

A TinyOS-Based Wireless Neural Sensing, Archiving, and Hosting System

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Abstract—We have designed and tested a comprehensive wireless neural recording system. The system amplifies, digitally encodes, transmits, archives, hosts, and displays multiple channels of neural recordings from any number of un-tethered test subjects. The neural transmitter and receiver are modified TinyOS-based MICAz wireless sensor nodes that can sample, transmit, and receive neural data real-time at a rate of 44.8 kbps while consuming less than 100 mW of power. This data rate can be divided for recording on up to eight channels, with a resolution of up to 10 bits per sample. An archive server records the neural signals received by the Ethernet-based gateway receivers, and hosts them to browser-based clients over the Internet. This work demonstrates the viability of the TinyOS-based sensor technology as a foundation for chronic remote biological monitoring applications, and demonstrated a system architecture that can actively leverage advancements in distributed sensing, networking, and communications technologies.

Keywords—Brain-Machine Interface, EEG, Fast Ripples, Wireless, Telemetry, TinyOS, Epilepsy, Smart Dust, Single-Unit Recording.

I. INTRODUCTION

Electrophysiological recording is a powerful tool used by neuroscientists to investigate the mechanisms by which the brain creates and interprets signals. These studies help create an understanding of the brain function that accompanies emotions, as well as that which accompanies disease. Rhythmically varying electrical impulses (i.e., field potentials) of large neural populations vary at rates in the 1 to 100 Hz range [1]. This brain-wave activity has been correlated to specific physiological outcomes, such as sleep, excitation, and epilepsy. Field events composed of hypersynchronous action potentials result in oscillations in the 250 to 500 Hz range (otherwise known as fast ripples [2]), which have been observed in the epileptic zones of patients with temporal-lobe epilepsy [3]. Identifying the cells that synchronously deliver the action potentials that result in epileptic seizures requires extra-cellular signal acquisition in the 0.5 to 10 kHz range. In order to quantify neural activity, electroencephalograms (EEGs) and single-unit recordings are taken by measuring the potential difference between a pair of electrodes placed in or on the brain region of interest and at the frequency of interest.

Although neural recordings are frequently performed as acute experiments (e.g., < 6 hrs), some studies require chronic or longer-term measurements. For example, the study of epilepsy requires continuous recordings to be made over a

period of several days. Conventional neural recording techniques use a direct-wired connection between the subject and the measurement tool. Typically, this connection consists of a bundle of fine wires that can frequently limit animal behavior. In addition, the wired connection prevents the environment from containing natural elements such as tubes and tunnels. The constraints of such direct-wired connections have the potential for skewing the obtained results. A wireless recording system could be used to remove the aforementioned constraints. Such a wireless neural recording system must be capable of sensing, amplifying, and transmitting neural signals with a sampling frequency of at least double the maximum frequency of interest (i.e., approximately 250 Hz for EEG, 1.2 kHz for fast ripples, and 10 kHz for single units) per channel while being small, low cost, lightweight, and low power. The system also requires a receiver to receive, demodulate, and display the transmitted neural signals.

Existing approaches to develop a wireless neural measurement tool have ranged from designing a custom microfabricated recording and telemetry system [4] to the use of commercial-off-the-shelf (COTS) PC technology [5]. A performance comparison between existing methods of wireless neural recording system design has been described in [6]. This work builds upon the TinyOS-based 2-channel EEG recording system described in [6].

II. TINYOS AND THE MICA-BASED SENSOR NETWORK

Until recently, wireless devices consisted of complex, expensive, and high-power systems, such as cell phones, PDAs, and wireless-enabled laptop computers that target specific and highly-standardized applications that rely heavily on a powerful infrastructure (e.g., such as satellites, star-network base stations, etc...). Researchers at the University of California, Berkeley opted of a new approach in wireless-system design: one that involves low-cost embedded devices that can be implemented for a variety of applications [7]. This effort resulted in the development of the MICA platform: a self-configuring multi-hop (mesh) network platform for remotely monitoring distributed low-frequency phenomena [8].

The wireless sensor nodes, which are commonly referred to as “motes”, have been designed to operate using TinyOS and are currently being used in wildfire-instrumentation, habitat-monitoring, and global-positioning applications to mention just a few [9,10,11]. Prior work has successfully

demonstrated a 2-channel wireless neural recording system based on the MICA2 sensor network [6] through modifications of standard data-acquisition and communication protocols.

