A MICROWAVE RADIO FOR DOPPLER RADAR SENSING OF VITAL SIGNS

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***Abstract* — A microwave radio for Doppler radar sensing of vital signs is described. This radio was developed using custom DCS1800/PCS1900 base station RFICs. It transmits a single tone signal, demodulates the reflected signal, and outputs a baseband signal. If the object that reflects the signal has a periodic motion, the magnitude of the baseband output signal is directly proportional to the periodic displacement of the object. When the signal is reflected off a person's chest, this radio and baseband filters can detect heart and respiration rates from a distance as large as one meter from the target.**

I. INTRODUCTION

An estimated one hundred million Americans suffer from chronic health conditions including heart disease, lung disorders, and diabetes, and treatment for these conditions accounts for three-fourths of total US healthcare costs [1]. Consequently, there is a growing market for appliances that allow remote monitoring of health parameters and transfer of the recorded data to a physician, for convenience and cost reduction. Non-invasive sensing of circulatory and respiratory movements with a microwave Doppler radar [2] could be applied to such remote monitoring. Using telecommunications devices and frequencies for this remote sensing will facilitate the use of existing telecommunications networks to transfer patient data to health professionals [3].

Microwave Doppler radar monitoring of respiratory [4], cardiac [5] and arterial [6] movements was demonstrated with commercially available waveguide X-band Doppler transceivers in the late 1970's. A number of similar custom transceivers were developed in the mid-1980's, including a life detection system [7] and a superficial temporal artery monitor for military pilots [8]. All of these systems used the bulky and comparatively expensive radio components that were available at the time. Owing to the recent rapid expansion of wireless communications and information technology, inexpensive integrated radio circuits are readily available today. Smaller, lighter, and less expensive circuitry will diversify the feasible applications of this technology. In this paper, a compact prototype Doppler radar, using 0.25 μm silicon BiCMOS RFICs developed for DCS1800/PCS1900 base station applications, is described. Respiration and heart activity were successfully detected using this radio from distances up to one meter from the target.

II. DOPPLER RADIO ARCHITECTURE

According to Doppler theory, a constant frequency signal reflected off an object with a periodically varying displacement will result in a reflected signal at the same frequency, but with a time varying phase, $\phi(t)$. Analogous to the phase shift on a transmission line terminated with a load at a varying position, this time varying phase is directly proportional to the displacement, $x(t)$:

$$\phi(t) = \frac{4\pi}{\lambda} x(t), \qquad (1)$$

where λ is the wavelength of the signal. The reflected signal is effectively phase modulated (PM). If the change in displacement is small compared with the wavelength of the signal, the phase change will be small, and the PM signal can be directly demodulated by mixing it with a portion of the original signal. The demodulated signal is then directly proportional to the periodic displacement of the reflecting object. If this object is a person's chest, the demodulated signal is directly proportional to displacement due to respiration and heart activity. A microwave radio based on this principle was developed for such measurements.

A block diagram and photograph of the Doppler radio are shown in Fig. 1(a) and (b), respectively. A voltage-controlled oscillator is used to generate a constant frequency local oscillator (LO) signal. An active balun amplifier splits the signal into the RF output signal that drives the antenna and the reference LO signal that is used for demodulation. Another active balun amplifier splits this single-ended LO signal into a differential signal, which is required for the double balanced mixer. A third

