A Coherent Low IF Receiver Architecture for Doppler Radar Motion Detector Used in Life Signs Monitoring

Isar Mostafanezhad, Olga Boric-Lubecke, and Victor Lubecke

Department of Electrical Engineering, University of Hawaii at Manoa, Honolulu, HI, 96822 USA

Abstract — **Continuous Wave Doppler radar has been used in human life signs monitoring from a distance. Such systems are basically motion detectors that rely on phase modulation of the radar's reflected signal due to physiological motion which is of a low frequency nature and has significant signal content close to DC. Homodyne receiver architecture is simple, but has its own limitations including DC offset and contribution of low frequency noise from mixers and baseband amplifiers. A coherent low IF architecture has been proposed for this case to improve the performance. It will be shown that SNR is improved using a simple coherent low IF configuration. This is the first reported coherent low IF transceiver architecture for Doppler radar motion sensing.**

Index Terms — **Doppler radar, Coherent, Low IF, Biomedical monitoring, biomedical signal detection.**

I. INTRODUCTION

Doppler radar has recently been extensively used in non-contact cardiopulmonary monitoring [1]-[3]. A Continuous Wave signal in the microwave range is transmitted toward a human target. Physical motion caused by respiration and heart beat of the human subject phase modulates the transmitted signal and reflects it back to the transmit antenna, where it will be received and phase demodulated to yield heart and respiration rate of the subject. Physiological motion is known to be small [3], thus, the system has to be very sensitive to phase changes, which are caused by path length variations. A system constraint is the receiver's noise which ultimately limits the performance measures like received signal power and range. Physiological motion consisting of heart and respiration movements has a low frequency foot print typically in the range of 0.1-4Hz [1]-[3],[6].

Performance limits in Doppler radar sensing depend on phase noise and amplitude modulation noise sidebands of the local oscillator signal in the RF band, and mixer conversion loss and Flicker noise at base band[7]. In addition, transmit to receive isolation, as well as mixer LO and RF port isolation, limit the dynamic range of the system. In direct conversion systems, the LO signal can leak to the RF port resulting in self-mixing. This generates second harmonic, components and dc offset. While harmonics can be rejected by filtering, the dc offset will combine with the dc signal component [1] and may result in signal errors. Also the dc offset induces mixer Flicker noise even in passive mixers [8][9], and thus degrades the sensitivity of the system. Even though passive mixers do not use any dc bias, there is a significant dc offset at the mixer output due to finite port to port isolation and self mixing. There is also transmit-to-receive signal leakage which similarly reduces receiver dynamic range, in addition to the LO leakage[10].

A low intermediate frequency (IF) receiver architecture is commonly used in wireless communications [5] to avoid dc offset issues inherent to the direct conversion receiver. It is a type of heterodyne architecture with an IF low enough to be digitized. While this is a well-known receiver architecture, there are some specific considerations to be taken into account for Doppler radar heart sensing. The main advantage of the low IF receiver is that it avoids the region of highest Flicker noise in the mixer output. As shown in [7] , mixer Flicker noise is about 50 dB lower at an offset frequency of 100 Hz as compared to near-dc.

Direct conversion receivers need two separate RF receive paths to account for I and Q channels and since baseband outputs of the IQ demodulator have large DC components [5], they require proper DC cancellation methods as simple AC coupling circuits will not be sufficient[1].

With all the advantages low IF promises, there is still one unsolved problem which exists due to lack of phase correlation of transmit and receive Local Oscillators. Range correlation of transmit and receive signals plays an important role in a homodyne Doppler radar[4]. This problem can be solved by proposing a coherent Low-IF architecture. In this paper the coherent low IF method is proposed to down-convert the RF signal to a frequency of about 1KHz and not directly to DC, thus, it can avoid amplifier and mixer's 1/f noise. It will be shown that in addition to a simpler receiver system, particularly suitable for multiple receiver systems, a better noise performance is achieved. This is the first reported coherent low IF transceiver architecture for Doppler radar motion sensing.

