A Dynamic Real-time Capacitor Compensated Inductive Coupling Transceiver for Wearable Body Sensor Network

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Abstract

A real-time capacitor compensation (RCC) scheme is proposed for low power wearable inductive coupling transceiver. To compensate for the dynamic parameter variations in real time, the inductance value is monitored and its resonance frequency is adjusted by additive capacitors. RLC bridge for detection of the inductance variations and the dual-edge sampling comparator for recognition of the variance direction are proposed. The proposed transceiver consumes only 426.6μW (102.6μW for TRX and 324μW for CDR) in a 0.18μm CMOS technology. And the compensation time takes only 4.78μs, including 3μs of detection and 1.78μs for compensation process in worst case.

Introduction

Recently, wearable solutions for mobile computing and health monitoring system receive much attention, and wireless communication with integrated sensors has been adopted in daily healthcare monitoring system [1]-[2]. Especially, wearable inductor becomes a strong candidate for inductive coupling in wearable applications of less than 1cm distance [1]. For example, inductors in Fig.1 shows inductors made on a fabric, one is stitched and the other is printed. However, they suffer from static and dynamic variations during manufacturing process and operation. Stitching and printing on a fabric is not a precise technology leading to more than 10% variation of the inductance values. In addition, the human body is always moving to induce the fabric warp resulting in additional variations of inductance values. According to the measured values of the wearable inductor in Fig.1, their static and dynamic variances are up to 17% and 24%, respectively. The SNR degradation due to these variations amounts to 16.7dB which makes the wearable wireless communication very unreliable, and that's why inductive coupling has not been widely used in inter-clothes communication for wearable healthcare monitoring systems. In this paper, we propose a wearable inductive coupling transceiver with dynamic compensation of inductance values for robust communication. Especially, a Real-time Capacitor Compensation (RCC) scheme is proposed with binary-weighted capacitor banks of 500fF unit capacitance.

Wearable Inductive Coupling Transceiver

Fig.2 shows the block diagram of the proposed inductive coupling transceiver. It is composed of an On-Off Keying (OOK) transceiver, a Clock Data Recovery (CDR) circuit [3], and RCC block. The OOK transmitter can achieve low power consumption by generating 300ns-pulse data instead of 50% duty cycle. Also, RCC block enables the transceiver to operate continuously in dynamic wearable environment by adjusting its resonance frequency using 8 binary-weighted capacitors with 500fF unit capacitor. The total capacitance of the bank can be selected from 32pF to 159.5pF, and resonance frequency can be changed from 8MHz to 17.8MHz by 256 steps for a 2.5μH inductor. Since measured 3dB bandwidth of LC tank is 200kHz, 38kHz step frequency is enough for compensation. For 13.56MHz resonance frequency, inductors with values from 864nH to 4.3μH can be compensated. Fig.3 shows the OOK receiver circuit, which uses RLC bridge and a threshold comparator to pass the signal near carrier frequency with high selectivity. The difference between two threshold voltage V_{REFP} and V_{REFN} can be adjusted according to the mutual inductance of each inductive coupling. A debouncer circuit is added to hold the output for one clock period when the data is '1'.

Real-time Capacitor Compensation (RCC)

Fig.4 shows the principle of compensation and the circuit schematic of the proposed dual-edge sampling comparator. To achieve the real time compensation, RLC bridge is shared by OOK receiver and RCC block. During data transmission, RLC bridge and the dual-edge sampling comparator can detect the inductance variation using phase difference of LC tank as in (1):

$$\angle\theta_{INP} = \tan^{-1}\left(\frac{k_2\sqrt{C/L}}{R_1(1-k_1k_2)}\right) \quad (1).$$

while θ_{INP} is the phase of LC tank, L (or C) is the initial inductance (or capacitance), and k_1 (or k_2) is the ratio between initial and current inductance (or capacitance). The signals at positive and negative clock edge are compared together and determine the phase of LC tank. When both signals are equal, the compensation is not necessary. If one signal is larger than the other, the capacitance value should be increased or decreased to compensate the variation of L as shown in Fig. 4(a). The dual-edge sampling comparator shown in Fig.4(b) samples *INP* at positive and negative clock edge sequentially, and compares them to output *CAPUP* and *CAPDN*. The proposed RCC scheme accomplishes compensation to track the inductance variation in 6 steps, or 24 cycles (1.78μs), as shown in Fig.5. Compared to the conventional searching method like binary search in [4], the RCC scheme saves 8 cycles for compensation because the capacitance selection range is restricted within ±25% variation. The RCC scheme begins the compensation only 3μs after the inductor variation occurs. The compensation time is also reduced by 25% compared with the binary search resulting in 1.78μs in the worst case. And peak power consumption of 70.2μW can be achieved which is only 41% of [4].

