An Ultra-Wearable, Wireless, Low Power ECG Monitoring System

Chulsung Park and Pai H. Chou
University of California,
Irvine, CA 92697-2625 USA
Email: {chulsung, phchou}@uci.edu

Ying Bai, Robert Matthews, and Andrew Hibbs
Quantum Applied Science & Research (QUASAR), Inc.
5764 Pacific Center Blvd., Suite 107
San Diego, CA 92121, USA

***Abstract*— Wearable electrocardiograph (ECG) monitoring systems today use electrodes that require skin preparation in advance, and require pastes or gels to make electrical contact to the skin. Moreover, they are not suitable for subjects at high levels of activity due to high noise spikes that can appear in the data. To address these problems, a new class of miniature, ultra low noise, capacitive sensor that does not require direct contact to the skin, and has comparable performance to gold standard ECG electrodes, has been developed. This paper presents a description and evaluation of a wireless version of a system based on these innovative ECG sensors. We use a wearable and ultra low power wireless sensor node called Eco. Experimental results show that the wireless interface will add minimal size and weight to the system while providing reliable, untethered operation.**

I. Introduction

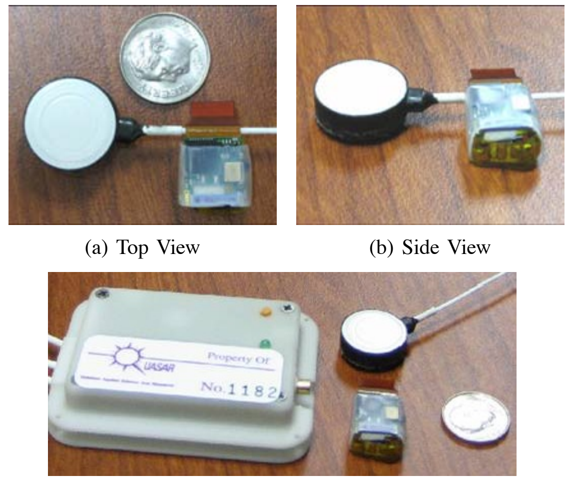
Electrocardiograph (ECG) is one of the most widely used biomedical sensing procedures to date. The heartbeat is the definitive indicator for a wide range of physiological conditions. Although ECG instruments were quite bulky, miniaturization in recent years has opened up brand new applications by enabling wearable versions to collect data in scenarios that were not possible before.

A. Current ECG sensors

Many wearable ECG systems have been proposed to date. Virtually all of them use some form of electrodes that must make electrical contact with the subject's skin surface. This necessitates the use of sticky pads, pastes or gel. While this method works for stationary patients, it suffers from several problems. First, the material used to construct the electrode or the paste could cause skin irritation and discomfort, especially if the subject is performing rigorous physical exercise and may be sweating. Another problem is that, during motion, the electrodes may become become loose, breaking electrical contact and causing high noise spikes in the data. Paste/gel-free resistive contact ECG sensors have been developed. Many of them still suffer from similar noise levels to "wet" electrodes, and the contact can still cause irritation problems as well as being more sensitive to motion.

B. Insulated Bioelectrodes

Recent breakthroughs have been made in the form of insulated bioelectrodes (IBEs). They can measure the electric potential on the skin without resistive electrical contact and with very low capacitive coupling. This has been made possible by a combination of circuit design and the use of a new, low dielectric material. These IBEs enable through-clothing measurements, and results over 40 subjects have shown them to be capable of over 99% correlation with gold standard conventional electrodes.



(a) Top View

(b) Side View

(c) Data-sampling Module

Fig. 1. QUASAR's ECG Sensor and Eco shown with a dime coin for scale

C. Wireless Enabled IBEs

To realize the full potentials of these IBEs, they need to be built in a miniature, wearable form factor and be wirelessly enabled. To accomplish this, we are integrating an existing wireless sensor node platform with the IBE. These IBEs can be very sensitive to outside noise sources and adding a digital wireless interface could introduce noise in different forms. Therefore, an important consideration in this case is to test the data quality in such a setup.