II. COHERENT DOWN-CONVERSION TO LOW-IF

Fig 1 shows a simple diagram of the low IF receiver system and its coherent counterpart. It is assumed that the input signal from the antenna has content around a carrier frequency of ω_{rf} , so the received RF signal will be:

$$r(t) = A(t)\cos(\omega_{rf} t + \varphi(t)) \qquad (1)$$

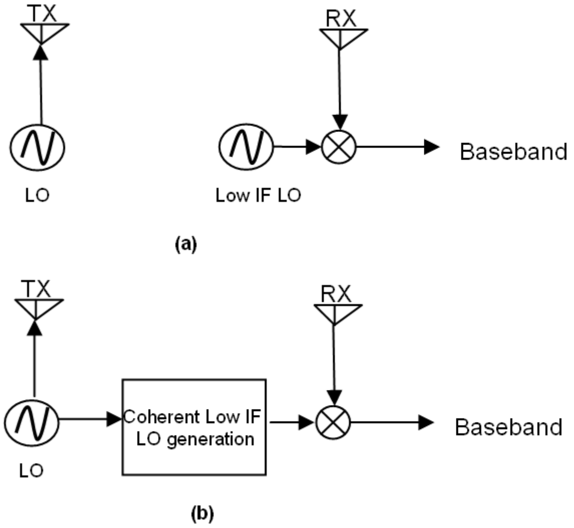

Fig 1 Simple diagram of a Low IF receiver (a) and a Coherent Low IF receiver (b)

Where A and φ generally determine the baseband content of the signal. This signal is then mixed with a local oscillator sine wave at a frequency of ω_{lo}, where:

$$\omega_{lo} = \omega_{rf} - \omega_{lif} \tag{2}$$

Resulting in:

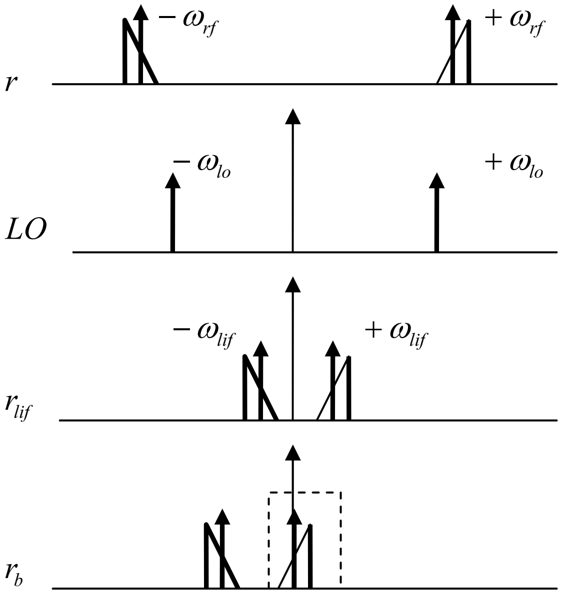

Fig 2 Signal spectrum in Low IF receiver

$$\begin{aligned} r_{lif}(t) &= r(t)\cos(\omega_{lo}t) \\ &= \frac{1}{2}A(t)\cos(\omega_{lif}t + \varphi(t)) + \frac{1}{2}A(t)\cos((2\omega_{rf} - \omega_{lif})t + \varphi(t)) \end{aligned} \tag{3}$$

The second term in (3) is a high frequency out of band RF signal in which we are not interested and will be rejected by the low pass filter at the output of the mixer. From this stage on, since ω_{lif} is a rather small frequency, the IF signal is digitized and DSP is applied to recover A and φ:

$$\begin{aligned} r_b(t) &= \frac{1}{2}A(t)\cos(\omega_{lif}t + \varphi(t))\exp(-j\omega_{lif}t) \\ &= \frac{1}{8}A(t)\exp(j\varphi(t)) + \frac{1}{8}A(t)\exp(-2j\omega_{lif}t - j\varphi(t)) \end{aligned} \tag{4}$$

