Doppler Radar Architectures and Signal Processing for Heart Rate Extraction

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Abstract – **In this paper heartbeat interval extraction methods using Doppler radar are reviewed. While single channel CW radar offers simple architecture and signal processing, this method is very sensitive to subject position. Quadrature radio architecture is used to overcome this limitation. The use of linear and non-linear demodulation methods was explored for heartbeat interval extraction, and it was demonstrated that heart rate variability analysis is feasible using quadrature Doppler radar.**

Keywords – **Doppler radar, physiological monitoring, heartbeat interval, heart rate variability.**

I. INTRODUCTION

Practical non-contact detection and monitoring of human cardiopulmonary activity could be a powerful tool for health care, emergency, military, and security applications. It would also be of value in emergency scenarios where first responders can benefit from any additional data for triage decisions, and in security screening situations where subjects must be detected and/or monitored in a manner that cannot be easily undermined. Doppler radar remote sensing of heart and respiration activity has shown promise to this end, with proof of concept demonstrated for various applications [1-3]. Through its non-invasive nature, this approach is well suited to applications where it is important to minimize disruption of the subject's activity, particularly where prolonged monitoring is needed. A robust Doppler radar system would be well suited to collection of long-term heart beat interval data for heart rate variability (HRV) diagnosis and prognosis [4]. Additional benefits of microwave Doppler radar include the versatile ability to function at a distance through clothing, walls, or debris. This allows the system to be applied both in medical health care scenarios, where some degree of subject cooperation can be assumed, and in emergency response or security applications, where subjects do not or cannot cooperate.

Alternative techniques for long-term medical monitoring typically require direct contact (ECG and Holter monitors, piezoelectric sensors), while minimally invasive techniques tend to require very accurate control or placement (laser Doppler vibrometer), which might not always be possible or desirable.

In this paper we present an overview of Doppler radar architectures used for heart rate extraction, including single channel and quadrature receivers. We discuss linear and non-linear demodulation methods for quadrature outputs, and demonstrate with experimental data that both methods yield high accuracy in 2.4 GHz systems. Finally we demonstrate feasibility of using Doppler radar for heart rate variability (HRV) analysis.

II. DOPPLER RADAR SYSTEM OVERVIEW

Doppler radar physiological monitoring has been known since 1970's. The use of Doppler radar was demonstrated for detection of respiratory rate in 1975 [5], and heart rate in 1979 [6], using commercially available waveguide X-band Doppler transceivers. A number of similar custom transceivers were also developed, including a life detection system operating at a distance of up to thirty meters [2], and a superficial temporal artery monitor for military pilots [7]. The use of CW, FM, and UWB radar has been explored for physiological sensing [8-9]. Doppler radar transceiver implementations range from using laboratory equipment, to integration on a printed circuit board [10], and on a single silicon chip [11]. Single channel and quadrature radar has been used, and linear and non-linear demodulation methods have been proposed [12-14]. Recent advances include separation of multiple subjects [15], and cancellation of unwanted motion [13, 16-17].

By the Doppler effect, an RF wave reflected at a moving surface undergoes a frequency shift proportional to the surface velocity. If the surface is moving periodically, such as the chest of person breathing, this can be characterized as a phase shift proportional to the surface displacement. If the movement is small compared to the wavelength, a circuit that couples both the transmitted and reflected waves to a mixer can produce an output signal with a low-frequency component that is directly proportional to the movement. This is the case when measuring chest surface motion related to respiration and heart activity. Figure 1 illustrates this concept. Internal body reflections are greatly attenuated (more severely with increasing frequency) and will not be considered here. We assume that a continuous wave (CW) radar system transmits a single tone signal at frequency *f*. This signal is reflected from a target at a nominal distance d_o, with a time-varying

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displacement given by *x(t)*. The reflected signal is amplitude, frequency and phase modulated. Assuming small periodic displacement of the target, we will further consider phase modulation only. At the receiver, if we neglect the residual phase noise, the signal is given by *R(t)* in Equation 1, where λ is the wavelength.

