A Wireless Sensor System for Biopotential Recording in the Treatment of Sleep Apnea Disorder

Lei Wang, Eric Noel, Cheung Fong, Ridha Kamoua and K. Wendy Tang

Abstract— **Development in micro-electronic-mechanical systems (MEMS), wireless communications and digital electronics recently have made it possible to develop small size, low-power, low-cost sensor devices. Such devices can integrate data processing, communications and sensing capabilities. A wireless sensor network (WSN) consists of a group of sensors, or nodes, linked by a wireless medium (infrared or radio frequency) to perform distributed sensing tasks. Wireless sensor networks will have many applications such as surveillance, environmental monitoring, security, and medical sampling. Many successful sensor applications have been deployed in very specialized networks, such as UCBerkeley's Smart Dust [1], MIT's μ-Adaptive Multidomain Power aware Sensors [2], and UCLA's Wireless Integrated Sensor Networks [3]. Sleep apnea is very common disorder that affects millions of Americans, which is characterized by brief interruptions of breathing during sleep. The goal of this project is to develop a wireless system capable of recording from a large number of electrodes (map human bodies' biopotentials) to diagnose the disorders of sleep apnea. This research focuses on: (1) developing application program for a project called "Sleep Apnea BioPotential Imager" based on Crossbow sensor network product [4]; (2) quantifying performance of this project.**

I. Introduction

Wireless Sensor Networks (WSN) have emerged as a new information-gathering platform with a large number of self-organized sensing nodes. These networks can be used in many environments such as intelligent battlefields, smart hospitals, earthquake response systems, and learning environments. In biomedicine or health field, sensor nodes can be deployed to monitor patients' health indicators and assist disabled patients. Through the self-organizing infrastructure, nodes are able to accept queries from remote sites, interact with the physical environment, respond to the sensor readings, and relay sensed information through its multi-hop sensor networks. Sleep apnea is a very common disorder that affects millions of Americans, characterized by brief interruptions of breathing during sleep. Population over 65 will grow threefold the next fifty years from 30M to 90M. Sleep disorders will grow from 70M to 100M in the same time frame [5]. Current diagnosis system consists of metal electrodes attached to the patient and connected with wires to external electronics for signal amplification, filtering, and processing. Such a system limits the free movement and comfort level of the patient. Our effort has been fulfilled to develop a wireless system capable of recording from a large number of electrodes that map the body's biopotentials (so our project is named as Bio Potential Imager).

Among many successful WSN systems, the Crossbow company's sensor networks, which is based on UCBerkeley's Smart Dust technology, are the leading ones [6]. Our research has been focused on Crossbow's TinyOS motes, for which we have developed the BioPotential Imager application as part of the Sensor Consortium Project [7]. In this paper, Section II overviews Crossbow's sensor networks basics; Section III covers the Sleep Apnea Project, including: a. Application Architecture, b. Performance Characterization of the Project; Section IV summarizes salient points.

Lei Wang, Cheung Fong, Ridha Kamoua, K. Wendy Tang are with Electrical and Computer Engineering Department, Stony Brook University, Stony Brook, NY 11794-2350, Email: leiwang, chfong, ridha, wtang@ece.sunysb.edu

Mr. Eric Noel are with AT&T Labs Research, Middletown, NJ 07748-0000, Email: eric.noel@att.com

II. Introduction To Crossbow Sensor Network

Crossbow Technology is the leading end-to-end solutions supplier in wireless sensor networks and the largest manufacturer of Smart Dust wireless sensors [6]. Crossbow's wireless sensor networking platform enables powerful, wireless, automated data collection and monitoring systems. MOTES / RADIOS (See Figure 1) are the hardware

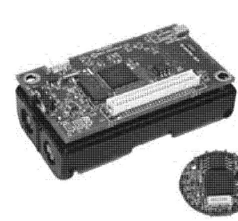

Fig. 1. Mica2 and Mica2dot Motes

platform which consists of Processor/Radio boards (MPR, Mote Processor Radio) commonly referred to as Motes. In Crossbow sensor network, the Multihop Routing protocol for sensornet called " Reliable Route" or " XMesh" on MAC layer is designed to satisfy the characteristics of WSN. The battery-powered devices run Crossbow's XMesh self-forming, micro-power, networking stack. In addition to running the XMesh networking stack, each Mote runs the open-source TinyOS operating system which provides low-level event and task management. To support developers, the MICA2 and MICA2DOT Motes come with Crossbow's

1-4244-0065-1/06/$20.00 ©2006 IEEE

Basic and Professional MOTE-KITs. By installing the application program into motes, sensor networks will automatically self-configure and route data to base stations, which are connected to local host computers or laptops. Through the base stations all applications can be accessed by the remote LAN or Enterprise systems [8] as depicted in Figure 2.

