Low-power low-data-loss bio-signal acquisition system for intelligent electrocardiogram detection

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Abstract: The research describes an intelligent electrocardiogram (ECG) acquisition system with low power and low data loss features. The system is constructed with ADS129X, MSP430X, CC254X Bluetooth low energy (BLE) with low power wireless communication protocol and smart phone for the ECG display. Two architectures, namely, with and without the microprocessor (MPU) and hinted handoff mechanism algorithm, are used to verify the data transmission loss between the BLE and the smart phone. The system not only employed low-power solution but also added full handshake and hinted handoff to achieve complete synchronization and accurate transmission reliability. The MPU method definitely enhanced the ECG packet loss rate and power saving rate to 0.63% and 49.78%, respectively.

Keywords: ECG, low-power, low-data-loss, bluetooth low energy

Classification: Circuits and modules for electronic instrumentation

References

[1] E. Spano, *et al.*: "Low-power wearable ECG monitoring system for multiple-patient remote monitoring," IEEE Sensors J. **16** (2016) 5452 (DOI: 10.1109/JSEN.2016.2564995).

[2] T. Sakamoto, *et al.*: "Remote heartbeat monitoring from human soles using 60-GHz ultra-wideband radar," IEICE Electron. Express **12** (2015) 20150786 (DOI: 10.1587/elex.12.20150786).

[3] S. Izumi, *et al.*: "A wearable healthcare system with a 13.7 µA noise tolerant ECG processor," IEEE Trans. Biomed. Circuits Syst. **9** (2015) 733 (DOI: 10.1109/TBCAS.2014.2362307).

[4] T. Sakamoto, *et al.*: "Accurate heartbeat monitoring using ultra-wideband radar," IEICE Electron. Express **12** (2015) 20141197 (DOI: 10.1587/elex.12.20141197).

[5] L. H. Wang, *et al.*: "Implementation of a wireless ECG acquisition SoC for IEEE 802.15.4 (ZigBee) applications," IEEE J. Biomed. Health Inform. **19** (2015) 247 (DOI: 10.1109/JBHI.2014.2311232).

[6] Y. C. Chu, *et al.*: "High-efficiency high-current drive power converter IC for wearable medical devices," IEICE Electron. Express **12** (2015) 20150953

(DOI: 10.1587/elex.12.20150953).

[7] S.-Y. Lee, *et al.*: "Low-power wireless ECG acquisition and classification system for body sensor networks," IEEE J. Biomed. Health Inform. **19** (2015) 236 (DOI: 10.1109/JBHI.2014.2310354).

[8] G. Kavya, *et al.*: "Wearable advanced single chip ECG telemonitoring system using SoPC," IEICE Electron. Express **11** (2014) 20140097 (DOI: 10.1587/elex.11.20140097).

[9] J. Qiu, *et al.*: "Ultralow power processor employing block instruction for ECG application," IEICE Electron. Express **13** (2016) 20150493 (DOI: 10.1587/elex.13.20150493).

[10] H. Kim, *et al.*: "A configurable and low-power mixed signal SoC for portable ECG monitoring applications," IEEE Trans. Biomed. Circuits Syst. **8** (2014) 257 (DOI: 10.1109/TBCAS.2013.2260159).

[11] L. Yan, *et al.*: "A 680 nA ECG acquisition IC for leadless pacemaker applications," IEEE Trans. Biomed. Circuits Syst. **8** (2014) 779 (DOI: 10.1109/TBCAS.2014.2377073).

[12] S. C. Lee, *et al.*: "A robust wearable u-healthcare plaform in wireless sensor network," J. Commun. Netw. **16** (2014) 465 (DOI: 10.1109/JCN.2014.000077).

[13] E. Nemati, *et al.*: "A wireless wearable ECG sensor for long-term applications," IEEE Commun. Mag. **50** (2012) 36 (DOI: 10.1109/MCOM.2012.6122530).

[14] S. Elisa, *et al.*: "Low-power wearable ECG monitoring system for multiple-patient remote monitoring," IEEE Trans. Biomed. Circuits Syst. **16** (2016) 5425 (DOI: 10.1109/JSEN.2016.2564995).