II. Background

Several wireless ECG monitoring systems have been proposed [1], [2], [3], [4], [5], [6]. All of them use conventional "wet" ECG sensors. For data sampling and wireless transmission, they use either existing standard wireless interfaces or general-purpose wireless sensor nodes. This combination results in many system-level drawbacks such as big form factor, low transmission speed, short battery lifetime, and lack of wearability. In this section, we first review the previous works and discuss their shortcomings. Next, we demonstrate the design goals of our system to resolve the discussed problems.

A. Related Work

The most recent work [1] is a system which uses the Tmote Sky platform [7] and a 3-lead system based on conventional ECG sensors. Tmote has an 802.15.4 radio interface (for Zigbee) at 250 Kbps and is controlled by the MSP430F1611 microcontroller. The authors designed an interface board between Tmote and ECG sensors. Also, they use a PDA for data collection and Wi-Fi or GPRS for the host interface. This system samples one ECG sensor at 1 KHz (16-bit resolution). However, this system is too obtrusive to be worn, considering its sensor node is larger than 66(L) × 32(W) × 15(H) mm^3. Also, its conventional ECG sensors must be attached directly onto the skin, which is another main obstacle towards wearability.

Other work done at Harvard University [2] used the MICA series [8] and Telos [9] platforms for their first prototypes. In order to make more integrated systems, they developed their own mote platform called Pluto. Pluto is functionally identical to Tmote Sky [7]. It measures 57(L) × 36(W) × 16(H) mm^3, which is still as large as Tmote Sky. It also uses standard ECG sensors.

Researchers at Imperial College developed their own wireless sensor node, called the BSN node. It measures 28(L) × 37(W) × 12(H) mm^3 (w/ a sensor board and w/o a battery). They used this platform to design a wireless ECG monitoring system [3]. This system also used the 802.15.4 radio and conventional ECG sensors.

Most systems use the 802.15.4 radio, even though it was originally developed for event-detection applications rather than real-time monitoring ones. There are two exceptions [4] [5]. The first one uses a CC1050 transceiver [10] (at 76.8 Kbps max), which is similar to MICA2's transceiver. The other one uses a Bluetooth interface (721 Kbps max). Neither radio interface was originally designed for real-time monitoring applications.

B. Design Goals

To address the problems descried above, we are designing a new ECG monitoring system. There are four main design goals: *Ultra-Wearability*, *High Throughput*, *Low Power*, *Universal Connectivity*.

Ultra-Wearability Wearability is the most crucial issue in designing a wireless ECG monitoring system. However, to the best of our knowledge, none of the existing miniature sensing systems can be considered truly wearable in the strict sense, not just because they are still bulky but also because conventional ECG sensors can cause skin irritation. Therefore, we are using QUASAR's innovative ECG sensor and an ultra-compact wireless sensor node specially designed for wearable applications.

High Throughput The other design goal is to achieve high network throughput, which is necessary for a low latency/real-time monitoring system. We decided to use a 1 Mbps proprietary radio instead of 802.15.4. Although in-sensor processing can reduce bandwidth demand, our chosen faster radio with a simpler Media Access Control (MAC) is actually more energy efficient, as discussed next.

Low Power Low power consumption is another highly important design goal. Low power consumption contributes not only to prolonged lifetime, but also to system miniaturization, because the size of a battery occupies more than 50% of system volume. It is well known that the most power hungry component in a wireless monitoring system is the wireless transceiver. Therefore, we carefully chose a very low power transceiver that consumes less than 10 mA in transmission mode (1 Mbps, 0 dBm) and 22 mA in receiving mode.

Universal Connectivity Universal connectivity means that the nodes should able to connect to virtually any computer on one of its communication interfaces. This versatility is necessary for applications that not only collect and record or replay data, but also integrate them with actuators and other infrastructures. Thus, we designed our system to be able to transmit data via most common communication interfaces including USB, Ethernet, and Wi-Fi.

