of the breathing and heartbeat of a patient in a clinic. In 1991, another X-band microwave life detection system for detecting humans trapped behind rubbles or obstacles [3] is proposed. In the earthquake or building collapse, the primary concern is to detect the person buried under the rubble or debris. With the vital sign detection system, the person buried under the debris can be detected and they can be rescued on time for medical aid. Such a system operates at lower frequency as high frequency cannot pass the through the thick debris. For such system, the operating frequency should be in L or S band. A new microwave life-detection system [4], operating at 1150 or 450 MHz, can be used to detect the heartbeat and respiration signals of the person buried in an earthquake rubble or a construction barrier of about 10-ft thickness. A digital signal processor for Doppler radar sensing of vital signs implemented in LabVIEW is described in [5]. Direct-conversion Doppler radars, operating at 1.6 and 2.4 GHz, designed on silicon chip is presented in [6]. The 2.4 GHz Doppler radar

✉ Harikesh Dalal
harikeshdalal2008@gmail.com

Ananjan Basu
ananjan_b@yahoo.com

Mahesh P. Abegaonkar
mpjosh@care.iitd.ernet.in

[1] Centre for Applied Research in Electronics (C.A.R.E.), Indian Institute of Technology, New Delhi, India

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uses the quadrature demodulation (I/Q) architecture to avoid null points, thus improving the detection sensitivity. A Ka-band heartbeat detection system using double side-band transmission for detecting the vital signs is discussed in [7]. As the frequency of operation increases, the sensitivity to detect the small displacement also increases, but at the cost of increased noise. In the Ka-band, the sensitivity of radar is high to detect small body motion. The measurement of the heartbeat is taken from the four sides of the body front, back, left, and right and the results obtained are compared. High accuracy is achieved when the measurement is taken from the back side of the human body as compared to other sides. The result also confirms that higher the transmitted power, better the accuracy and longer the distance which is an advantage for measurement of vital signs.

In the Doppler radar receiver, if the same source is used for the transmission as well as the local oscillator signal, then the phase noise of the received signal is correlated with that of the local oscillator. After mixing of the signals, the correlated portion of the phase noise is suppressed leaving a residual phase noise spectrum at baseband that is far below the phase noise at the radio frequency. It was also shown in [6] that in the direct-conversion receiver, the demodulation sensitivity is dependent on the phase relationship of the received signal and the local oscillator. The null points can be avoided with in-phase and quadrature (I/Q) receiver. Other techniques such as double-sideband transmission [8], complex signal demodulation [9], and arctangent demodulation [10] have also been proposed to eliminate the null-detection point problem. Due to the non-linear phase modulation, harmonics of the respiration and heartbeat are generated. The respiration signal is strong as compared to heartbeat signal, so, the harmonics of respiration signal are strong. These harmonics can interfere with the heartbeat signal and may reduce the accuracy of detection. Careful selection of carrier frequencies is very important in such analysis as given in [11].

A heterodyne quadrature demodulation architecture to eliminate the DC offset calibration for arctangent demodulation is discussed in [12]. The theoretical and experimental analysis of multi-frequency radar systems for monitoring vital signs is described in [13]. The multi-frequency architecture improve the detection sensitivity of vital signs. A concurrent multiband system is best suited as the hardware is shared thus reducing the size and cost of the system. Due to these facts, a concurrent multiband RF system is proposed in [14, 15]. The performance of a single band vital sign detection system can be improved by using concurrent multi-band operation. A multi-band system employs different RF frequencies. The received signals from various RF bands are correlated to decrease the noise floor and vital sign information can be obtained, enhancing the overall system performance. In [16], the dual frequency Doppler radar for vital sign detection operating at 5.75 and 35 GHz, is discussed to suppress the inference from the operator as this may affect the down-converted signal. Adaptive filtering is used to suppress the inference and increase the accuracy. The detection of vital sign, when human body is in motion, is extremely challenging. Such a system is described in [17] which uses the wavelet transform. Any other motion such as body motion or motion due to respiration, affects the wavelet coefficient on some scale factor. The wavelet coefficient which are increasing due to heartbeat, are found and in this way the body motion effect can be suppressed from the measurement. The method which uses the magnitude of the antenna reflection coefficient is discussed in [18]. The reflection coefficient variation of an antenna is used to detect the vital sign information of human body. The main advantage of this method is no additional hardware is needed such as signal source and antenna. Thus a compact vital sign detection can be designed and this can be integrated to other communication systems easily.