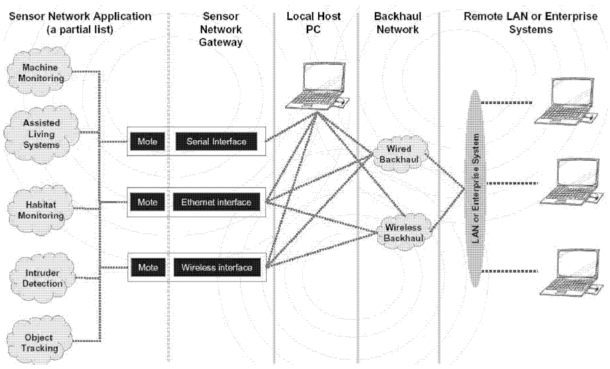

Fig. 2. Sensor Network Architecture

Sensor and data acquisition cards (MTS and MDA) mate directly to the Mote Processor Radio boards, see Figure 3. The industry's widest range of sensor support includes both direct sensing as well as interfaces for external sensors. GATEWAYS such as the Stargate 'Gateway' and the Mote Interface Boards (MIB), allow developers to interface Motes to PCs, PDAs, the WWW, and existing wired/wireless networks and protocols.

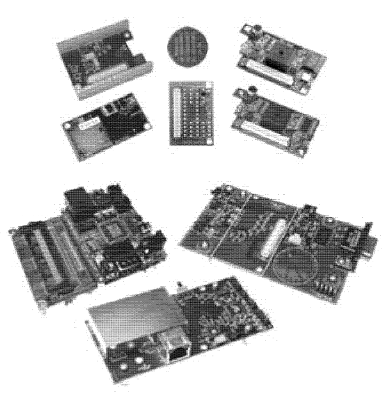

Fig. 3. Sensor/Data Acquisition board (left) and MIB board (right)

The TinyOS operating system is open-source, extendable, and scalable. The TinyOS system, libraries, and applications are written in nesC, a new language for programming structured component-based applications. The nesC language is primarily intended for embedded systems such as sensor networks. NesC has a C-like syntax, but supports the TinyOS concurrency model, as well as mechanisms for structuring, naming, and linking together software components into robust network embedded systems.
The principal goal is to allow application designers to build components that can be easily composed into complete, concurrent systems, and yet perform extensive checking at compile time. TinyOS defines a number of important concepts that are expressed in nesC. First, nesC applications are built out of components with well-defined, bidirectional interfaces. Second, nesC defines a concurrency model based on tasks and hardware event handlers, where data races are detected at compile time. NesC code modules are wired together allowing fluent-C programmers to customize existing applications written and distributed by Crossbow Technology.

III. Sleep Apnea Project and Performance Quantification

A. System Prototype and Overview

Sleep apnea is very common disorder that affects millions of Americans, which is characterized by brief interruptions of breathing during sleep. Below are human body's signal which can indicate the activities of sleep apnea:

- Electromyogram (EMG): A graphical record of the electrical activity of a muscle
- Electrocardiogram (EKG/ECG): Measures heart activity.
- Electroencephalogram (EEG): Measures brainwave activity

Current approaches for the diagnosis of sleep apnea include recording and tracking the body surface potential associated with brain waves (EEG), eye movements (EOG), muscle tone (EMG), and heart rate (ECG). As we described in Section I, such diagnosis system limits the free movement and comfort level of the patient.
The goal of this project is to develop a wireless system capable of recording from a large number of electrodes that map the body's biopotentials (hence we call our project BioPotential Imager). We developed our application on Crossbow's platforms based on the unrestricted ISM band with sufficient data transmission rate (38.4kbps). Our application will allow patients to move freely or change position as they wishes. This is a significant improvement over the current setup because if patients can not sleep normally, the diagnosis may be erroneous.

