

A Wireless ECG Plaster for Real-Time Cardiac Health Monitoring in Body Sensor Networks

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Abstract— In this paper we present a wireless ECG plaster that can be used for real-time monitoring of ECG in cardiac patients. The proposed device is light weight (25 grams), wearable and can wirelessly transmit the patient’s ECG signal to mobile phone or PC using ZigBee. The device has a battery life of around 26 hours while in continuous operation, owing to the proposed ultra-low power ECG acquisition front end chip. The prototype has been verified in clinical trials.

Index Terms—Electrocardiography, ECG-on-Chip, Wearable devices, Real-time monitoring

I. INTRODUCTION

Cardiac arrhythmias and coronary heart disease (CHD) constitute significant public health burdens. Researches show that US\$173 billion is spent every year for treatment of heart related disorders in USA [1]. Atrial fibrillation (AF), a common arrhythmia, afflicts nearly 9% of persons over 80 years old [2], and is associated with increased stroke risk. Another arrhythmia, ventricular arrhythmia, can cause sudden cardiac arrest. Early diagnosis presents an opportunity for preventive treatment. However, many patients with cardiac arrhythmia or silent myocardial ischemia remain undiagnosed and untreated, because abnormal ECG changes often occur sporadically and are easily missed. Hence, a better ECG monitoring device is necessary.

The commonly used solutions like ambulatory Holter systems are often bulky with many wires stuck on patient’s chest. The operational life of the Holter is limited within 72 hours, and ECG data are analyzed offline for diagnosis of problem. One major shortcoming of the existing ambulatory Holter systems is extremely low diagnostic yield at 10-13% [3]. In addition, such devices use traditional ECG electrodes, which are not comfortable as there are multiple wires hanging around the body. And such devices usually aren’t weatherproof; therefore the patient is expected to avoid water contact in the area where the device is fixed. All these, compromises patient’s comfort level and affects his lifestyle.

In this paper we present a wireless ECG plaster prototype device, which can be used for real-time monitoring of ECG in cardiac patients. This device, when placed on patient’s chest,

continually records single-lead ECG and wirelessly streams it to a remote station for diagnosis. The skin contact electrodes have been printed on flexible substrates with consideration for easy wearability. A highly integrated, low power chip with low noise amplifier, ADC and low pass filters were developed in-order to reduce the power consumption and the number of discrete IC components.

The paper is organized as follows. The system design is presented in Section II. Section III describes the design of ECG front-end chip. Clinical trial details and discussion are reported in Section IV. The conclusion is drawn in Section V.

II. SYSTEM DESIGN

The overall system includes two parts: (1) a wireless ECG acquisition plaster, and (2) a personal gateway (or remote station) as shown in Fig 1. The ECG plaster contains a custom designed ECG front-end chip, a microcontroller, and a ZigBee transceiver. The personal gateway can be either a mobile phone or a PC with an USB ZigBee interface. The plaster records the ECG and wirelessly transfers the data to remote data center through the personal gateway.

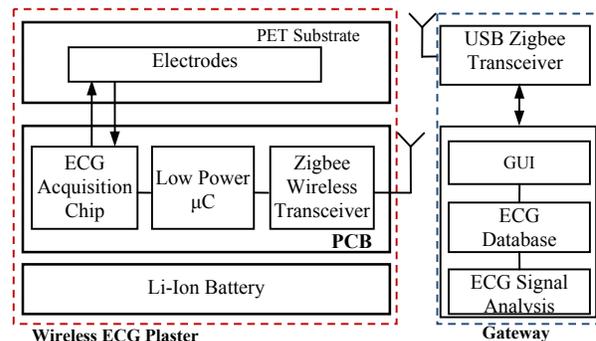


Fig. 1. System Architecture

The ECG acquisition chip is designed for low power use. The details will be presented in Section III. For wireless communication, ZigBee (TI CC2420) is selected as it offers sufficient data rate at reasonable power consumption. The MCU (TI MSP430) is used for ZigBee baseband and for ECG data management. The plaster was designed with user comfort and ease of use in mind. Hence, it does not affect the daily activities of users. In addition, the plaster is sealed with splash and water-proof material, so the patient can take shower with the plaster.

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A prototype of wireless ECG plaster is shown in Fig. 2. It consist of: (1) a specially designed skin electrode plaster for acquiring the ECG; (2) a miniature printed circuit board (2.8cm x 2.4cm) with our proprietary ECG front end chip; and (3) a high density 650mAH rechargeable Lithium Ion battery. To minimize power consumption, the data is buffered using MCU internal memory before sending to the gateway wirelessly. The maximum range of ZigBee transmission is about 15 meters in the room. The operational time is around 26 hours for each charge.