The direct down-conversion Doppler radar is sensitive to target position, so detection sensitivity is reduced. To improve the detection sensitivity quadrature demodulation architecture is used [19]. Here by using the in-phase and quadrature phase baseband signal, the detection sensitivity can be increased. In this architecture the DC offset can be removed which effect the vital sign information. By using the in-phase and quadrature phase signals in a quadrature receiver system using arctangent demodulation [19], the vital sign information data is obtained regardless of the target's position. The null detection problem in the vital sign detection radar is eliminated using complex signal demodulation technique, described in [20]. Using this complex signal demodulation, the random body movement is cancelled out, which is very serious problem for non-invasive vital sign detection.

The vital signs for human body are heart rate, respiration rate, body temperature and blood pressure. For a healthy person all these parameters are normal. The non-invasive detection of vital sign of human body is the key challenge for the researchers. The continuous research is going on in many part of the globe to improve the noncontact health monitors. The heart related diseases are the largest in this modern world. For monitoring the heartrate, there exist a wide range of instruments available to the medical personnel. For the monitoring of heartrate, electrocardiogram (ECG) is the common tool. The ECG monitor the activities of the heart for the diagnoses and treatment of these diseases. The most commonly used tool in heartbeat monitoring is the electrocardiogram (ECG), which monitors the electrical activity of the heart. To monitor the actual movements of the heart, ultrasound can be used both for imaging and displaying various heartbeat parameters. Other methods span from the large and expensive Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) machines which can provide detailed images of the entire human body, to simple pulse oximeters which can monitor the pulse through a small device placed on the finger.

Now, with microwave Doppler radar phase modulation, non-contact respiration and heartbeat monitoring offers an attractive alternative to commonly prescribed chest strap monitors. A conventional vital sign architecture is shown in Fig. 1. An unmodulated radio frequency signal is transmitted toward the human body, where it is phase-modulated by the periodic physiological movement and reflected back to the receiver. The relevant waveforms here are:

$$S_{transmitted}(t) = \cos[2\pi.ft + \psi(t)]$$

$$S_{reflected}(t) = \cos\left[2\pi.ft - \frac{4\pi d}{\lambda} - \frac{4\pi x(t)}{\lambda} - \psi\left(t - \frac{2d}{c}\right)\right]$$

$$S_{baseband}(t) = \cos[4\pi \mathrm{x(t)}/\lambda + \Delta\psi(t) + \phi(t)]$$

$$x(t) = x_h(t) + x_r(t) \quad when \quad x(t) <<< \lambda$$

Then $S_{baseband}(t) \approx \frac{4\pi x(t)}{\lambda} + \Phi(\mathrm{t})$
where $S_{transmitted}(t)$ is transmitted signal, $S_{reflected}(t)$ is reflected phase modulated signal from the human body and $S_{baseband}(t)$ is demodulated baseband signal.

$\psi(t)$ is the phase noise due to signal source and subsystem of transmitter, $\psi\left(t - \frac{2d}{c}\right)$ is the phase noise contributed by medium noise and source. $x_h(t)$ is heart movement and $x_r(t)$ is chest movement due to respiration.

The radar receiver captures the reflected signal and demodulates it to extract the vital sign signal components. There are several advantages to a non-contact measurement method: physically, it neither confines nor inhibits the subject and does not cause discomfort or skin irritation as electrodes and straps do. The continuous monitoring and analysis of vital signs is important making the detector ideal for long-term continuous monitoring. Also, reliability can be increased since patients are unaware of the measurement and are therefore less likely to alter their respiration. Additionally, accuracy is enhanced due to the lack of surface-loading effects that have been shown to reduce the accuracy of some other measurement methods.

