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Wearable Patient Monitoring Application (ECG) using Wireless Sensor Networks

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Abstract— **In this paper, we discuss a design for a wearable electrocardiograph device constructed with small, low-powered "mote" sensors for use in wireless sensor networks. A wearable, wireless three-lead electrocardiograph sensor module is utilized and the initial tests are presented that illustrate the viability of this design. This device can be integrated into a suite of wearable wireless sensors used for patient monitoring and other applications.**

I. INTRODUCTION

Wireless sensor networks constructed with small, low-powered sensors called "motes" can be employed in a variety of applications. Motes can act as a communications platform and can support a very wide array of sensing and signaling devices. The mote used for this application is the tMote Sky developed at UC Berkeley and produced by the MoteIV Corporation [1].

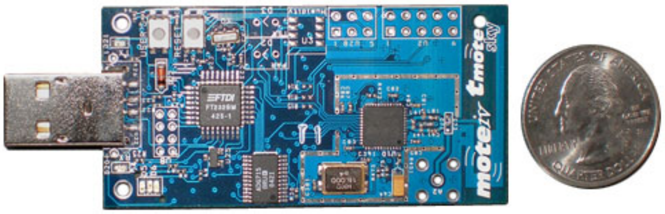

Fig. 1. Picture of the tMote Sky developed at UC Berkely. The device is very small and uses very little power.

The proposed electrocardiograph (ECG) application of mote technology is part of the Wireless Infrastructure for Networks of Distributed Sensors (WINDS) research being conducted at the University of Nebraska-Lincoln Peter Kiewit Institute in conjunction with the University of Nebraska Medical Center (UNMC). WINDS and UNMC are jointly involved with research and development of applications for mote-based wireless sensor networks for use in medical care applications.

The processing capabilities and versatility of the tMote Sky allow for many additional features to be integrated with the ECG device, such as RFID tag technology and patient tracking systems. As an application of the emerging mote technologies, the proposed ECG device is intended to provide hospitals with a feature-rich, inexpensive alternative to existing wireless cardiac-monitoring solutions.

In the following sections, background information on ECG units will be presented and details of the proposed design and test results will be discussed.

II. BACKGROUND

Electrocardiograph devices are the most widely employed tool used for cardiac monitoring. Two different classes of ECG devices are in general use today. The "standard" ECG generally involves the connection of between twelve and fifteen conductive leads to a patient's chest and/or extremities via adhesive pads. The device records a short sampling of the heart's electrical activity between various pairs of electrodes. Each pair of leads provides a unique depiction of the heart's electrical impulses as they are conducted through surrounding tissue. An experienced cardiologist can rapidly interpret a standard ECG tracing to diagnose a wide range of possible ailments. However, because standard ECG traces only represent a short sampling of patient data, cardiac conditions which are irregular or intermittent may not be identifiable.

To address this shortcoming, many hospitals employ another class of ECG, called stress or Holter monitoring, to monitor patients in intensive care. Medical personnel deploy an ECG device that uses fewer electrodes (usually three or five), which provides a less detailed sampling of cardiac activity over an extended period. The cardiac rhythm is generally shown on a near-by display so that the patient's general cardiac condition can be monitored continuously. A physician may advise continuous monitoring if it is suspected that a patient has a cardiac problem, such as an irregular heartbeat, that occurs intermittently.

Many ECG machines, both standard and continuous, are marketed as "portable," but this does not always indicate that they are small and unobtrusive. Many such devices receive power from an electrical outlet and are sufficiently heavy that they must be mounted on a cart and wheeled from one location to the next. Wireless sensor networks have the potential to significantly improve this situation. Battery-operated, wirelessly-networked sensor units are particularly advantageous because of their low cost, small size, and ease of deployment and integration with existing hospital computer systems.

Among the available products in this area [3-4], some are similar to the proposed system in this paper, However, we believe, our ECG system has the advantages longer transmission range, smaller size, standard wireless component, and overall cost.

The BioPatch is one of the disposable devices in this area that transmits data over a short range of less than four meters to a Treo cellular phone, which forwards data to a centralized processing facility over the public telephone network. We believe that the major drawback of this system

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is that data is updated to hospital personnel only every 2-4 hours and the system depends upon the cellular telephone network to relay data. The proposed ECG device can deliver data in real-time to any terminal in the hospital and does not depend on a network external to the hospital.

The ECG device proposed in this paper uses a three-lead system and can provide continuous ECG data as well as store and forward data. It is more flexible than existing solutions because it is modular and can readily be combined, for example, with mote-based patient locating systems that can be seamlessly integrated into existing networks. The intended use of the proposed ECG device is to allow medical personnel to monitor a patient's general cardiac condition over the course of a hospital stay and to monitor for intermittent or irregular cardiac conditions such as a heart murmur.