III. System Design

In order to achieve the design goals described in the previous section, we are developing a new ECG monitoring system that takes

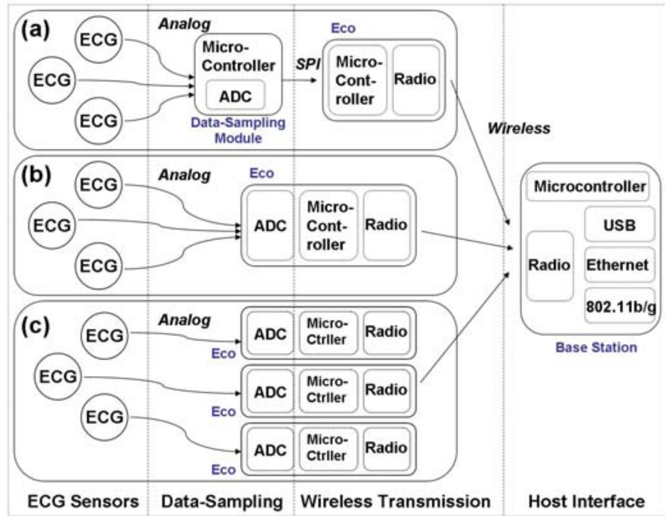
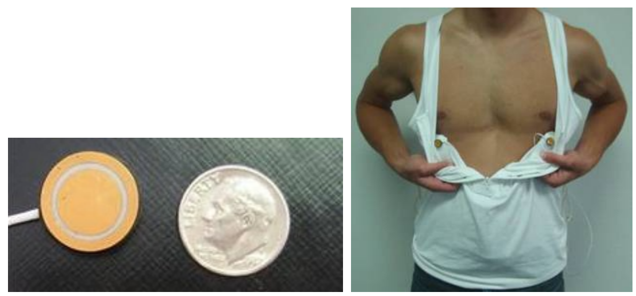


Fig. 2. System Architecture of ECG Monitoring System



(a) Top View (b) Attached on T-shirts

Fig. 3. (a) QUASAR ECG Sensors, (b) Sensors attached on a T-shirts and worn on a human body

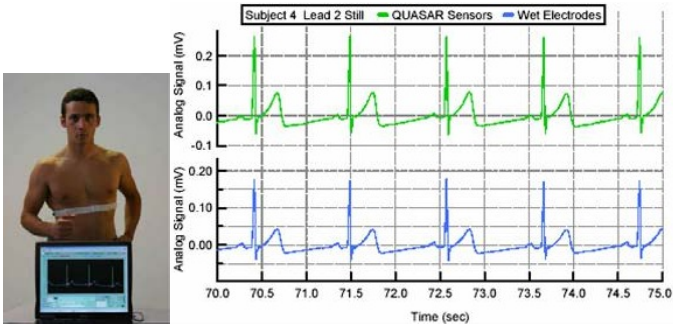
advantage of QUASAR's ECG sensors [11] and Eco wireless sensor nodes [12]. The QUASAR sensor is a wearable, tiny, low-power ECG sensing device, and Eco is an ultra-compact, low-power wireless sensor node.

Fig. 1 (a) and (b) show the QUASAR ECG sensor and Eco with a US dime coin for reference of scale. They are similar in size, power, and are well matched in terms of data rate. This section first shows various system architectures for an ECG monitoring system that integrates these two technologies. Next, we examine the specifications of the QUASAR ECG sensor, Eco node, and the base station in detail.

A. System Architectures

Our ECG monitoring system can be functionally divided into four subsystems: ECG Sensors, Data Sampling, Wireless Transmission, and Host Interface. ECG signals are first digitized by ADCs and transmitted wirelessly to a base station that interfaces with a host computer via USB, Fast Ethernet, or 802.11b. We propose three different system architectures as shown in Fig. 2.

The first architecture [Fig. 2(a)] consists of multiple ECG sensors, a data-sampling module, an Eco node, and a base station. In this architecture, the system has a separate data-sampling module, which contains a microcontroller unit (MCU) and ADCs as shown in Fig. 1(c). All signals from ECG sensors are first sampled and buffered in this module. Then, data are fed to Eco via SPI and transmitted wirelessly to the base station. This architecture uses two MCUs to



(a) Setup (b) ECG data comparison

Fig. 4. (a) QUASAR ECG sensor worn by subject, (b) Data Comparison: Green trace is from QUASAR sensor, Blue trace is from conventional electrode

distribute workload. The MCU in the data-sampling module is dedicated to sampling signals. The other MCU in the Eco node handles wireless data transmission. By adopting this two-MCU architecture, we can achieve very accurate data sampling (low jitter) as well as high communication throughput and low latency [13]. In addition, the system can have separate high resolution ADCs and increase monitoring granularity without changing the main MCU. However, this architecture imposes extra cost and volume for the data-sampling module, and it also needs a data transmission protocol between the two MCUs.

