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Noise Considerations for Remote Detection of Life Signs with Microwave Doppler Radar

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Abstract— **This paper describes and quantifies three main sources of baseband noise affecting physiological signals in a direct conversion microwave Doppler radar for life signs detection. They are thermal noise, residual phase noise, and Flicker noise. In order to increase the SNR of physiological signals at baseband, the noise floor, in which the Flicker noise is the most dominant factor, needs to be minimized. This paper shows that with the consideration of the noise factor in our Doppler radar, Flicker noise canceling techniques may drastically reduce the power requirement for heart rate signal detection by as much as a factor of 100.**

I. Introduction

Direct-conversion microwave Doppler radar has been introduced for non-contact cardiopulmonary monitoring [1-2], with potential for health monitoring and personnel detection. Doppler radar systems generally transmit a continuous wave signal while receiving and demodulating the signal's reflection from a target. According to Doppler theory, when the target has time-varying movement with zero net velocity, the reflected signal is phase-modulated in proportion to the position of the target rather than the velocity. A stationary human body presents two independent time varying sources of motion with zero net velocity: the respiration and cardiac activities.

The sensitivity of a microwave direct conversion Doppler radar for vital sign detection depends significantly not only on the strength the respiration and cardiac signals but also the effect of noise at both RF and base-band frequencies. The noise floor contributions include the thermal noise of the receiver, the residual phase noise of the local oscillator, and the Flicker noise generated by the DC offset of the mixer due to the Tx and LO leakage. In order to increase the sensitivity of the vital sign Doppler radar, the Flicker noise needs to be minimized.

This paper presents that even when Flicker noise is not minimized, heart rate signal can still be detected as the target is 17 m away from the radar. This paper also shows that Flicker noise canceling techniques may reduce the power requirement for heart rate signal detection by as much as a factor of 100.

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II. Baseband Noise Floor Characterization

There are three main sources of noise in radar hardware affecting detection of physiological signals: thermal noise, residual noise, and Flicker noise. These three noise sources are taken in account separately at RF frequency and then combined at baseband after a mixer, as shown in Figure 1. The calculation and measurement of these noise sources is presented below.

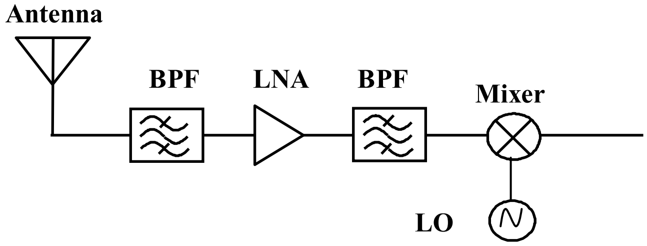

Fig. 1: A direct conversion receiver. The noise contributions are assessed at the mixer output.

A. Thermal noise

Thermal noise is characterized to be White Gaussian noise which has zero mean and does not vary with frequency. The thermal noise power can be expressed by:

$$P_{N,\ thermal} = 4\ kTB\ , \tag{1}$$

where k is Boltzman's constant, T is the room temperature, and B is the bandwidth of the receiver. The noise power of thermal noise at baseband, after the mixer, is given by:

$$N_{B,\ thermal} = 8\ G_{CL}\, G_{RX}\, (NF)\ (kTB)\ , \tag{2}$$

where G_{CL} is the conversion loss of the mixer (dB), G_{RX} is the gain of the receiver (dB), and NF is the noise figure of the receiver (dB).

Giving G_{CL} = 5 dB, NF = 5 dB, and B = 30 Hz as used in our Doppler-radar, the thermal noise was calculated to be – 146 dBm.

B. Residual phase noise

Residual phase noise is described by the range correlation theory, which states that when the transmitted and the local oscillator signals come from the same source and the received signal is a time-delay version of the transmitted signal, and that the phase noise on the received signal is correlated with that of the local oscillator signal. As these two signals are mixed at the mixer, the correlated portion of the phase noise is cancelled, leaving only the residual phase noise. The amount of correlation is determined by the time delay between the local oscillator and the received signals, which is equivalent to the target range in the vital signs detection application of our Doppler-radar [3-4].

The noise power of residual phase noise can be expressed by Equation 3:

$$S_{\Delta\Phi}(f_o) = S_{\Phi}(f_o)[4\sin^2(2\Pi\frac{Rf_o}{c}), \qquad (3)$$

where $S_{\Delta\Phi}(f_o)$ is the baseband phase noise spectral density (dBc/Hz), $S_{\Phi}(f_o)$ is the RF phase noise spectral density (dBc/Hz), R is the target range (m), f_o is the offset frequency (Hz), and c is the speed of light ($3x10^8$ m/s).