$$R(t) \approx \cos\left[2\pi f t - \frac{4\pi d_o}{\lambda} - \frac{4\pi x(t)}{\lambda}\right] \qquad (1)$$

This received signal is related to the transmitted signal with a time delay determined by the nominal distance of the target, and with its phase modulated by the periodic motion of the target. The information about the periodic target motion can be extracted if this signal is multiplied by a local oscillator (LO) signal that is derived from the transmitted signal (Fig. 1). When the received and LO signals are mixed and then low-pass filtered, the resulting baseband signal contains the constant phase shift dependent on the distance to the target, d_o, and the periodic phase shift resulting from chest motion. If received signal and the LO are in quadrature, and for displacement small compared to the wavelength, the baseband output is approximately proportional to the time-varying periodic chest displacement, $x(t)$. The amplitude of the chest motion due to respiration is expected to be on the order of 10 mm, and due to heart activity on the order of 0.1 mm [18-19]. Even though exact shape of the heart signal depends on the location of the observed area on the thorax, overall characteristics and frequency content are similar throughout the chest. Since microwave Doppler radar is expected to illuminate whole chest at once, the detected motion will be an average of local displacements associated with particular chest areas.

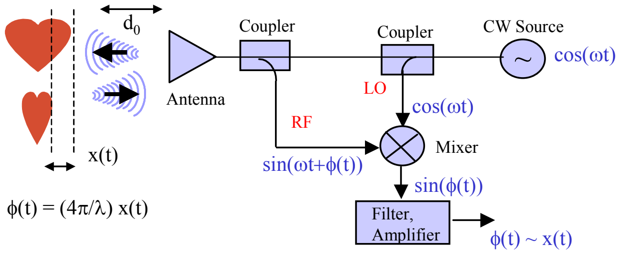
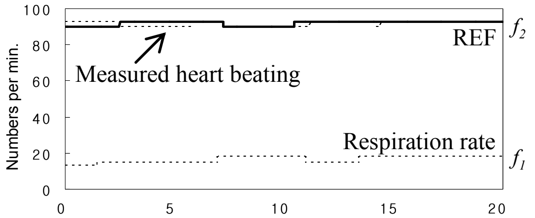
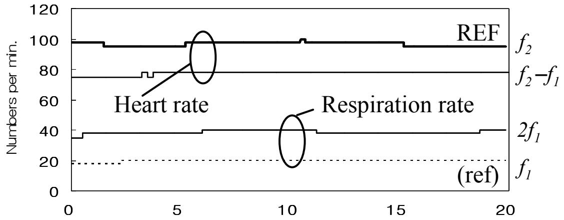


Figure 1. Vital signs remote monitoring Doppler radar system concept. Physiological signals are measured from a distance, d_0, by monitoring a body-scattered radio signal for a periodic Doppler phase shift φ(t) that is proportional to chest displacement, x(t).

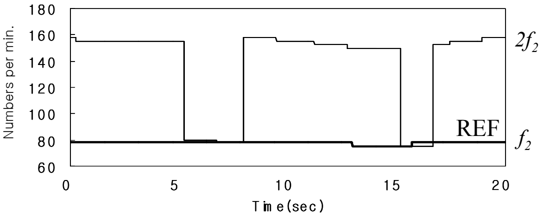
Doppler radar shown in Fig. 1 is a single channel, direct conversion, CW radar. Major limitations of the single channel configuration is detection sensitivity to target position due to a periodic phase relationship between the received signal and local oscillator (Eq. 1), resulting in "optimum" and "null" extreme target positions [20]. Fig. 2 shows experimental results for heart rate extracted from a single channel output in optimum and null positions. At the optimum point (a) the Doppler measured heart rate corresponds closely to the reference. At the null point during continuous breathing (b), the Doppler measured heart rate and reference differ by the respiration reference frequency, while with breath-holding (c) it jumps between either double (case II) or equal to the actual frequency (case III).