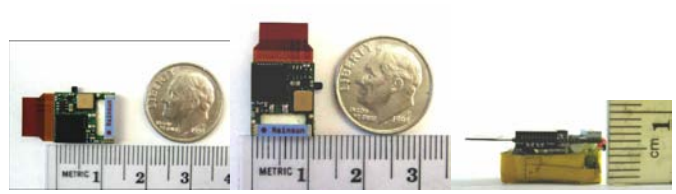
The second architecture [Fig. 2(b)] uses the Eco for both data-sampling and wireless transmission. All the ECG signals are directly fed to the ADC channels on the Eco node. The ADC built into the main MCU on the Eco node digitizes and transmits data according to its timing requirements. In this architecture, one Eco has to run all sensing and communication tasks by itself. Therefore, system performance is degraded as the number of ECG sensors increases.

Another system issue is that the number of ECG sensors that can be monitored simultaneously is limited by the number of Eco's ADC channels (8 channels in this case). Multiplexing also means that the samples on multiple channels cannot be taken precisely at the same time. However, this is a very simple and low cost design, which is suitable when the system is equipped with only two or three ECG sensors.

The third architecture [Fig. 2(c)] uses one Eco node for each ECG sensor. This architecture is similar to the second one in the sense that the Eco node performs both sampling and communication tasks, except that an Eco node serves only one ECG sensor in this case. Therefore, we can achieve higher throughput and lower latency as well as lower jitter. This is also a more reliable and distributed architecture than the other two. However, we need a sophisticated MAC protocol to coordinate the wireless traffic among several Ecos. The cost will increase in proportion to the number of monitoring points.

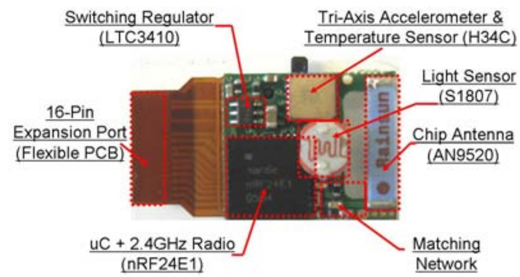
B. ECG Sensor

QUASAR's sensor (Fig. 3) is a compact ECG sensor that does not require skin preparation, gels, or adhesives. It includes not only a sensing device, but also signal conditioning circuitry such as low-noise amplifiers and voltage reference chips. Its output signal range is adjustable from differential (−4.5 V to 4.5 V) to single-ended (0 V to 4.5 V). It measures only 15 mm (in diameter) × 3.8 mm (in height) and weighs 5 g. Also, it consumes only 1 mW active power on average. These features enable our monitoring system to be

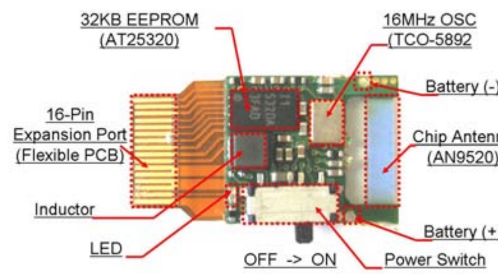


(a) Length (b) Width (c) Height

Fig. 5. Eco Dimensions: 13(L) × 11(W) × 7(H) mm



(a) Top View



(b) Bottom View

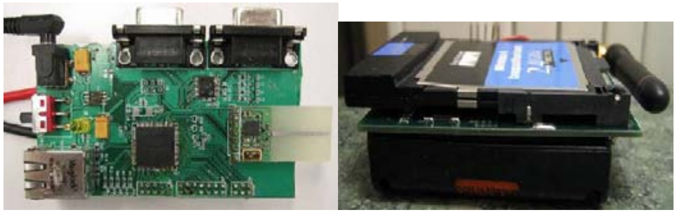
Fig. 6. Eco PCB: (a) Top View, (b) Bottom View

truly wearable. This sensor measures ECG signals using capacitively coupled electrodes that do not require ohmic contact. As shown in Fig. 4, QUASAR's sensors have at least equivalent and often superior signal quality and artifact rejection compared to the standard wet/resistive ECG sensors.

