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# Through the Wall Respiration Rate Detection of Multiple Human Subjects Using Hilbert Vibrational Decomposition

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**Abstract**—In this paper, through-the-wall detection of multiple human subjects is demonstrated using Doppler radar, with the help of Hilbert Vibrational Decomposition (HVD). The proposed Doppler radar can detect multiple human subjects behind a wall by respiration rate estimation. With different breathing conditions resembling real-life scenario, respiration signals of human subjects are extracted. The algorithm works in many real-life situations and detects the respiration rate of human subjects. It is expected to find use in the earthquakes, building collapses and security applications.

## 1. INTRODUCTION

Non-invasive detection of vital signs of human beings with the help of Doppler radar is a growing field of research. This technology finds application in situations such as building collapses, earthquakes, medical-care, and security. To detect a human subject through a wall or under debris, an RF signal is transmitted towards the human subject. The reflected signal from the human subject is phase modulated due to the periodic motion of the chest. So all breathing/respiration signal information is in phase of the reflected signal. Using a continuous wave (CW) Doppler radar, the vital signs of a human being can be extracted. The operation of such a CW radar is simple and is discussed in [1]. The detection of the vital sign depends on the reflected signal from the human subject. The reflected signal from the human subject varies with the orientation of the subject with respect to the radar as the radar cross section (RCS) of human subjects changes with orientation [2]. The detection of heartbeat and respiration at short distances using a frequency-tuning technique in Ka-band was discussed in [3]. This technique avoids the null detection problem, but the noise level increases at higher frequencies.

Through-the-wall detection of human subject is a challenging task. The penetration of RF signal through a wall decreases with increase in frequency. So these systems should be operated at lower frequencies for better penetrability. The use of multiple frequencies for through the wall detection of human subject increases the sensitivity, and a dual-band FMCW radar was described in [4] for short range detection of vital signs, but the detection of multiple human subjects was not addressed. UWB radar also finds application in through-the-wall detection of human subjects, imaging, detection of moving targets, etc. UWB radars for detection of vital signs of a human subject were discussed in [5–10]. Signal processing plays a very important role in vital sign detection using Doppler radar. Various algorithms such as parameterized demodulation, singular value decomposition (SVD), adaptive cancellation of clutter, constant false alarm ratio (CFAR) and correlation were proposed to extract vital signs from the received noisy signal [7–11]. But these signal processing algorithms do not separate the vital signs of multiple subjects. Through-the-wall detection of multiple human subjects using UWB radar was discussed in [12]. UWB radars are costly, with poor SNR due to large bandwidth, and have long processing time. For vital sign detection FFT and S-transform are also used which do not extract the vital signs of multiple human subjects.

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Through-the-wall respiration detection of a human subject, by varying the respiration rate, with different positions of human subject with respect to the radar and different backgrounds behind the human subject was discussed in [13]. In this paper, through-the-wall respiration rate detection of multiple human subjects using the HVD algorithm is proposed. The HVD algorithm is applied on the received signal to extract the respiration signal of the human subjects. The respiration rates of human subjects are close to each other which make the extraction of the respiration signals very difficult. The HVD algorithm provides good frequency resolution for extraction of respiration rates of multiple subjects from the noisy signal. Many combinations of human subject breath rates are taken into the consideration to collect the reflected signals from the human subjects to resemble a real life situation. In all situations, the algorithm works well in the extraction of the respiration rate. In this work, measurements are taken when three human subjects are present behind the wall, and all human subjects are breathing at different rates.

## 2. DOPPLER RADAR AND HILBERT VIBRATIONAL DECOMPOSITION ALGORITHM

### 2.1. Doppler Radar

Noninvasive detection of respiration rate of human subject uses Doppler Effect. According to Doppler theory when the object is moving with a velocity, the frequency of the reflected wave is changed, but when the object is moving with net displacement zero, the reflected wave from the object is phase modulated. The RF wave is impinged by the antenna on the human subject, and the reflected wave from the human subject carries the information in phase. The phase of reflected wave changes with periodic movement of the chest of the human subject. The total chest movement $x(t)$ is the sum of movements due to the respiration and heartbeat [3]. The transmitted and reflected signals can be written as:

$$S_{\text{Transmitted}}(t) = A_c \cos(\omega t + \theta) \tag{1}$$

$$S_{\text{Reflected}}(t) = A'_c \cos\left[\omega t - \frac{4\pi d}{\lambda} - \frac{4\pi x(t)}{\lambda} + \theta(t)\right] \tag{2}$$

where $A_c$ is the amplitude of transmitted signal, $\lambda$ the free space wavelength, $d$ the distance of radar from the subject, $\theta$ the initial phase, and $\theta(t)$ includes phase noise. The respiration signal is much stronger than the heartbeat signal. The harmonics of the respiration signal also decrease the sensitivity of heartbeat detection. Here, the respiration rate is measured because the phase change due to respiration