The first term is the desired complex down-converted signal, while the second term is easily removed using a real filter. The process and the effect on the signal spectrum is depicted in Fig 2

III. MEASUREMENT SETUP

The measurement set-up is shown in Fig 3. A two antenna bi-static configuration has been used. As it can be seen, both the coherent low IF and direct conversion I and Q paths are implemented concurrently for comparison. Off the shelf coaxial components have been used to construct the radar. An IQ up-converter is used to generate the coherent low IF LO at 2.4GHz+667Hz. It is basically a single side band (SSB) modulator[11] which up-converts the low IF carrier. An HP 83640B signal generator operating at 2.4 GHz is used as the main signal source. It is important to keep in mind that low IF LO is also derived from the same 2.4 GHz source. The reason is the range correlation benefits of down-converting the received signal using the same transmit signal, which are discussed in [4]. A simple RCCR circuit is used to generate the 90 degree phase shift needed for suppressing the 2.4GHz-667Hz component.

The splitters are RPS-2-30 and ZFM4212 mixers from Mini-circuits are used for the down and up conversion. The transmit CW microwave at the transmitter antenna input was measured to be -1.7dBm. A pair of ASPPT2988 antennas were used which have 8 dBi gain and 60 degrees beam-width. Finally, the I and Q mixers' outputs are low pass filtered and amplified by passing through a SR560 LNA (cutoff 30Hz, 46 dB gain). The coherent low IF mixer's output is amplified with the same gain but a bandwidth of 1KHz, to allow passing of the 667Hz low IF signal. Finally all baseband signals are then recorded by a NI USB6259 16 bit data acquisition device to the PC at a sampling rate of 10KHz. The amplifiers of the direct conversion path are DC coupled, since the signal has a significant amount of spectral content around DC. The coherent low IF carrier spectrum is provided in Fig 4. As it can be seen, the 2.4G+667Hz is the dominant component and the 2.4G-667Hz is about 30dB lower than the designated carrier.

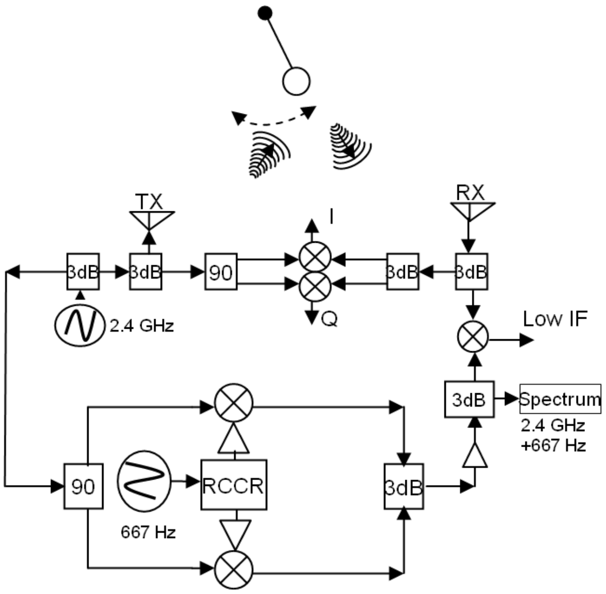

Fig 3 Measurement setup. Note the Coherent Low IF generation path.

