A Low Energy Injection-Locked FSK Transceiver with Frequency-to-Amplitude Conversion for Body Sensor Applications

Joonsung Bae and Hoi-Jun Yoo
Dept. of EE, KAIST, 373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea
E-mail: joonsung@eeinfo.kaist.ac.kr

Abstract

An energy-efficient 915MHz FSK transceiver for wireless body sensor network (BSN) applications is implemented in 0.18um CMOS technology with 0.7V supply. A transceiver architecture based on injection-locked frequency divider (ILFD) is proposed for the low energy consumption. In the receiver, through the ILFD in the signal path, the received FSK signal is converted to amplitude-modulated signal which is applied to the following envelope detector. In the transmitter, the ILFD is used as digitally-controlled oscillator (DCO) which replaces the frequency synthesizer to eliminate the crystal oscillator (XO). The receiver and transmitter consume 420uW and 700uW, respectively, at -10dBm output power with a data rate of 5Mb/s, corresponding to energy consumption of 84pJ per received bit and 140pJ per transmitted bit.

Introduction

The emerging area of wearable or implantable BSN requires low energy transceiver to extend its battery life time. Since the energy consumption is the power consumption multiplied by its usage time, low power transceiver with fast turn-on time should be employed under tight duty cycle control. There have been 2 modulation schemes widely used in energy-efficient transceiver, which can be detected by non-coherent architecture. One is OOK and the other FSK. OOK has the advantage of receiver side because it is suitable for simple envelope detection [1]-[2] and super-regenerative [3] architecture. However, in transmitter side it is strongly susceptible to interferers and requires linear PA to send an amplitude-modulated signal. On the other hand, FSK has the merit of transmitter side because its constant envelope nature with zero crossing data permits use of an efficient nonlinear PA by directly modulating the oscillator [4]-[5]. Nevertheless, the receiver architecture is more complex than envelope detector based architecture.

In this paper, we propose a low energy FSK transceiver for BSN by combining only the strong points of OOK and FSK. That is, the efficient direct modulation FSK transmitter and the simple envelope detector based receiver are employed. The reason why this is possible is that we adopt ILFD as frequency-to-amplitude converter in receiver and DCO in transmitter. Fig.1 shows overall transceiver architecture. In the receiver, the tuned LNA amplifies the received FSK signal. Through the ILFD, the LNA output is uniquely converted to amplitude modulated signal which is directly fed to the envelope detector, and then base band signal is 1-bit quantized by demodulator. In the transmitter, the ILFD is used as DCO and the FSK data is transmitted by directly modulating the DCO with digital data. All inductors in the transceiver are low-cost off-chip devices with Q-factors less than 13.

Frequency-to-Amplitude Conversion

The proposed injection-locked FSK transceiver is based on the property that the incident frequency of injection locked oscillator (ILO) can be discriminated by ILO's output amplitude, which means frequency-to-amplitude conversion. Following the analysis in [6], we redraw conceptual diagram of ILO with LC tank which resonates at w_o in Fig. 2(a). Now suppose the ILO oscillates at w_1 and injection locking occurs by proper I_{inj}. For simplicity, we assume I_{inj} is much smaller than I_{osc} and the output amplitude of ILO is proportional to I_T; then the phase difference between I_{osc} and I_{inj} (θ) reaches $-\pi/2$ and $\pi/2$ at the edge of the locking range [6]. From the phasor diagram of Fig. 2(b), $|I_T|$ is given by $|I_T|^2 = |I_{inj}|^2 + |I_{osc}|^2 + 2|I_{inj}||I_{osc}|\cos\theta,\ (-\pi/2 \le \theta \le \pi/2)$ However, as plotted in Fig. 2(c), the ILO output amplitude is not one-to-one mapped to the incident frequency. In order to fully utilize the locking range, which is limited by incident power, ILFD is adopted to shape one-to-one relation instead of ILO. Fig. 3(a) shows conceptual diagram of ILFD using mixer which translates I_{inj} to $w_{inj}-w_0$. As depicted in Fig. 3(b), it is equivalent to injection of I_{inj} at $w_{inj}-w_0$ directly into the oscillation loop with $-\pi/2$ phase shift between I_{inj} and I_{osc}. From the phasor diagram of Fig. 3(c), $|I_T|$ can be now written as $|I_T|^2 = |I_{inj}|^2 + |I_{osc}|^2 + 2|I_{inj}||I_{osc}|\cos(\theta-\pi/2),\ (-\pi/2 \le \theta \le \pi/2)$ The output amplitude of ILFD is a monotonically increasing function of the incident frequency, giving one-to-one relation as shown in Fig. 3(d). Therefore, frequency-to-amplitude conversion by using ILFD makes it possible to use energy-efficient envelope detection receiver.

