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A Wireless ECG Acquisition and Classification System for Body Sensor Networks

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Abstract—**This paper demonstrates a wireless ECG acquisition and classification system with a bio-signal processor (BSP), a super regenerative transceiver, and a digital signal processor (DSP). The BSP, which is implemented with low complexity architecture, includes only a low noise amplifier with chopping techniques and a high-pass sigma-delta modulator (HPSDM). The super-regenerative on-off keying (OOK) transceiver is applied for the low power, short range transmission and low date rate wireless communication. For the signal processing and analyzing, the DSP circuit is adopted in the receiver. The whole system is implemented in a TSMC 0.18μm 1P6M CMOS process under the supply voltage of 1.2 V. In the near body node, the power consumption including a BSP and a transmitter is 587μW only. With two PR44 zinc-air batteries of 605mAh, the near body node circuit can be operated about 100 days. In the receiving node, the power consumption with a receiver and a DSP is 926μW.**

I. INTRODUCTION

Body sensor networks (BSNs), which can be used without having to visit a hospital, have become popular, and provide both users and doctors with significant health information [1] [2]. However, building an accurate, convenient home healthcare center for long-term use presents a significant challenge to IC and system designers. In [3], an analog IC has been proposed for wireless ECG acquisition system, the communication is fit for the 802.15.4 2.4GHz standard (ZigBee), but the power consumption at near body nodes, including the analog front-end circuit and transmitter, is too high to be used for a long time. Moreover, the architecture is also more complex than the architecture proposed in this paper.

This paper proposes a low-power wireless bio-signal acquisition and classification system with sufficient capability despite low circuit complexity. This system can be used in wearable wireless ECG acquisition systems, and consists of three blocks: a bio-signal processor (BSP), an on-off keying (OOK) transceiver, and a digital signal processor (DSP). The acquired bio-signal is processed by a chopper-based continuous time feedback amplifier (CBCTA) and a switched-capacitor high-pass sigma-delta modulator (HPSDM) in the BSP. The digitized bio-signal is then directly transmitted to the DSP via a super regenerative transceiver. The digitized bio-signal is down-sampled to the desired band and classified according to heart symptoms. The classified information can be sent to an intelligent mobile phone, help to ECG-signal record. As the mobile clinical assistant [1], the user can observe the results, or even send the result to the cloud sever of a hospital.

The structure of this paper is as follows. Section II describes the proposed system and the measurement results are shown in Section III. Finally, Section IV is the conclusion of the paper.

II. SYSTEM OVERVIEW

Fig. 1 shows the proposed wireless ECG acquisition and classification system. This system can be divided into three main parts: 1) BSP. 2) OOK Transceivers. 3) DSP. Firstly, the ECG signal can be acquired, amplified and digitized by the BSP circuit. Secondly, the digitized ECG signal is sent through the OOK transmitter and recovered on the receiving node. Thirdly, the digitized ECG signal is analyzed by the DSP circuit, and classified into a normal beat or an abnormal ECG signal.

The proposed system has several features that distinguish it from conventional wireless ECG acquisition systems. 1) The system's simplified analog front-end circuit provides high performance and low power dissipation. 2) In the transmitter node, the baseband signal with quantization noise provides fine tolerance of transmission error without requiring baseband processors such as encryption, encoders, or circuit debuggers. 3) The digitized bio-signal is transmitted via a super regenerative OOK transceiver, and the DSP features powerful and precise signal detection and classification functions. 4) A monitoring and control service (MCS), usually a personal computer or intelligent mobile phone, bridges the communication between heart disease classification and cardiologists. The cardiologists can inspect or verify the classification results using the MCS, and the coefficients of the classification algorithm can be fine-tuned to suit specific cardiac patients. The detail techniques of each part are introduced below:

A. BSP circuit

Fig. 2 demonstrates the amplifying and digitizing circuit blocks. The difference differential amplifier (DDA) is used to prevent interference between the differential input and the feedback factor and to provide programmable gains of 20dB, 24dB, and 28dB. The HPSDM directly processes the chopper signal at the amplifier output. The carrier data is encrypted by the noise as a result of noise shaping and chopper techniques in the transmitter, which is important for secure BSN communication. In this study, the main ECG signal is chopped to a center frequency of 25.6kHz to avoid interference coming from the low-frequency noise of the amplifier. The 3rd-order feed-forward HPSDM with 1-b

