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System-on-Chip Based Doppler Radar Occupancy Sensor

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***Abstract*— System-on-Chip (SoC) based Doppler radar occupancy sensor is developed through non contact detection of respiratory signals. The radio was developed using off the shelf low power RF CC2530 SoC chip by Texas Instruments. In order to save power, the transmitter sends signal intermittently at 2.405 GHz. Reflected pulses are demodulated, and the baseband signals are processed to recover periodic motion. The system was tested both with mechanical target and a human subject. In both cases Doppler radar detected periodic motion closely matched the actual motion, and it has been shown that an SoC based system can be used for subject detection.**

I. Introduction

WITH the nearly 50% projected increase in global energy use by 2035, and with most of it still coming from fossil fuels, energy efficiency and energy conservation are becoming increasingly important. In the US, the residential and commercial users account for 42% of total energy consumption [1]. While in residential areas about 30% of electricity is used for lighting and heating, ventilation, and air conditioning (HVAC) systems, in commercial buildings, lighting and HVAC systems account for over 50% of electricity consumption, and in hotels they can represent up to 80% of the utility bill [2].

Research has shown that occupancy sensors can save up to 80% of energy used for lighting and HVAC systems, also resulting in significant financial savings [3]. This is particularly relevant to the coastal tourism, as energy consumption in hotels is significantly higher than in residential and even commercial buildings. However, currently available occupancy sensors, most commonly passive infrared (PIR) and ultra-sonic (US) sensors have significant drawbacks, including high rates of false alarm and failure to detect stationary subjects [3]-[4].

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Doppler radar motion sensing systems have been used to detect the physiologic movement since the 1970s [5]. Over the past decade, the falling cost and reduced size of electronic components required to create Doppler radar sensors, have enabled numerous technological advances including single chip integration [6], and novel applications, including wearable [7], contact [8], and non-contact physiological monitoring [9]. These same forces are now making Doppler radar technology feasible for occupancy monitoring applications. In addition, the advent of integrated low-power microprocessor/RF-transceivers provides a new platform for combination of sensing, processing and communications [6] which can form the core of a wireless smart sensor network for applications such as "smart building" systems.

Detection of human subjects using Doppler radar, based on heart signals, was proposed in [11]. In this paper, we explore the feasibility of Doppler radar occupancy sensor detecting respiratory signals. Significant challenge for wide adoption of occupancy sensors is to demonstrate reliable system performance at low power and low cost. Thus we pursue occupancy sensor design with a commercially available low cost, low power SoC. The system was tested both with mechanical target and a human subject, demonstrating that periodic motion can be accurately detected using this low cost, low power system.

II. System overview

Non-invasive detection of vital signs, such as heart rate and respiration rate, is possible using a radar microwave system, due to a Doppler shift caused by body movements during respiratory and circulatory contractions and expansions. According to Doppler theory, received signal from an object with a periodically movement contains the same frequency, but with a time varying phase $\varphi(t)$. Since, chest displacements due to respiratory effort are periodic, these movements will produce varying phase, proportional to displacement, $x(t)$ [6]:

$$\varphi(t) = \frac{4\pi}{\lambda} x(t) \tag{1}$$

where λ is the wavelength of the signal. This phase variation could be demodulated using linear or non-linear (arctangent) demodulation to obtain an output signal with a low frequency component that is directly proportional to the object displacement [12].

Doppler radar motion sensing system typically sends a continuous wave signal, which is reflected off of a target and then demodulated in the receiver. For lowering the power consumption for our system, signal has been sent intermittently rather than using continuous wave transmission. As long as the signal repetition rate is significantly higher than the rate of measured periodic motion, periodic motion can be recovered with sufficient accuracy. Fig. 1 shows the block diagram of the system. The SoC CC2530 IEEE 802.15.4 compliant RF transceiver was employed as signal source for radar. TI CC2530 uses ZigBee technology, which is a short-range, low power, low data rate, low-cost wireless network technology. This chip has different operating modes, making it suited for systems where low power consumption is considered [10].

The modulation format for the TI chip CC2530 is offset – quadrature phase shift keying (O-QPSK) with half-sine chip shaping. This is equivalent to MSK modulation. Each byte is divided into two symbols, 4 bits each. Each symbol is mapped to one out of 16 pseudorandom sequences, 32 chips each. The chip period is 1μs. Finally, the chip sequence is transmitted at 2 Mchips/s. The chip has the multiple access capability and uses carrier sense multiple access with collision avoidance [10].