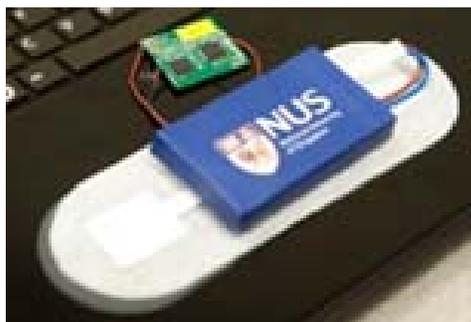


Fig.2 Wireless ECG Plaster prototype

The firmware for ECG plaster performs the following tasks: ECG front-end and microprocessor initialization, managing ECG data buffering, and scheduling the ZigBee transceiver.

Fig. 3 shows a sample application of GUI interface on PC for receiving and displaying ECG data. It receives ECG data package from wireless ECG plaster by using an USB ZigBee transceiver. In order to avoid signal interference from other wireless devices, the GUI interface can switch among 15 wireless channels. This also allows up to 15 patients to be monitored simultaneously. In addition, there are several function buttons in the GUI interface for changing parameters of the plaster, such as sample rate, overall gain and low-pass filter. These buttons are located at the right side and bottom part of the GUI.



Fig. 3. GUI interface for PC.

III. ECG ACQUISITION CHIP

For a low-power weak-signal pickup device, one of the most essential links along the acquisition chain is its analog processing frontend and analog-to-digital interface. The

required low noise, low distortion analog capabilities always conflict with the limited power budget. Unfortunately such situation does not scale down with process technology as well as in digital domain, and in fact usually gets worse with more advanced process nodes. In our proposed ECG plaster, we use a proprietary biomedical data acquisition frontend chip that employs and extends the solutions we demonstrated in [4][5].

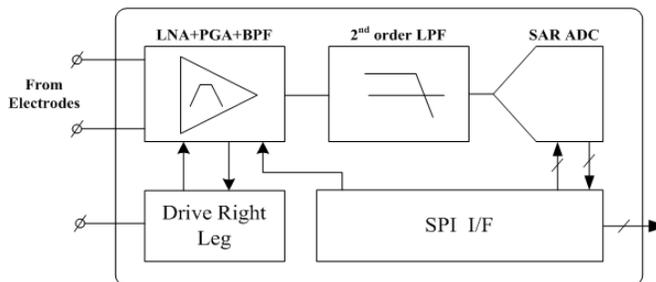


Fig. 4. Architecture of Proposed ECG Acquisition Chip

As shown in the block diagram in Fig. 4, the chip houses a fully featured bio-signal acquisition frontend, with all necessary tuning functions to cater for different input conditions. The front-end amplifier has on-chip high-impedance DC-blocking inputs that can be directly applied to ECG electrodes. The amplification stage consists of a low noise front-end amplifier with band-pass function and a programmable gain amplifier (PGA) employing the flip-over-capacitor technique [4], as shown in Fig.5. Both op-amps are biased in subthreshold mode to ensure optimal noise efficiency against power. During startup or after an input interruption event such as electrode falloff, a reset signal is asserted to eliminate the large time constant associated with the high-pass filter, such that the preamplifier can quickly resume operation. A series of secondary low-pass filters then provides further suppression to the out-of-band residues such that lower sampling frequency (in this case 3 times of signal bandwidth for over 20-dB attenuation) that favors lower wireless bit rates can be used. Following the analog processing modules, a 12-bit charge redistribution SAR ADC quantizes the conditioned ECG signal based on the sampling speed set by the microcontroller, and encodes the data into 16-bit SPI frames.

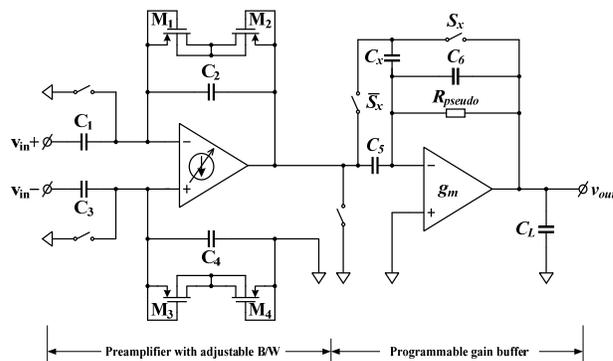


Fig. 5. Circuits for the ECG front-end

Alongside the main signal path, supporting circuits help to ensure the signal integrity, among which two micro-Watt right-leg drivers (DRL) prove to be most effective in counteracting common-mode interferences (namely power line interference) and excessive electrode contact resistance. Here DRL1 employs a novel sensing structure, where the common-mode interferences are directly extracted from the main signal path without the need of dedicated sensing circuitry, facilitating further power saving. The concept is illustrated in Fig. 6.