(a) Optimum case



(b) Null case I



(c) Null case II&III

Fig 2. Measurement history data for both respiration and heart rate with single channel receiver, at either optimum (a) or null points (b), and (c). At the optimum point (a) the Doppler measured heart rate corresponds closely to the reference for all. At the null point during continuous breathing (b), the Doppler measured heart rate and reference differ by the respiration reference frequency, while with breath-holding (c) it jumps between either double (case II) or equal to the actual frequency (case III). From [20].

III. QUADRATURE DOPPLER RADAR SYSTEMS

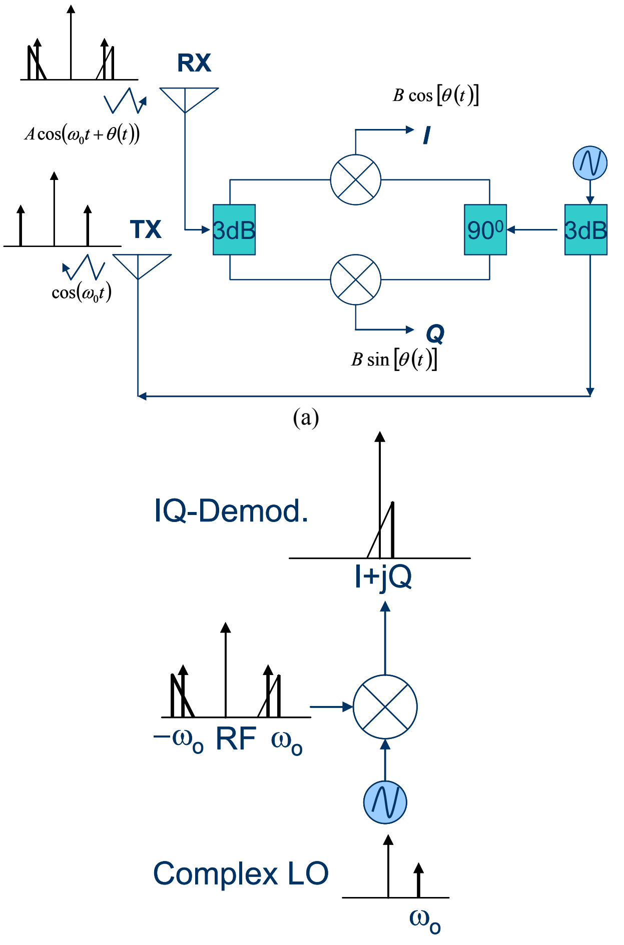
A quadrature Doppler radar receiver with channel selection has been proposed to overcome detection sensitivity to target position [11]. This method selects the better of quadrature (I and Q) channel outputs, and is thus limited to the accuracy of a single channel. A frequency tuning technique with double-sideband transmission has also been proposed for Ka-band radar [21], however this technique requires more complex hardware with a tunable intermediate frequency. Quadrature Doppler radar system block diagram is shown in Fig. 3 (a). A quadrature receiver includes two down-conversion mixers; one mixer is driven with the LO with no additional phase shift ("in-phase" or "I" channel), and the other with the 90 degrees phase shift LO ("quadrature" or "Q" channel). Real signals in time domain have positive and negative frequency components. Assuming that the transmit signal is of the form:

$$\cos(\omega_0 t) \tag{2}$$

it contains two symmetric components at ω_0 and $-\omega_0$ as illustrated in Fig. 3 (b). If the real RF signal is converted to baseband using a single channel homodyne receiver (Fig. 1), this results in the folding of the spectrum, which is manifested as detection sensitivity to target position. However, a quadrature receiver can be used for single side-band detection that results in full phase recovery. In this case, a real RF signal is effectively mixed with the complex LO signal (Fig. 3 (b)), resulting in full spectrum recovery. Figure 4 (a) shows an example of the received I and Q signals obtained using a 2.4 GHz system. In this case I signal is closer to the optimum phase relationship resulting in a significantly larger amplitude than the Q signal.