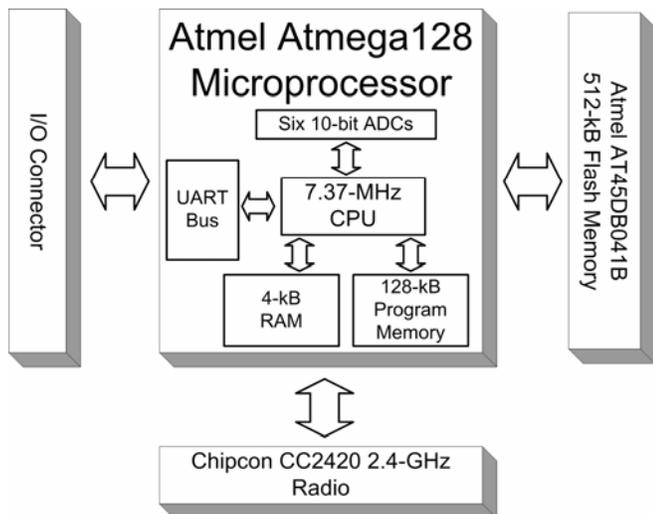


Fig. 1. System-level schematic of MICAz mote.

Both motes used in this work are of the MICAz type, which is produced by Crossbow Technology, Inc. [12]. One MICAz mote is used as a transmitter, and is thus attached to the subject via a neural preamplifier circuit. The other mote is used as a receiver, and is interfaced to an MIB600CA Ethernet gateway (also produced by Crossbow Technology, Inc.). A basic system schematic of the MICAz mote is displayed in Figure 1. The MICAz has six input channels, each with its own 10-bit analog-to-digital converter (ADC). Data is processed by an Atmel Atmega128 microprocessor with 512 kB of flash memory. Data transmission and reception is handled by a Chipcon CC2420 radio chip, which is IEEE 802.15.4 compliant. When the two 1.5-V dry-cell batteries are installed, the MICAz is approximately the size of a matchbox ($58 \times 32 \times 15$ mm). The Ethernet Gateway is used to send the neural recordings over the Internet (or LAN) to the archive server.

The work in this paper has been directed toward implementing specific timing and communications protocols for maximum data-acquisition and transmission rates. Such high data rates can enable one or more motes to perform wide-band multi-channel wireless neural recordings from several freely moving subjects simultaneously.

III. SYSTEM DESIGN

The overall system design can be divided into two major components: hardware and software. A neural preamplifier circuit is required to properly amplify and level-shift the differential neural signals. TinyOS software components implement data-acquisition, signal-transmission, signal-reception, and wireless media-access protocols optimized for achieving maximum data throughput. An archive server is used as a repository of neural recordings and a host for the

browser-based client. The browser-based client interprets and displays the previously-recorded data in a graphical format.

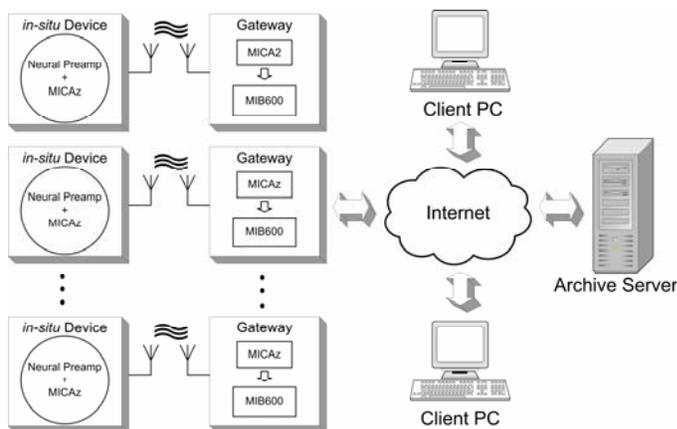


Fig. 2. Top-level diagram of the neural interface system.

A. Hardware

Each channel is sensed differentially by a pair of electrodes. A neural preamplifier circuit is used to take the differential signals and amplify, level-shift, and convert them into a single-ended waveform ranging from 0 V to the MICAz-battery voltage (nominally 3 V) in order to be properly digitized by the MICAz ADCs. A preamplifier circuit for recording EEGs has been designed to interface directly with the MICAz mote. The heart of the neural preamplifier is an Analog Devices AD627 Instrumentation Amplifier. The gain of the AD627 can be set by an external resistor. The output has been referenced to half the supply voltage by a simple resistive divider followed by a voltage-follower circuit. To avoid high-frequency noise from being aliased into the sampled signal, the AD627 output is followed by an RC-filter with a cutoff frequency that should be set to half the sampling frequency of the channel.

B. Software

TinyOS-software components have been written to implement data-acquisition and wireless media-access control protocols for the transmitting MICAz. The receiving MICAz will operate on a standard TinyOS component to receive packets and broadcast them over an Ethernet connection via the mote's UART serial connection to the MIB600CA. The UART is set to 115200 bits per second on both the MICAz and MIB600CA.

