Wireless Non-Contact Detection of Heartbeat and Respiration Using Low-Power Microwave Radar Sensor

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Abstract—**This paper reviews the recent developments of a non-contact vital sign (heartbeat and respiration) detection system using low power microwave radar sensor. Two key techniques are employed in this system. The technique of double-sideband transmission and detection replaces the quadrature detection and simplifies the architecture. The other technique of using short wavelength (high frequency carrier) improves the sensitivity while reducing the transmitted power. Theories and experimental results of these techniques will be described. Theory of nonlinear Doppler phase modulation discovered through the use of short wavelength will be presented and its potential applications will be discussed.**

Keywords—wireless, non-contact, vital sign, heartbeat, respiration, microwave, radar, sensor, low-power, double-sideband, nonlinear.

I. Introduction

Using microwave Doppler radar to detect physiological movements can be traced back to the early 1970s [1]-[6]. This technique enabled non-contact detection of vital signs of humans or animals from a distance away, without any sensor attached to the body. Compared to either infrared or visible light, microwave has greater penetration capability through the building materials, which brings unique property to many civilian and military applications. Recent developments in the early 2000s have demonstrated the feasibility of integrating this function into modern wireless communication devices operating in L and S bands [7]. The first integrated vital sign radar sensor chip using silicon CMOS was also demonstrated [8]. The chip integrates all the radio frequency (RF) circuits including a free-running oscillator that provides transmission signal and servers as the reference [9].

Recently, the detection of vital signs using higher microwave frequency near millimeter-wave was proposed [10]. It shows the advantage of increasing sensitivity while reducing the transmitted power. An architecture using double-sideband transmission and detection was also proposed [11]. It replaces the quadrature receiver architecture previously used to alleviate null-point detection problem. By using these two key techniques, a system was built and several experiments were conducted. The results show improvements in detection range and accuracy. It also shows the improved sensitivity to detect small physiological movements. In a demonstration, the system was able to detect both heartbeat and respiration signals from four sides of a human body [12]. Surprisingly, the detection of heartbeat from the back of human body shows the best accuracy among all four cases. Based on this finding, an experiment of measuring a sleeping subject's vital signs overnight was carried out by placing the radar sensor on the ground underneath the bed [13]. These results were further analyzed and an interesting phenomenon of nonlinear Doppler phase modulation was discovered. A theoretical model was developed to explain the results [14]. The model can be used to predict the best carrier frequency for vital sign detection, which depends on the body type of subject under test [15].

The theoretical model brought another important finding. The nonlinear Doppler phase modulation produces harmonics of the periodic movement being detected. The signal levels of these harmonics maintain a fixed ratio as a function of the absolute amplitude of the periodic movement, regardless of the overall signal strength received. This suggests that an accurate detection of periodic movement amplitude without calibration can be achieved in an inexpensive way [16]. The chest movements due to heartbeat and respiration can also be estimated.

This paper reviews these theories and techniques developed in the past three years. The system hardware and software are described and the measurement results are discussed. Potential applications in science, engineering, and medicine will be discussed.

II. Performance Improvement by Short Wavelength

Based on the theory in [9], when the displacement of physiological motion is relatively small compared to the wavelength and the received signal is in quadrature with the reference (ϕ=90°), the small angle approximation is valid and the received baseband signal is proportional to the heartbeat and respiration displacements $x_h(t)$ and $x_r(t)$, respectively:

$$B(t) = \cos\left(\frac{4\pi x_h(t)}{\lambda} + \frac{4\pi x_r(t)}{\lambda} + \phi\right) \cong \frac{4\pi x_h(t)}{\lambda} + \frac{4\pi x_r(t)}{\lambda} \qquad (1)$$

It can be seen from (1) that the received baseband signal strength increases as the wavelength decreases, which means for the same displacement, smaller wavelength should produce larger Doppler phase shift. This suggests that the sensitivity to detect small vital sign movement should improve. It was reported that the typical chest wall movement due to respiration is on the order of 1mm whereas the typical chest wall movement due to heartbeat is smaller than 0.1mm [17]. For a vital sign radar transmitting 3-GHz carrier, the phase shift due to heartbeat is less than 0.36°. Increasing the frequency by ten times will increase the Doppler phase shift as well as the detected signal strength (voltage) by 10 times (20dB). This additional gain in signal can increase the detection range and/or decrease the required transmission power. A transceiver at Ka-band was designed and built for this purpose. The test result shows that the detection range can be extended and the transmitted power can be reduced. Detection distance of greater than 2m while using less than 20-µW transmitted power was achieved [10]. This power level is much lower than those used in previous systems.

