An impulse radio duty-cycled radar with ultra-wideband VCO using frequency hopping technique

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Abstract This paper presents a pulse-based radar with ultra-wideband voltage controlled oscillator for vital-sign application. A series of digital-assisted duty-cycled probing pulses with frequency hopping technique is proposed to mitigate unwanted narrowband interferences, thereby increasing overall system signal-to-noise ratio and then enabling high resolution detection. The RF generator is utilized by an on-chip VCO with the characteristic of wide-band response by digitally switching loaded capacitor array for frequency hopping. The conventional ultra-wideband channel is further divided into several sub-channels for vital-sign sensing. An impulse radio Doppler radar is implemented and integrated with the digital-assisted oscillator to detect physiological information.

Keywords: frequency hopping, ultra-wideband, radar

Classification: Integrated circuits

1. Introduction

The trend of healthcare development is to capture one’s body physiological information and provide long-term monitoring, which can rely on a non-contact and real-time vital-sign radar to detect the movement of chest with reciprocal characteristic [1, 2, 3]. The Doppler radars [4, 5] with continuous wave (CW) or frequency modulated continuous-wave (FMCW) are widely used in long distance detection, vital-sign sensing, and through-wall detection [6, 7, 8] due to its excellent tracking ability and high sensitivity. However, most of the CW-based radar exhibit high power consumption and complex circuit in comparison to the pulse-based radar. Therefore, a pulse-based ultra-wideband (UWB) radar features a non-contact, compact, low-power, and easy-implemented device for long-term monitoring. There had been many prior works focusing on increasing tracking resolution and lowering noises such as the issues of DC offset and adjacent interference for a pulse-based radar system [9, 10, 11].

In this paper, we adopt an UWB radar [12, 13, 14, 15, 16, 17, 18, 19] with frequency hopping technique to mitigate the narrowband interference and then detect vital signs. The RF generator with wide switchable oscillated frequencies as the sequential narrow radio pulses is utilized in the transmitter of radar. In addition, the low duty-cycled probing pulse is also incorporated into the entire system to alter pulse width and proceed low-power sensing.

2. Radar system

The proposed architecture of the impulse radio duty-cycled Doppler radar with UWB VCO is shown in Fig. 1. The digital-assisted VCO is incorporated into the RF generator as the source of radar system to perform frequency hopping technique by digitally switching oscillated frequencies with 5-bit control mechanism (B0–B4). The followed doubler servers the purpose of doubling the oscillator frequency at the desired frequency hopping band (5~6 GHz) and the PA further boosts the output power level to detect human vital signs. After that, the continuous wave (CW) is converted into the periodical pulses for real-time detection. In addition, the switches alter the transmitting and receiving modes for a pulse-based radar architecture [12]. All the circuit block are implemented in commercial chips except the integrated VCO and its corresponding buffer. Therefore, the pulse-based transmitted signal with frequency hopping technique can be emitted to the investigated subject and back to the matched filter receiver for obtaining the physiological data by the correlation between the returned echoes and referenced pulses with a fixed delay time. The receiver of the sensing radar is composed of a low noise amplifier, demodulator, and analog baseband processing circuit.

Fig. 1. The proposed pulse radar system architecture.
To further investigate the sensing behavior of chest movement, the output signal $Z(t)$ is expressed as

$$Z(t) = \frac{E_t E_r}{2} n T_0 \cos[\phi(t) + \Delta \phi],$$

where $E_t$ and $E_r$ are the maximum amplitudes of the emitted and received signals, respectively; $T_0$ is the time period of the probing pulses and $n$ is a whole number of oscillation periods; $\Delta \phi$ is the phase shift between the sensor and object. Moreover, the phase difference $\phi(t)$ is defined as the spreading time with an instantaneous phase value from the emitted wave to the investigated object and back to the antenna.

The continuous wave with single carrier frequency is widely used in the radar system. For a pulse-based UWB radar system, a narrow RF pulse width helps extend the operating bandwidth larger to meet the requirement of United States Federal Communications Commission (FCC) regulations [20, 21, 22]. However, the transmitted power with low duty-cycled RF pulses might suffer the in-band narrowband interferences from the sensing environment as shown in Fig. 2. The frequency hopping technique can be utilized in the radar system to increase sensing resolution. Thus, the RFVCO with capabilities of switching carrier frequencies and covering wideband property is essential to relieve the impact of narrowband interference. The carriers at different frequencies are distributed in the series of probing pulses at a fixed repetition frequency. In this work, the probing frequency band is determined at 5~6 GHz and divided by several sub-channel, which can be controlled by the MCU.