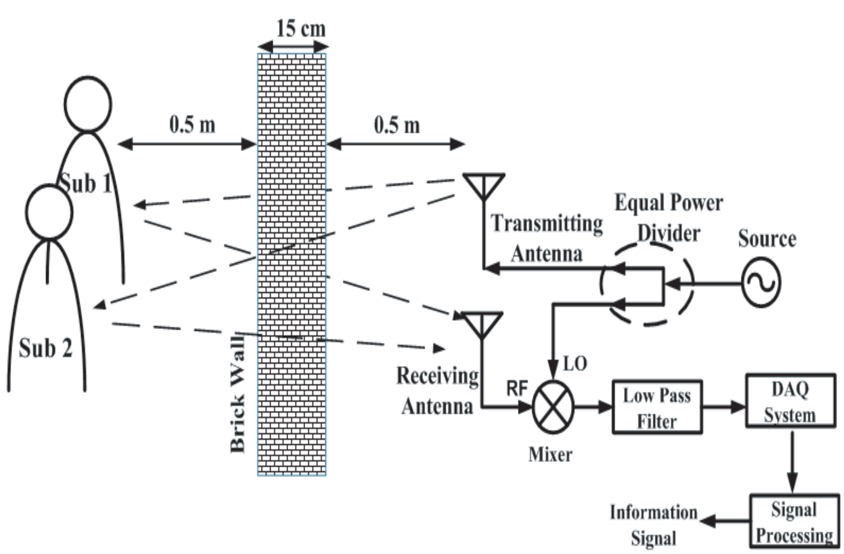



**Figure 1.** Block diagram of direct demodulation system.

is large. Fig. 1 shows the direct demodulation system. When the same source is used for the transmitter and receiver, the noise level is reduced due to homodyne effect and thus increases the detection sensitivity of the Doppler radar. After direct demodulation, the output of the mixer is passed through a low-pass filter to remove the higher frequency components. The baseband signal is given by:

$$B(t) = P + Q\left(\frac{4\pi x(t)}{\lambda} + \Delta\phi(t)\right) \tag{3}$$

where $P$ is the dc offset, $Q$ a constant, $\Delta\phi(t)$ the residual phase noise, and $x(t) \ll \lambda$.

### 2.2. Hilbert Vibration Decomposition (HVD) Algorithm

The block diagram of the Hilbert Vibration Decomposition (HVD) is shown in Fig. 2. The Hilbert Vibration Decomposition (HVD) method decomposes the vibration components at lower frequencies [16]. The Hilbert Vibration Decomposition (HVD) is an iterative algorithm to extract the dominant vibration component from a signal. The multicomponent signal oscillates around the largest energy component. To extract the largest energy component from the signal $B(t)$, instantaneous frequency (IF) of signal $B(t)$ is estimated, then the IF is passed through a low-pass filter to obtain the instantaneous frequency $\omega_1$ of the largest energy component, and instantaneous amplitude $A_1(t)$ is estimated. After calculating $\omega_1$ and $A_1$, the largest energy component of the signal is obtained; this signal is subtracted from the initial signal $B(t)$; and new signal is obtained. After each iteration, the remaining signal contains lower energy components. The process is repeated to decompose the multicomponent signal into several components. The advantage of this method is that the frequency resolution is not dependent on the harmonics amplitude ratio.

