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A novel low-power transceiver topology for noncontact vital sign detection including the power management technique

Chie-In Lee [a,b,*], Yan-Ting Lin [a], Yu-Her Chen [a], Wei-Cheng Lin [a]

[a] Department of Electrical Engineering, National Sun Yat-Sen University, No. 70 Lienhai Rd., Kaohsiung 80424, Taiwan
[b] Institute of Communications Engineering, National Sun Yat-Sen University, No. 70 Lienhai Rd., Kaohsiung 80424, Taiwan

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ABSTRACT

In this paper, power management technique utilized in the direct down-conversion non-quadrature transceiver is presented for the low-power application of vital sign detection. The simultaneous switching noise (SSN) and overshoot and undershoot of the transient waveform distortion resulting from a pulse signal will give rise to interference with a vital sign signal. The pulse width, rise/fall time, and period of pulse bias are analyzed to mitigate the interference in this investigation. Significant issues about direct-current (DC) offset and noise confronted by the presented technique are addressed based on mathematical analysis. In radio-frequency (RF) transceiver architecture including power amplifier (PA), low-noise amplifier (LNA), and mixer, the current-reused (CRU) topology is utilized to achieve low DC power consumption. The post-layout simulation results exhibit that power consumption of the transceiver using the optimized pulse bias is reduced to 40% of the power consumption for transceiver applying the DC bias. In addition, DC offset and null detection point can be alleviated by tunable phase shifter.

1. Introduction

The noncontact Doppler radar sensor requires ultra low-power circuit and high accuracy to detect the vital sign signals for long-term health care [1–3] and life detection [4]. To improve detection accuracy, many topologies have been presented. The quadrature architecture designed for a wireless communication system [5,6] is utilized to detect the vital sign with channel selection [1,2]. In addition, the double-sideband transmission system with wide frequency tuning range [3] is presented to eliminate the null detection point. However, these structures require several active components so that the direct-current (DC) power consumption of the whole system increases [7]. The direct down-conversion non-quadrature topology can be implemented in the low-power vital sign detection system due to less active components required. In the front-end circuit design, several circuit architectures have been developed for low-power application [8–10]. Complementary structure has been presented [8] at the expense of a degraded power gain to provide low-voltage capability. To enhance the gain in low-power design, the current-reused (CRU) configuration [9,10] is proposed to merge the currents required for two transistors into a single current path such that supply current can be reduced. Power consumption is only half of the cascade topology, and gain can be approximately the same with the result of the cascade topology. From another point of view, the power management technique can be employed to further improve efficiency [11–13]. The buck–boost converter can provide dynamic power supply to the power amplifier (PA) so as to prolong the battery life. However, the switching voltage may produce simultaneous switching noise (SSN) [14,15] as well as overshoot and undershoot. These voltage ripples should be mitigated to acceptable level in order to avoid interference with the vital sign signals.

Our previous research presented a high linearity and low-power low-noise amplifier (LNA) design with nonlinear cancellation technique [16]. In this paper, a low-power direct down-conversion non-quadrature transceiver with the power management technique that is applied for the noncontact vital sign detection is presented for the first time. SSN and transient waveform distortion are analyzed and minimized to improve detection accuracy of the presented system with pulse bias. For the transceiver design, the CRU topology is employed to further reduce DC power consumption of the whole system.

2. Power management technique and vital sign detection theory

The main subject of this work is to design a low-power radio-frequency (RF) transceiver for the application of vital sign detection and to maintain detection accuracy simultaneously. Fig. 1 shows novel direct down-conversion non-quadrature transceiver

* Corresponding author at: Department of Electrical Engineering, National Sun Yat-Sen University, No. 70 Lienhai Rd., Kaohsiung, Taiwan 80424.
Tel.: +886 7 525 2000 4110; fax: +886 7 525 4199.
E-mail address: chiein@mail.ee.nsysu.edu.tw (C.-I. Lee).

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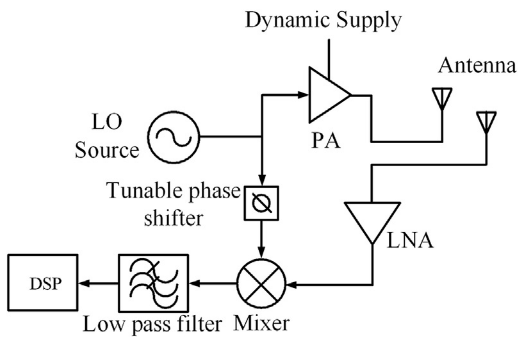

Fig. 1. The novel direct down-conversion non-quadrature transceiver with the power management technique and the tunable phase shifter.

with the power management technique. This is the first time that the power management technique with pulse bias is implemented in the presented PA to further decrease power consumption and to alleviate interference of the SSN, overshoot, and undershoot. Fig. 2 describes the design procedure for the presented vital sign sensor with SSN and overshoot/undershoot considered. In the active state of pulse bias, maximum output power of the PA is 9.3 dBm as the drain voltage is operated at high voltage (V_H) of 2.6 V. For the sleep state, the minimum output power is -7 dBm at low voltage (V_L) of 0.6 V. When the pulse signal is applied to the circuits, variation of the pulse bias will produce signal reflection at the boundary due to transmission line discontinuities [17]. The reflection leads to instantaneous change of the current and voltage at each node, causing overshoot and undershoot and hence significant ripple in the transmitted signal as shown in Fig. 3(a). Besides, SSN can be generated in power and ground planes due to the rapid change in current flowing through parasitic inductor of the power supply [14,18]. Therefore, to investigate the influence of the pulse signal on the presented system, the microstrip lines, the circuit layout, and the bonding wires of the presented system are considered in the simulation. On the other hand, a DC offset effect can occur in direct down-conversion non-quadrature architecture when a RF signal at the same frequency with the local oscillator (LO) frequency is mixed with the LO signal. Significant issues about DC offset and noise confronted by the presented technique will be addressed based on mathematical analysis.