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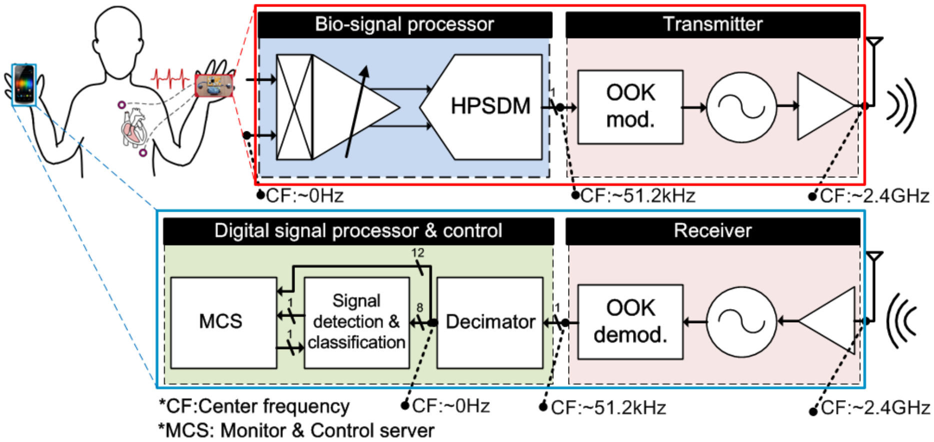
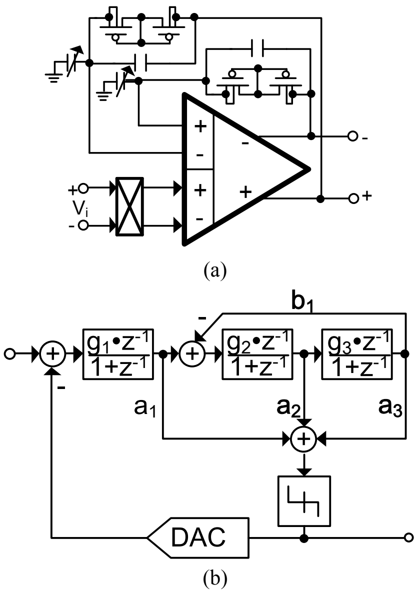


Fig.1. Block diagram of the proposed wireless bio-signal acquisition and classification system.



(b)

Fig.2. Schematic of BSP circuits. (a) Chopper based continuous time amplifier. (b) 3rd 1-b HPSDM with feed-forward topology.

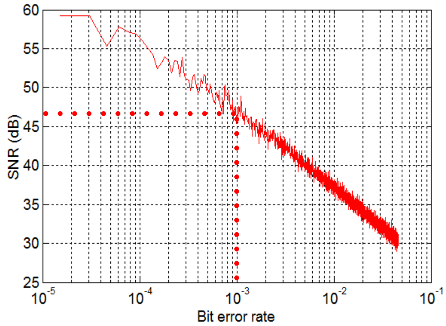


Fig.3. Bit error rate versus the SNR of the received data.

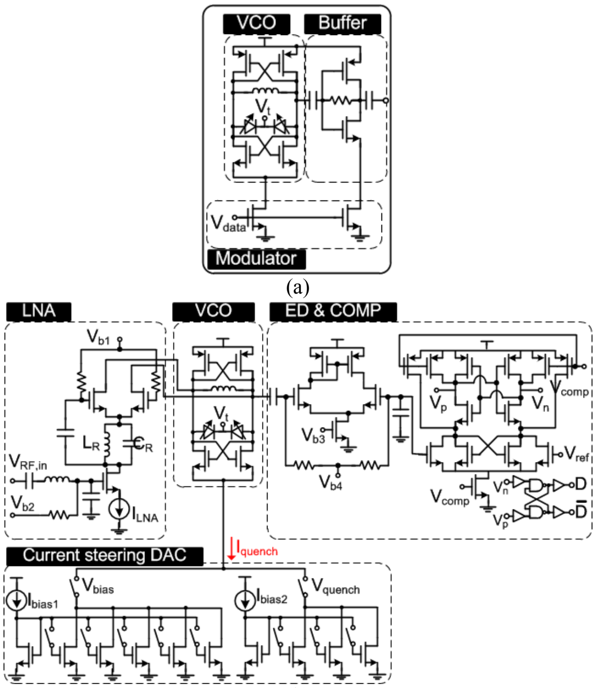
quantizer and an oversampling ratio of 128 not only acts as an essential digitizer, but also extends the bandwidth of the signal, thereby giving the device the ability to resist or tolerate bit error during transmission [4]. Fig. 3 illustrates the bit error rate (BER) versus signal-to-noise ratio (SNR) of the received data based on intercepting 50,000-point data from a 1-bit stream output of HPSDM. The maximum SNR without channel noise is 59dB under a 50-Hz sinusoidal input. Additive white Gaussian noise is included in the channel model to evaluate the BER versus SNR at the DSP output, revealing that a received SNR of 48 dB can maintain a BER of 10^{-3} without any en-/decoder or error debugger in the wireless communication.