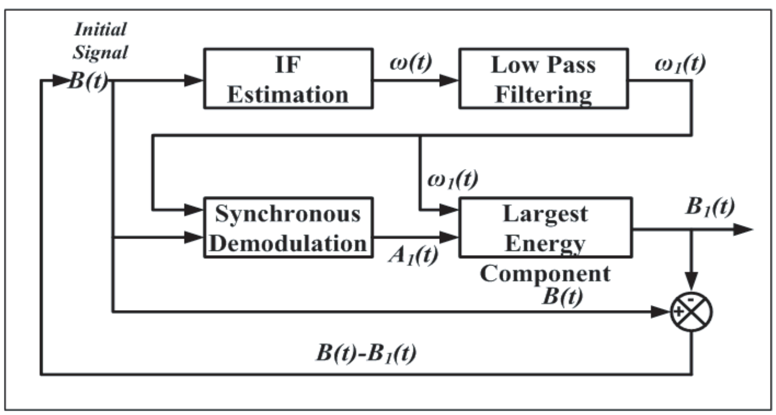



**Figure 2.** Block diagram of Hilbert vibrational decomposition (HVD).

## 3. MEASUREMENT SETUP AND EXPERIMENTAL RESULTS

Figure 3 shows the measurement setup for through the wall respiration detection of human subjects. All measurements are taken to resemble the real life scenario. The brick wall thickness is about 15 cm. The frequency of operation is 2.4 GHz. The S-band horn antennas are used for transmitting and receiving the RF wave. The reflected signal from the human subjects is down-converted to the baseband signal which contains respiration signal of the human subjects present on the other side of the wall. The horn antennas are placed 0.5 m away from the wall, and the human subject is 0.5 m away on the other side of the wall. The 15 dBm power is transmitted towards the human subjects. The same microwave source is used for LO and transmitter to reduce the overall noise of the system. The data are collected for 50 seconds to get better frequency resolution. The measurements are taken, when two human subjects are breathing at different rates. The reflected signal from the multiple human subjects has the respiration information in its phase. So the phase of the reflected signal is used for the respiration signal detection.


**Figure 3.** Experimental setup for through the wall measurement of respiration rates.

Using direct FFT without applying the HVD algorithm, the respiration rates of human subjects cannot be extracted. The spectrum contains the harmonics due to the respiration signal of other subjects as well as its own harmonics. Also, the breathing rate of a human subject varies over the time which makes the detection difficult.

### 3.1. Respiration Rate Detection of Two Human Subjects

To detect the human subjects behind the wall, the respiration signal of the human subjects is used because the respiration signal is stronger than the heartbeat signal. The respiration signal of human subject is the largest energy component in the down-converted signal, so with the HVD algorithm, the respiration signal is extracted. The HVD also suppresses the harmonics and increases the detection

**Table 1.** Human subjects breathing conditions.

| Human Subject | Slow Breathing (Hz) | Normal Breathing (Hz) | Fast Breathing (Hz) |
|---|---|---|---|
| Slow Breathing and Normal Breathing | | | |
| Sub 1 | 0.1 | - | - |
| Sub 2 | - | 0.22 | - |
| Slow Breathing and Fast Breathing | | | |
| Sub 1 | 0.16 | - | - |
| Sub 2 | - | - | 0.46 |
| Both Normal Breathing | | | |
| Sub 1 | - | 0.26 | - |
| Sub 2 | - | 0.33 | - |
| Normal Breathing and Fast Breathing | | | |
| Sub 1 | - | - | 0.44 |
| Sub 2 | - | 0.26 | - |
| Both Fast Breathing | | | |
| Sub 1 | - | - | 0.64 |
| Sub 2 | - | - | 0.4 |