1   Introduction

In recent years, cardiovascular diseases (CVDs) have become among the serious threats to human health. Heart diseases remain the leading cause of mortality all over the world. Several treatments for patients with heart diseases are delayed because of untimely disease detection, which eventually leads to death [1]. The heart is the most vital organ. It is constantly and regularly expanding and contracting. Blood is pumped from the veins into the heart and arteries and synchronously generates electrical excitement with mechanical contraction. Electrocardiogram (ECG) is a monitoring system that can record the potential difference between two electrodes attached to the body surface through wires [2].

The ECG is a synthetic waveform reflecting the potential changes during the process of heart excitement generation, transmission, and recovery. However, the ECG signal is among the oldest human bioelectric technology applied to medical treatments. The medical profession can currently generate assessments and diagnostics on CVD through ECG analysis [3]. Thus, a timely, accurate, and complete extraction of ECG signals and the availability of effective analysis and diagnostic methods are significant and relevant topics for research [4].

Wang et al. [5] proposed a wireless biosignal acquisition system-on-a-chip (SoC) specialized for ECG monitoring. The proposed SoC can effectively acquire ECG signals based on measurement results. To achieve both high current and high power efficiency, Chu et al. [6] presented a switched-inductor-based AC-DC buck

converter implemented on a 0.18 μm manufacturing process for transcutaneous powered wearable devices. A low-power biosignal acquisition and classification system for body sensor networks is proposed by Lee et al. [7] Three main parts of the system are proposed, including a high-pass sigma delta modulator-based biosignal processor, a super-regenerative on-off keying transceiver of low-power feature for short-range wireless transmission, and a simple digital signal processor for electrocardiogram (ECG) classification. Kavya et al. [8] deal with the wearable telemonitoring feature for the 12 lead ECG interpretation. It is implemented adopting Altera IPcore-based multicore architecture instead of using the application on a single processor or FPGA solution.

The paper presents a low power wireless ECG detection for personal healthcare monitoring [9]. It also proposes a high integration and high-reliability portable device with ADS129X analog front-end (AFE) for ECG signal acquisition and CC254X Bluetooth low energy (BLE) for wireless communication. Currently, the low power Bluetooth (BT) application is widely used because of its high penetration rate in cellular phones [10]. The hinted handoff mechanism algorithm is the one of novel technique proposed to reduce the wireless transmission loss, furthermore, added MPU as the master controller to decrease the BLE controller operation loading and to regulate the transmission data to achieve the low power consumption and low packet loss rate. According to the actual human ECG measurement results, the ECG signals can be acquired and transmitted using the proposed system [11].

2   System architecture

The first version of the proposed system comprises AFE and BLE chips, as shown in the Fig. 1(a). The BLE is the master control that regulates the work process of AFE using the serial peripheral interface (SPI) bus. The ADS129X uses a built-in amplifier to enhance weak analog ECG signals from the electrodes. The amplified ECG signals are then converted to digital signals. The digital signals are subsequently stored into the output register, ready for the backend system. BLE reads the obtained digital signals, which are converted in AFE and saved to memory. The stack of BLE is then used to send data packets that can be accessed through smartphones.

The second method uses a microprocessor (MPU) MSP430X instead of the CC254X as the master control to reduce computation loading and to enhance the BLE transmission efficiency, as shown in Fig. 1(b). The MPU reads the data from the ADS129X and saves it. The system sends the ECG data to the BLE via an SPI bus when adequate data have been collected. BLE stack is then used to send the data packets to a phone.

CC254X in the first method works not only as the master chip of ADS129X that collects ECG data from AFE but also as the slave for the transmission between the phone and Bluetooth, sending ECG data to the phone using the BLE stack. The central processing unit (CPU) load of the BLE is relatively high, leading to a slow BT speed when sending data and reducing the operating speed of the entire system. MPU is integrated into the system between the AFE and the BLE, thereby serving as a master chip of AFE to release the CPU from the BLE and to facilitate its

specific use for BT data sending. This integration improves the system speed and stability. Considering these details, the second proposed method has a more reasonable design for our purpose than the first proposed method.