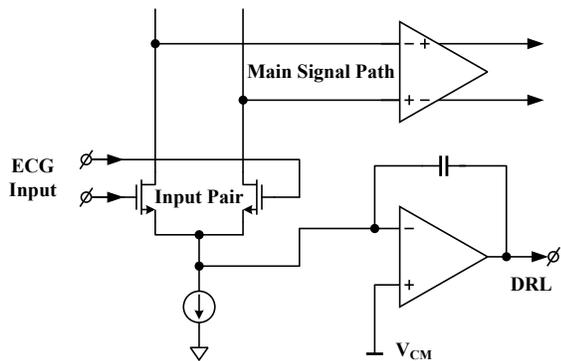


Fig. 6. Concept of low power DRL circuit with direct common-mode extraction

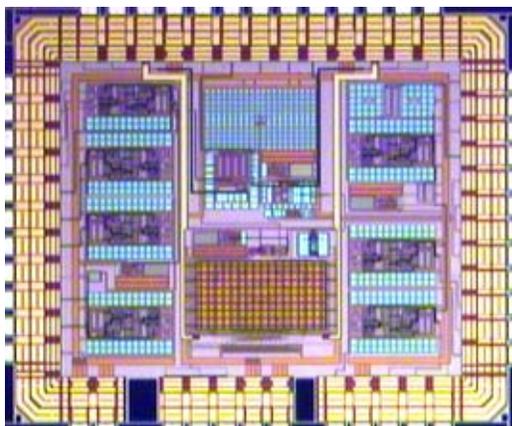


Fig.7 Chip micro photo

Table 1. Performance Summary

Supply Voltage	1.8 ~ 3.6 V
Technology	0.35 μ m
Low-pass Frequency	50 Hz ~ 8 kHz tunable
Gain	47 ~ 64 dB tunable
Input-referred Noise	3 μ V _{rms} (0.05 ~ 500 Hz)
THD @ FS Output	< 1%
Sampling Freq	up to 25 kS/s
ADC ENOB	> 10.3
Interface	SPI slave
Current @ 3 V, ECG mode with DRL	18 μ A

With all the innovative power saving measures implemented, the entire chip consumes less than 18 μ W and 50 μ W when operates at 1.8 V under ECG mode with DRL turned off and on, respectively. Some of the key specifications are summarized in Table 1. The chip die photo is shown in Fig. 7.

IV. CLINICAL TRIAL AND DISCUSSION

To verify the accuracy of the system, clinical trials were conducted by Cardiologists at two hospitals, i.e. National University Hospital and Singapore General Hospital. The Radio frequency channel is centered at 2.405G Hz. Channel bandwidth is 5MHz. The ECG signal sampling rate is set to 100Hz. The amplifier gain is set to 47dB and 56dB, respectively for two trials.

The first trial was to verify the accuracy of the device. A wireless ECG plaster and a commercial Holter were placed on the subject at the same time. The setting of the two devices is shown in Fig. 8. Recording time is set as one hour for each trial. During the recording, the subject can freely move around in the clinic.

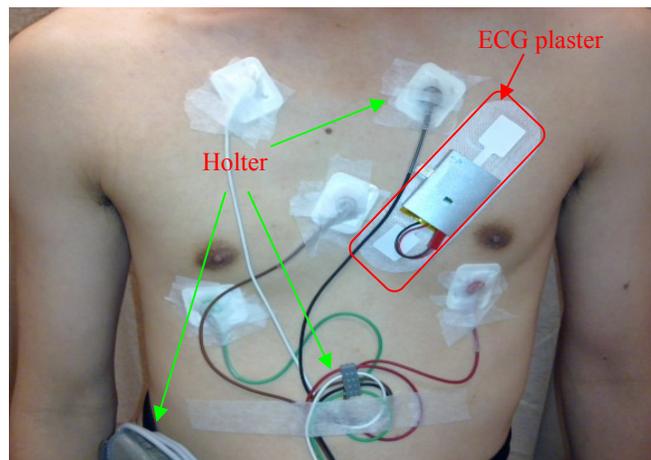


Fig. 8. The positions of the wireless ECG plaster and Holter

The second trial was to verify the reliability and stability of the device and wireless link. A healthy male adult subject was monitored by wireless ECG Plaster for more than 40 hours. In order to extend the operational hour, two 650mAh batteries were combined in this trial. The subject was isolated in a special ward designed for clinical trial. The plaster was pasted on the position V2 to V4. A laptop with an USB ZigBee transceiver is used to collect the data.