C. Eco Wireless Sensor Node

Eco is an ultra-compact and low power wireless sensor node developed by the coauthors at UC Irvine. It measures only 13 mm(L) × 11 mm(W) × 7 mm(H) and weighs 2 grams (Fig. 5). Also, it consumes less than 10 mA in transmission mode (0 dBm) and 22 mA in receiving mode. Its maximum data rate and RF range are 1 Mbps and 10 m, respectively. Considering its small form factor and low power consumption, Eco is very suitable for real-time biomedical signal monitoring applications, which require relatively high throughput, low latency, and high wearability.

Fig. 6 shows photos of the Eco hardware. Eco uses Nordic VLSI's nRF24E1, a 2.4 GHz RF transceiver with an embedded 8051-compatible MCU (DW8051). The MCU has a 512-byte ROM for a bootstrap loader, a 4 KB RAM for the user program, SPI (3-wire), RS-232, and a 9-channel ADC. The ADC is software-configurable for 6–12 bits of resolution. A 32 KB serial (SPI) EEPROM stores the application program. The nRF24E1's 2.4 GHz transceiver uses



(a) Fast Ethernet (b) 802.11b

Fig. 7. Base Stations for ECG monitoring System

a GFSK modulation scheme with 125 frequency channels that are 1 MHz apart. The transmission output power is also software-configurable for four different levels: -20 dBm, -10 dBm, -5 dBm, and 0 dBm. The RainSun chip antenna (AN9520) measures 9.5 mm(H) $\times$ 1.5 mm(W) $\times$ 1 mm(H) and has a maximum gain of 1.5 dBi.

In addition, Eco has a 3-axial acceleration sensor, Hitachi-Metals H34C, which measures acceleration from -3 g to $+3$ g and temperature from 0 – 75°C. Eco also has a light sensor (S1087).

Eco's power subsystem includes a regulator (LTC3410), battery protection circuitry, and a custom 40 mAh rechargeable Li-Polymer battery. LTC3410 is an adjustable boost regulator whose output voltage is set to 2.7 V. Its maximum output current is 300 mA, and its average efficiency over a Li-Polymer battery's output voltage range (3.0 V – 4.2 V) is higher than 90% at Eco's maximum operating current of 30 mA.

Eco has a flexible-PCB type expansion port that has 16 pins. This expansion port includes two digital I/O pins, two analog input lines, SPI, RS232, and voltage inputs for a regulator and battery charging. This port enables Eco to interface with other sensing devices such an image sensor, gyroscope, pressure sensor, or compass. We can charge the battery and program the EEPROM via this expansion port.

D. Base Station

As shown in Fig. 7, we have developed three different types of base stations: *USB*, *Fast Ethernet*, and *802.11b/g*. The *USB* one uses nRF24E1 as a wireless transceiver and MCU. Also, it uses Silicon Lab's CP2102 UART-to-USB bridge (Max. 12 Mbps). The *Fast Ethernet* one uses Freescale's MC9S12NE64, which has an HCS12 16-bit core and the Fast Ethernet interface (100 Mbps). It uses the nRF2401 as its wireless transceiver. The *802.11b/g* base station use a PIC18F8720 MCU, nRF2401 transceiver and Linksys' WCF12 CF 802.11b card (Max. 11 Mbps).

IV. Evaluation

In this section, we evaluate our ECG monitoring system in terms of size, weight, power consumption, sampling rate, and latency. We considered the second system architecture (in Fig. 2), which has the lowest hardware cost among the three architectures. It also represents the lower bound in terms of performance and data quality.