Once the I and Q outputs are available, channel selection can be used to simply choose the output closer to the optimum point. In this case, the chosen output is approximately proportional to the physiological displacement. However, in most cases neither output will be at the optimum point, resulting in the loss of information. I and Q outputs can be further combined for more accurate phase demodulation and physiological signal recovery. Two demodulation methods of quadrature outputs have been proposed: linear (complex) and non-linear (arctangent) [12-13]. Linear demodulation essentially rotates the data to the optimum position, and at lower frequencies, and for small displacements this technique yields accurate results. Figure 4 (b) shows the heart rate extracted from linearly demodulated quadrature signals, compared to the heart rate extracted from the finger pressure pulse reference, with the agreement better than 1 beat per minute for most of the interval.

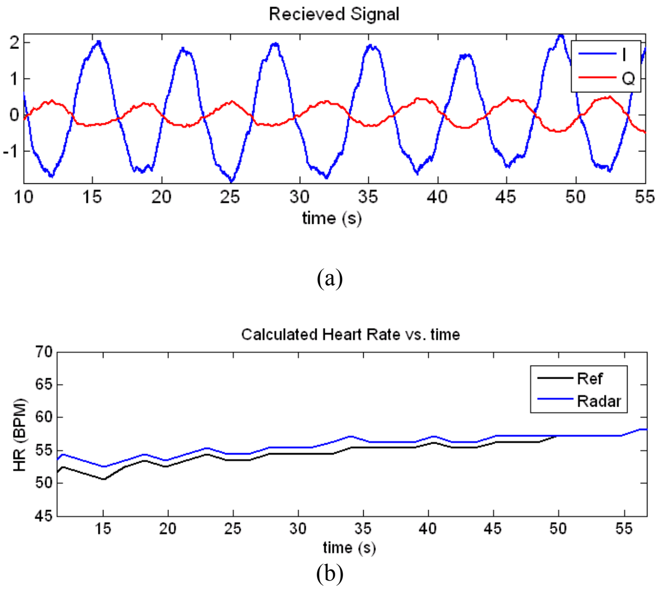
In [12], we proposed to combine quadrature outputs using arctangent demodulation with DC offset compensation. The arctangent demodulation overcomes the sensitivity to the



(a)

(b)

Figure 3. Quadrature Doppler radar system block diagram (a), and signal spectrum (b). In this architecture, real transmit signal modulated by physiological motion is mixed with the complex LO signal for full spectrum recovery.



(a)

(b)

Figure 4. Quadrature Doppler radar outputs (a), and calculated heart rate compared to that obtained from a finger pulse sensors, as a function of time (b). In this case I channel is closer to the optimum phase relationship resulting in significantly larger amplitude that the Q signal (a). Linear demodulation was used to recover phase information that was used to obtain heart rate (b).

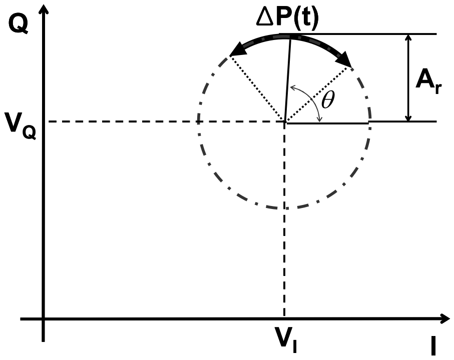


Figure 5. Complex constellation of quadrature outputs due to the phase change ΔP(t) resulting from the target's periodic motion, The constant phase shift θ is related to the distance to subject, the phase change at the surface of a target, and the phase delay between the mixer and antenna.

target position, while also extending the reliable phase deviation detection range that is limited by small angle approximation in single channel receivers. The DC offset compensation ensures that unwanted DC components produced by receiver imperfections and clutter reflections are removed, while DC information required for accurate arctangent demodulation is preserved. Arctangent demodulation results in high accuracy of detected heart interval for larger displacements.