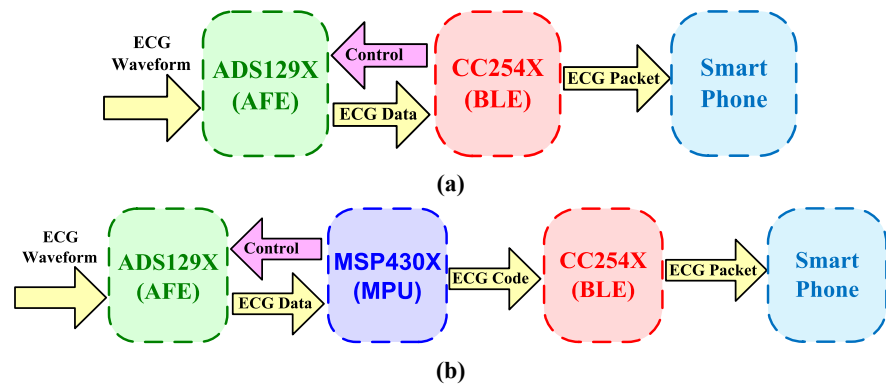## 3 System and circuits design

Fig. 1. System proposal. (a) First proposal. (b) Second proposal.

The system hardware consists of ECG acquisition circuits (i.e. ADS129X), microcontroller (i.e. MSP430X) for data processing, and low power BLE wireless transmission (i.e. CC254X). The electrode leads acquire a low ECG signal. AFE circuit samples and processes the obtained biosignal and then sends this signal to the microcontroller. The MPU sends the ECG data to the BLE module when an adequate amount of data has been collected.

ADS129X is an analog-to-digital converter (A/DC) that can synchronously sample, amplify, and convert weak ECG signals. AFE uses a built-in programmable gain amplifier (PGA) to enhance weak signals. The device exhibits an excellent analog-to-digital conversion function that converts ECG signals to digital signals so that the master chip can perform the signal processing. ADS129X is small, is easy to carry, and has low power consumption, which are the requirements of a medical equipment [4]. As society progresses, high demands for the quality of life increases. Smart wearable devices with good and stable performance and low power consumption have recently been developed [5], and low power consumption has been a significant feature of the wearable devices. The MPU MSP430X, because of its low power feature, was selected for the proposed design. CC254X is used as a wireless transceiver operating in the 2.4 GHz industrielle, scientifique and medicale (ISM) band, and it incorporates an enhanced 8051 core processor, programmable flash memory, random access memory, and other peripheral interface connectors.

Fig. 2(a) shows the interface between the AFE and the MPU. Their communication includes register configuration and data processing. MPU sends predefined command words to accomplish the register configuration of the AFE, and executes the initialization processes of the AFE. Data processing comprises two phases. In the first phase, AFE samples and converts the analog ECG signal from the input electrode leads. In the second phase, MPU reads the ECG data that were completely converted into the memory using the SPI bus. The SPI bus includes four signal

lines, namely, chip select (CS), serial clock (SCLK), data out (DOUT), and data in (DIN).

MPU first pulls high START to facilitate the AFE to enter the communication state. Moreover, MPU configures the port as general purpose input output (GPIO) and enables falling edge interrupt. AFE sets data ready (DRDY) to low and generates an interrupt command when data conversion is completed to notify the MPU to read the data. MSP430X begins to read the 6-byte data once when it receives the interrupt signal of the DRDY. MSP430X will receive 1 byte of the completely converted data on the DOUT line, and six cycles of continuous operation can accomplish data transmission from a single collection point. The high three bytes refer to useless flags that are excluded. It also removes lower bytes of valid data to save memory and compress the data, thereby leaving only 2 bytes of useful data and stored in memory. When the MPU finishes reading the 6-byte data and then turn off to make it to enter into sleep mode until an external interrupt generated by DRDY restarts it. The approach is proposed to significantly reduce system power consumption.