Implementation Results

Fig.6 presents the chip microphotograph of the proposed inductive coupling transceiver. The core size of the OOK transceiver and RCC block are 0.041-mm^2 and 0.097-mm^2, respectively, in a 0.18μm CMOS technology. The measured data transmission waveform and BER characteristic are shown in Fig.7. The reported maximum data rate is 4Mbps and the maximum communication range is 3cm with BER<10^{-3}. Fig.8 shows the capacitor compensation result of the wearable inductors. The resonance frequency variation among several LC tanks is reduced from 24% to 0.29% after compensation with the adjusted capacitance. And the SNR is also enhanced by 13.36dB. Table I summarizes the performance of the proposed inductive coupling transceiver chip. The power consumption of the complete transceiver is 426.6μW (102.6μW without CDR) at 1.8V supply when the data rate is 4Mbps. The performance comparison with the previous works is summarized in Table II. The proposed inductive coupling transceiver chip consumes the lowest power with even dynamic compensation of its characteristics. The proposed transceiver also shows the fastest compensation time with real-time variance detection.

Conclusion

A real-time capacitor compensated inductive coupling transceiver is implemented for wearable body sensor network. The proposed RCC scheme with RLC bridge and the dual-edge sampling comparator enables the parameter variation to be compensated in real time. Total compensation time takes only 4.78μs in worst case, including 3μs of variance detection. The overall transceiver chip consumes 426.6μW (102.6μW without CDR) at 1.8V supply voltage and an area of 2.7mm^2.

References

[1] Jerald Yoo, et al., "A 5.2mW Self-Configured Wearable Body Sensor Network Controller and a 12µW 54.9% Efficiency Wirelessly Powered Sensor for Continuous Health Monitoring System," *ISSCC Dig. Tech. Papers*, Feb., 2009.

[2] A. C-W. Wong, et al., "A 1V, Micropower System-on-Chip for Vital-Sign Monitoring in Wireless Body Sensor Networks," *ISSCC Dig. Tech. Papers*, pp.138-602, Feb., 2008.

[3] Hyejung Kim, et al., "A 1.12mW Continuous Healthcare Monitor Chip Integrated on a Planar Fashionable Circuit Board," *ISSCC Dig. Tech. Papers*, pp.150-603, Feb., 2008.

[4] Jerald Yoo, et al., "A 1.12pJ/b Resonance Compensated Inductive Transceiver with a Fault-Tolerant Network Controller for Wearable Body Sensor Networks," *Proc. of A-SSCC*, pp.313-316, Nov., 2008.

[5] D. Guermandi, et al., "A 1V 250kpps 90nm CMOS Pulse Based Transceiver for Cm-range Wireless Communication," *Proc. of ESSCIRC*, pp.135-138, Sep., 2007.

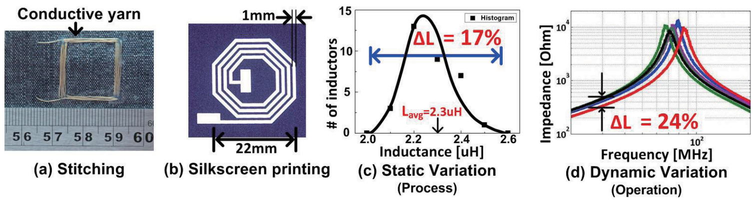

Fig. 1. Wearable inductors (a), (b) and their variances (c), (d)