Minicircuits ZFSC-2-2500 coupler was used to split the signal source output into the transmitter antenna and local oscillator paths with 90 degree phase difference. The Antenna Specialist (ASPPT2988) antenna was used with 8 dBi gain and 60 degree E-plane beamwidth for transmitting and receiving antenna. Both human and a mechanical moving object with periodic movements have been used as target for our measurements. The frequency of the mechanical subject periodic movement was 0.13 Hz, and it had linear periodic mechanical movement about 17 mm. Fig. 2 shows the artificial moving target simulating respiratory motion, which is used for measurements. The usable range depends on several factors such as transmitting power, antenna characteristics, and oscillator phase noise. In both cases the target was placed one meter away from the antennas. The human subject was in seated position.

The received signal which is scattered form the target is fed into a Minicircuits ZFM4212 mixer. It was mixed down to baseband, using small portion of the transmitted signal as a local oscillator. Stanford Research System Model SR560 Low Noise Amplifier is used for amplification and filtering. The mixer's output is amplified by a factor of 200, and subjected to 6 dB/octave high-pass filtering at 0.03 Hz to remove DC offset. Then, 6 dB/octave low-pass filtering with 30 Hz cutoff frequency is applied. Finally, signal is recorded by a TI DAQ9801 data acquisition device to the PC with the sampling rate of 1kHz. Measurements for both mechanical and human subject were made in an anechoic chamber. Measurements on human subject were done under the IRB protocol number CHS 14884.

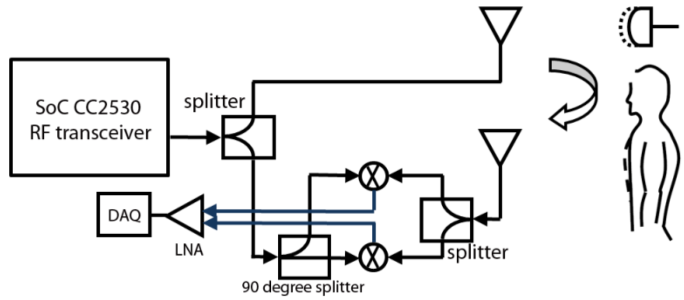


Fig.1. Block diagram of the Doppler radar system using TI CC2530 SoC.

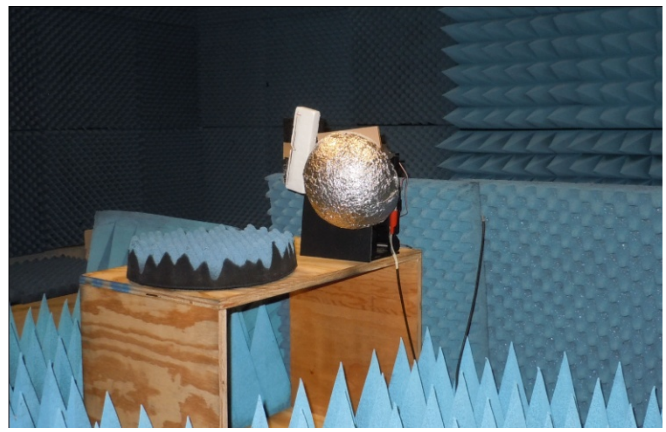


Fig.2. Mechanical target with periodic motion simulating respiratory movements.

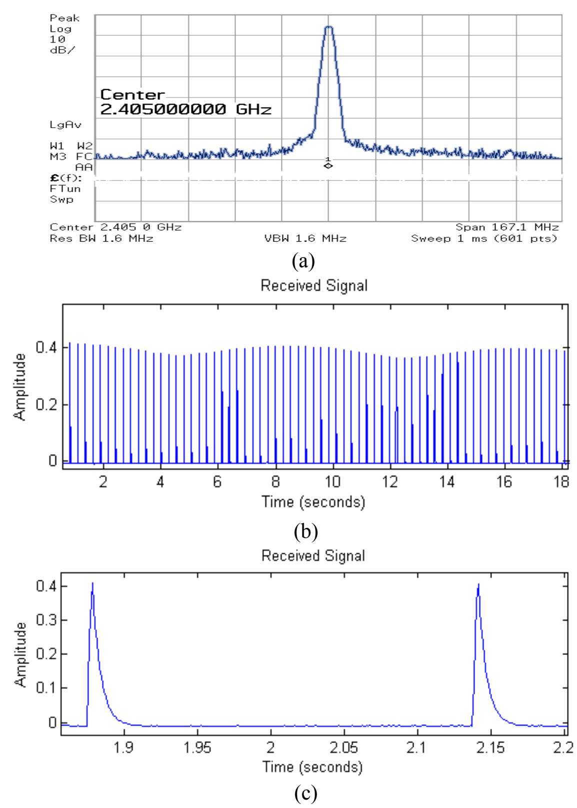


Fig.3. (a) Transmitted signal spectrum, IEEE 802.15.4 channel 11 with 2.405 GHz center frequency (b) Received signal modulated by the respiratory motion (c) Two consecutive pulses of received signal.