Fig. 2(b) shows the interface between the BLE and the MPU. Two extra handshake control lines, namely A and B, achieve synchronous communication. The BLE and the MPU function as master and slave during SPI communication, respectively. First, BLE pulls the high signal A, and the MPU checks whether the data number is adequate for the 6-byte data. MPU then pulls the high B to instruct CC254X to read the data. Second, BLE sets the CS and sends the SCLK to begin transmitting 6-byte data. Subsequently, BLE pulls down a signal after completion of data transmission. Thus, communication between the master and slave machines of transferring 6-byte data is completed.

The BLE transmission between the CC254X and the phone, and the ECG detection flow chart from signal acquisition to display are described in Figs. 2(c) and 2(d), respectively. The operating system abstraction layer (OSAL) initializes the hardware and SPI, and prepares to read the ECG data collected by the MPU. After initializing the layers, the OSAL enters the main loop to check whether the electrical signal and the BT data read events SBP_GATHERPERIODIC_EVT and SBP_PERIODIC_EVT, respectively. The OSAL will execute the corresponding event handler (i.e., GatherPeriodicTask (GPT) and ECGPeriodicTask (ECGPT)) when one of these two events occurs. During the GPT process, the BLE reads and saves the ECG data from the MPU via the SPI bus. The function of the ECGPT is to ensure that the BLE protocol stack sends the ECG data to the phone. The OSAL checks whether these processes occur after event processing is completed.

In the first version of the proposed system, the considerable data packet loss during transmission between the BLE and the mobile phone is a fatal problem. To address this problem, the hinted handoff mechanism is added into the data transmission process to verify the packet in the bidirectional communication between the BLE and the phone. If the packet is correct, the BLE then sends the data to the phone. Otherwise, the BLE resends the packet until the data are correct. Consequently, the addition of a hinted handoff mechanism into the proposed system effectively solves the data packet loss.
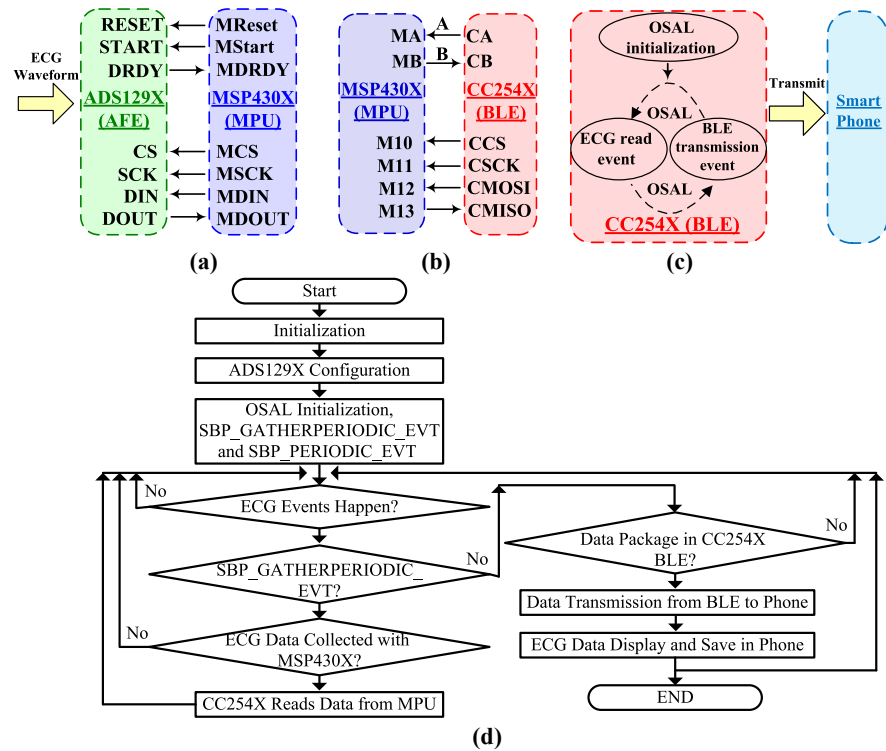
Fig. 2. Interface design (a) between AFE and MPU, (b) between BLE and MPU, (c) BLE transmission, and (d) ECG signal acquisition flow chart