1) Application Architecture: As mentioned before, we used Crossbow platform (configuration shown in Figure 4). It consists of a microcontroller with internal ash program memory, data SRAM and data EEPROM, LEDs, a low-power radio transceiver (typically will be CC1000), UART bus, 51 pin I/O connectors which can be connected to interface boards or sensor boards and 10 bit ADC. Crossbow's sensor networks mainly utilize ISM (Instrumental Scientific Medical) band at 315/433/900Mhz to communicate. It also support new wireless technologies such as Zigbee and 802.15.4. The CC1000 on Mica2/Dot uses FSK with Manchester encoding, while CC2420 on MicaZ uses O-QPSK (offset quadrature phase shift keying) with half sine pulse shaping [9]. Table

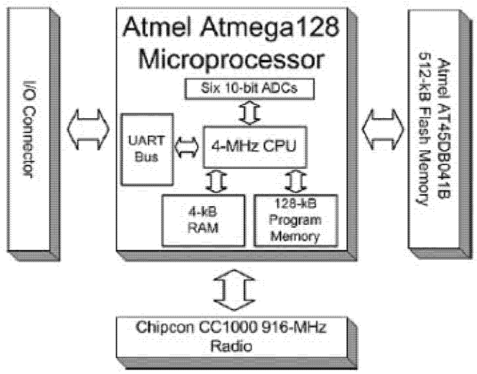

Fig. 4. Schematic for the hardware configuration

1 shows the radio bands and their corresponding Mote Processor Radio platforms:

Operating bands	MPR models	Radio Tranceiver
868/900MHz	MPR400/500	CC1000
433MHz	MPR410/510	CC1000
315MHz	MPR420/520	CC1000
2400MHz	MPR2400	CC2400(802.15.4)

Table 1: Radio bands and Mote Processor Radio platforms

Our experimental setup (Figure 5) consists of one Gain controlled operational amplifier, ECG/EMG/EEG electrodes and Crossbow platform (MPR400/MDA300/MIB510).

The MICA2 motes are powered by two 1.5-V dry-cell batteries. The MIB510 serial PC interface is used as base station allowing motes to communicate with a PC. After the base station receives the information, the information is unpacked into separate data points. Each data point represents a sample of the original signal at the specific time. To reconstruct the whole signal, each data point should be joined together. This can be achieved by using the Oscilloscope GUI provided by TinyOS. Before running Oscilloscope GUI, we started SerialForward. SerialForward is a program which forwards the data packet to all applications that needs the data from the wireless network.

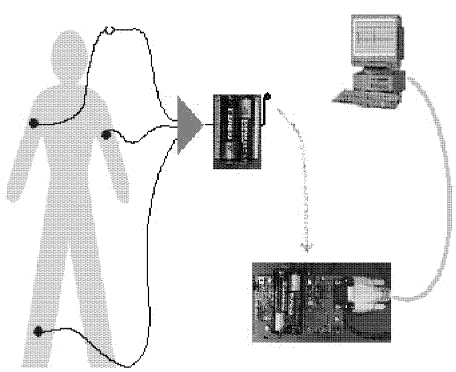

Fig. 5. Bio Potential Imager's Prototype

2) Design Considerations: In terms of wireless transmission platform, we have the option of using infrared or radio frequency transmission. Infrared transmission require line of sight communication. We have, therefore, selected Radio Frequency transmission for implementation on the Crossbow platform. Instead of multiple TX/RX Individual amplification at each electrode with filtering/processing done at RX station, we chose to use single TX/RX with central amplification/filtering/processing on patient's mote due to cost, patient's convenience and data processing consideration. The sampling rate of the final design was 50Hz far less than 400Hz, twice of the maximum frequency of human body signal (Nyquist Theorem). Due to messaging overhead and limited data rate, we achieved a data rate of 1.6 kbps which limits our electrode sampling rate to 50 Hz.