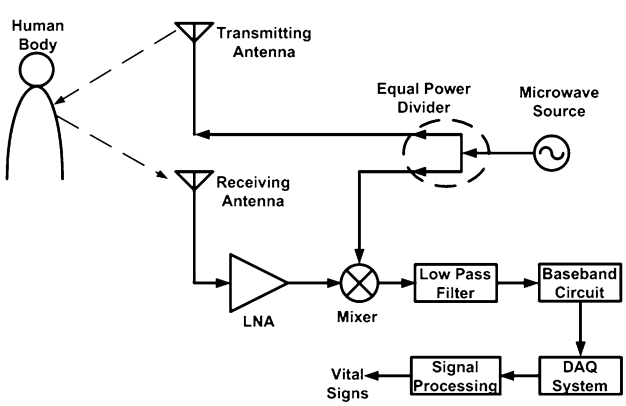

Fig. 1 Conventional vital sign detection architecture

2 Radar cross section (RCS) measurement of human body in X-band

The RCS in general is an important property of radar, and is usually denoted by σ. It is a measure of how well an object reflects incident radar power as a function of frequency and aspect angle. As part of the radar equation, σ is a necessary number for signal to noise ratio (SNR), detection computations and the understanding of radar signals in heartbeat and respiration monitoring. To find the optimum frequencies for the detection of heartbeat and respiration rate is very important as the reflected wave from the human body is dependent on RCS. The frequencies used for the heartbeat and respiration detection are for which the RCS is largest. The reflection is to be strongest when the person was facing the receiving antenna. The RCS of any object is measured by taking a reference object for which the RCS is known. Here, for the measurement of RCS of human body, the front side of human body can be modelled by a cylinder of radius 20 cm and back side by a flat plate of 20×20 cm^2. The RCS measurement setup is shown in Fig. 2.

To obtain calibrated recordings of the human heartbeat and respiration, four separate radar recordings are to be recorded:

1. Measurement of the empty room for clutter subtraction,
2. Measurement of a metallic plate for calibration,
3. Measurement of a metallic cylinder for calibration and
4. Measurement of a person sitting still (from front side and back side of body).

All measurements are performed in an anechoic chamber to avoid strong reflections off the walls and to reduce the multipath components. Between each recording, the only change was the target in the scene. In this way, the radar and antenna behavior and the clutter was constant for each of the four recordings. The background reading are taken to remove the unwanted reflection and coupling between the transmitting and receiving antenna. The RCS of human body is calculated by using the Friis equation.

The measured RCS of human body is shown in Fig. 3. The RCS of human body increases with the frequency. The measured RCS is larger for the back side of body as compared to the front side. So the reflected signal is stronger from back side. So the detection sensitivity of heartbeat is more when measurement are done from the back side of human body as compared to front side. In front side measurement, the chest movement due to respiration signal which is stronger as compared to heartbeat signal, reduces the sensitivity of heartbeat detection.