The data-acquisition component initializes an independent hardware-based timer (Timer3) to trigger ADC sampling events. The analog input signals are digitized as 8-bit integers ranging from 0 (ground) to 255 (battery voltage) and subsequently stored in the microprocessor's RAM. Once 110 readings are taken, a header indicating the source mote ID, packet size, final reading ID number (for time referencing), and CRC (cyclic redundancy check) bytes are copied to the radio buffer for subsequent transmission.

Due to the hardware constraints of the MICAz processor, TinyOS does not support the prioritization (or preemption) of tasks, but rather processes tasks on a FIFO basis. Tasks must run to completion before the next task in the queue is handled, which can cause delays in sensitive time-synchronized events (such as ADC sampling). By profiling the TinyOS kernel, tasks that require substantial CPU time can be identified and split into smaller tasks. For example, copying data from RAM to the radio buffer causes ADC sampling to briefly halt because the associated task duration is longer than that of a single sample period. The intermittent stopping of the ADCs results in varying sampling intervals (or sampling jitter). Sampling jitter results in unwanted distortion in the reconstructed output signal. To alleviate this problem, the copy instruction is split into multiple tasks. Execution of each task requires CPU time that is less than a single sample period, thus minimizing the interruption of ADC sampling. Even with the aforementioned protocol in place, sampling jitter is still present, as depicted in Figure 3. Sampling jitter can be further improved by 1) scheduling data batches to be transferred once every integer number of sampling periods, and 2) identifying other tasks that could cause delayed sampling events. These approaches will be investigated in future work.

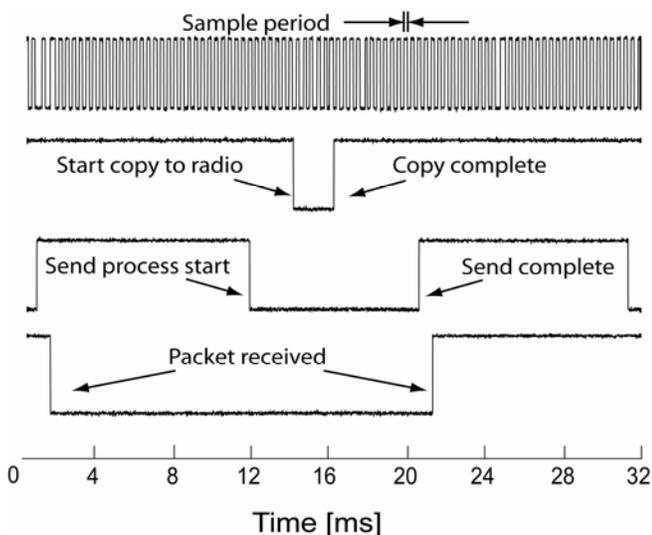


Fig. 3. Timing diagram illustrating sampling events with respect to data transmission.

The archive server is a database that polls the Internet/LAN for subscribed MIB600CA gateways. Tables are generated on the database on a per-session basis. The client is a Java-based program has been designed for use on any networked PC with a Java-enabled browser to search and retrieve archived data. This program acquires data from the archive server, and displays them either as raw data points, or a reconstructed waveform. Signal reconstruction is performed by upsampling the original signal and passing it through an 8th-order Chebyshev filter.

IV. EXPERIMENTAL TESTING

Experimental testing was performed in two categories: bench testing and *in-situ* testing. Bench testing was performed to assess the specific performance metrics of the system, such as data rate, range, power consumption, and signal resolution. *In-situ* testing was used to evaluate the overall performance of the system in its respective application environment.

A. Bench Testing

To assess the performance of the client-side signal-reconstruction program, as well as the total bandwidth of the data-acquisition and transmission system, an extracellular neural recording dataset was used. The data was originally acquired *in vivo* from freely moving rats using five four-channel MOSFET input operational amplifiers mounted in the cable connector to remove movement artifacts. Data were recorded wide band (0.1 Hz to 5 kHz) and sampled at 10 kHz/channel (16 channels) with 12-bit precision. The resulting signal is highpass filtered at 100 Hz with a 36-dB rolloff. The dataset was programmed into an HP 33120A arbitrary waveform generator whose output was connected directly to the ADC of the transmitting MICAz. The input and received/reconstructed action potentials are shown in Figure 4.