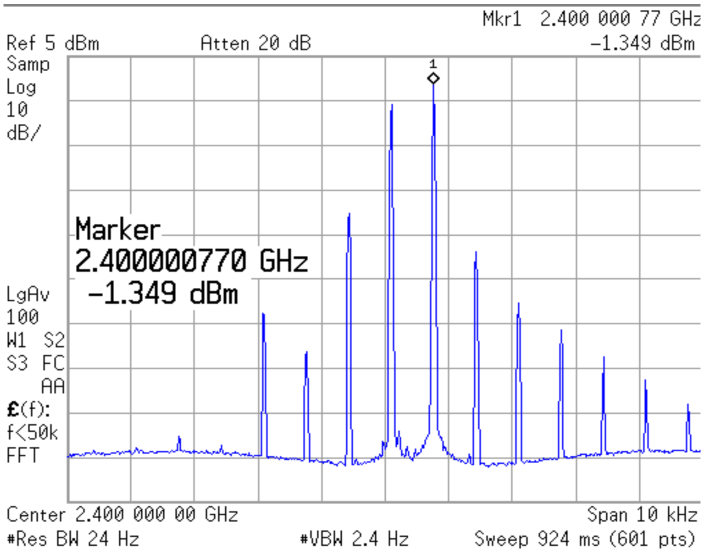

Fig 4 Spectrum of the Coherent Low IF carrier

Goal of this measurement is to benchmark the noise performance of the two different configurations. Power spectral density of baseband signals is calculated to give an estimate of the background noise and signal power. In order to have a predictable source of motion, a hanging ball oscillating at a frequency of 1Hz is used as a target to produce the motion that the radar can sense.

IV. EXPERIMENTAL RESULTS

The coherent low IF output signal is band-pass filtered and multiplied by a complex exponential at 667Hz and then low pass filtered. This procedure results in a complex baseband signal comparable to the I+jQ outputs of the direct conversion channel. Time-domain plots of the direct conversion and low IF baseband signals are plotted in Fig 5. The target under measurement is a hanging ball, and the motion is picked up by the radar and it can be seen as periodic signals on I and Q channels. As Fig 5 indicates, while this motion can be detected with both systems, coherent low IF I and Q traces are clearly less noisy. Fig 6 shows the calculated output spectrum from both systems. The coherent low IF spectrum exhibits the noise floor that is about 10dB lower than for direct conversion spectrum, while the signal power at 1Hz is the same for both coherent low IF and direct conversion. This indicates that the SNR improvement of about 10dB has been achieved by using a coherent low IF receiver architecture.

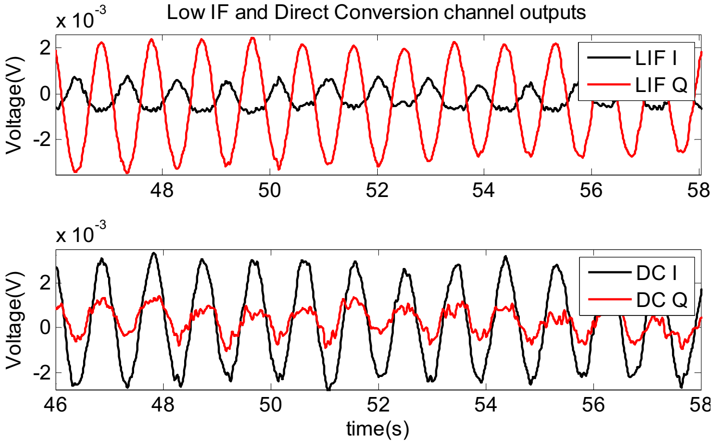

Fig 5 Baseband I and Q signals from direct conversion and coherent low IF receiver paths.