Transceiver Implementation

Fig. 4 shows transceiver schematic focused on ILFD with receiver and transmitter mode. In the receiver mode, the ILFD plays a role in frequency-to-amplitude converter. As shown in gain and S11 curve of Fig. 4(a), the LNA with a tuned L_1C_1 load amplifies the received FSK signal and L_2C_2 tank is used for 50ohm impedance matching. The ILFD with L_3C_3 tank oscillates at half the incident frequency and L4 is introduced to resonate with parasitic C_4 at the incident frequency to enhance the locking range of ILFD. The C_C, in series with L_4, serves as a dc block. The amplitude-modulated ILFD output signal is then applied to the following energy-efficient envelope detector. In the transmitter mode, the ILFD with programmable capacitor bank C_{bank} is utilized as DCO. The PA reuses the L_2C_2 tank for the load impedance to effectively drive antenna as displayed in Fig. 4(b). Resonating at double the DCO fundamental frequency, L_4C_4 tank filters out any harmonic frequency but the second harmonic. Especially, the DCO replaces frequency synthesizer to eliminate the XO, allowing more efficient duty cycling. The DCO can be tuned of a desired frequency with 100kHz accuracy by 8bit capacitor bank [Fig. 4(c)] and the frequency drift over temperature variation can be easily compensated thanks to ILFD based architecture. The DCO phase noise is -120dBc/Hz at 1MHz offset, and the stabilization time is less than 500ns.

Implementation Results

Fig. 5 presents the chip microphotograph of the transceiver fabricated in 0.18um CMOS process. The area of the chip is 1.1mm×1.5mm. The total power consumption (TABLE I) for the receiver and transmitter are 420uW and 700uW, respectively, with -10dBm output power. The spectrum measurement results (Fig. 6) describe (a) transmitter output spectrum at a data rate of 5Mb/s with frequency deviation of 5MHz, (b) mapping between output amplitude of ILFD and incident frequency at 50ohm load, (c) ILFD output spectrum with 2.5Mb/s received signal and (d) ILFD output spectrum with 5Mb/s received signal in the receiver mode. The results of Fig. 6(b), (c), and (d) are obtained by using test buffer (PA). The oscilloscope measurement results (Fig. 7) shows ILFD output waveforms at 50ohm load with demodulated data and eye diagram at a data rate of 5Mb/s. From the measurement results of Fig. 6 and Fig. 7, the frequency-to-amplitude conversion property of ILFD is verified and it enables energy efficient transmitter and envelope detector based receiver architecture. The performance summary and comparison with recent low energy transceivers [1]-[5] are summarized in TABLE II.

Conclusion

A novel ILFD based transceiver with one-to-one frequency-to-amplitude conversion is proposed and implemented for body sensor applications. The efficient FSK direct modulation transmitter and envelope detection receiver enables ultra low energy data transmission. As a result, the transceiver achieves the most energy-efficient performance compared with state-of-the-art works.

References

[1] D. C. Daly et al., "An Energy-Efficient OOK Transceiver for Wireless Sensor Networks," *IEEE JSSC*, vol. 42, no. 5, pp. 1003-1011, May 2007.

[2] N. M. Pletcher et al., "A 52uW Wake-Up Receiver with -72 dBm Sensitivity Using an Uncertain-IF Architecture," *IEEE JSSC*, vol. 44, no. 1, pp. 269-280, Jan. 2009.

[3] B. Otis et al., "A 400uW-RX, 1.6mW-TX Super-Regenerative Transceiver for Wireless Sensor Networks," *IEEE ISSCC*2005

[4] B. W. Cook et al., "Low-Power 2.4-GHz Transceiver With Passive RX Front-End and 400-mV Supply," *IEEE JSSC*, vol. 41, no. 12, pp. 2757-2766, Dec. 2006.