III. MOTE OVERVIEW

The tMote Sky uses the IEEE 802.15.4 standard for wireless transmission of data and has an indoor transmission range up to fifty meters depending on the prevalence of obstructions [1]. It is programmable and can interface with a PC via USB. The tMote Sky features multiple configurable analog and digital input/output ports in a bus configuration so that multiple expansion boards can be used simultaneously.

The mote-based wireless networking structure developed by the WINDS group [2] is constructed by configuring motes as base-stations connected to computers via USB. Data can be forwarded from the computers using existing network infrastructures such as 802.11 wireless Ethernet or 802.3 Ethernet to relevant destinations such as data servers or end-user applications.

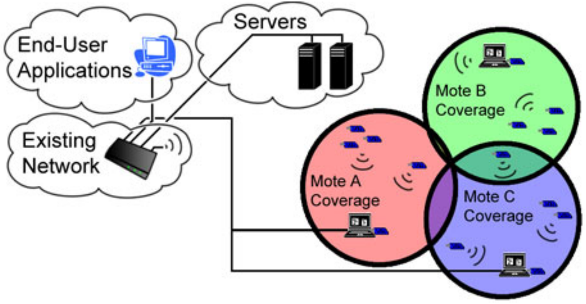

Fig. 2. Diagram of how the mote-based wireless sensor network integrates with existing network infrastructure. The computers act as bridges and are capable of direct, multi-cast, or broadcast data transmission over the existing network. Additionally, the motes can communicate with each other directly if in range or by using the base-station motes and existing network infrastructure [2].

IV. DESIGN CHALLENGES

Several challenges must be overcome in order to create a truly wearable ECG device. The biggest challenge to creating a small, inexpensive ECG amplifier is finding a way to eliminate low-frequency noise such as 60-Hz "hum" without the use of bulky filters. Another challenge which must be met is achieving a battery life measured in weeks using small, lightweight, and inexpensive batteries. A large, heavy battery cannot be used in a device designed to be convenient and comfortable to wear, so minimizing average power dissipation is very important. Also, the ECG device should be able to communicate using standard wireless protocols in order to facilitate integration into existing hospital network infrastructures.

V. CONNECTING THE PATIENT

The electrical current passing through the patient should never be large enough to cause any harm or give any sensation to the patient. Patient-circuit isolation is commonly achieved in existing ECG designs using optical isolation, which can be bulky and expensive. In this design, patient-circuit isolation is achieved through 220 kΩ resistors placed between the inputs and the signal cables. The worst-case current through the patient is less than 14 μA, which is far below the threshold of sensation or harm.

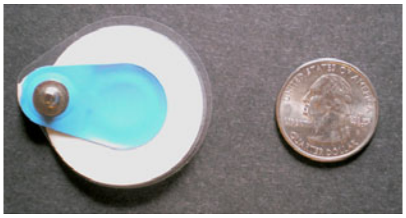

Fig. 3. Picture of the Blue Sensor electrodes made by the Ambu company. The ECG lead cable clips onto the raised metal area on the flap at the side of the pad.

Disposable Blue Sensor electrodes produced by the Ambu company [5] were used in testing. They are pre-loaded with a low-impedance wet Ag/Cl gel that is better than solid gels at reducing skin impedance, which is important for obtaining a clean signal. A tab connector allows for the cable to move around without disturbing the electrode-skin contact, which reduces movement artifacts significantly. Unshielded cables were used because they are smaller and cost less than shielded cables.

VI. INPUT STAGE

Typical ECG signals are very faint – usually on the order of 1 mV to 5 mV – and can be corrupted by noise many times larger than the signal itself. Fortunately, most of the noise is either above the bandwidth of the ECG signal or common-mode with respect to the electrodes. In order to take advantage of this, the mote is set to sample at a rate just sufficient for the ECG bandwidth and an amplifier with a very high common-mode rejection ratio (CMRR) is used.

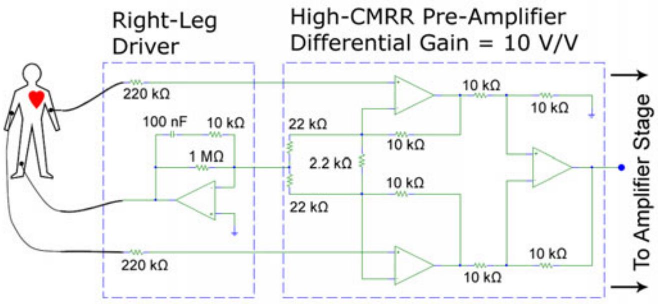

Fig. 4. Circuit diagram of the input stage of the proposed design. The input stage exhibits a typical CMRR of over 100 dB (V/V).