Giving the phase noise of -143 dBc/ Hz at 1 Hz offset frequency of the signal generator (HP E4433B) used in our Doppler radar, the baseband phase noise was calculated for target range varying from 1 m to 20 m.

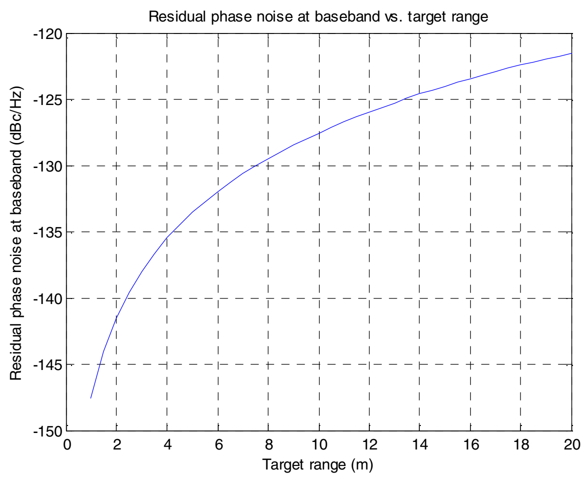

Fig. 2: Residual phase noise for target ranges from 1m to 20 m away from the radar.

C. *Flicker noise*

In passive resistive mixers, Flicker noise is generated by a DC offset [5-7]. This DC offset is the result of LO self mixing components such as the Tx leakage from the transmitting to the receiving chains of a transceiver, and of the reflected LO leakage by the RF matching circuit.

In a transceiver system, the Tx leakage is due to a poor isolation between Tx and Rx chains. This Tx leakage, along with the received RF signal, is delivered to the RF port and mixed with LO signal at the mixer. The self mixing component, Tx leakage, produces a DC offset at the mixer output. In addition, the LO leakage of the mixer RF port is due to a poor isolation between the LO and RF ports in a mixer. This leakage is reflected by the RF matching circuit; hence, it also produces the self mixing component.

Figure 3 shows our measurement setup to measure the DC offset within a mixer. The RF port is 50-ohm terminated so that only the LO signal can contribute to the operation of the mixer. Also LO port is supplied by 7 dBm to achieve the lowest conversion loss of the mixer. The DC offset due to LO leakage is shown in Figure 4. The corresponding Flicker noise is shown in Figure 5.

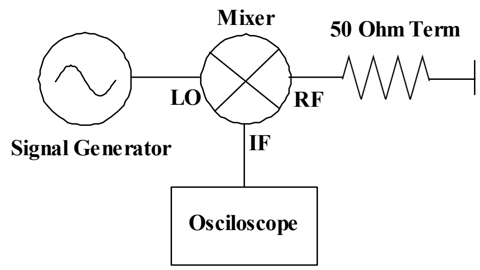

Fig. 3: Measurement setup of DC offset due to LO leakage.

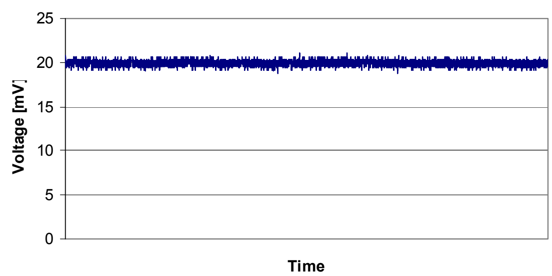

Fig. 4: Measured DC offset at the mixer output.

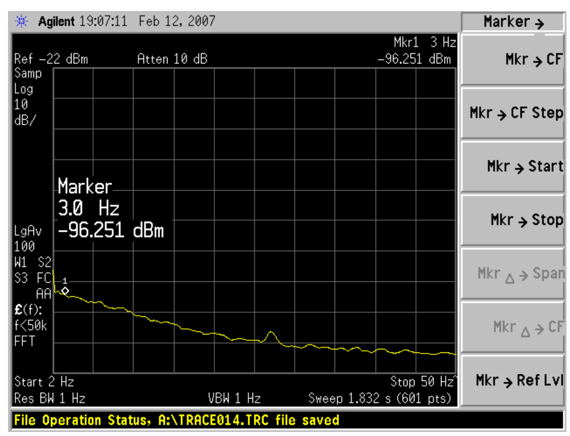

Fig. 5: Measured Flicker noise at the mixer output. At 1 Hz offset, Flicker noise was measured to be approximately -90 dBm at 1 Hz.