3) Testing our Project: In testing our project, we used a signal generator to generate a simulated heart beat signal of 2Hz. This generated signal is sent to a data acquisition board MDA300 attached on a remote mote. The mote then transmits the signal wirelessly to another mote connected with a MIB510 interface board which acts as a base station and is connected to a laptop computer. See Figure 6 and Figure 7 for our experiment setup and its diagram.

For testing purpose, we plotted the received signal at the laptop (exported from the oscilloscope) and compared with the generated signal from the signal generator. Figure 8

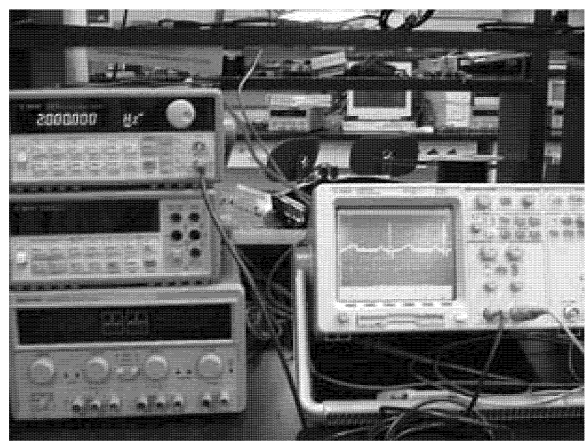

Fig. 6. Experiment setup

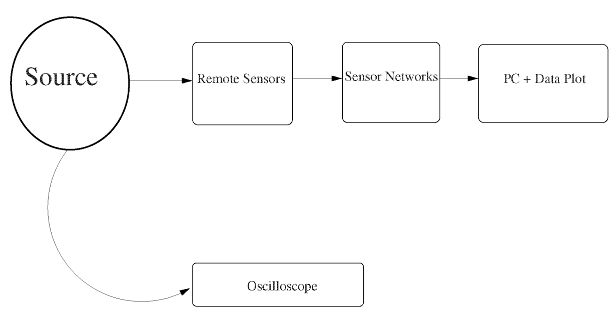

Fig. 7. Experiment setup diagram

shows both of the original signal and the received and Figure 9 shows the difference between them in percentage error. Indeed, we can conclude that difference has a mean percentage error of less than 2%.

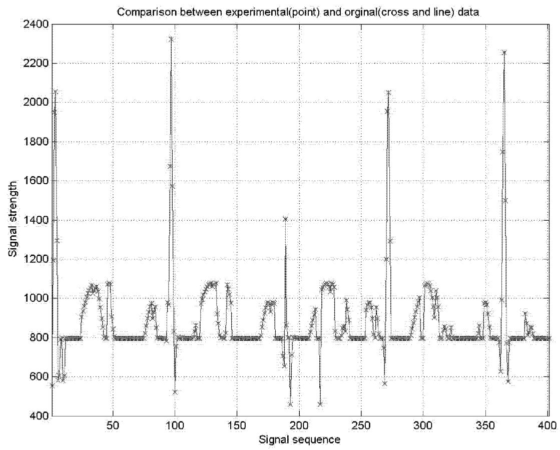

Fig. 8. The original (line) heartbeat wave and experimental (point) result

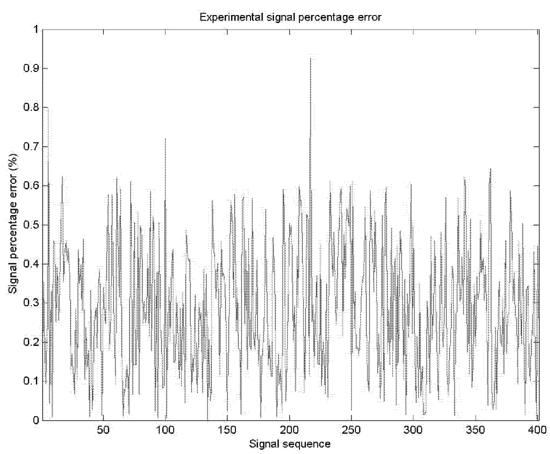

Fig. 9. Signal Percentage error

B. *Quantification of Sleep Apnea Project*

In this section, we provide some quantification measure of the performance of our sleep apnea project. More specifically, we verify the power drain time of the system, provide a projection on the number of motes (biopotential recordings) that can be supported by the system while maintaining quality communication.