Fig.9 shows two ECG records from the reference commercial Holter (Channels 1 and 2) and the proposed wireless plaster, respectively. We use several methods to verify the quality of ECG obtained using our device.

A. Average Heart Rate and QRS peaks.

The data collected from the proposed device and reference Holter are analyzed using popular QRS detection algorithms

[6] in Matlab. From the simulation it was observed that the number of QRS peaks detected by the algorithm, in a 1 hour ECG data set obtained from a patient using both devices, varies by only 0.4%. A few QRS peaks were missing in our device due to the error caused in Zigbee wireless transmission. The average Heart rate estimated using both data sets for the same patient is 99.05bpm and 99.48bpm, respectively.

B. RR Interval

In order to establish the equality of ECG obtained from both devices, we compute the RR interval for every beat in the ECG signal. The average differences in RR interval obtained using both devices are found to be less than 1% of the reference device. The histograms showing the RR interval for both data sets are shown in Fig. 10.

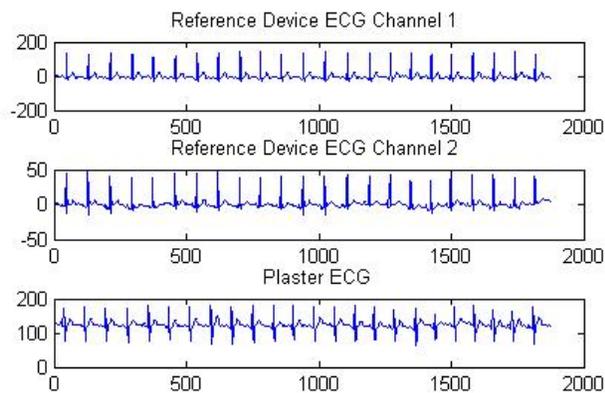


Fig. 9: ECG Signal: Plaster Device Vs Reference Holter Monitor

The data recorded for 40 hours in the second trial shows the proposed wireless ECG plaster works reliably. The normal daily activities do not have significant impact on the plaster.

V. CONCLUSION

In this paper we have presented a wireless ECG plaster for real-time cardiac health monitoring. The proposed device is wearable, light weight and can wirelessly transfer the patient's ECG signal to a remote monitoring station, where it can be analyzed in detail. The device has a battery life of around 26 hours using a 650mAH rechargeable Lithium Ion battery while performing continuous ECG recording. The proposed device has been compared with a reference ECG Holter for accuracy. The results show that the accuracy of ECG acquisition using the proposed device is very good, and the variation in key ECG parameters obtained from proposed device and the reference device is acceptable for clinical usage. Also the stability of device for long-term operation has been checked from a continuous 40-hour ECG recording trial.

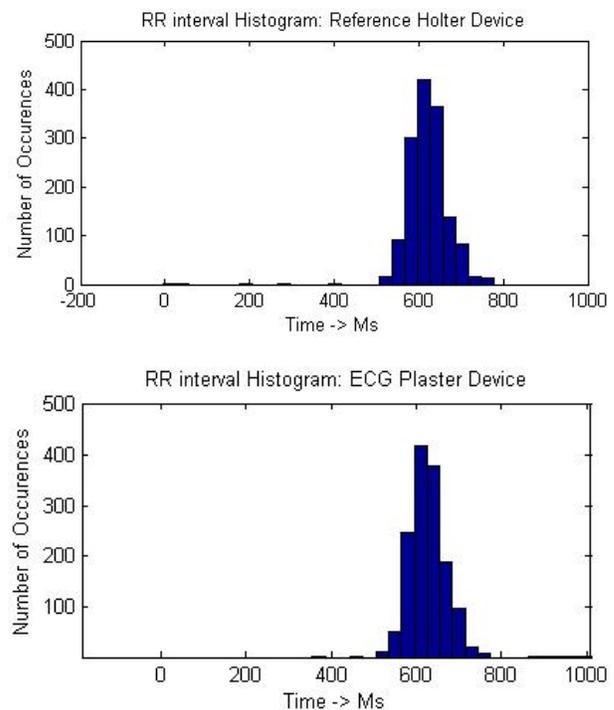


Fig.10: RR Interval histograms: ECG plaster Vs Reference Device

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