Assuming that the target's motion variation is given by $\Delta x(t)$, the quadrature baseband output assuming balanced channels can be expressed as:

$$B(t) = A_r \exp\left[\theta + 4\pi\Delta x(t)/\lambda\right], \tag{3}$$

where θ is the constant phase shift related to the phase change at the surface of a target and the phase delay between the mixer and antenna. Applying arctangent demodulation [12] to the ratio of the quadrature outputs, phase information linearly proportional to target's motion can be extracted as:

$$\phi(t) = \arctan\left(\frac{B_Q(t)}{B_I(t)}\right) = \arctan\left(\frac{A_r \sin(\theta + p(t))}{A_r \cos(\theta + p(t))}\right) = \theta + p(t), \tag{4}$$

where $p(t) = 4\pi\Delta x(t)/\lambda$ is the superposition of the phase information due to the target's motion. However, dc offsets in quadrature channels act as a linear transform on the I and Q components, and thus arctangent demodulation output becomes:

$$\phi'(t) = \arctan\left(\frac{B_Q(t)}{B_I(t)}\right) = \arctan\left(\frac{V_Q + A_r \sin(\theta + 4\pi\Delta x(t)/\lambda)}{V_I + A_r \cos(\theta + 4\pi\Delta x(t)/\lambda)}\right), \tag{5}$$

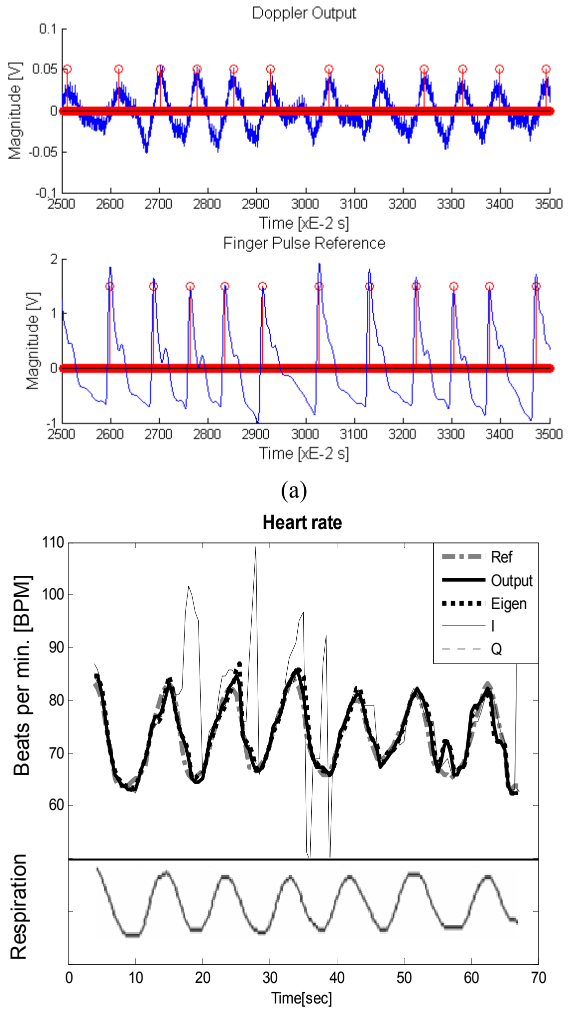
where V_I and V_Q refer to the dc offsets of each channel resulting from the finite port to port isolation of the transceiver as well as from clutter reflections [12]. The dc signal contains this dc offset as well as the dc information associated with target's position required for accurate demodulation. As shown in Fig. 5, when there is only one source of periodic motion, the complex plot of quadrature outputs forms a fraction of a circle that has a radius of signal amplitude, A_r, with its center offset by the dc offset of each channel. This property allows proper elimination of dc offset and preservation of all the desired information including ac and dc signals associated with target's periodic motion, with the latter being the magnitude of the radius projected on each axis when the center of the arc formed by target motion is tracked back to the origin of the complex plot. We have proposed this "center tracking" technique in [22].