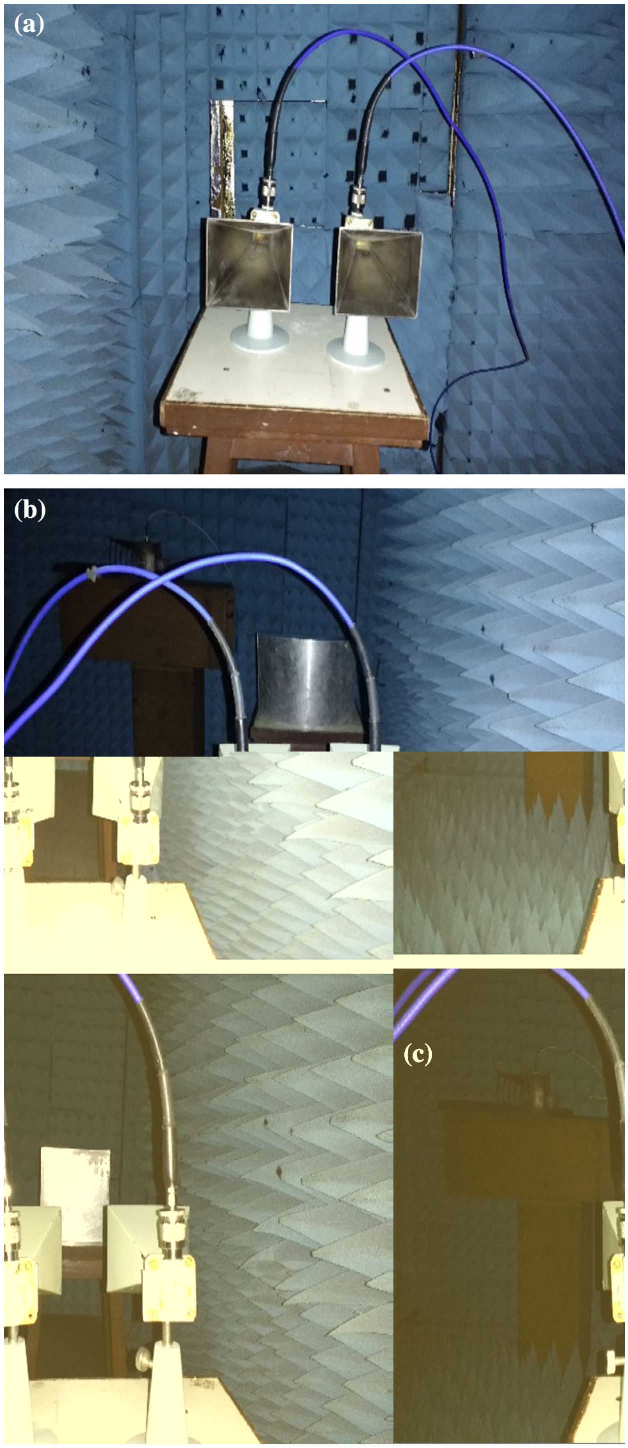

Fig. 2 **a** Horn antenna used for RCS measurement, **b** measurement setup for a metallic cylinder for calibration, **c** measurement setup for a metallic plate for calibration