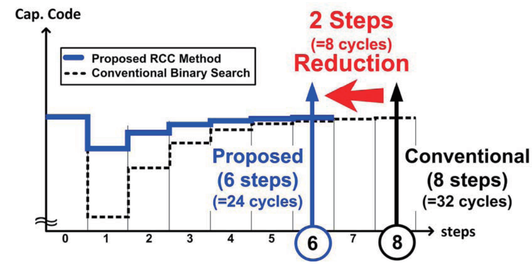

Fig. 5. Comparison of RCC and conventional method

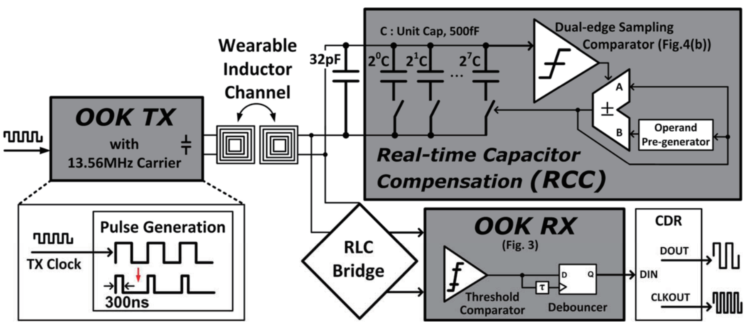

Fig. 2. Proposed inductive coupling transceiver chip architecture

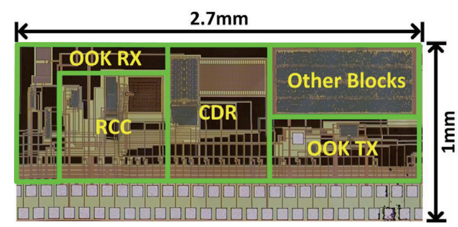

Fig. 6. Chip Microphotograph

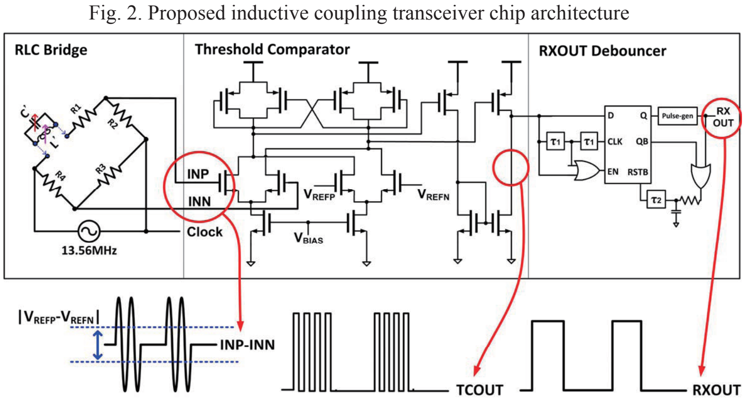

Fig. 3. OOK RX circuit

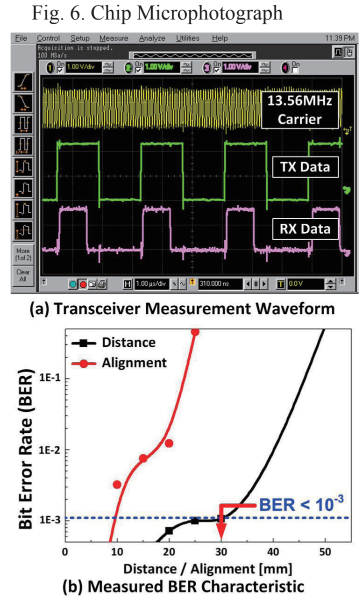

Fig. 7. Measurement result
(a) Transceiver waveform
(b) BER characteristic

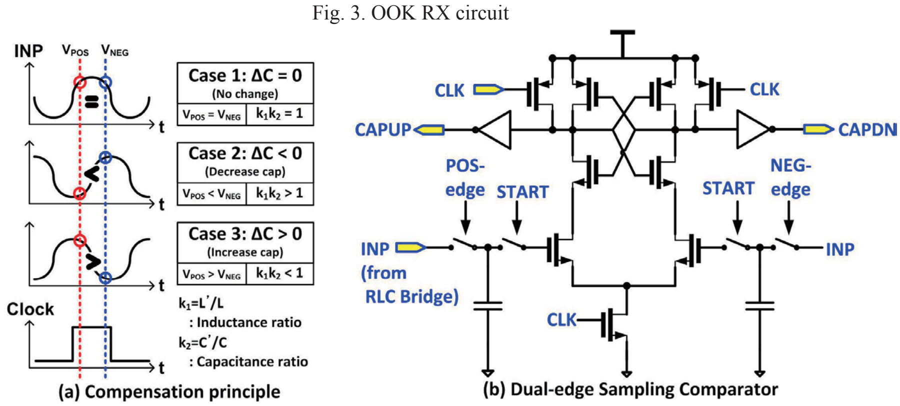

Fig. 4. Proposed RCC block (a) Compensation principle (b) Dual-edge Sampling Comparator

TABLE I. THE PERFORMANCE SUMMARY

Technology		0.18µm CMOS	
Supply Voltage	**Core**	1.8V	
	I/O	3.3V	
Data Rate		Up to 4Mbps	
Comm. Distance		3cm (BER < 10^{-3})	
Power Consumption (at 4Mbps)	**TX**	3.6µW	**102.6 µW**
	RX	28.8µW	
	RCC	70.2µW	
	CDR	324µW	
	Total	426.6µW	
Die Area		1mm x 2.7mm (include pads)	

TABLE II. THE PERFORMANCE COMPARISON

	Ref. [4]	Ref. [5]	**This Work**
Technology	0.25µm	90nm	0.18µm
Power Consumption (TRX + Comp.)	210µW (with 2.5V)	187µW (with 1V)	**102.6µW (with 1.8V)**
Comp. type / # of steps in worst case (Total cap)	Periodically Check / 10 steps (Total: 2^{10})	Not Supported	**Real-time / 6 steps (Total: 2^8)**
Application	WBSN	Cm-range Wireless	WBSN

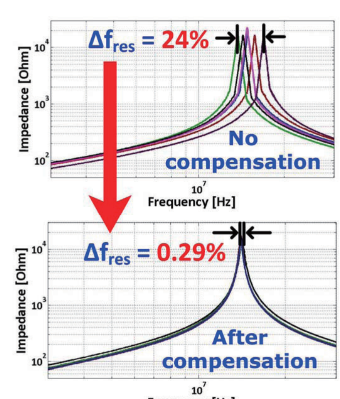

Fig. 8. Measured capacitor compensation result