In addition to the improvement in the combination of sensitivity/range/power, another advantage of operating at higher frequency is the smaller antenna size. By using an array of small antennas, the directivity can be increased. With phased array technology, a vial sign scanner is feasible.

III. DOUBLE-SIDEBAND TRANSMISSION AND DETECTION

As indicated in [9], there exists null-points in detection every quarter wavelength from the target. If the vital sign radar is located at a null point, the received RF signal and the reference are not in quadrature and the small angle approximation used in (1) is no longer valid. On the other hand, if the vital sign radar is located at an optimum point, these two signals are in quadrature and (1) is valid. This is similar to the phase noise measurement using FM discriminator technique [18]. To avoid this null-point detection problem, quadrature receiver architecture was used in [9]. This ensures at least one of the I/Q channels is not at null point.

Another approach of solving the null-point detection problem was proposed in [11]. The system used double-sideband transmission and detection architecture, which achieved the same purpose as the quadrature receiver. The system block diagram is shown in Fig. 1. The radar transceiver using indirect-conversion architecture transmits two carriers LO2+LO1 and LO2-LO1 simultaneously after mixing LO1 and LO2. There is no image rejection and no quadrature generation, which makes the system simple and easy to be integrated on a chip. Since two carrier frequencies are used, if one results in null-point detection, the other will not when LO1 is properly adjusted. This tuning capability also allows the null-point locations to be tuned out, unlike the fixed null-point locations when quadrature receiver is used. Since the two transmitted frequencies are the upper and lower sidebands of LO2, the two detection channels are down-converted and combined at IF.

The implementation of indirect conversion also helps the reduction in DC offset due to LO leakage, as compared to the direct conversion architecture. Even though indirect conversion is used, the double-sideband architecture makes monolithic integration still feasible.

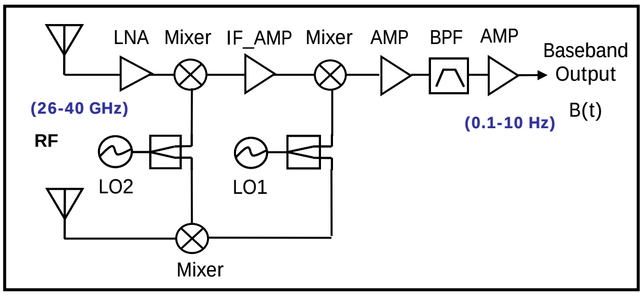

Fig. 1: Double-sideband radar architecture [11].

Fig. 2 shows the output spectrum of the double-sideband transmission. The two sidebands USB and LSB can be seen whereas the LO2 leakage at 27.1GHz also appears. The LO2 leakage does not affect the vital sign detection as its down-converted baseband signal carrying the vital sign information will not pass through the 2nd stage down conversion.

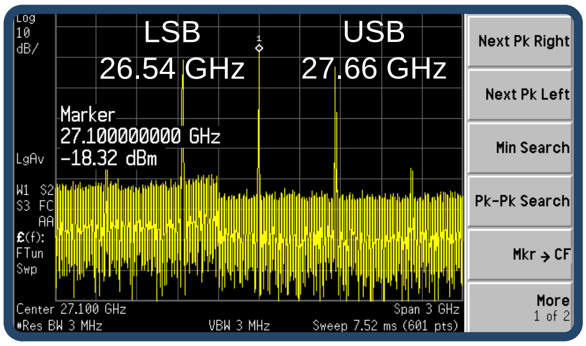

Fig. 2: Output spectrum of the double-sideband system.

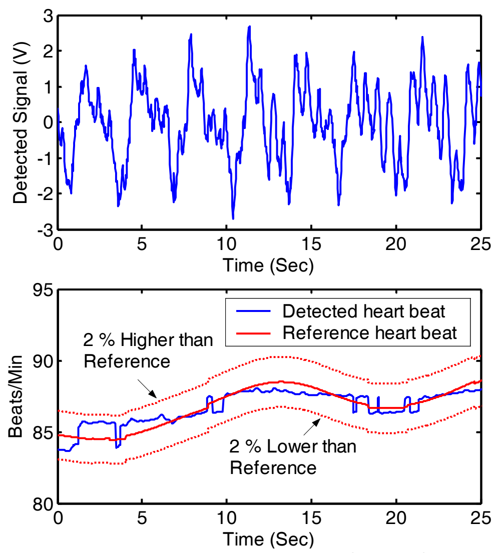

Fig. 3: Baseband time domain waveform of the detected vital sign (top) and calculated heartbeat rate (bottom).