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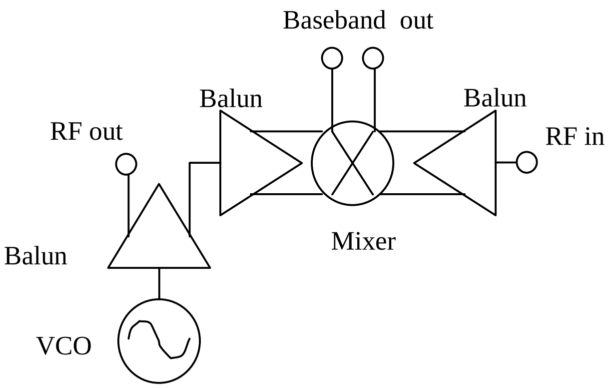
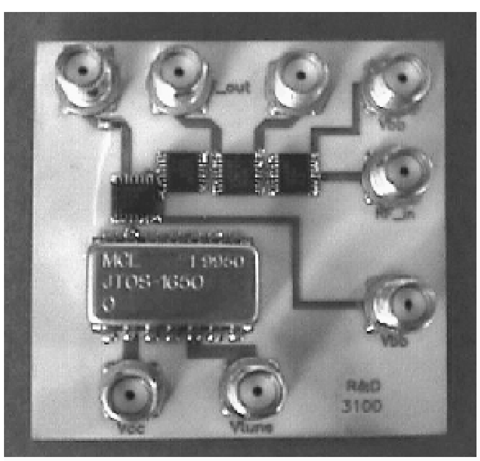
active balun amplifier splits the single-ended RF input from the antenna into a differential signal, which is connected to the mixer's balanced RF port. The RF input is the signal that is reflected off the target, with its phase modulated by the target's displacement. Since the LO is a portion of the original signal, the mixer downconverts the RF signal to a baseband signal with a magnitude proportional to the displacement associated with respiration and heart activity. Isolation of about 20 dB is required between the RF output and input signals. This can be achieved either with two separate antennas, or with one antenna and a coupler or circulator.



(a)



(b)

Fig. 1. Block diagram (a), and a photograph (b) of Doppler radio. Custom RFICs, developed for DCS1800/PCS1900 base stations, were used for this radio.

An active balun amplifier [9] developed for DCS1800/PCS1900 base station applications was used as a power splitter in this radio. The active balun operates at frequencies up to 2 GHz. The circuit can be operated with any supply voltage between 1.5 V and 5 V, with the best output signal phase and amplitude balance and highest gain obtained with a 5 V supply. The bias current varies linearly with the supply voltage, and the power consumption varies from 13.5 mW to 325 mW. This buffer was fully integrated on a 0.25 μm silicon BiCMOS process in a 1.8 mm by 1.6 mm chip. It was packaged in an exposed pad TSSOP-16 package, which has a 3 mm by 5 mm footprint.

A fully differential CMOS resistive ring mixer [10], also developed for DCS1800/PCS1900 base station applications, was used for direct demodulation in the receiver. This is a broad-band mixer that can operate with an RF signal up to 2500 MHz and with an IF signal from DC to 300 MHz. Though the mixer achieves its best linearity performance at high LO drive, it can be operated with LO drive as low as 4 dBm and still have conversion loss less than 7 dB. The mixer requires no bias and therefore consumes no DC power. This mixer was fully integrated on a 0.25 μm silicon CMOS process in a 1.2 mm by 1.5 mm chip. It was packaged in an exposed pad TSSOP-16 package, identical to that of the active balun amplifier.

A commercially available VCO, the Mini-Circuits JTOS-1650, was used as a signal source. With the recommended supply voltage of 12 V, this VCO consumes 360 mW. By tuning a control voltage from 0 V to 14 V, the frequency is varied from 1.09 GHz to 1.99 GHz, with an output power of 5 mW. The oscillator was in a BK377 package, with a 13 mm by 20 mm footprint. Alternatively, the size and power consumption of this radio could be reduced by using a low power, custom designed BiCMOS VCO [11], which draws 20 mA for a 36 mW total DC power consumption, in a more compact TSSOP-16 package.

The circuit board was built on a Rogers RO-4003 substrate with a dielectric constant of 3.38 and a thickness of 0.5mm. SMA connectors were used for all the inputs, outputs, and DC bias (Fig. 1(b)). The RF signals were routed to the SMA connectors via 50 Ω lines, which were 1.1 mm wide on this material. The board dimensions were 50 mm by 50 mm.