D. *Total noise floor at baseband*

Figure 6 summarizes the relationship between signals and noise in a direct conversion microwave Doppler radar at RF and baseband frequencies. Since physiological signals (received signals) including respiratory and cardiac signals are small, they are very sensitive to the noise. Therefore, it is important to understand the sources and strength of noise in the system.

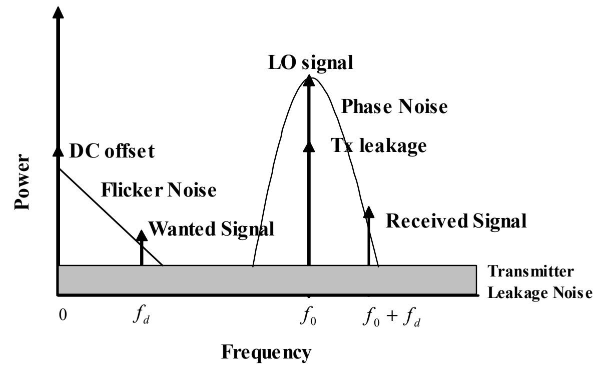

Fig. 6: Signal vs. Noise in a direct conversion Doppler radar for vital signs detection application

The thermal noise was calculated to be -146 dBm. The Flicker noise was measured to be approximately -90 dBm at 1Hz. The residual phase noise was calculated to vary from -147 dBm to -122 dBm when the human subject is 1m to 20 m away from the antenna, respectively.

Based on our calculation and measurement, the total noise floor at baseband, in the system with the very stable local oscillator, is dominated by the Flicker noise. Flicker noise in passive unbiased mixers is generated by the DC offset in the mixer due to self mixing components described above.

III. NOISE CONSIDERATIONS IN OUR MICROWAVE DOPPLER RADAR

Figure 7 shows the setup of calculating the power of the signal, which is reflected from the chest of the human subject back to the antenna, using the radar equation [8].

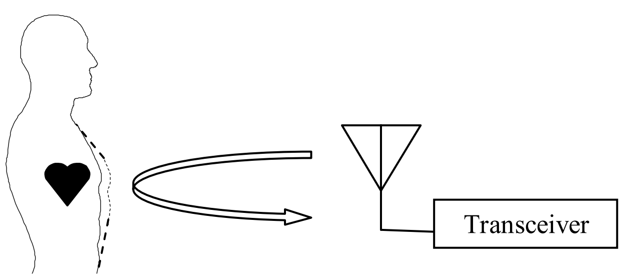

Fig. 7: Direct conversion microwave Doppler radar measurement setup

In our Doppler radar system, the transmitted power of the antenna is 0 dBm, the antenna gain is 7 dBi, the wavelength is 12.5 cm corresponding to a frequency of 2.4 GHz, and the radar cross section is 0.39 m^2.

A. *Without Flicker noise canceling*

Figure 8 shows the received signal power of a subject who is 1m to 20 m away from the antenna. The noise floor, which is dominated by the Flicker noise, was approximated to be -90 dBm.

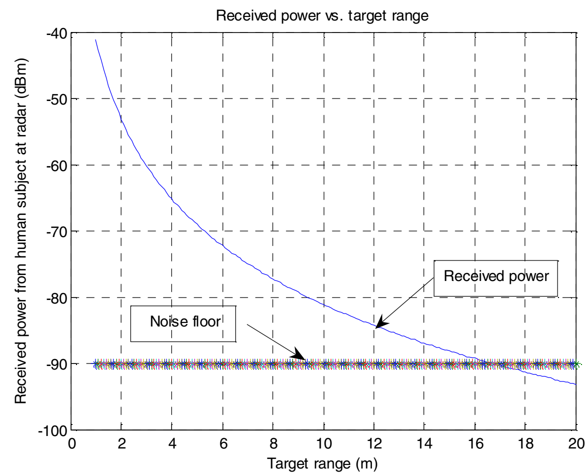

Fig. 8: Received signal power vs. noise floor for target ranges from 1m to 20 m away from the radar

As the subject is farther away from the antenna, the received signal power decreases due to the space loss between the subject and the antenna. Hence, the SNR decreases. As the subject is about 17 m away from the antenna, the noise floor is as strong as the received signal; consequently, the heart signal will not be detected beyond this distance.