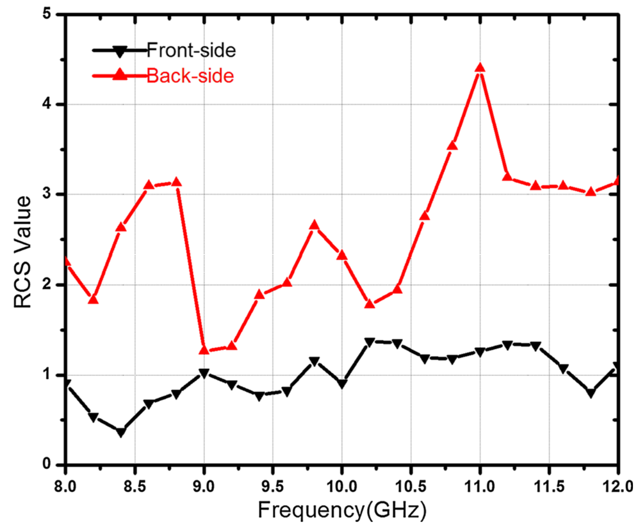

Fig. 3 RCS of human body from front and back side

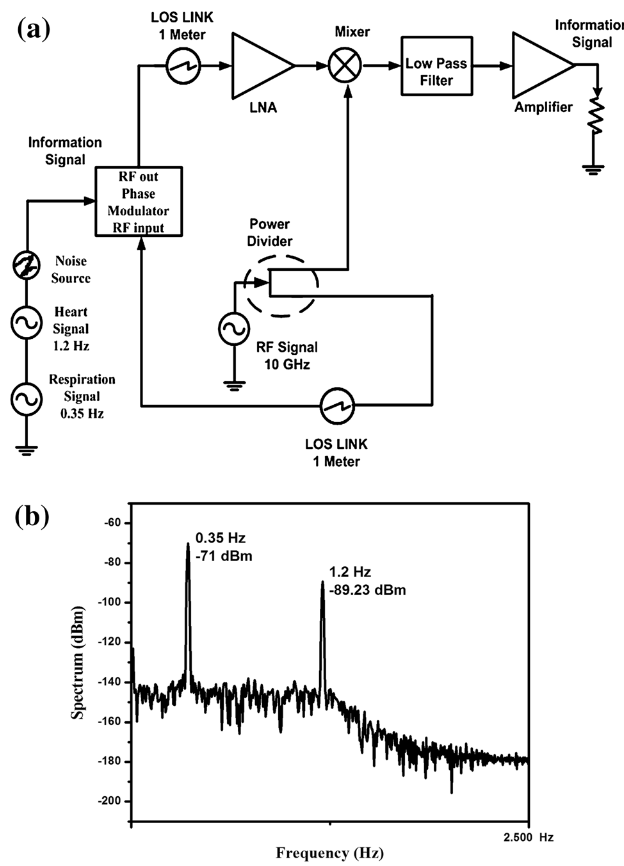

Fig. 4 **a** Schematic of direct down-conversion demodulation architecture, **b** spectrum of base-band signal

2.1 Design of vital sign system

The vital sign detection architectures are designed in ADS 2009. In all types of architectures are designed at 10 GHz and the distance between the radar and subject is kept 1 m. The distance is modeled by LOS link at 1 m. For vital sign, two sinusoidal sources are used. For the heartbeat and respiration signal source of 1.2 and 0.35 Hz is used respectively. The noise is added using the noise source. A phase modulator is used to resemble the reflected signal.

The reflected signal is amplified and then down-converted using the mixer. After the mixing of the signals, the down-converted baseband signal is passed through a low pass filter to remove the high frequency components. To remove the DC offset capacitor is used. Following are the main architecture simulated in the ADS:

1. Direct down-conversion Architecture Design
2. Double down-conversion Architecture Design
3. Quadrature Demodulation Architecture Design

2.2 Direct down-conversion architecture design

The direct-conversion architecture, shown in Fig. 4a. This is the simplest architecture of the Doppler radar used for the vital sign detection. In this architecture, the null point are present at every λ/4 distance between the radar and human subject. At the null position, the down-converted baseband signal is dominated by harmonics and inter-modulation of information signal which makes the desired signal undetectable. The spectrum of the output baseband signal is shown in Fig. 4b. So the output respiration has a frequency of 0.35 Hz and heartbeat signal has frequency of 1.2 Hz.

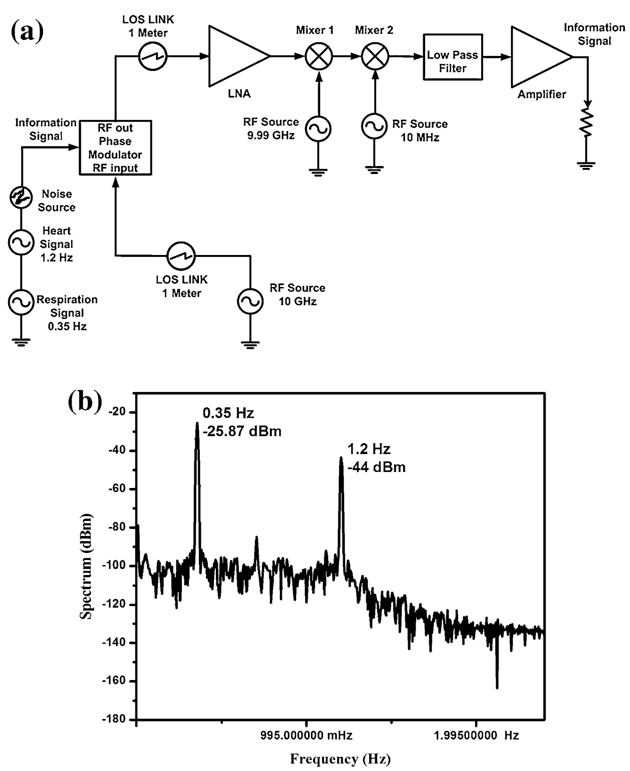

Fig. 5 **a** Schematic of double down-conversion demodulation architecture, **b** spectrum of base-band signal