Prior to our power drain experiment, we also verify the battery capacity of Duracell MN 1500 Alkaline cell battery via a three terminal adjustable regulator, the LM 317 circuit as shown in Figure 10 (in our experiment, C1 and C2 are set to zero hence $V_{out} = 1.25(1 + R_2/R_1) + I_{adj}(R_2)$. Indeed, our experiment indicates the battery capacity is 2788 mA-hour, this number is in agreement with 2800

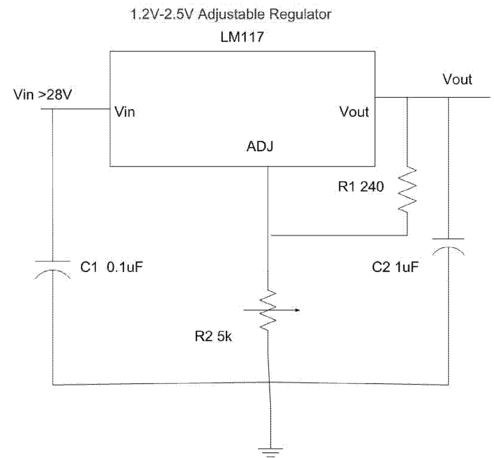

Fig. 10. LM317 diagram

mA-hour in Duracell's technical table [10]. To quantify the power drain time of our system, we ran the system at two different reporting time intervals, one at 8 second and the other at 1 second. In both cases, the distance between the base station mote and the one connected to the data acquisition board was the same and we monitored the communication quality to be at least 99%. The total time it took to drain the system (or to have communication quality dropped below 99%) was 4 days and 8 hours for the case with a communication interval of 8 second; and 4 days in the case of 1 second as the communication interval. This small difference can be explained because Crossbow's application programs set 100% duty cycle as a default (in files called CC1000cConst.h and CC1000RadioIntM.nc) in spite of different reporting times. From Crossbow Power Management table [11], one can find 2800 mA-hour and 100% duty cycle correspond the battery life of 4.3 days (see Table 2) for a glance.

Current		Duty Cycles	
		100%	99%
Micro Processor (Atmega128L)			
Current operation	6 mA	100%	1%
Current sleep	8 μA	0	99%
Radio			
Current in receive	8 mA	75%	0.75%
Current in transmit	12 mA	25%	0.25%
Current sleep	2 μA	0	99%
Logger			
Write	15 mA	0	0
Read	4 mA	0	0
sleep	2 μA	100%	100%
Sensor Board			
Current operation	5 mA	100%	1%
Current sleep	5 μA	0	99%
Battery Capacity 2800	mA-hour	Battery life 4.3 days	Battery life 13 moths

Table 2: Experiment set-up parameters and battery life

To provide a projection on the number of motes and hence the number of biopotential recordings supported by our system, we use the well known network throughput equation for pure-Aloha and slotted Aloha [12]: $S = G \times (1 - G/N)^{N-1}$, where N is the number of identical nodes, G is channel traffic (the average number of packet transmission attempted per transmission period T) and S is network throughput (the average number of successful transmission per transmission period T). For pure-Aloha $S_{max} = 0.184$ and $G = 0.5$ [12], hence the equation needed to be solved to get the node number N is: $0.184 = 0.5(1 - 0.5/N)^{N-1}$. For slotted-Aloha the equation is $0.368 = (1 - 1/N)^{N-1}$ [12]. We found the projected number of nodes supported by our system is between 50-100 nodes. Using the CSMA/CD throughput equation $S = \frac{T}{T + 2\tau \times \frac{1-(1/k)^{k-1}}{(1/k)^{k-1}}}$ where k is the node number, S is the throughput, τ is propagation time over channel and T is transmission time [12], we found the number of node should be 50-100 in order to keep throughput high (with a message length of 448bits [13]). To further verify this projection, we also simulated our system via TinyViz, a graphical user interface of PowerTossim [14]. PowerTossim is an event-driven simulation environment for TinyOS application. We found that, indeed, up to 100 nodes can be supported by our system. In the future, we plan to verify this number experimentally.