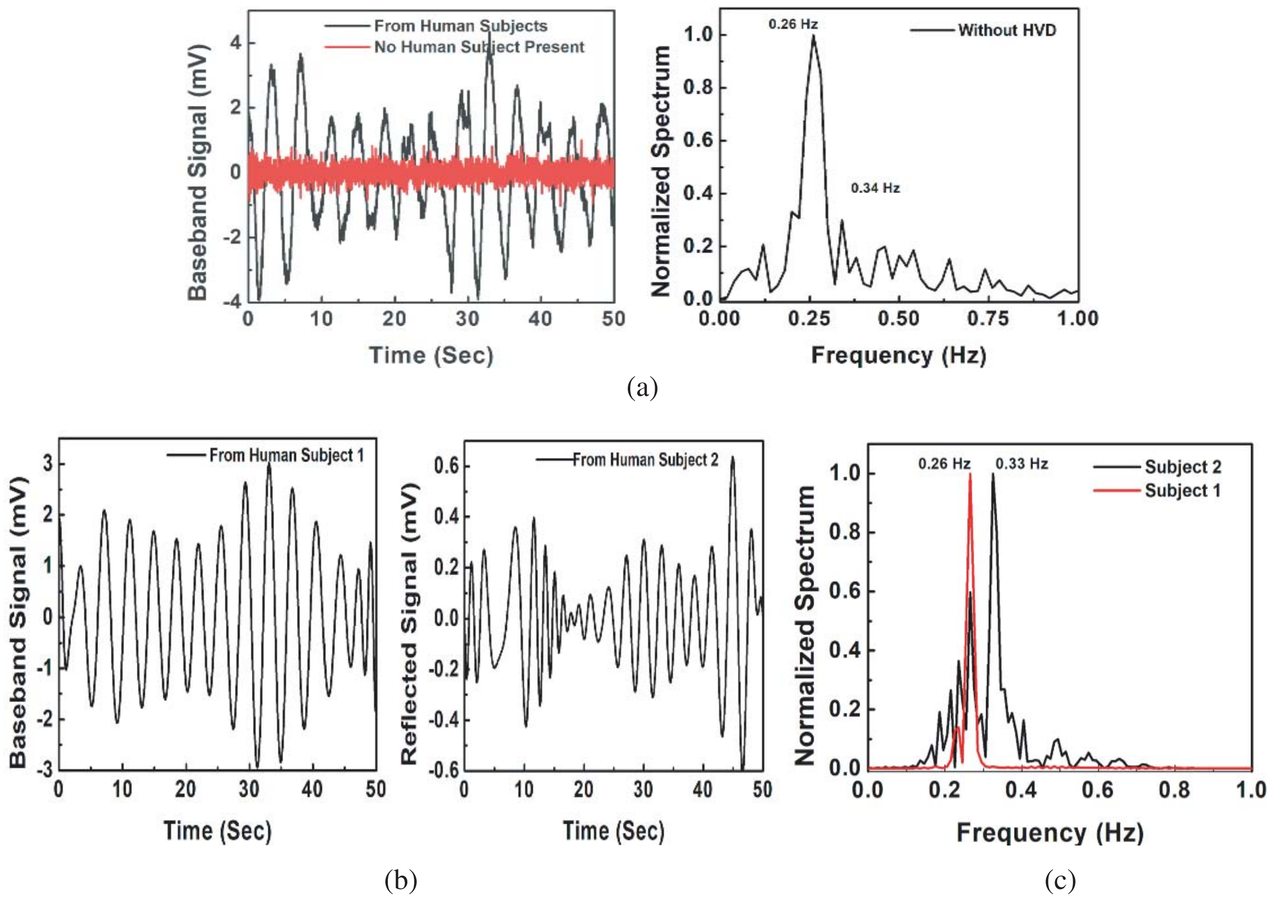
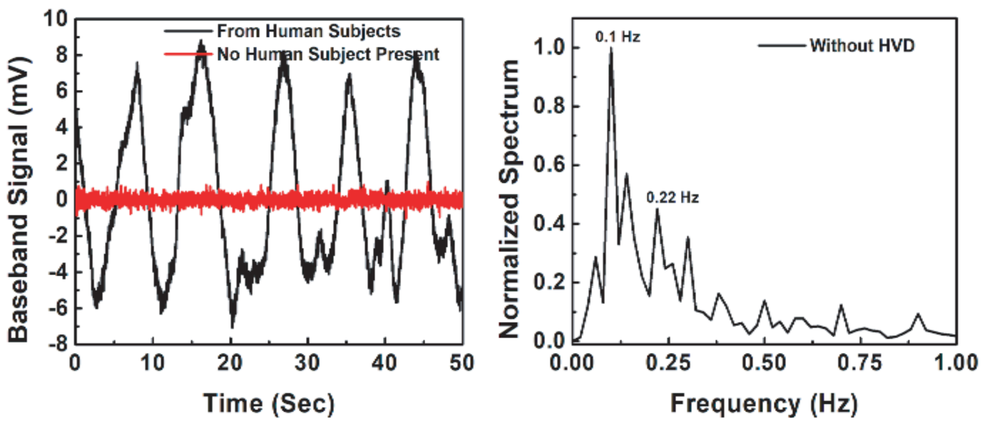