The transmitted signal of a transmitter influenced by transient waveform distortion due to pulse bias can be expressed as follows:

$$T(t) = A(t)\ \sin(2\pi f t + \varphi) \tag{1}$$

where $T(t)$ is the transmitted signal from the transmitter, f is the carrier frequency, and φ is the residual phase that is accumulated in the system. The ripple voltage of the transmitted signal due to transient waveform distortion is given by $A(t)$. When this transmitted signal is reflected by a human subject at a nominal distance d_0, the periodic body movements $x(t)$ due to human cardiopulmonary activity will be modulated in the phase of the received signal according to the Doppler theory [2]. In addition, voltage amplitude variation still exists in the received signal along with the vital sign signal. Therefore, the received signal $R(t)$ can be expressed as

$$R(t) = R_r(t)\sin\left[2\pi f t - \frac{4\pi}{\lambda}x(t) - \frac{4\pi d_0}{\lambda} + \varphi\right] \tag{2}$$

where $R_r(t)$ is the amplitude of the received signal with the time-varying ripple voltage and λ is the wavelength of the RF signal. Information about the human cardiopulmonary activity can be demodulated through the mixer with an LO signal, which is derived from the transmitted signal. Note that the phase noise from LO can

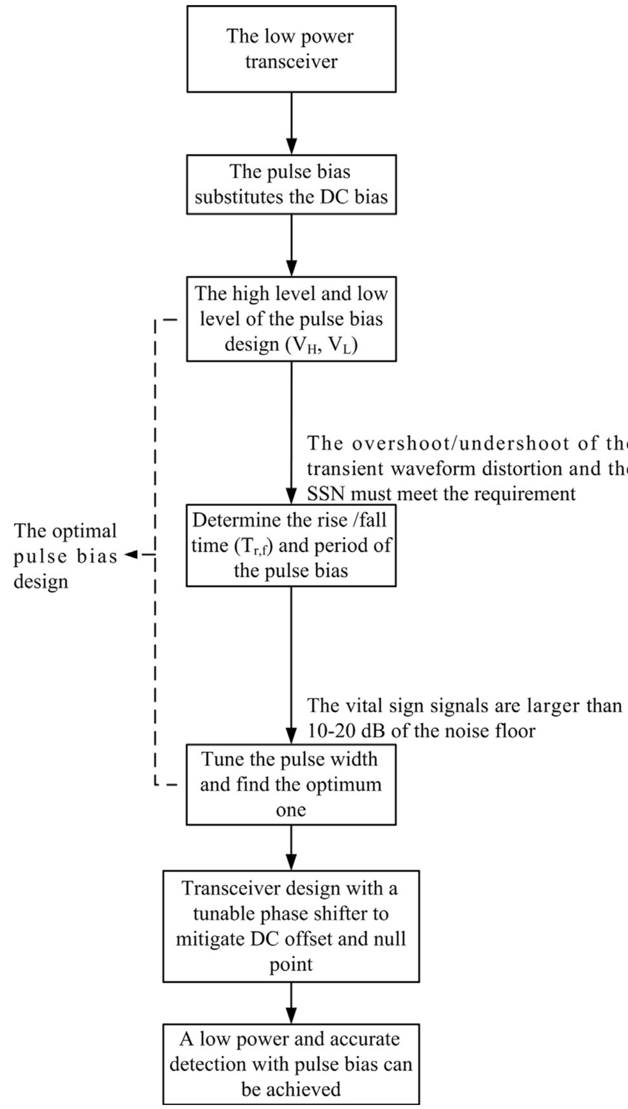

Fig. 2. The flow chart describes the design process for the power management technique based on the vital sign detection.

be neglected due to range correlation [2,19]. Therefore, a detected signal in the baseband $B(t)$ can be expressed as

$$B(t) = B_r(t)\ \cos\left(\varphi_B - \frac{4\pi x(t)}{\lambda}\right) \tag{3}$$

where

$$\varphi_B = \varphi - \frac{4\pi d_0}{\lambda} - \varphi_{LO} \tag{4}$$

$B_r(t)$ is the amplitude of the baseband signal with the time-varying ripple voltage and φ_{LO} is the phase of the LO signal. Based on the Taylor series expansion, the baseband signal shown in Eq. (3) can be approximated as

$$B(t) = B_r(t)\ \sin\ \varphi_B \cdot \frac{4\pi}{\lambda} \cdot x(t) + B_r(t)\ \cos\ \varphi_B \tag{5}$$

High-order terms of the expansion are neglected under the condition $x(t) << \lambda$. The first term on the right-hand side of Eq. (5) contains the vital sign signal as well as the ripple voltage at baseband $B_r(t)$. This ripple voltage can be a significant noise source, which can overwhelm the vital sign signal, degrading the detection accuracy. The second term on the right-hand side of Eq. (5)