III. Experimental Result and Discussion

Frequency spectrum of transmitted signal is shown in Fig 3(a). The center frequencies for the 16 channels which are defined by IEEE Standard 802.15.04 begins at 2.405 GHz and ends at 2.480GHz. Channel 11 has been used in our measurements with center frequency 2.405 GHz. The power of the transmitted signal is -4 dBm. The average power consumption of the chip with evaluation board is 17 mW.

Reflections from moving targets will results in phase/frequency shifts, while reflections from stationary clutter only result in DC offset. Phase shift at the reflection surface also causes DC offset. In addition, RF interference is not phase correlated with the signal; thus, it only increases the DC offset of the output signal. Fig. 3(b) shows LNA's output in which the amplitude of the signal is modulated by respiratory motion. Two consecutive pulses are depicted in Fig.3(c). The pulse period is about 256 ms or pulse repetition frequency is 3.77 Hz. Output signals are post processed using MATLAB to extract the envelope and perform frequency domain analysis for finding target periodic movement's rate.

Due to pulsed nature of received signal, common methods of envelope detection such as Hilbert transform, and squaring and low pass filtering were not successful. The block diagram for finding the target periodic movement is shown in Fig. 4. Filtered respiration signals are fed into the local maximum algorithm with a neighborhood threshold which is selected based on signal amplitude. The time instances when peaks are greater than their neighborhood by the threshold are stored in an array. The peak values and the time at which they occur are stored in separate arrays. Fig. 5(a) shows the peaks which are detected by the algorithm. As the peak signals are not equally spaced, it is necessary to perform an interpolation to achieve uniform signal before carrying out frequency domain analysis. Cubic spline interpolation technique is used for this purpose. This method gives smoother waveform than linear interpolator. Fig. 5(b) illustrates the result of the interpolation. After reconstructing the signal, FFT was applied to calculate subject's movement rate during the measurement interval. Fig. 5(c) upper part shows periodic movement rate of the mechanical target (f = 0.13 Hz).

Fig. 6 depicts results of the experiment with a human subject. Upper trace shows respiration effort signal recorded using piezo-electric sensor as a reference. Fig. 6 (b) and (c) traces are envelope and interpolated version of the demodulated received signal. DC drift in figure 6 (b) and (c) may be due to a slow moving clutter in the background. Bottom traces illustrates the respiration rate of a human subject (f = 0.29 Hz). Respiration rate is successfully extracted, and is in accordance with the reference signal.

The main advantage of the system is lower power consumption by intermittent transmission rather than continuous wave transmission. Another benefit is using low cost off-the-shelf RFICs for wireless respiratory measurements, and occupancy detection. The cost of the off the shelf System on Chip is on the order of $10.

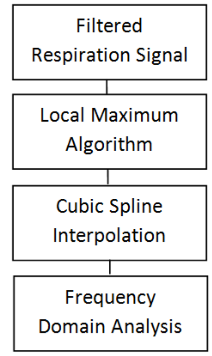
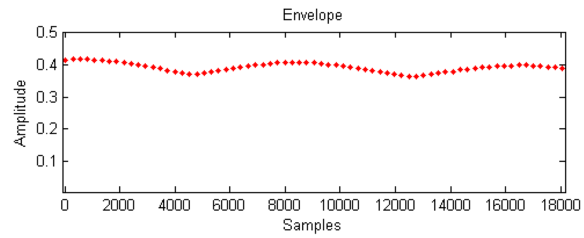
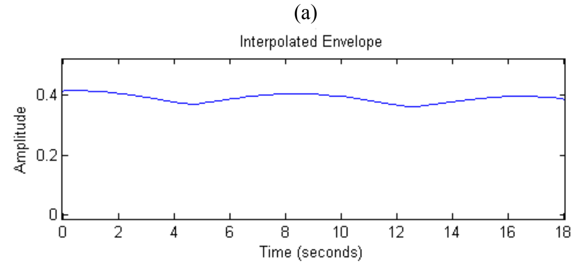


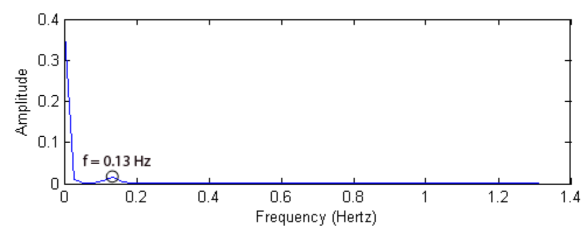
Fig.4. Block diagram of the algorithm for extracting the target movement rate.