Fig. 3 shows a typical example of the detected baseband time-domain waveform (top) and the calculated heartbeat rate (bottom) within a 25-second window. A reference heartbeat rate measured by a wired finger-tip pulse sensor was also recorded for comparison. The wireless non-contact detection shows very good accuracy, compared to the reference. The baseband data is processed in real time by a laptop computer through a USB data acquisition module. This gives the system a capability to detect the variations in heartbeat and respiration rates from a distance away, which is a unique feature for many applications.

IV. NONLINEAR DOPPLER PHASE MODULATION

The system was used to detect the heartbeat from four sides of a body. Good accuracy was achieved in all four cases. Surprisingly, it was found that the detection from the back had the best accuracy. Further analysis showed that it is due to the harmonic interference from respiration signal [14]. While short wavelength improves the sensitivity, it also results in nonlinear phase modulation when the respiration displacement $x_r(t)$ in (1) becomes relatively large that the small angle linear approximation is no longer valid. As a result, harmonics are generated from cosine transfer function in (1). When detecting heartbeat from the back, the displacement due to respiration is significantly reduced and its harmonics are reduced too. This explains why the detection from the back has the best accuracy. A theoretical model was developed to describe this nonlinear Doppler phase modulation effect. Assuming that the heartbeat and respiration movements are both sinusoidal and have frequencies ω_h and ω_r, amplitudes m_h and m_r, respectively, (1) can be expanded in Fourier series as

$$B(t) = \mathrm{Re}\left(\sum_{k=-\infty}^{\infty} J_k(\frac{4\pi m_r}{\lambda}) e^{jk\omega_r t} \sum_{l=-\infty}^{\infty} J_l(\frac{4\pi m_h}{\lambda}) e^{jl\omega_h t} \cdot e^{\phi} \right) \\ = \sum_{k=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} J_l(\frac{4\pi m_h}{\lambda}) J_k(\frac{4\pi m_r}{\lambda}) \cos(k\omega_r t + l\omega_h t + \phi) \quad (2)$$

where $J_n(x)$ is the nth-order Bessel function of the first kind.

It is shown in (2) that the nonlinear property of cosine transfer function not only causes the undesired effect of harmonics interference, but also causes intermodulation between respiration signal and heartbeat signal. Therefore the detected strength of a desired signal (respiration or heartbeat) is determined by both the signal itself and the other signal (heartbeat or respiration). Fig. 4 shows a spectrum of vital sign detected from the front. The harmonics of respiration movement can be clearly identified. In some cases when the respiration rate increases or its movement becomes larger, the correct reading of the heartbeat rate will be affected.

This model can be used to predict the optimum carrier frequency for vital sign detection. From Section II, the theory indicates that the shorter the wavelength, the better the sensitivity. However, the carrier frequency should not be too high to have significant harmonics from respiration affecting the accurate reading of heartbeat rate. Therefore there exists an optimum carrier frequency.

Based on the simulation result using m_r = 1.2mm and m_h = 0.08mm, the optimum carrier frequency was found to be around 27GHz [15]. This explains why this frequency was experimentally determined in previous experiments even though the carrier frequency of the system could be tuned from 22 to 40GHz.

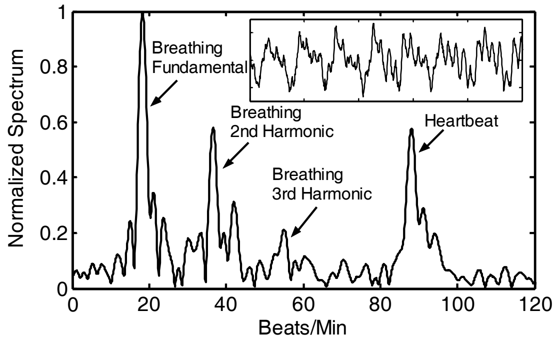

Fig. 4: Spectrum of vital sign signal detected from the front. (Inset: corresponding time-domain waveform.)