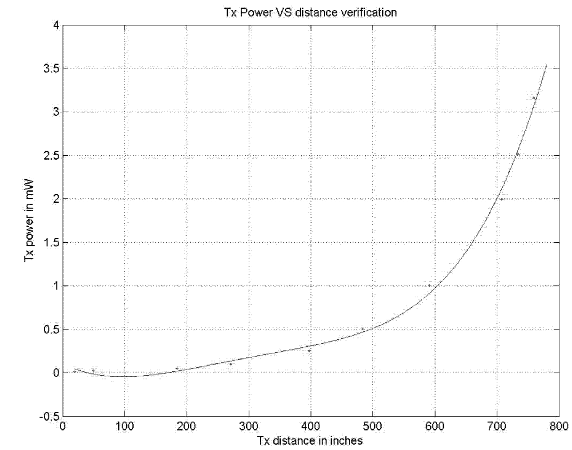

Fig. 11. Power VS distance

IV. Discussion

As part of our implementation of the sleep apnea project, we have also investigated the issue of power and distance. Obviously, as the transmission distance increases, more power is needed to maintain the same transmission quality. Figure 11 is the experimental result of the amount of power needed to maintain a 99% transmission quality as defined by Surge-View, a performance monitoring interface of the motes. An empirical formula for the Tx power function of distance in Figure 11 is deduced: $TxPower(inmW) = 5.1801^{-11}d^4 - 6.111^{-8}d^3 - 2.6407^{-5}d^2 - 0.0035932d + 0.1064$.

The radiation pattern is a graphical depiction of the relative field strength transmitted from or received by the antenna. Antenna radiation patterns are taken at one frequency, one polarization, and one plane cut. The patterns are usually presented in polar or rectilinear form with a dB strength scale. Patterns are normalized to the maximum graph value, 0 dB, and a directivity is given for the antenna. After we did research on radiation pattern for Crossbow Mica2's loop-shaped antenna in [15], motes should be put on the same plane where Base station is to get the consistent result. And the antenna loops should always FACE each other by having a same axis, otherwise if they form a 90o degree, the signal strength will be very reduced.

In order to evaluate power consumption, some application programs were simulated in PowerTossim. All simulations were executed for 60 virtual/simulated seconds and all values for power are in milli-joules(mJ). Power Profiling analysis provided direct view of power consumption for each application. Since Reliable Route (Crossbow's ad-hoc protocol) is stable and fair [16] [17], each node consumes almost the same amount of power in total, each node also consumes almost the same amount of power for different corresponding component. For illustration see Figure 12 PowerTossim output for the Surge-Reliable application. The left most graph compares the total consumption of each node with its component power consumption inside. The right most graph compares the difference among radio, EEPROM, LED and CPU power consumption across all nodes.

Figure 13 is similar as Figure 12 right most graph but averaged over all simulated applications. We conclude the radio component consume most power. Given the tested application were based on Reliable Route we expect the same for our prototype.