Commercially available motion sensors typically operate at higher frequency bands, such as X-band. The main benefit of working in the telecommunications bands, such as the DCS1800/PCS1900 band, is that the hardware needed to build radios at these frequencies is readily available. Also, lower frequencies offer advantages for lower cost monolithic integration, since at these frequencies it is possible to use inexpensive silicon CMOS and BiCMOS processes.

III. TESTING PROCEDURE AND RESULTS

An experimental setup with a single antenna and a coaxial power splitter was used to make the measurements discussed below, and is shown in Fig. 2. A Mini-Circuits power splitter, part ZFSC-2-2500, provided 17 dB of isolation between input and output signals. A commercially available Antenna Specialists ASPPM2988 1900 MHz patch antenna with 65° by 80° beam width was used. Measurements were performed at 1892 MHz, which required a VCO tuning voltage of 12 V. The subject was seated at a varying distance, d, fully clothed, facing the antenna, and breathing normally (Fig. 2(b)). A finger pressure pulse sensor (UFI-1010 pulse transducer) was used during the measurements to provide a reference signal for heart activity. The IF output was filtered with Stanford Research Systems Model SR560 Low Noise Amplifiers, which both amplify and filter the signal. The resulting voltage waveforms were digitized with an HP Infinium digital oscilloscope.

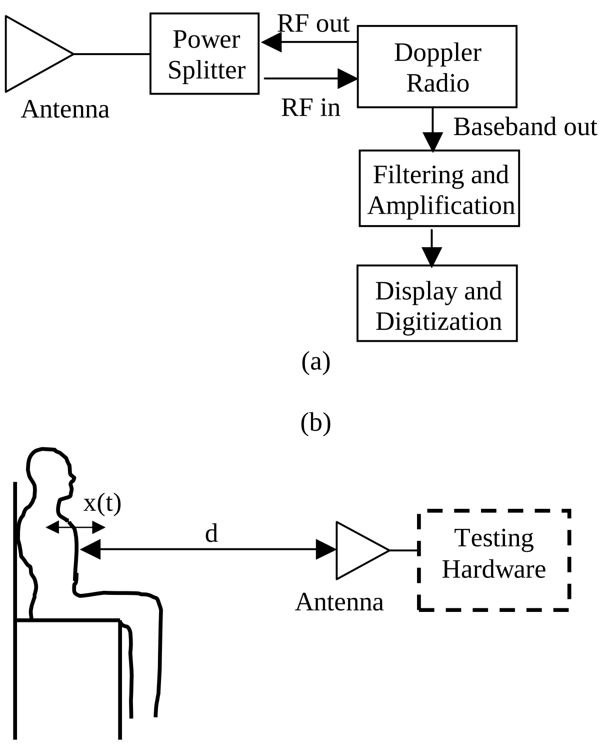


Fig. 2. Testing setup: (a) hardware block diagram and (b) placement of target.

The baseband signal was initially filtered with a band-pass filter between 0.03 Hz and 10 Hz, to remove the DC component and minimize out of band noise and aliasing error. The respiration signal was clearly visible after this filtering stage, but it could be better resolved with an additional low-pass filter. The heart signal was isolated using a 6 dB roll-off 1 Hz to 3 Hz band-pass filter. The first filtering stage provided most of the amplification, which was adjusted to produce the clearest output signal.

The measurement was made in two ways, using the on-board VCO, and using a modified board with an external LO from a signal generator with the same output power of 5 mW. This made it possible to determine the contribution of noise from the VCO, and to independently evaluate the rest of the circuit. At distances less than one meter using the on-board VCO, the interval between "beats" in the heart signal was clearly evident and corresponded to that of the pulse reference, indicating that heart rate could be determined accurately using this Doppler radio. Signals obtained using the on-board VCO with the subject one half meter from the antenna are shown in Fig. 3. The mixer output was filtered and amplified to produce voltage waveforms representing respiration (top trace) and heart (middle trace) signals, with a reference (bottom trace) signal from the finger pulse sensor included for comparison.