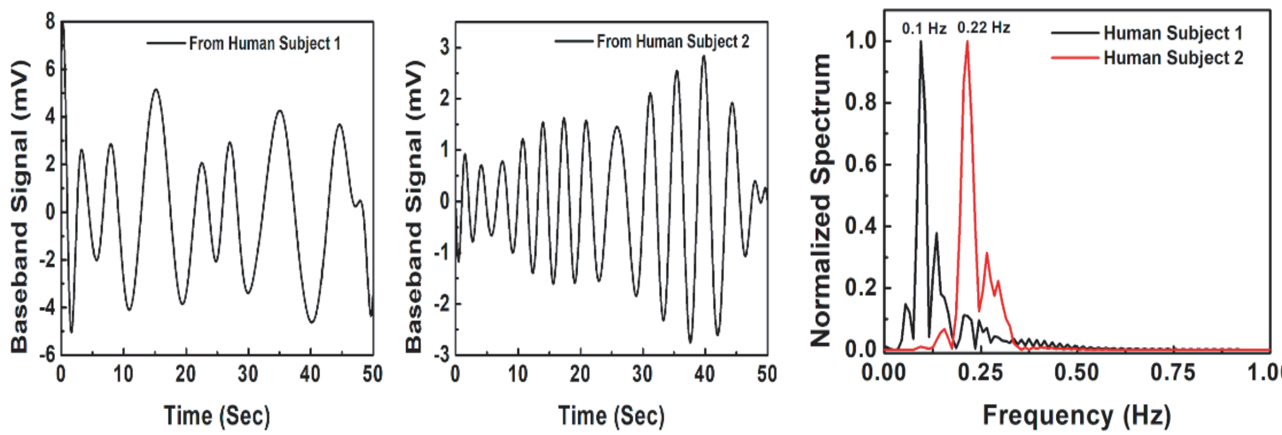

**Figure 4.** When both human subjects are breathing normal, (a) respiration signal without HVD and its normalized spectrum, (b) extracted respiration signals with HVD and (c) normalized spectrum of extracted respiration signals.

sensitivity of the respiration rate. When two human subjects are present and both are breathing normal, the results are shown in Fig. 4. After removing the dc offset, the baseband signal and its normalized spectrum are shown in Fig. 4(a). When no human subject is present, the received signal shows no variation in its spectrum, and noisy signal is received. This noise is due to the presence of other objects, wall, and background, shown in Fig. 4(a). Fig. 4(b) shows the extracted respiration signals of the human subjects using the HVD algorithm. The respiration signal is correlated with itself not with the noise, so the extracted signal is auto-correlated and further decreases the noise level. After auto-correlation, the normalized spectrum of the extracted respiration signals with HVD is shown in Fig. 4(c). The HVD algorithm provides good frequency resolution in extraction of the respiration signals of multiple human subjects.

Figure 5 shows the results when one human subject is breathing normal, and the other is breathing slow. The reflected signal and its normalized spectrum are shown in Fig. 5(a). The extracted respiration signals of human subjects using the HVD algorithm are shown in Fig. 5(b). After auto-correlation, the normalized spectrum of extracted respiration signals is shown in Fig. 5(c). The harmonics due to the other human subject are suppressed in the extracted component of the respiration signal. A summary of the results is presented in Table 1. These conditions of the measurement are set to resemble the real life scenario. All possible combinations are taken into account. The measurement is also taken when the distance between the human subjects is changed. When distance between the human subjects is 1 meter, the respiration rates are extracted. As the distance is increased further, the human subjects are out of the range of the antenna beam, so the reflected signal from them becomes very weak, and the detection of the respiration signals becomes difficult.




(a)




(b) (c)

**Figure 5.** When two human subject are present one normal breathing and other slow breathing, (a) respiration signal without HVD and its normalized spectrum, (b) extracted respiration signals with HVD algorithm and (c) normalized spectrum of extracted respiration signals.

### 3.2. Respiration Rate Detection of Three Human Subjects

The detection of respiration rates becomes more difficult when three human subjects are present. The reflected signals from the subjects interfere with each other. Also the reflected signals from the subjects have different variations in their spectrums which affects the extraction of the respiration signals. The measured results when three human subjects are present are shown in Fig. 6. Three subjects are breathing at different rates — one is breathing normal; the second one is breathing slower than normal; and the third one is breathing faster than normal. The reflected signal contains the three subjects' respiration signal information. The baseband signal and its normalized spectrum are shown in Fig. 6(a). One subject respiration signal interferes with other subjects' respiration signals, making the extraction of individual signal difficult. After extraction of the respiration signals of human subjects, the auto-correlation of signal is taken to enhance the accuracy of detection, then by using the FFT, the spectrum of the respiration signal is estimated. The normalized spectrum of the extracted respiration signals with HVD is shown in Fig. 6(b). The spectrum shows that the harmonics are suppressed while fundamental component is extracted. The respiration signal is extracted from the noisy signal, shown in Fig. 6(c).