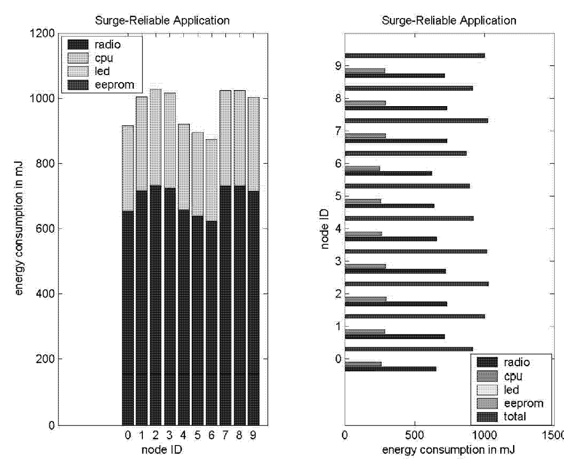

Fig. 12. Surge Power Analysis

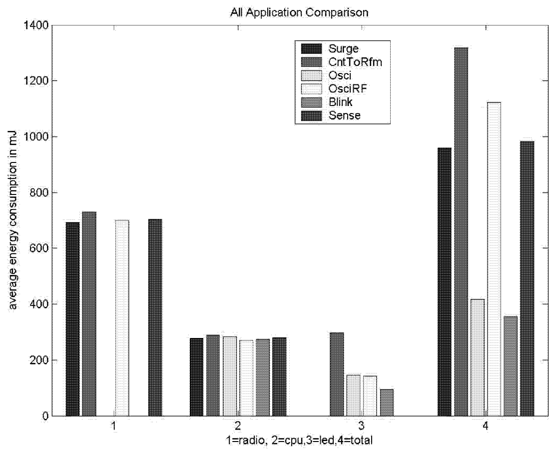

Fig. 13. Specific Consumption Comparison for applications

V. Conclusion

The vision of this project is to create a wireless sensor network that records biopotential readings of patients with sleep apnea using the "motes" provided by Crossbow Technology Inc. It is an ongoing project. Thus far, we have successfully recorded and transmitted the recording of one biopotential sensor. We are currently working on the use of multiple motes to record and transmit multiple biopotential readings. At a first glance, the project seems trivial as only system integration is involved. However, as we proceed with the project, we found that the capable sampling rate of MDA300 is far below the human body's biopotential frequency and FCC regulation limit our transmission rate. Thus we need to solve these problems in the future. Upon complete integration of these sensors, a more research oriented issue is the establishment of an efficient sensor networks that can support large number of simultaneous users in a hospital or assisted living environment.

VI. Acknowledgement

This project is supported by the Sensor Consortium in Stony Brook University and is funded by the National Science Foundation under Grant No. EEC-0332605. The goal of the consortium is to promote and increase awareness of entrepreneurship and technology transfer activities on Long Island with a focus on national security and medical sensor systems. Any opnions, findings and conclusions or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

[1] J. M. Kahn, R. H. Katz and K. S. J. Pister, " Mobile Networking for Smart Dust" ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom 99), Seattle, WA, August 1999.
[2] μ-Adaptive Multi-domain Power aware Sensors at MIT, http://www-mtl.mit.edu/research/icsystems/uamps/
[3] Wireless Integrated Sensor Networks at UCLA, http://www.janet.ucla.edu/WINS/
[4] Crossbowweb Web, http://www.xbow.com
[5] " Health, United States, 2004" http://www.cdc.gov/nchs/data/hus/hus04trend.pdf027 Sept. 2004.
[6] Joseph M. Hellerstein, Wei Hong, Samuel R. Madden, " The Sensor Spectrum: Technology, Trends, and Requirements" ACM SIGMOD Volume 32 , Issue 4 (December 2003)
[7] Sensor Consortium in Stony Brook University, http://www.ee.sunysb.edu/ sensorconsortium/
[8] Crossbow Seminar in Boston, Multihop-Mesh-Network PDF, Presentation of Day one, Boston,Dec/12/2004.
[9] Crossbow Seminar in Boston, Introduction to Sensor Networks PDF ,Presentation of Day one, Boston,Dec/12/2004.
[10] " LM317 data sheet" http://www.national.com/pf/LM/LM317.html
[11] " Crossbow Power Manangement Table" www.Crossbow.com/Support/Support-pdf-files/PowerManagement.xls
[12] Tarek N. Saadawi, " Fundamentals of Telecommunication Networks" 1994,Wiley Interscience.
[13] Crossbow Seminar in Boston, Wireless Communications PDF,Presentation of Day one, Boston,Dec/12/2004.
[14] Victor Shnayder, Mark Hempstead, Bor-rong Chen and Matt Welsh, " Simulating the Power Consumption of Large-Scale Sensor Network Applications" UNDER SUBMISSION
[15] Radiation Pattern for Antenna, https://ewhdbks.mugu.navy.mil/RADIAPAT.HTM
[16] Alec Woo, Terence Tong, David Culler, " Taming the Underlying Challenges of Reliable Multihop Routing in Sensor Networks" SenSys03,November 5C7, 2003, Los Angeles, California, USA.
[17] A. Woo and D. Culler, " Evaluation of efficient link reliability estimators for low-power wireless networks" Technical Report UCB//CSD-03-1270, U.C. Berkeley Computer Science Division, September 2003.