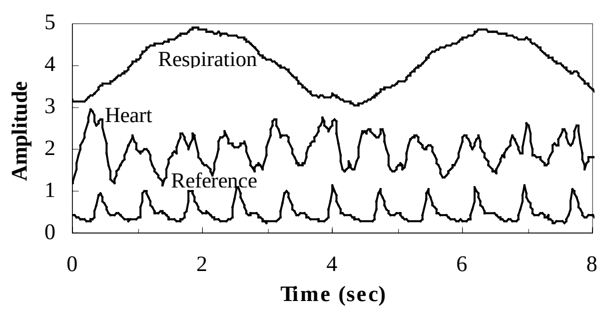


Fig. 3. Respiration (0.3-10 Hz), heart (1-3 Hz), and pressure pulse reference signals (voltage waveforms) with the subject one half meter from the antenna and the voltage controlled oscillator as the local oscillator.

At distances of one meter and beyond, the signal to noise ratio decreased due to increased free space loss, and it was more difficult to extract the heart data when using the on-board VCO. The data obtained with the subject one meter from the antenna using the signal generator, and on-board VCO, is shown in Fig. 4(a) and (b), respectively. The top trace corresponds to the pre-filtered signal containing both breathing and heart information, the middle trace to the band-pass heart signal, and the bottom trace to the pressure pulse reference. In both cases, periodic heart activity is evident in the top traces, however it is noisier when the on-board VCO is used (Fig. 4(b)). After band-pass filtering, the heart signal (middle trace) shows the same number of intervals between beats as the reference signal (bottom trace) in both cases. This indicates that although the signal from the VCO has higher noise, it is still possible to extract the heart rate at distances as large as one meter while using the VCO as the signal source.

Heart and respiration rates can be extracted from the data by finding all local maximums and discarding those below a threshold to avoid errors caused by noise or motion artifacts [12]. The average time interval between successive beats is the period of the signal, which can be inverted to determine the rate. Respiration and heart rates were found to be 14 breaths/min (0.23 Hz) and 84 beats/min (1.4 Hz), respectively, with the heart rate consistent with the rate obtained using the pressure pulse sensor.

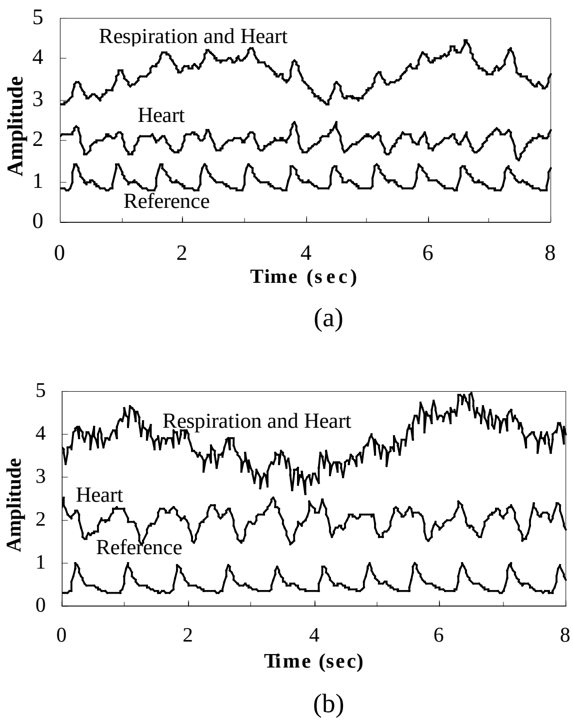


Fig. 4. Respiration and heart signal (0.03-10 Hz), heart signal (1-3 Hz), and reference signal from finger pulse sensor with the subject one meter from the antenna. The local oscillator is a signal generator (a), and a voltage controlled oscillator (b).

V. Conclusion

A novel microwave Doppler radio assembled using custom RFICs for DCS1800/PCS1900 base station applications has been described. The radio can detect heart and respiration rates of a subject at distances as large as one meter. The result demonstrates the feasibility of monolithic integration of Doppler radios in low cost silicon technology and the potential for future implementation of remote monitoring of vital signs in wireless communication networks.

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