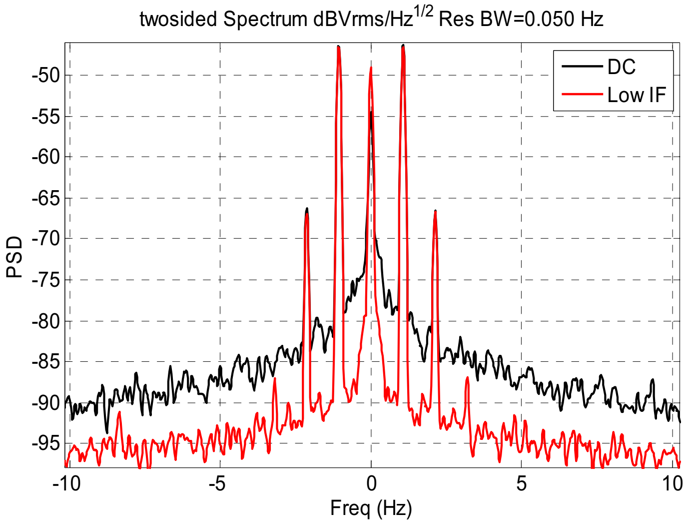

Fig 6 Baseband signal spectrum for the two receiver paths

V. CONCLUSIONS

Direct conversion Doppler radar has a very simple and easy to deploy configuration, but issues with DC cancellation, a need for two RF signal paths and most importantly Flicker noise from mixer and baseband amplifiers limits its performance. To overcome these issues a coherent low IF architecture has been proposed in which the received signal is coherently demodulated to an IF frequency suitable for direct digitization and further signal processing. A benchmark configuration and test shows an improvement in SNR of about 10dB at 1Hz as compared to direct conversion architecture. This benefit can be crucial in low power and long range performance. In the meantime a simple single RF path in the receiver makes it suitable for multiple antenna/receiver applications where hardware complexity can become a limiting factor.

ACKNOWLEDGEMENT

This work was supported in part by the NSF, under grants ECS0428975 and ECS0702234.

REFERENCES

[1] B.-K. Park, O. Boric-Lubecke, and V. M. Lubecke, "Arctangent demodulation with dc offset compensation in quadrature Doppler radar receiver systems," *IEEE Trans. on Microwave Theory Tech.*, Vol. 55, No.5, pp.1073-1079, May 2007

[2] A. Droitcour, V.M. Lubecke, J. Lin, and Olga Boric-Lubecke, "A Microwave Radio for Doppler radar Sensing of Vital Signs," *IEEE MTT-S Int. Microwave Symp. Dig.*, Phoenix, AZ, USA, vol. 1, pp. 175-178, May 2001.

[3] A. Driotcour, *Non-Contact Measurement of Heart and Respiration Rates With a Single-Chip Microwave Doppler Radar*, PhD dissertation, Stanford University, 2006.

[4] A. Droitcour, O. Boric-Lubecke, V.M. Lubecke, J. Lin and G. T. Kovacs, "Range Correlation and I/Q Performance of Benefits in Single Chip Silicon Doppler Radars for Non-Contact Cardiopulmonary Monitoring," *IEEE Trans. on Microwave Theory Tech.*, Vol. 52, No.3, pp.838-848, March 2004.

[5] J. Crols and M. S. J. Steyaert, "Low-IF topologies for high-performance analog front ends of fully integrated receivers," *IEEE Trans. on Circuits and Systems II: Analog and Digital Signal Processing,* Vol. 45, No. 3, pp. 269-282, 1998

[6] B. Lohman, O. Boric-Lubecke, V. M. Lubecke, P. W. Ong, and M. M. Sondhi, "A Digital Signal Processor for Doppler Radar Sensing of Vital Signs," in *Proc. IEEE 23rd annu. Engineering in Medicine and Biology Society Conf.,* vol. 4, 2001, pp. 3359-3362.

[7] S. Yamada, V. Lubecke, and O. Boric-Lubecke, "Cancellation Techniques for LO Leakage and DC Offset in Direct Conversion Systems," IEEE IMS2008, June 2008.

[8] W. Redman-White, D.M.W. Leenaerts, "1/f Noise in Passive CMOS Mixers for Low and Zero IF Integrated Receivers"

[9] M. Margraf, G. Boeck, "Analysis and Modeling in Low-Frequency Noise in Resistive FET Mixers," IEEE Trans. on Microwave Theory and Tech., Vol. 52, No. 7, pp 1709-1718, July2004.

[10] C.-Y. Kim, J.G. Kim, J.H. Oum, J.R. Yang, D.-K. Kim, J.H. Choi, S.-W. Kwon, S.-H. Jeon, J.-W. Park, S. Hong, "Tx Leakage Cancellers for 24 GHz and 77 GHz Vehicular Radar Applications" Microwave Symposium Digest, 2006. IEEE MTT-S International June 2006 Page(s):1402 – 1405.

[11] J. G. Proakis, *Communication Systems Engineering*, Prentice Hall, 2nd ed, 2001.