B. *Super-regenerative OOK transceiver*

Because the bio-signal acquisition circuit can tolerate transmission error, the super-regenerative transceiver with on-off keying (OOK) modulation at 2.4GHz can be adopted in the BSN to achieve low power consumption. As shown in Fig. 4, the transmitter consists of a complementary cross-coupled pair oscillator and a self-biasing buffer with OOK modulation. The receiver consists of a low-noise amplifier (LNA), an oscillator, a quench generator, an envelope detector (ED), and a comparator. In order to recover the RF signal to the baseband signal, the RF signal is received and amplified by the LNA, the down converted by the oscillator. Based on the timing control of the receiver, the bias digital-to-analog converter (DAC) and quench DAC are used to control the I_{quench} during Q-enhancement and super-regenerative modes to enhance the start-up time and the bandwidth [5].

C. *DSP circuit*

The main functions of the DSP and control circuit shown in Fig. 5 are beat (signal) detection and classification. This setup differs from fast Fourier transform processors because of its balancing of the time and frequency domains. The discrete wavelet transform (DWT) is quite commonly used to analyze low frequency bio-signals, and can be easily implemented by digital circuits [6]. The digitized ECG signal at the decimator output is fed into the 4th-order DWT processor to calculate the coefficients of [W1, W2, W3, W4, S4], which can be used to extract ECG signals. The W4 coefficient is adopted in the beat detection algorithm to evaluate the frequency location of the ECG beats. Because the maximum human heart rate does not exceed 220 beats per minute (BPM), the beat detection window can be defined as 32 points with a 120Hz sampling rate to cover the maximum BPM occurrence. The maximum peak can be easily detected by comparing the local peaks within 32 points of the detection section. For the ECG classification algorithm, the classification data of eight symptom information is diagnosed on the MCS by cardiologists, who then feed the result back to program the weight of the coefficients comparison. This new feature, with programmable DSP, will help cardiologists to customize the proposed device to suit different cardiac patients.



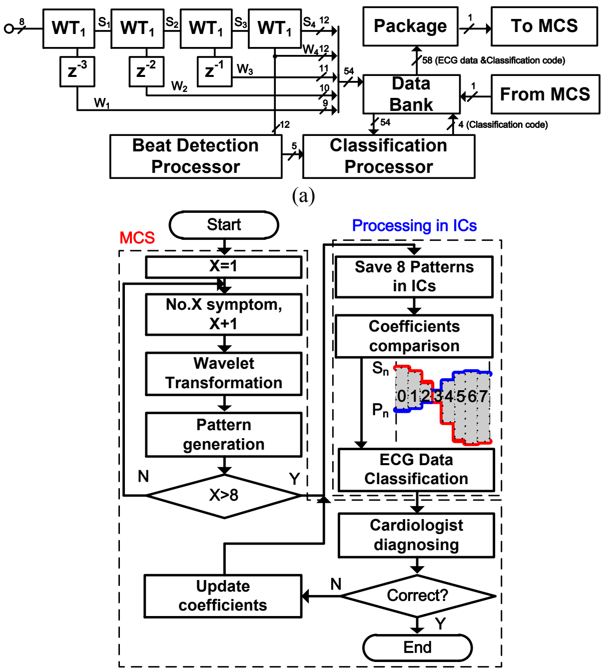
(a)

(b)

Fig.4. Circuit diagram of the proposed super-regenerative transceiver. (a) transmitter. (b) receiver.

III. EXPERIMENTAL RESULT

Fig. 6 illustrates the measurement environment, including: 1) BSP, 2) communication between transmitter and receiver, 3) digital signal demodulator, 4) signal detection and classification, and 5) MCS on the intelligent mobile phone. The detailed verification is described as follows. First, the ECG conductive adhesive electrodes were selected as the ECG test electrode. We then used the Wilson circuit to acquire the most common ECG signals: Lead I, II, & III. Next, we chose the common signal Lead II to demonstrate the overall system. The 2.4GHz omnidirectional SMD antennas were used for the communication between transmitter and receiver, and the distance was set within one meter. Since the DSP chip was still being fabricated at this point, the beat detection and classification DSP circuit of the proposed system were verified using the Altera cyclone IV FPGA. For the convenience of the cardiologists, a Bluetooth device was embedded in the FPGA to allow wireless communication between the DSP and the MCS, and the MCS was built into an intelligent mobile phone. The cardiologists can feedback the results to program the DSP to enhance their diagnosis. The demonstration can be used to realize our proposed scenario and to verify our proposed ICs, which is also a topic of interest for cardiologists. Fig. 7 shows the ECG classification results, included the heart rate and the different ECG categories, on the intelligent mobile phone. The test ECG patent was referred to from the MIT-BIH database and the classified ECG signals was match to the database [7]. Table I and Table II shows the features and specification of each part of circuit, respectively.