(a)



(b)



(c)

Fig.5. (a) Envelope of the received signal reflected from the mechanical target (b) interpolated version of the peaks which are not evenly distributed (c) frequency domain analysis, mechanical subject periodic movement's rate (f = 0.13 Hz).

Respiratory motion was selected for occupancy sensor subject detection for two reasons: it is an order of magnitude larger than chest motion due to heart-beat and thus possible to detect with lower power and lower system complexity, and it enables detection of stationary human subjects. On the other hand, reliable stationary subject detection is the main limitation of the current occupancy detection systems based on ultrasonic or infrared sensors.

IV. Conclusion

Low cost, low power, pulsed Doppler radar was demonstrated using off the shelf SoC CC2530 as an occupancy detection sensor. It has been shown that periodic motion can be extracted using intermittent data transmission instead of sending CW signal which consumes more power. Digital signal processing techniques have been employed to process baseband signals. Further research will include developing algorithms for determining human presence based on recovered respiratory patterns.

V. Acknowledgment

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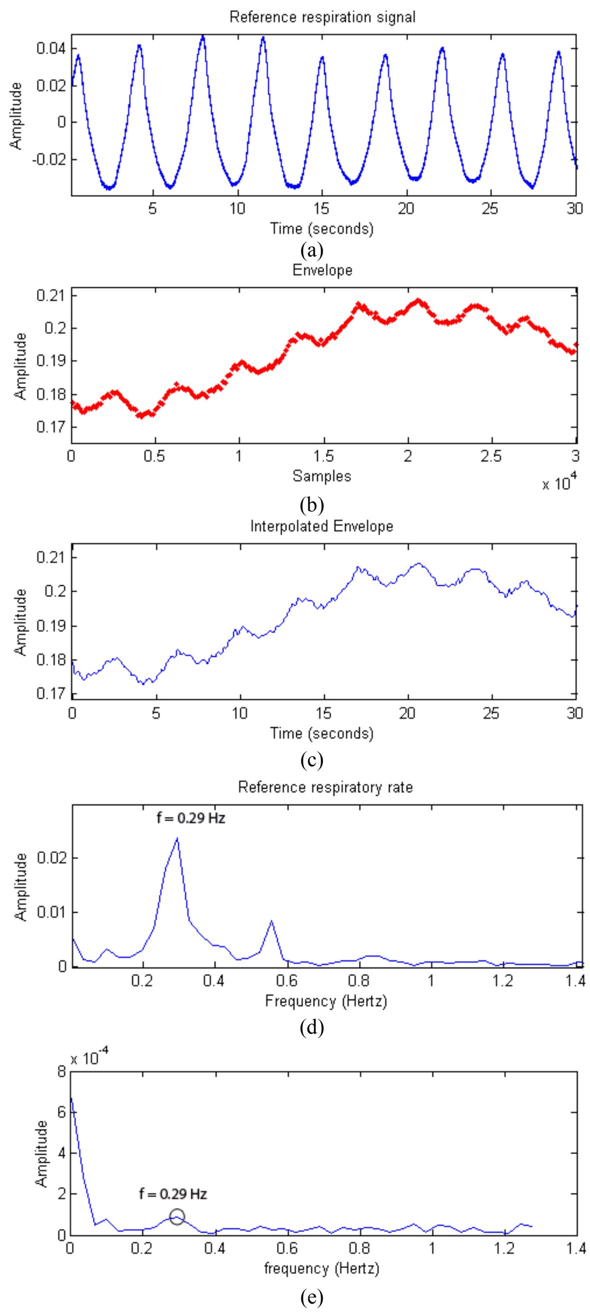

Fig.6. (a) Respiration effort signal recorded using piezo-electric sensor (b) envelope of the demodulated radar signal containing chest periodic motion (c) interpolated version (d) spectrum of the piezo-electric reference(e), and spectrum of the interpolated Doppler radar respiratory signal. The respiratory rate is successfully extracted from interpolated received signal (f = 0.29 Hz).

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