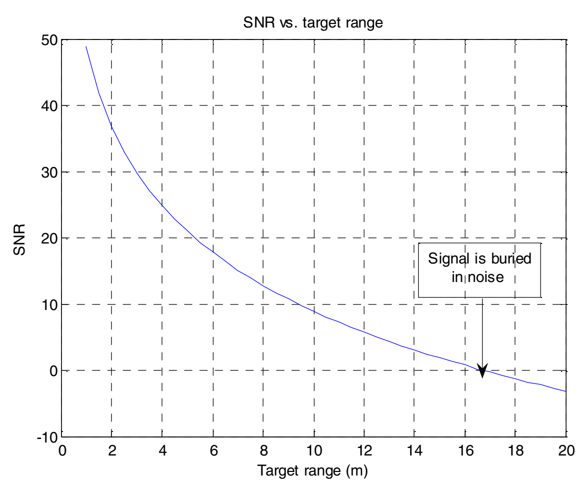

Fig. 9: SNR at various target ranges. Heart signal of a human subject can be detected as the subject is up to 17 m away from the radar system

B. *With Flicker noise canceling*

In order to increase the sensitivity of our Doppler-radar for vital signs detection application, we have developed two different techniques to reduce Flicker noise for transceiver and receiver systems due to self mixing components.

In a transceiver system, the Tx leakage is due to a poor isolation between Tx and Rx [9]. Since both Tx leakage and LO leakage are present at the same LO frequency but with different phases, a phase shifter, which is inserted between the circulator and the mixer, was used to control the phase difference between the two leakage signals. The DC offset is minimum when the Tx leakage signal and LO leakage signal reflected by RF matching circuit are 180 degree out of phase and maximum when the two signals are in phase. This technique reduces the offset voltage by 60 mV and Flicker noise by 21.7 dB.

In a receiver system, the self mixing component caused by the reflected LO leakage induces the DC component. In order to eliminate this DC offset, a bypass circuit consisting of a phase shifter and an attenuator is connected between the LO and RF ports of the mixer. The attenuator maintains the same magnitude as the LO leakage signal. The phase shifter generates a signal that is 90 degree out of phase compared to the LO leakage signal. As a result, the LO leakage signal is cancelled out from the new signal of same magnitude and 90 degree phase difference. By using this canceling method, the offset voltage decreases by 20 mV to almost 0V and Flicker noise is reduced by 19.3 dB.

As an approximation if Flicker noise is reduced by 20dB, the SNR increases by 20 dB. Therefore, the minimum power required for adequate hear signal detection, or alternatively target range, is expected to increase.

To confirm our expectation, first, the residual phase noise was simulated for farther target range, as shown in Figure 10, to make sure that the Flicker noise is still the major noise factor in the noise floor. As the residual phase noise only increases by 6 dB as the subject is 20 m to 40 m away from the radar, we confirm that the Flicker noise is dominant as the target range increases.

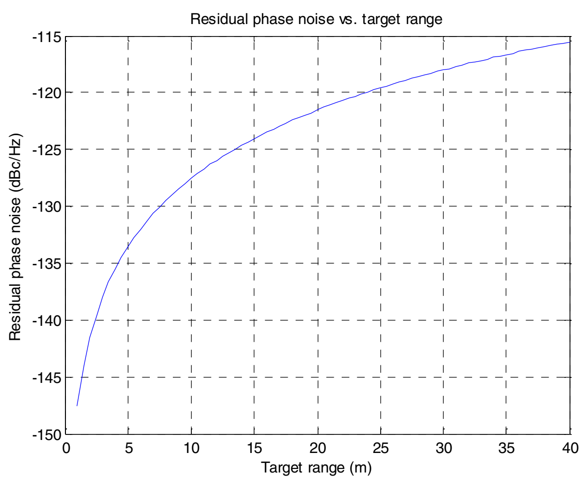

Fig. 10: Residual phase noise for target ranges from 1m to 20 m away from the radar.

Since the noise floor is dominated by the Flicker noise, a 20 dB reduction in Flicker noise is equivalent to a 20 dB increase in the received signal power.

IV. CONCLUSION

In this paper, three sources of noise in a direct conversion microwave Doppler radar for vital signs detection application are characterized. The Flicker noise caused by a DC offset due to both Tx and LO leakage is shown to be the dominant factor in the receiver system. This paper shows that Flicker noise canceling techniques may reduce the power requirement for heart rate signal detection by as much as a factor of 100. This study is important in understanding the target range for adequate heart rate detection in order to design a sensitive and accurate Doppler radar.

ACKNOWLEDGMENT

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