4 Experiment result and discussion

Fig. 3(a) shows the printed circuit board (PCB) physical map of the ECG acquisition system in which the PCB is illustrated to be constructed with three components such as ADS129X, MSP430X, and CC254X. The small area of PCB is $5.5\,\mathrm{cm} \times 3.0\,\mathrm{cm}$ to miniaturize the whole system. Two conductive patches are connected to the two electrodes, which will be attached on the left and right sides of the patient's chest skin. The optimum distance between the two electrodes is 20 cm. The auxiliary chest belt is employed to secure the electrode patches in order to acquire stable ECG signals. The experiment method is described in Fig. 3(b). When the smart phone successfully connects via the Bluetooth communication protocol, the CC254X uses the BLE stack to send the packets to the phone. Moreover, the collected data are displayed with the mobile terminal. The experiment results are shown in Fig. 3(c) and Fig. 3(d).

Two architectures without and with MPU (Figs. 1(a) and 1(b)) are employed to detect the ECG signal. Without the assistance of the MPU and the hinted handoff mechanism algorithm, the data transmission from the BLE to the smart phone is unstable, and the ECG data are lost, seriously. In contrast, the MPU decreases the CC254X loading and regulates the transmission data to achieve the low power consumption and low packet loss rate, ensure that the ECG data transmission is stable, and prevent the loss of ECG data. The experiment results are illustrated in Figs. 3(c) and 3(d).

In Fig. 3(c), the system without the MPU and the hinted hand off mechanism algorithm, which the ECG signals received and displayed in smart phone, are

extremely unstable and lose a lot important information. Otherwise, with the MPU and the hinted hand off mechanism algorithm in the proposed system, the ECG data-loss is effectively reduced, as shown in Fig. 3(d).
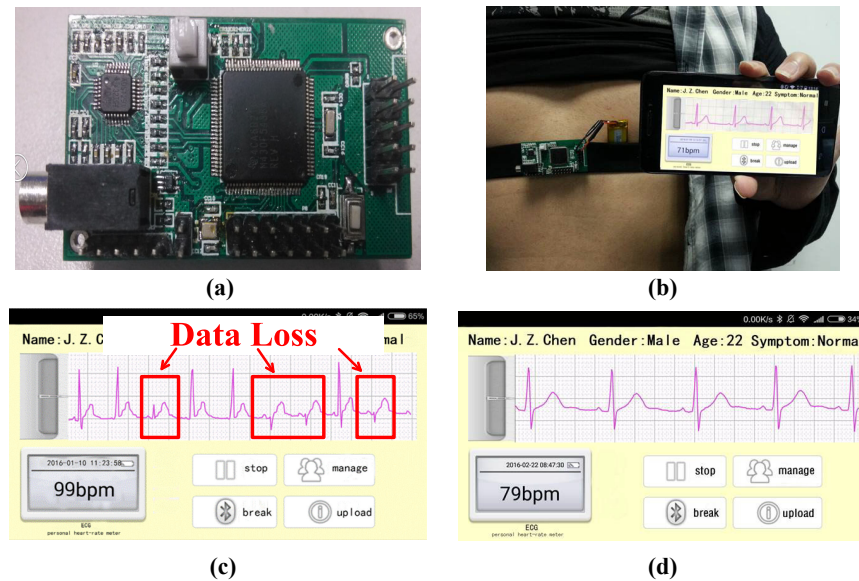

Fig. 3. (a) PCB physical map, (b) the experiment results of human ECG detection, (c) the experiment results with data loss, and (d) the experiment results without data loss

The CC254X not only functioned as a master control but also synchronously functioned as a slave to code and to transmit the ECG data via BLE protocol. Overloading, which causes data loss, remains the greatest problem. The ECG transmission packet loss rate, which is between CC254X and smart phone, without and with MPU and proposed algorithm are illustrated in Table I, and the related packet loss rate are 13.26% and 0.63%, respectively.