Most of the information contained in an ECG signal lies below 30 Hz, so signals above 30 Hz can be considered noise. The minimum sample rate necessary to recover the data is given by the Nyquist criterion as twice the bandwidth of the signal, or 60 Hz. In practice, however, sampling at the minimum rate will cause distortion. The mote is set to sample at 133 Hz, which is four times the data bandwidth.

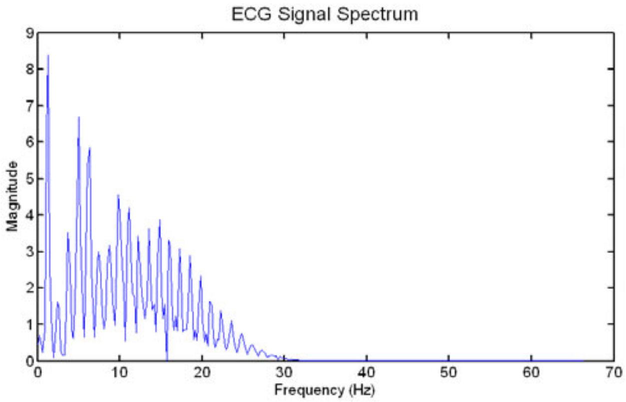

Fig. 5. Fast Fourier Transform of typical ECG data.

Instrumentation amplifiers typically exhibit a very high CMRR, so a compact, low-power, low-noise instrumentation amplifier is placed at the heart of the design. This configuration features a CMRR of over 100 dB (V/V). The resistor values are large enough that an insignificant amount of average power is dissipated, but are small enough that an insignificant amount of thermal noise is generated.

In order to further reduce common-mode noise, a right-leg driver is used. This amplifier injects common-mode signals back into the patient to cancel them out. In effect, common-mode signals are "bootstrapped" to ground through the amplifier. The resulting common-mode rejection ratio improves significantly when skin impedance is reduced by the electrodes.

VII. AMPLIFIER STAGE

The amplifier stage features a compact, low-noise, low-power signal amplifier and a two-pole active high-pass filter. A notable characteristic of the output stage is that there is no low-pass filter. Digital filtering can be employed instead of analog filtering to eliminate noise above 30 Hz, allowing the device to be smaller and the cost to be lower.

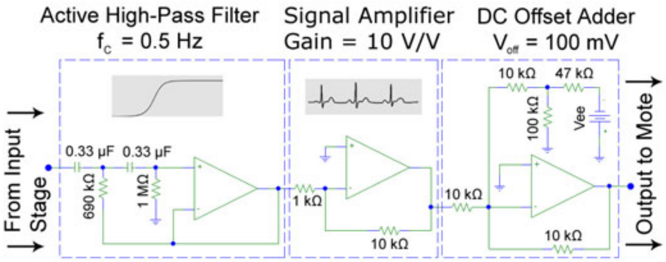

Fig. 6. Circuit diagram of the amplifier stage of the proposed design.

Not all filtering can be performed digitally. Patient DC offset and baseline drift can cause the signal to be "clipped" in the amplification stage. This type of signal distortion cannot be removed with digital filtering. An active high-pass filter (f_C = 0.5 Hz) is necessary to remove these unwanted signal components.

It is important to minimize measuring error. The tMote Sky ADC measures data from 0 V to 1.5 V in steps of 366 μV so the quantization error is given by:

$$\% \, Error = \frac{366\mu V}{Signal\ Amplitude} \tag{1}$$

The quantization error would be approximately 0.366% for a 100 mV signal, 0.0732% for a 500 mV signal, and 0.000244% for a 1500 mV signal. There is a significant difference in quantization error between the 100 mV and 500 mV signals. There is not much improvement between 500 mV and 1500 mV, as thermal noise begins to dominate when quantization error drops near zero.

It is also important to minimize power consumption. For a typical zero-offset 500 mV peak-to-baseline ECG signal, the average signal value is approximately 80 mV. The typical ADC load resistance for the tMote Sky is rated at 2 kΩ, so the average power for a zero-offset 500 mV ECG signal is:

$$P_{500mV} = \frac{80mV^2}{2k\Omega} = 3.2\mu W \tag{2}$$

The average power consumption is negligible for a 500 mV peak-to-baseline ECG signal. The peak signal amplitude is set at 500 mV because quantization error is very low while an insignificant amount of average power is dissipated. The typical input signal level is between 1 mV and 5 mV, depending on the patient, so a gain of 100 V/V is employed. The tMote Sky can only measure positive signals between 0V and 1.5V, so a DC offset must be added after amplification because ECG traces can exhibit significant negative deflections. Although this will add significantly to the average power consumption of the device, it is necessary to prevent clipping.