### 3.3. Range Detection When Single Human Subject is Present

When the human subject is in front of the radar, the reflected signal is strong. In this case, the respiration signal can be extracted easily. As the offset between radar and human subject is increased,

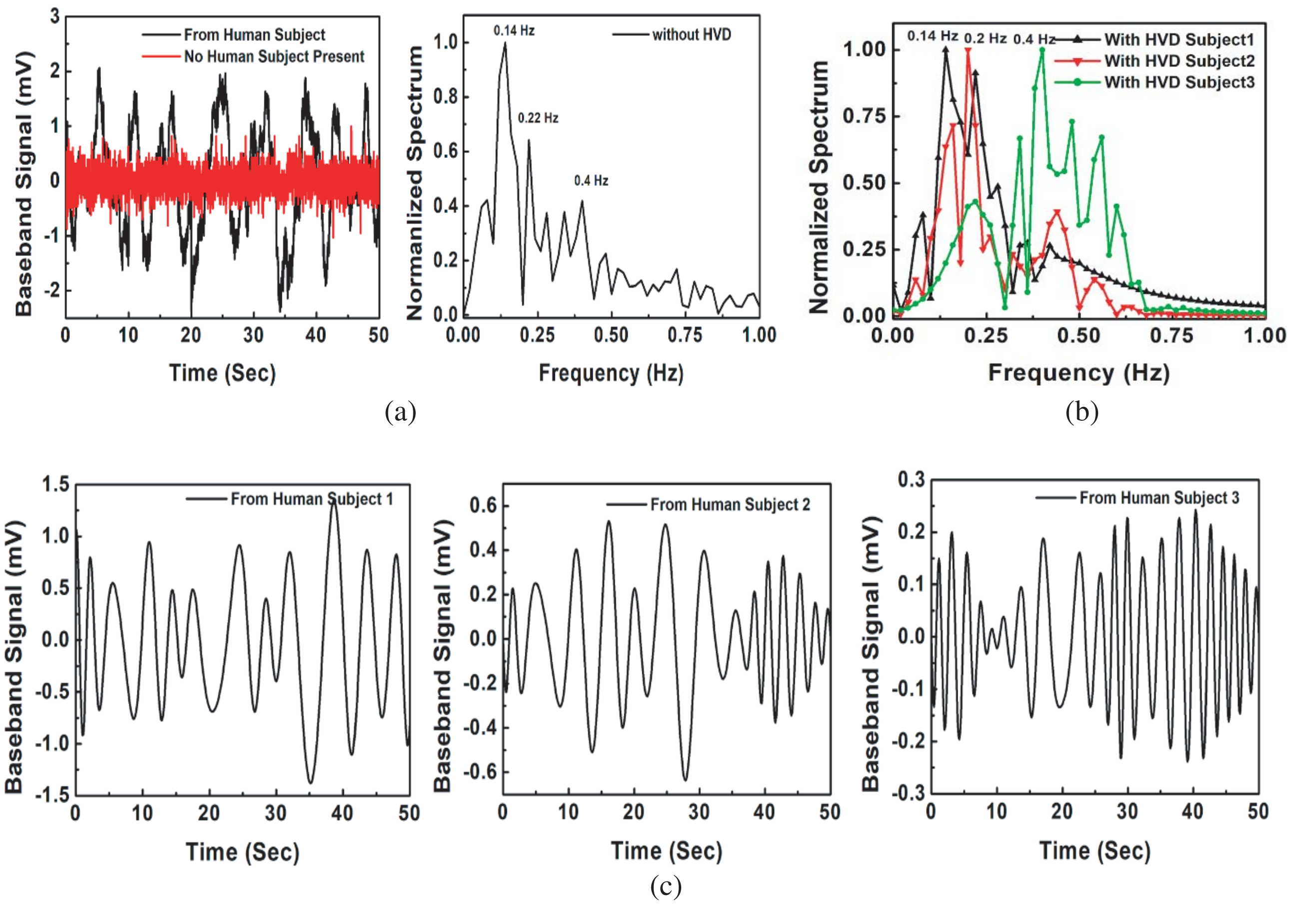


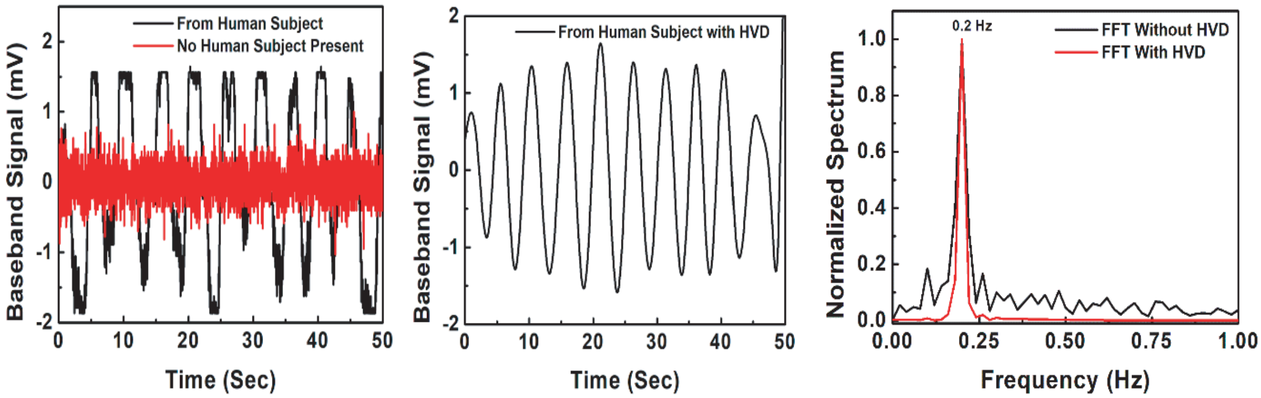

**Figure 6.** When three human subject are present — all breathing at different rates, (a) respiration signal without HVD and its normalized spectrum, (b) normalized spectrum of extracted respiration signals with HVD algorithm and (c) extracted respiration signals with HVD algorithm.

the reflected signal is contaminated with noise, and the signal becomes weaker. Initially, the radar is 0.5 meter away from the wall, and the human subject is 0.5 meter away on the other side of the wall. For taking the measurements, the radar is moved away from the initial position to 1 meter and 2 meter. As the radar is moved farther from the initial position, the level of the signal decreases, and noise level increases. When the distance between the human subject and radar is 3 m, the detected respiration signal without HVD and extracted signal with HVD are shown in Fig. 7(a). The normalized spectrums of the respiration signal without HVD and with HVD are shown in Fig. 7(b). The harmonics present in the received signal are suppressed, and only fundamental component of respiration signal is extracted. Table 2 lists the measured respiration rate by varying the distance of subject from the radar, when the human subject is in front of the radar and breathing at different rates — slow, normal, and fast.

The vital signs of multiple human subjects are extracted using the HVD algorithm which is not