[5] J. Bae et al., "A 490uW Fully MICS Compatible FSK Transceiver for Implantable Devices," *IEEE Symposium on VLSI Circuits*2009

[6] B. Razavi, "A Study of Injection Locking and Pulling in Oscillators," *IEEE JSSC*, vol. 39, no. 9, pp. 1415-1424, Sep. 2004.

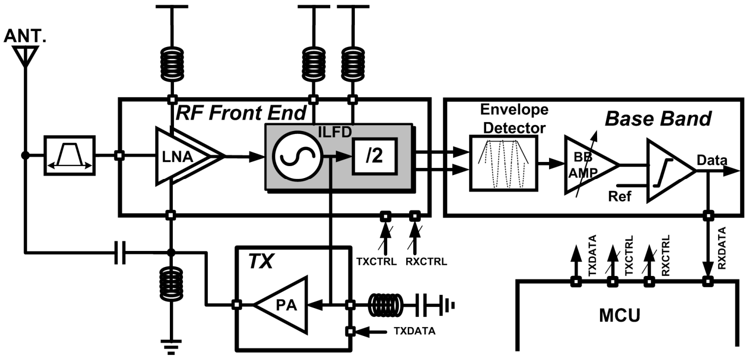

Fig. 1. Transceiver architecture

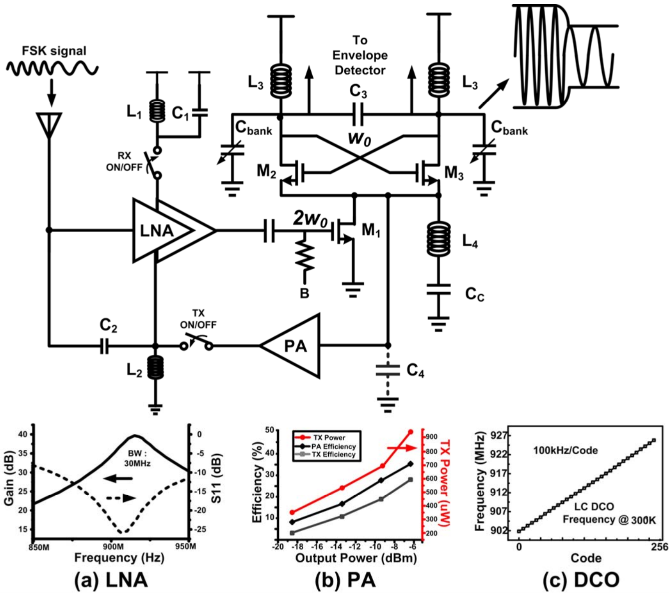

Fig. 4. Transceiver implementation

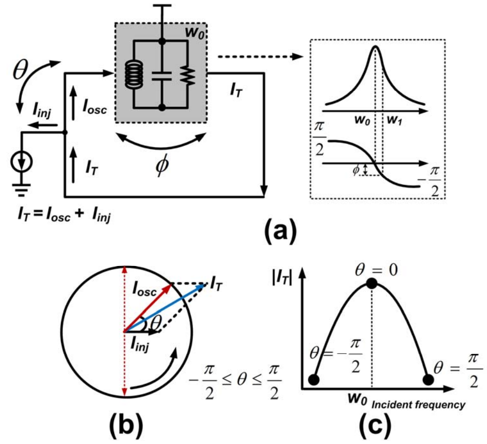

Fig. 2. Frequency-to-Amplitude conversion of ILO

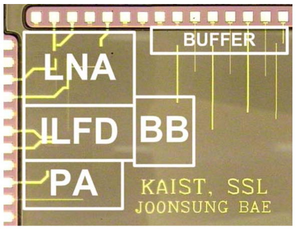

Fig. 5. Chip microphotograph

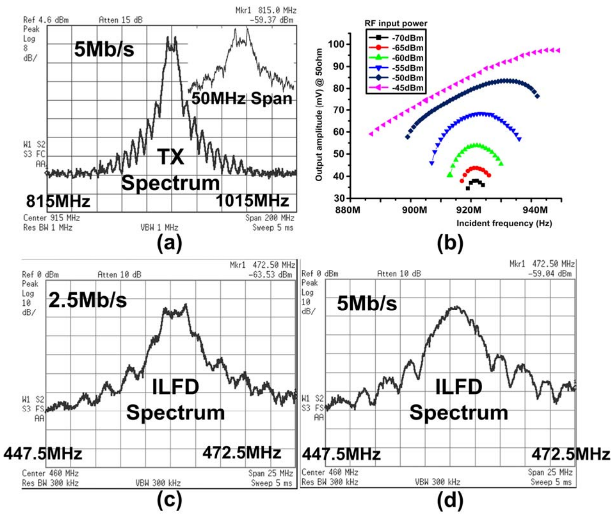

Fig. 6. Spectrum measurement

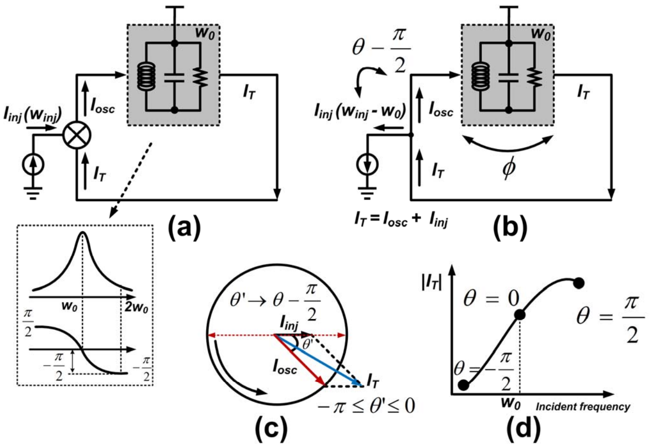

Fig. 3. Frequency-to-Amplitude conversion of ILFD

TABLE I
Power summary

Receiver	
LNA	280uA
ILFD	300uA
Base Band	20uA