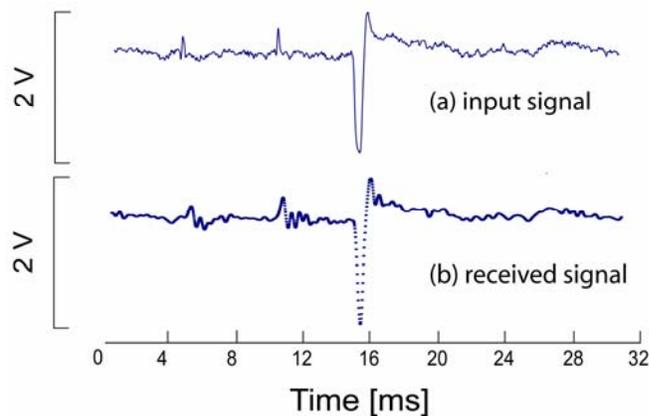


Fig. 4. Input and received/reconstructed simulated action potential.

The range of the neural transmitter was tested in a noisy laboratory environment equipped with monitors, oscilloscopes, microwaves, cordless telephones, WiFi, and a refrigerator. The system data-loss rate was assessed by measuring the total number of packets lost per ten thousand transmitted (which corresponds to approximately 1 million data points). As shown in Figure 5, the rate of packet loss is relatively constant over a 7-meter range, and subsequently begins to increase as the base station is separated from the mote by 8 meters or more. It is theoretically possible to retransmit a lost packet once without sacrificing data throughput, since the radio spends half its time in an idle state (see timing diagram). This approach will be investigated in future work.

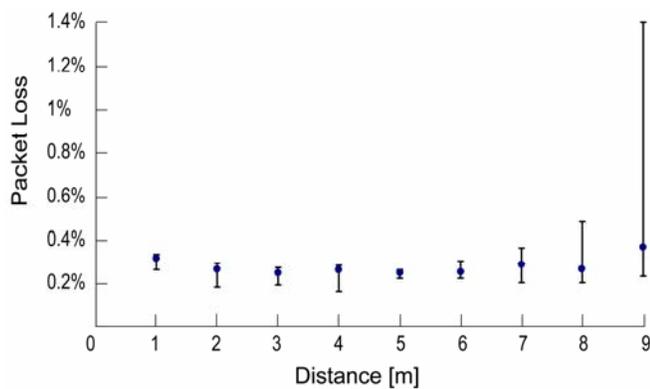


Fig. 5. Data loss as a function of distance between the transmitter and the base station in a noisy laboratory environment.

B. In-Situ Testing

The system was tested with a living mouse in a typical laboratory environment (Fig 6). Normal brain activity has been captured, followed by seizures induced by injecting kainic acid at 15 mg/kg to model temporal-lobe epilepsy [1]. The system parameters are summarized in Table 1.

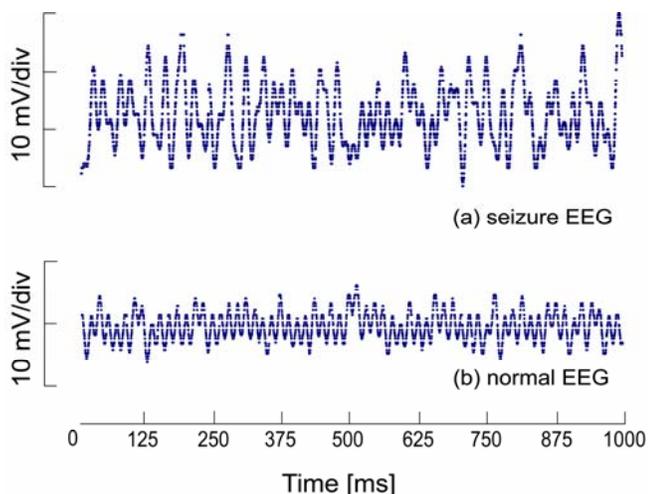


Fig. 6. Recorded normal and induced seizure activity.

TABLE I
SYSTEM PERFORMANCE SUMMARY

Max. # of Channels	8
Max.Total Data Throughput	44.8 kbps
Transmission Frequency	2.4 GHz
Communications Scheme	O-QPSK
Power Supply	3 V
Max. Power Dissipation	96.9 mW
Transmission Range	8 m
System Clock Frequency	7.37 MHz
Dimensions (cm)	5.8 x 3.2 x 0.5
Total Weight (w/o battery)	18 gr

V. CONCLUSIONS

In this paper, we have demonstrated a TinyOS-based wireless neural sensing, archiving, and hosting system. The data-acquisition and transmission throughput of the system was sufficient to record one channel of single-unit activity from any number of freely moving and behaving rodents, while the data archiving and hosting capabilities of the system allow users to conduct experiments and browse data from anywhere on the Internet. The system exhibited considerable sampling jitter, an issue which we hope to address by further investigating the MICAz task queue and synchronizing task processing with respect to sampling events. In addition, we hope to reduce packet loss by enabling the receiving mote to request re-transmission of a lost packet via the transmitting mote.

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