### 3. Circuit design

An oscillator as the sensing source is a key component for a vital-sign radar [23, 24, 25, 26, 27, 28]. Due to the requirement of wide dynamic range, the capacitor array with 5-bit digital control is first incorporated into the LC tank of an oscillator to alter resonant frequency. Nevertheless, the array of MIM capacitors occupies large chip area. MOS capacitance is hence adopted to perform a 5-bit binary-weighted switched-capacitor array which in turn tunes the oscillator center frequency. Next the voltage controlled mechanism at the differential varactors is also implemented in the core circuit design for covering the entire frequency band. The oscillated frequencies between each bit are continuous by the control tuning voltage ($V_{\text{tune}}$). Fig. 3 and 4 illustrate the proposed schematic of the VCO, and hopping frequency planning of the probing signals by digital-assisted switching and analog control voltage tuning, respectively. The PMOS-based VCO with cross couple topology lowers the flicker noise and then improves the overall phase noise [29, 30].

Furthermore, the output buffer is also designed for facilitating circuit measurement, as depicted in Fig. 5. To achieve wideband performance, the switched LC tank with 3-bit capacitor control helps alter the its resonant frequencies to the corresponding oscillated frequencies for compensating the adequate effective transconductance. To exhibit its performance, a testkey of the RF VCO is designed and measured, fabricated in the TSMC 0.35 SiGe BiCMOS technology. The photograph of the testing oscillator, displayed in Fig. 6, occupies chip area of $1.5 \times 1.23$ mm$^2$ and consumes 17 mA at the core circuit under 3.3 volt supply voltage. Fig. 7 shows the measured oscillation frequencies approximately operated at 2.5~3 GHz with the control 5 digital bits (00000 to 11111) and voltage tuning range from 0 volt to 3.3 volt. In addition, the measured phase noise at each bit versus tuning voltage is shown in Fig. 8. The phase noise lower than $-125$ dBc/Hz can be achieved by a larger tuning voltage (>1.7 V). The worse phase noises occur at the relatively lower tuning voltage corresponding to lower oscillating frequencies due to the insufficient
transconductance in the oscillator core for a fixed loaded inductor. Although this issue can be improved by increasing power consumption, the voltage tuning range from 1.8 volt to 3.3 volt for performing continuous frequency band is quite enough. Therefore, both the digital and analog tunings of the overlap frequency covering can achieve an optimal tradeoff between transconductance gain and power consumption. Besides, the FOM for the worse case at tuning voltage of 1.8 volt is around $-171$ dBc/Hz. The measured oscillation frequencies approximately operated at 2.5~3 GHz with the control 5 digital bits (00000 to 11111) and voltage tuning range from 0 volt to 3.3 volt. Additionally, the measured phase noise at each bit versus tuning voltage lower than $-125$ dBc/Hz approximately can be achieved, as listed in Table I.

### 4. Experimental results

This paper implemented a pulse-based vital-sign radar sensing system on a standard FR4 PCB with an integrated LC-tank VCO as its probing source. The photograph of the radar board and testing environment setup are displayed in Fig. 9, with the physical sizes of $10 \times 5$ cm$^2$ and 128 mA current consumption under 5 V supply voltage. As depicted in Fig. 9, vital-sign monitoring is setup and measured by a $2 \times 2$ patch antenna array and the entire radar board. The RF pulse generator driven by the wideband VCO, duty-cycled conversion, and a doubler generates a series probing radio pulse with around 15 ns pulse width, shown in Fig. 10(a), to an investigated subject. The reflective pulses are further received and correlated by the referenced waves to obtain physiological data. The distance between the sensing radar and human is fixed at 15 cm. Fig. 10(b) exhibits the frequency response of radiated pulse. It is worth saying that a narrow pulse width gives rise to a broadband response with 200 MHz bandwidth, operated at 5.2 to 5.4 GHz. However, for frequency hopping consideration, the switching channels are limited at the desired band of 5 to 6 GHz due to the wide sub-channel. The bandwidth of sensing signal can be narrower by a band-pass filter at RF front-end.

In addition, Fig. 11 illustrates measured pulse repetition rate at 2 MHz, by straightforwardly probing digital controlling switches on the radar board, Ref and T/R switches for controlling transmission/receiving modes, and delay line control by digital signal processing. To
analyze the heart and breathing rate information. Fig. 12 shows the measured raw data of breathing and heart rates in frequency domain. The oscilloscope is used to measured analog vital-sign output signals. The measured raw data are further shown in frequency spectra to observe the repetitive behavior from subject. It is observed that the physiological data exhibit frequency points at 0.2 Hz (12 bpm) and 1.1 Hz (66 bpm), respectively. The measured results show that successful detection of vital signs can be achieved based on the proposed radar system.

5. Conclusion

The impulse radio duty-cycled radar, driven by a wideband VCO as the probing source, is presented in the paper. The 5-bit binary weighted digital control and analog voltage tuning are employed to the RF VCO, exhibits a wideband response, which can be used for frequency hopping technique. Therefore, the undesired narrowband interferences can be relieved. The vital-sign signals are further detected by the proposed sensing radar. To demonstrate this concept, this non-contact and real-time radar is analyzed, designed, and measured.

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