(a)

(b)

Fig.5. (a) Block diagram of the DSP and control circuit. (b) classification algorithms.

TABLE I
SUMMARY OF FEATURES

Function	JSSC'11 [8]	Zio®Patch [9]	This Work
Process / Chip Area.	0.18 μm / 25 mm^2	N/A	0.18 μm / 7.43 mm^2 (total)
Wireless Transmission	✓	×	✓
Bio-signal Acquisition	✓ (10-bit)	✓ (10-bit)	✓(10-bit)
QRS-Detection	×	✓ (Off Line)	✓(On Line)
Bio-signal Classification	×	✓ (Off Line)	✓(Any 8 Kinds)
Impedance Variance	✓	×	×
Power consumption	5.3mW /2.8mW	N/A	0.587mW(front-end) /0.926mW(back-end)

IV. CONCLUSION

This paper demonstrates a bio-signal acquisition and classification system with wireless telemetry in the TSMC 0.18μm standard CMOS process. The total power consumption of the acquisition front-end circuit is only 586.5μW at 1.2V supply voltage. Fitted with two 605mAh PR44 zinc-air batteries, the wearable wireless ECG acquisition system, including digitizing and transmitter, can operate for about 100 days. To correctly diagnose heart disease based on the MIT-BIH arrhythmia database, the required accuracy in terms of beat detection and classification are 99.44% and 97.25%, respectively. These rates can be improved by the revision of the weight of coefficients comparison suggested by cardiologists.

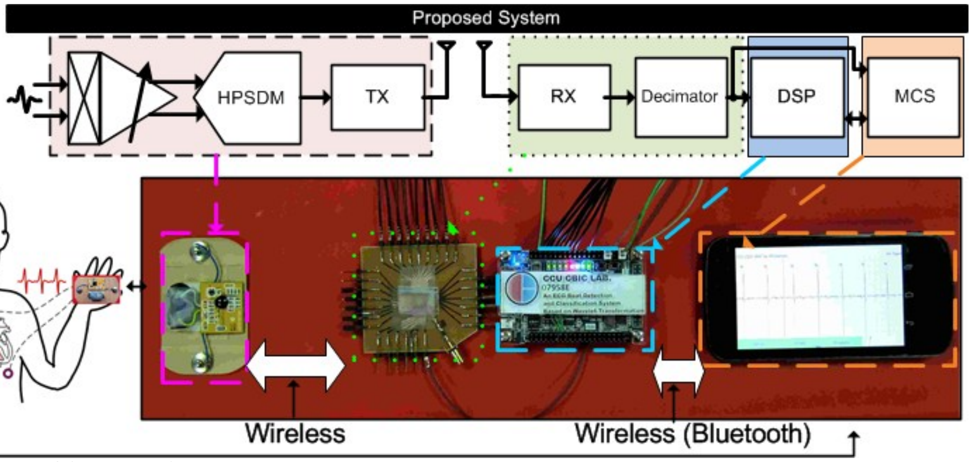


Fig.6. Measurement environment of the proposed system.

TABLE II
SUMMARY OF MEASURED PERFORMANCES

General specifications		
Technology	TSMC 0.18μm 1P6M standard CMOS process	
Chip Area	$1.52\times1.55mm^2$ (AFE +TX) $1.28\times2.04mm^2$ (RX + Decimator) $1.57\times1.57mm^2$ (Detection & Classification)	
Carrier frequency	2.4GHz	
Supply voltage	1.2V	
Bio-signal processor (analog front-end circuit)		
Chopper-based amplifier	Power consumption	17μW
	Chopper frequency	25.6kHz
	Mid-band gain	20/ 24/ 28dB
HPSDM (ADC)	Power consumption	37.5μW
	Bandwidth	200Hz
	Sampling frequency	51.2kHz
	Resolution	10bits
Wireless Transmission		
Transmitter	Power consumption	532μW
	VCO tuning range	2.17-2.59GHz
	Output power	-16.36dBm
	Energy per bit	106pJ/bit
Receiver	Power consumption	440μW
	Max. data rate	5Mbps
	Energy per bit	88pJ/bit
Digital signal processor		
Decimator	Power consumption	480μW
	sampling frequency	51.2kHz
Signal detection & classification	Power consumption	5.967μW
	operation frequency	120Hz
	Available symptoms	Any 8 Kinds

ACKNOWLEDGMENT

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Fig.7. Results of classified ECG signal on the intelligent mobile phone.

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