**Table 2.** Human subject in front of radar.

| Distance | Slow Breathing (Hz) | Normal Breathing (Hz) | Fast Breathing (Hz) |
|---|---|---|---|
| 1 m | 0.1 | 0.24 | 0.74 |
| 2 m | 0.12 | 0.22 | 1.05 |
| 3 m | 0.1 | 0.30 | 0.9 |




(a) (b)

**Figure 7.** When antennas are 2 meter away from the initial position and human subject is breathing normal, (a) respiration signal without HVD and with HVD algorithm and (b) normalized spectrum of respiration signal.

**Table 3.** Through the wall detection methods.

| Ref. | Radar Type | No. of Subjects | Signal Processing | Signal separated |
|---|---|---|---|---|
| [12] | UWB | 2 | S-Transform | No |
| [14] | UWB | 2 | FPGA Based | No |
| [15] | FMCW | 2 | Self-Injection Locking | No |
| Proposed | CW | 3 | HVD | Yes |

possible by direct FFT. The proposed approach is very simple as compared to the other methods. Comparison of the proposed work with other known methods is shown in Table 3.

## 4. CONCLUSION

Through the wall respiration rates detection of multiple human subject using the HVD algorithm is discussed in this paper. The Doppler radar works at 2.4 GHz for the detection of human subjects. When two or three human subjects are breathing at different rates and present on the other side of wall, the respiration rates of human subjects are extracted from the noisy signal. The harmonics and noise level due to the presence of other human subjects are suppressed using this algorithm which increases the detection sensitivity. The presence of human subjects in all real life scenarios are detected, i.e., when human subject is in front of the radar or behind the wall. By increasing the transmitting power, through the wall detection range can be further increased.

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