2.3 Double down-conversion architecture design

The double down-conversion architecture, shown in Fig. 5a. The double conversion receivers are selective and improve the image frequency rejection. So the overall detection sensitivity of system increases. The distance between the subject and antenna is modelled by LOS link of 1 meter. Here two mixer and one low pass filter is used as shown in Fig. 5a. The reflected signal is first down-converted to 10 MHz using the mixer and again down-converted to baseband using the other mixer. The advantage of the architecture is that the information signal is less effected due to noise and thus increasing the detection accuracy. But the system become bulky and costly. The spectrum of the output baseband signal is shown in Fig. 5b. So the output respiration has a frequency of 0.35 Hz and heartbeat signal has frequency of 1.2 Hz.

2.4 Quadrature demodulation architecture design

The quadrature demodulation architecture, shown in Fig. 6a. The quadrature demodulation has the potential to detect the

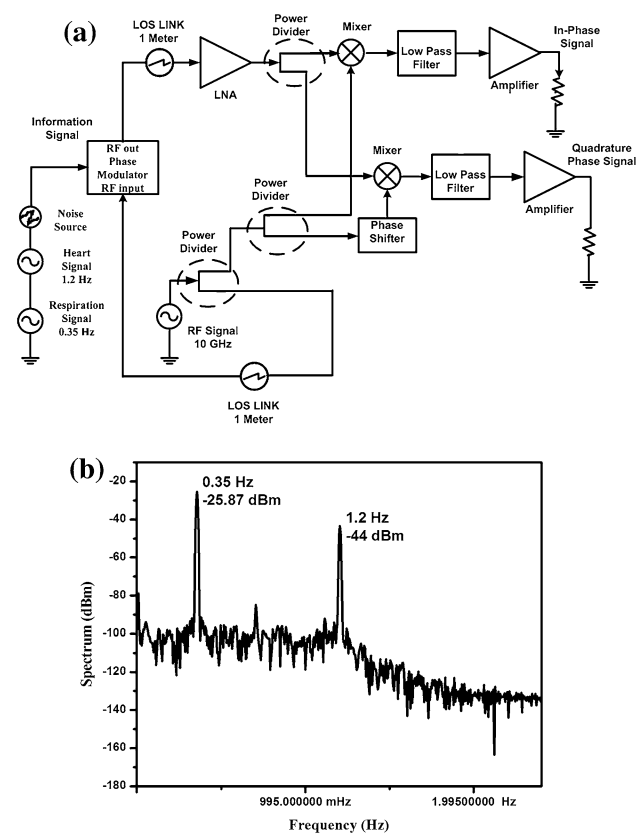

Fig. 6 **a** Schematic of quadrature demodulation architecture, **b** spectrum of base-band signal small frequency or phase changes. The null point problem between the radar and human subject is solved by this architecture. The reflected signal from the target is splitted into in-phase and quadrature phase channels. These signal are down-converted using the two mixers giving the baseband information signal. Both baseband signal contains the identical information but are in phase quadrature. So when one signal is at its maximum, the other signal is at its minimum and vice versa. The spectrum of the output baseband signal is shown in Fig. 6b. So the output respiration has a frequency of 0.35 Hz and heartbeat signal has frequency of 1.2 Hz.

3 Conclusion and future work

The non-invasive detection of vital sign of human body is offers the simple way of monitoring the health parameters as the other method will require the electrode for monitoring the heart parameter. By using the Doppler radar, it would be possible to manufacture an inexpensive and portable device to perform health monitoring. The RCS of human body increases with the frequency, so at higher frequency the detection sensitivity is higher as compared to lower frequency. The future work will include the measurement of the RCS at higher frequency bands and the extraction of the vital sign information from the down-converted signal efficiently by removing the clutter noise and separate out the heartbeat signal from the respiration by using proper signal processing to improve the sensitivity and accuracy of detection.

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