A. Size, Weight, and Power Consumption

The total size and weight of the monitoring system are simply the sum of those of the ECG sensor and Eco, because our system does not require interface circuitry. Note that the signal conditioning circuitry is already included inside the ECG sensor. The total size of our system is about 26(L) $\times$ 15(W) $\times$ 7(H) mm^3 including one sensor, a wireless transceiver, and a battery. To the best of our knowledge, our system is the smallest wireless ECG monitoring system to date. The entire system weighs less than 17 grams and consists of one Eco plus three ECG sensors. Our ECG system consumes less than 30 mW max while in operation. When it is powered by the 40 mAh Li-Polymer battery, it can last for more than 12 hours at 20% duty cycle, 1 Kbps sampling rate.

B. Sampling Rate and Latency

In the second system architecture, three ECG sensors are connected to one Eco. The size of one data sample is 12 bytes (4 bytes per sensor, 12-bit resolution, differential input). Our system can sustain sampling at 1 KHz. The measured latency is under 300 μs.

V. Conclusions

We are developing a truly wearable, wireless ECG monitoring system. Our system integrates novel capacitive ECG sensors, which have demonstrated 99% correlation with conventional electrodes, with Eco, an ultra-compact, low power wireless sensor node. Future work includes tighter integration of QUASAR's sensor and Eco and improving wireless performance and power efficiency.

Acknowledgments

This work was sponsored in part by NSF-CAREER Award CNS-0448668, Army Phase II SBIR W91ZLK-04-P-0235, and Air Force Phase I SBIR FA8650-04-M-6526.

References

[1] C. Otto, A. Milenkovic, C. Sanders, and E. Jovanov. Final results from a pilot study with an implantable loop recorder to determine the etiology of syncope in patients with negative noninvasive and invasive testing. *The American Journal of Cardiology*, 82:117–119, 1998.

[2] Victor Shnayder, Bor-rong Chen, Konrad Lorincz, Thaddeus R.F. Fulford-Jones, and Matt Welsh. Sensor networks for medical care. Technical report, Harvard University, 2005.

[3] B. Lo, S. Thiemjarus, R. King, and G.Z. Yang. Body sensor network - a wireless sensor platform for pervasive healthcare monitoring. In *Adjunct Proceedings of the 3rd International Conference on Pervasive Computing*, May 2005.

[4] Joshua Proulx, Ryan Clifford, Sarah Sorensen, Dah-Jye Lee, and James Archibald. Development and evaluation of a Bluetooth EKG monitoring sensor. In *Proceedings of the IEEE International Symposium on Computer-Based Medical Systems (CBMS)*, 2006.

[5] Rune Fensli, Einar Gunnarson, and Torstein Gundersen. A wearable ECG-recording system for continuous arrhythmia monitoring in a wireless tele-home-care situation. In *Proceedings of the IEEE International Symposium on Computer-Based Medical Systems (CBMS)*, 2005.

[6] Eugene Shih, Vladimir Bychkovsky, Dorothy Curtis, and John Guttag. Continuous medical monitoring using wireless microsensors. In *Proceedings of SenSys*, page 310, November 3–5 2004.

[7] Moteiv. Tmote Sky Zigbee-based WSN platform. `http://www.moteiv.com/`.

[8] Crossbow. MICA2/MICA2DOT wireless sensor platform. `http://www.xbow.com/`.

[9] J. Polastre, R. Szewczyk, and D. Cullar. Telos: Enabling ultra-low power wireless research. In *The 4th International Conference on Information Processing in Sensor Networks(IPSN'05)*, April 2005.

[10] Chipcon. ISM band wireless transceiver. `http://www.chipcon.com/files/CC1050_Data_Sheet_1_2.pdf`.

[11] Robert Matthews, Neil J. McDonald, Igor Fridman, Paul Hervieux, and Tom Nielsen. The invisible electrode – zero prep time, ultra low capacitive sensing. In *Proceedings of the 11th International Conference on Human-Computer Interaction*, July 22–27 2005.

[12] Chulsung Park and Pai H. Chou. Eco: Ultra-wearable and expandable wireless sensor platform. In *Third International Workshop on Body Sensor Networks(BSN2006)*, April 2006.

[13] Chulsung Park, Pai H. Chou, and Mazanobu Shinozuka. Duranode: Wireless networked sensor for structural health monitoring. In *The 4th IEEE International Conference on Sensors*, Nov. 2005.