Since the system can be used to measure vital signs from four sides of the body and best accuracy is actually achieved when measuring from the back, an experiment was carried out to demonstrate the overnight continuous monitoring of heartbeat and respiration of a sleeping subject (Fig. 5). The system is placed on the ground underneath the bed. During the measurement period, the subject could move the position. The result indicates good agreement between the wireless detected heartbeat rate and the reference using wired finger-tip pulse sensor (Fig. 6) [13].

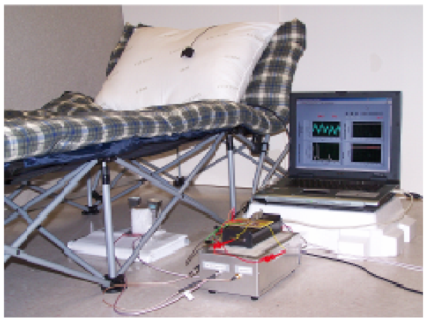

Fig. 5: Setup for overnight monitoring of vital signs.

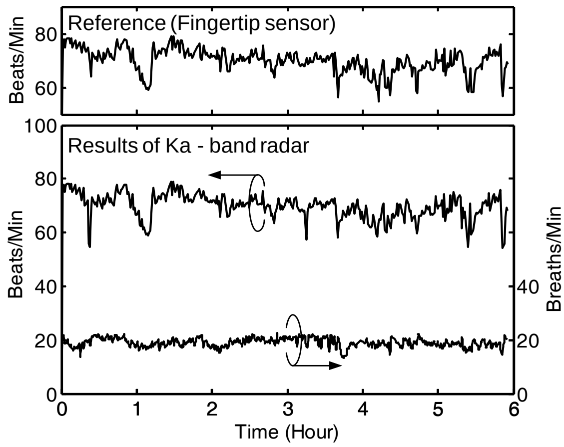

Fig. 6: Overnight measurement result. (a) Reference from finger-tip pulse sensor. (b) Wirelessly detected heartbeat rate and respiration rate.

V. ACCURATE MEASUREMENT OF PERIODIC MOVEMENT

The model of nonlinear Doppler phase modulation not only explained the harmonic interference effect. It also helped the discovery of an important application – accurate measurement of a periodic movement's amplitude without calibration. For a single tone periodic movement, $x(t)=m\sin(\omega t)$, eq. (2) is reduced to

$$B(t) = 2 \cdot \sum_{k=1}^{\infty} J_{2k}(\frac{4\pi m}{\lambda}) \cdot \cos 2k\omega t \cdot \cos\phi - 2 \cdot \sum_{k=0}^{\infty} J_{2k+1}(\frac{4\pi m}{\lambda}) \cdot \sin(2k+1)\omega t \cdot \sin\phi \quad (3)$$

The cosine transfer function transforms the periodic movement into a number of harmonics with Bessel functions as the coefficients. The signal levels of these harmonics are determined by these coefficients. While the signal levels may be changed due to the variation of gain in RF channel, the ratio among them will not change. This ratio is determined by the amplitude of the periodic movement. This implies that the amplitude can be accurately determined by measuring the ratio of harmonics, which will remain the same regardless of the transmitted power, the distance from the subject, and the gain in receiver chain. No calibration is needed. Such a system can be used as a low-cost vibrometer to accurately measure the amplitude and frequency of mechanical vibration [16]. It can also be used to estimate the amplitude of physiological movements. To measure very small vibrations, millimeter-wave or higher frequencies can be used to achieve higher sensitivity.

VI. APPLICATIONS

The major application for this vital sign radar sensor is home healthcare. With low cost integration technologies, the vital sign sensor can be made small and inexpensive for home users. Monitoring sleep apnea of infants or even adults is an example of application. Many adults suffered from sleep apnea without knowing it, until they went through the tests in sleep labs [19]. A simplified portable instrument with non-contact physiological motion sensor would make it much easier to self-diagnose at home and improve the quality of life for many people. In additional to healthcare, the system can also be used for scientific research, security, rescue, and military missions.

VII. CONCLUSION

A wireless non-contact vital sign radar sensor is presented in this paper. The system can detect and display the detected heartbeat and respiration in real time. Operating at around 27GHz, the short wavelength increases the sensitivity of detection. The double-sideband transmission and detection method solves the null-point detection problem and simplifies the system architecture. Long-term measurement results demonstrated the robustness of this system. Nonlinear Doppler phase modulation was discovered and a model was developed to explain the experiment result. A method of accurately measuring periodic movement amplitude is described. In summary, the system and technology can be used for many applications in science, engineering, and medicine.

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