Total Power	**420uW**
Transmitter	
DCO	300uA
PA	700uA
Total Power	**700uW**

TABLE II Performance summary and comparison

Reference	[1]	[2]	[3]	[4]	[5]	This work
Technology	0.18um	90nm	NA	0.13um	0.18um	0.18um
Supply	1.4V	0.5V	0.9V	0.4V	0.7V	0.7V
Modulation	OOK	OOK	OOK	FSK	FSK	FSK
Frequency band	915MHz	2GHz	1.9GHz	2.4GHz	400MHz	915MHz
Sensitivity	-37dBm	-72dBm	-100.5dBm	NA	-70dBm	-73dBm
Data rate	1Mb/s	100kb/s	5kb/s	300kb/s	250kb/s	**5Mb/s**
TX output power	-11.4dBm	-	250uW	300uW	-16dBm	-10dBm
Power consumption	RX: 500uW TX: 3.8mW	52uW	RX:400uW TX: 1.6mW	RX: 330uW TX: 1mW	RX: 490uW TX: 400uW	**RX: 420uW** **TX: 700uW**
Energy per bit(RX)	0.5nJ/b	0.52nJ/b	80nJ/b	1.1nJ/b	1.96nJ/b	**84pJ/b**
Application	WSN	Wake up Receiver	WSN	WSN	Implantable BSN	BSN

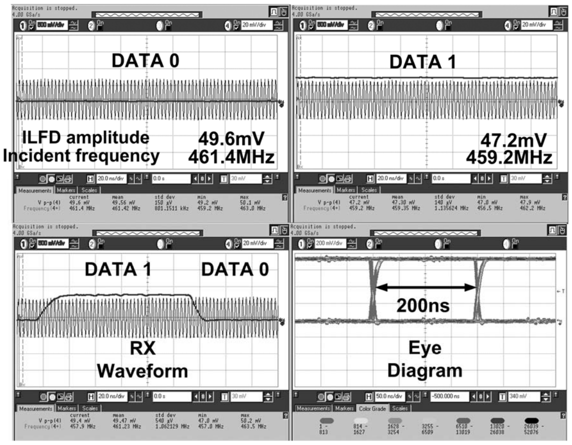

Fig. 7. Oscilloscope measurement