VIII. SOFTWARE IMPLEMENTATION

In order to demonstrate and test the ECG device, a graphical user interface (GUI) was developed. The GUI is programmed in Java and implements code provided by the makers of Tiny OS in order to receive packet information in real time. The raw packet data stream is then decoded and graphed on the screen.

IX. PERFORMANCE EVALUATION

A prototype based on the proposed circuit was constructed on a breadboard for testing. Matlab was used to plot and manipulate data because digital filters can be quickly designed and implemented using the Matlab FDATool. Also, data can be quickly manipulated and displayed using built-in functions. The following ECG trace data were passed through Matlab.

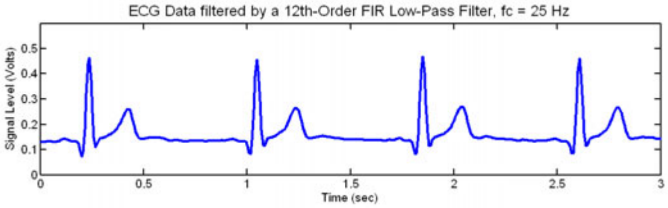

Fig. 8. ECG data filtered by a 12th-order digital FIR low-pass filter with a cutoff frequency of 25 Hz. An FIR rather than IIR filter is used because the poor impulse response of IIR filters causes distortion of the QRS complex.

The trace shown in fig. 8 was collected in an environment in which significant 60 Hz "hum" noise was present. The cables used to connect the patient to the prototype were unshielded copper conductors approximately three feet in length. Notice that there is very little signal distortion after digital filtering is performed and the baseline of the signal is very stable. The signal quality is comparable to that of existing commercial ECG devices.

X. CONCLUSION

We have proposed a wirelessly networked sensor-based ECG device that offers features not currently available in many commercial devices. The device uses inexpensive parts and the signal quality is comparable to existing ECG devices. The proposed ECG device is unique in that it is a patient monitoring module that can be employed by a mote-based wireless sensor network and can be integrated with technologies such as RFID tags and patient tracking. Data can be sent in real time to any terminal in the hospital using existing network infrastructures and can be forwarded through the internet to any other destination at which the data is needed.

The packet data streams used in testing were unencrypted. However, integrating encryption algorithms being researched by the WINDS group with this application is a part of the work in progress for this project. Data encryption is necessary in order to meet the high standards of medical facilities and to comply with regulations regarding dissemination of patient data such as the Health Insurance Portability and Accountability Act (HIPAA) of 1996.

The support software for the ECG device is under development. An end-user application is being developed that hospital personnel will be able to use to bring up patient information and current/past ECG waveforms. A signal processing routine will allow hospital personnel to search past trace history for abnormal rhythms. The software will be able to sound an alert should a patient under observation exhibit an abnormal rhythm. Hospital personnel will be able to display patient data along with ECG traces such as an image of the patient, patient history, current medications, current care needs, and so forth. A secure database will store patient information until it is requested.

The wearable, wireless nature of the proposed ECG device when used in conjunction with other technologies such as RFID tags and patient tracking systems will allow patients greater freedom to move about the hospital while allowing medical personnel to quickly locate the patient in case of emergency. The research conducted during this project has indicated that it will be possible to produce an ECG device that can provide hospitals with a small, inexpensive, and flexible alternative to existing wireless cardiac monitoring systems.

XI. ACKNOWLEDGEMENTS

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REFERENCES

[1] tMote Sky wirelessly networked sensor development kit by the MoteIV Corporation, http://www.moteiv.com/products-tmotesky.php

[2] H.S. Hamza, S. Wu, J.S. Deogun, "EDIVER: An Efficient Distance Vector Routing Algorithm for Wireless Sensor Networks," Proceedings of the International Conf. Communications, Seoul, Korea, May 16-20, 2005.

[3] LifeSync by GMP Wireless Medicine, Inc., http://www.wirelessecg.com

[4] BioPatch by Telzuit Medical Technologies, Inc., http://www.telzuit.com

[5] BlueSensor ECG electrodes by Ambu Corp., http://www.ambu.com

[6] V. Shnayder, B. Chen, K. Lorincz, T.R.F. Fulford-Jones, "Sensor Networks for Medical Care," Harvard Univ., Cambridge, MA, Tech. Rep. TR-08-05, Apr. 2005.

[7] T.R.F. Fulford-Jones, G. Wei, M. Welsh, "A Portable, Low-Power, Wireless Two-Lead EKG System," Proceedings of the 26th Annual International Conf. IEEE EMBS, San Francisco, CA, Sept. 1-5, 2004, pp. 2141-2144.

[8] A.M. Mahdy, J.S. Deogun, J. Wang, "Mobile ad hoc Networks: a Hybrid Approach for the Selection of Super Peers," Proceedings of the 2nd IFIP International Conf. Wireless and Optical Communications Networks, 2005, pp. 280-284.