IV. HEART RATE VARIABILITY

The rhythm of the heart has not only encouraged enduring fascination for cardiologists, but has also inspired works of art and has been used to define the tempo of music [23]. Although music tempo may imply steady periodicity, a healthy heart is actually a "fractal heart" [24], with a high degree of complex variability in beat-to-beat intervals. Heart Rate Variability (HRV) describes the time variation in beat-to-beat interval (RR interval), and reflects the manner in which the cardiovascular regulatory system responds to demands, stress, and illness. Medical research has associated lowered HRV with aging, decreased autonomic activity, sleep apnea, diabetic neuropathy, and increased risk of sudden cardiac death after acute myocardial infarction (MI) [25-26]. Research in psychology indicates that depression, panic disorders, and anxiety have a negative impact on autonomic function. Autonomic imbalance caused by significant mental and emotional stress increases risk of acute MI followed by sudden cardiac death [27]. Multiple pharmacological studies suggest that HRV is a useful indicator to quantitatively measure physiological changes during treatment [28]. As the number of clinical studies involving HRV in various health aspects and conditions grows, HRV stands out as one of the most promising methods for the future of general health evaluation. HRV is traditionally acquired through electrocardiogram (ECG) which requires that patients be tethered to electrodes and sensing devices, which limits its application. While ECG signals are usually sampled at 1 kHz to provide 1-ms resolution, it has also been demonstrated that HRV parameters can be extracted accurately with a heart rate interval accuracy of 10 ms [25, 29].

Since Doppler radar heart signals provide a measure of mechanical motion of the chest due to heart motion, these signals do not exhibit peaks as sharp as ECG signals. However, our recent efforts to verify the feasibility and potential impact of Doppler radar on HRV measurements have demonstrated that heart signals can be extracted with accuracy on the order of 10 ms for still subjects in a seated position [30-31]. The system operated at 2.4 GHz, with 0-dBm power level at the antenna connector, using a patch antenna. Coaxial microwave components and laboratory signal source were used for these experiments. The Doppler radar includes 2.4-GHz patch antenna (Antenna Specialists ASPPT2988), an external signal source (Agilent 83640B), two zero-degree power splitter (Mini-Circuits ZFC-2-2500), one ninety-degree power splitter (Narda 4033C), and two mixers (Mini-Circuits ZFM-4212). A Narda 4923 circulator was used to isolate transmit and receive signals, with a measured RF to LO isolation of -22 dB. The baseband output signals are amplified and filtered with low-noise amplifiers (Stanford Research Systems SR560) and then digitized with the onboard ADC of a data acquisition card (National Instruments NI-DAQ PCI-6259). The experimental set-up was run using Matlab for data acquisition and signal processing in real time. The subjects were seated at a 1 meter distance from an antenna facing the chest, and finger pressure pulse was used as a reference for heart rate extraction. Fig. 6 (a) shows sample data from the Doppler radar output after demodulation and filtering (top), and finger pulse reference output (bottom), clearly indicating that all peaks have been successfully detected with Doppler radar [30]. Figure 6 (b) shows the heart rate extracted from Doppler radar from single channel (I and

Q), using arctangent demodulation (Output), and using linear demodulation (Eigen), and the rate from the finger pulse reference (Ref), and Doppler radar extracted respiration signal (bottom). After the demodulation, the autocorrelation with statistical analysis was used to extract the heart rate information for both radar and reference signals [11, 31]. This method was demonstrated to yield the highest accuracy for Doppler radar data, due to typically low signal-to-noise ratio [32]. As shown in Fig. 6 (b), both linear and non-linear demodulation result in high heart rate accuracy, while non-linear data follows reference more closely. It is also evident that single channel data (I channel in particular) exhibits high errors. Note that the cyclical heart rate variation in time, due to RSA, corresponds to the respiration signal obtained using arctangent demodulation. In this case standard deviation of the Doppler intervals was within 10 ms of the reference intervals.



(a)

(b)

Fig. 6. Doppler radar output signal (top) and finger pulse reference (bottom) obtained using a quadrature Doppler radar (a) (from [30]), and extracted heart rate versus time compared to respiratory signal (b).

V. CONCLUSION

Doppler radar single channel and quadrature receivers have been used for heart rate extraction. Linear and non-linear quadrature demodulation methods have been demonstrated suitable for heart rate extraction with the accuracy on the order of 1 beat per minute. Accurate heartbeat interval extraction is required for HRV analysis. We have demonstrated that it is possible to extract heartbeat intervals using quadrature Doppler radar with sufficient accuracy for HRV analysis.

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