Table I. Comparison table of ECG transmission packet lost rate with and without MPU and algorithm

Timer setting SBP_PERIODIC_EVT Times = 20 ms, SBP_GATHERPERIODIC_EVT Times = 5 ms	ECG Packet Transmission Times	ECG Packet Loss	ECG Packet Loss Rate
Without MPU and Algorithm	98	13	13.26%
With MPU and Algorithm	633	4	0.63%

The measurement current consumption of the proposed system, that in sleep mode and work mode with and without low power design technology, is illustrated in Fig. 4. If the MSP430X into sleep mode, the current consumption of the proposed system is approximate 214.8 uA, as shown in Fig. 4(a). When the MSP430X wake up and into the work status, the current consumption with and without low-power design are 12.9 mA (i.e., Fig. 4(b)) and 25.69 mA (i.e., Fig. 4(c)), respectively, which the power saving rate is about 49.78%.
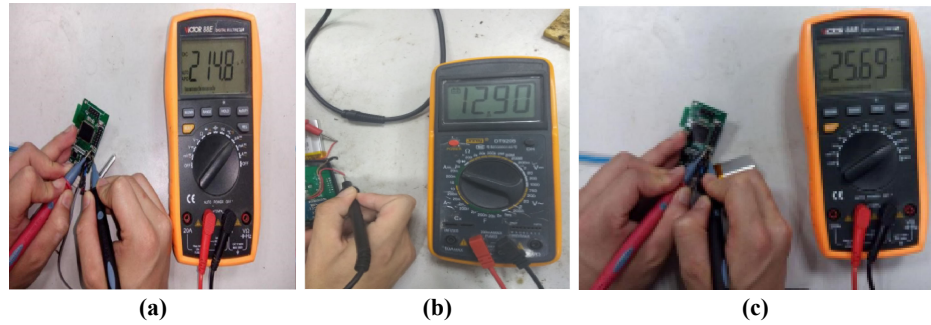
Fig. 4. (a) the sleep current, (b) the work current with the low-power design, and (c) the work current without the low-power design

The performance comparison with proposed system and previously is summarized in Table II. According to the measurement result that the maximum power consumption and current consumption of the proposed low-power system are 26 mW and 12.9 mA, respectively. Moreover, with the MPU and the hinted hand off mechanism algorithm, the ECG packet loss rate is effectively reduced from 13.26% to 0.63% to reach the low power and high reliability system. Although the power dissipation [14] is smaller than proposed system, the wireless communication of proposed is BT protocol widely used than ZigBee.

Table II. Summarized performances of the proposed system and its comparison with previously proposed system

		This work	[12]	[13]	[14]
Power Dissipation (mW)	ADS129X	0.35	-	-	0.4
	MSP430X	1.1	-	-	-
	CC254X	11.55	-	-	-
	Total	26	150	51	12
Current Consumption (mA)		12.9	41.8	17	4.7
Battery Capacity (mAh)		350	500	256	650
Life Time (h)		30	12	15	160
Device Size (mm^2)		55 ∗ 30	-	-	65 ∗ 34
Reliability		High	Medium	-	High
Wireless Communication Protocol		BT	ZigBee	Ant	ZigBee
Application		HRV Analysis	-	-	-

5 Conclusion

This research presents an intelligent ECG acquisition system, in which devices with and without MSP430X are compared. Data are transmitted via Bluetooth low energy (BLE) for wireless communication and displayed in a phone to examine the expected functions. The presented methods have solved three problems. 1) The power consumption is reduced by selecting suitable system architecture and by constructing low-power hardware and software. A 350 mAh lithium battery can supply power to the system that performs continuous detection for over 30 h. 2)

Hinted handoff algorithm is added into the data communication process, achieving high reliability data transmission between the BLE and the smart phone. 3) Two architectures with and without MPU MSP430X are compared to decrease the data loss transmitted by the ECG signal between the BLE and the smart phone. Evidently, the architecture with MPU exhibits improvement in system stability and transmission efficiency. The proposed intelligent ECG acquisition system is employed in a single-lead device. Furthermore, it will be improved to multi-lead devices in order to accurately diagnose the cardiovascular diseases.

Acknowledgments