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Battery-operated High-bandwidth Multi-channel Wireless Neural Recording System using 802.11b

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Abstract—**This paper reports the design of a battery-operated, high bandwidth, multi-channel wireless medical telemetry system. The system is capable of transmitting 2.3Mbps of raw streaming data using the IEEE 802.11b protocol. In a typical application, the system was used to collect data from micro-wire electrodes implanted in the ventral striatum of an awake and behaving rat. The complete system weighs 87g (without battery) and consumes 2.7W.**

I. INTRODUCTION

THERE has been a tremendous need for a lightweight wireless neural recording system capable of transmitting 50-100 channels in real-time [1]. The main drivers for this need have been the neuroscience community examining neural firing correlates from behaving animals [2]. Neurologists/neurosurgeons have also been exploring such systems as an effective tool to interface locked-in patients to the outside world [2, 3, 4]. The reported multi-channel wireless neural recording systems use custom-made analog wireless transceivers with varied frequencies of transmission [5-13], are too bulky & heavy to be applicable for small animal research [14], or do not permit action potential recordings [15, 16]. In addition, multiple path fading and interference are also some critical design issues for systems operating in an RF hostile environment such as hospitals. For example, in February 1998, there was an incident at Baylor University Medical Center in Dallas, TX, where interference from a high-definition television test signal generated by a local station disrupted the operation of critical cardiac telemetry equipment [17]. Multi-path fading is more severe in analog systems but digital transceivers can use multi-path signals constructively. Even though the overhead in processing data is larger and more complex in digital systems; such systems provide substantial improvements in performance, most notably when the subject is in motion. In this paper, we present a complete wireless telemetry system capable of transmitting 2.3Mbps of continuous raw streaming data. Using the designed system, we successfully transmitted 4 channels of real-time neural data from the ventral striatum of an awake and behaving rat.

Our data transmission protocol conforms to the IEEE 802.11b standard using the Direct Sequence Spread Spectrum modulation scheme. The protocol is well suited to transmit large amounts of data and is robust against interference. In addition, since it is widely used in consumer wireless-LAN applications, there are many companies developing embedded modules to support this protocol with a continuous push towards faster, more power-efficient, and smaller modules. Our 4-channel wireless neural recording system has a pass-band extending from 500Hz to 6kHz and can measure neural signals in the range of $50\mu V_{p-p}$-$1mV_{p-p}$. It uses a Digi Connect EM (Digi International, MN, USA) embedded processor board to process the data serially at 2.3Mbps and transmit it using the 802.11b protocol.

II. SYSTEM COMPONENTS AND DESIGN

The wireless recording system can be broadly sub-divided into the analog front end and 802.11b wireless digital transmitter. A block diagram of the whole system is shown in Fig. 1. Neural action potentials are typically in the 500Hz–5KHz frequency range. A sampling rate of 20KHz is more than enough to faithfully reproduce the waveforms.

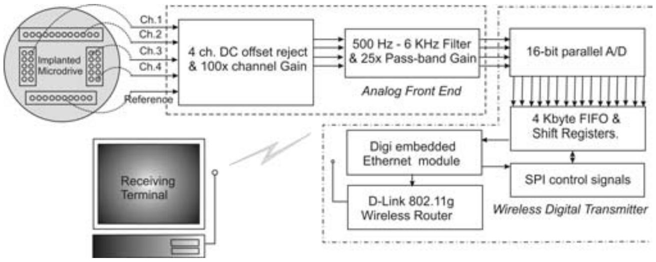

Fig. 1. Block diagram of the wireless system.

The total data rate can be expressed as: $BW=20,000NxR$, where N is the number of channels and R is the resolution of the Analog-to-Digital converter (A/D). For example: A 4-channel system with 16-bit resolution would require 1.28 Mbps (Mega bits per second) of raw data to be transmitted. Most commercially available wireless-LAN

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transceivers are tailored to packetize and transfer large files of data between terminals rather than transmitting a continuous stream of high-speed real-time data. In real-time applications the transmitter cannot ignore incoming data, hence, one has to buffer such data and transmit it much faster so as not to overflow the buffers.

A. Analog Front-End

The analog front end consists of a series of buffers, amplifiers, and filters to condition each of the 4 channels. A detailed circuit diagram of the analog front end is shown in Fig. 2.

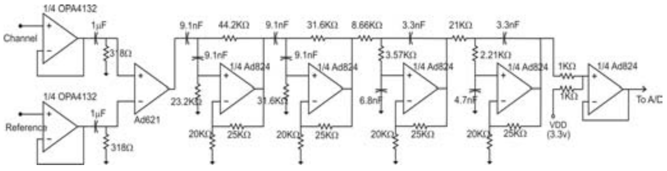

Fig. 2. Schematic of the analog front end of one of the recording channels.

At the input, low-noise, quad, unity gain buffers (OPA4132, Texas Instruments Inc., TX, USA) were used to provide large input impedance to microwire recording tetrodes. The tetrodes have impedances of the order of 0.3–1MΩ at 1kHz. The buffers were followed by a single pole 500Hz high pass filter using 1µF SMD capacitors to reject the large DC offsets generated at the electrode-electrolyte interface [18]. Instrumentation amplifiers (AD621, Analog Devices Inc., MA, USA) were used to subtract the common mode noise between the neural channel and the reference electrode and to amplify the difference by 100x. Fourth order high-pass filters (corner frequency of 500Hz) and fourth order low-pass Butterworth filters (corner frequency of 6kHz) followed the instrumentation amplifiers to reject out-of band signals [19]. Quad op-amps (AD824, Analog Devices Inc., Ma, USA) were used for superior matching and reduced PCB area. The filters were also designed to provide a 25x pass-band gain. Finally, the bipolar signals were level-shifted to fit in the 0–2V unipolar range of the A/D.

B. Digital Wireless Transmitter

The Digi Connect EM embedded processor module can support serial input data using the SPI (Serial Peripheral Interface) interface. To input the data into the Digi Connect EM module using SPI format, we first directly connected a commercially available SPI A/D (MAX1047, Maxim Integrated Products Inc., CA, USA) to the module. However, it was realized that the data could not be processed continuously. The Digi module could take a burst of samples without interruption between samples by setting up a Direct Memory Access transfer from the SPI port; however, transferring that packet from the SPI driver into the Ethernet driver required two time slices of operating system scheduling. The interrupt response and scheduling latency caused gaps in the sampling and data were lost intermittently. An external FIFO (First In First Out memory block) was therefore used to continuously collect data while the previous packet (set of samples) was processed through the drivers & operating system and sent out via the network. We could not allow the FIFO to get completely full or we would lose data, so we relied on the *Half-Full* flag to trigger the next packet transfer. The transmitted time slices were 10 milliseconds each, so the FIFO needed to buffer a minimum of 20 milliseconds of data. At 80-kilo samples per second sampling speed, 20 milliseconds would contain 1600 samples. The FIFO size was determined by the requirement that 20 milliseconds of data fill the FIFO half full or less. Hence, we decided to use a 4Kbit FIFO. This level of buffering led to loss-less transmission of data. The timing was analyzed by looking at the software code and verified by using an oscilloscope. The analog signals from the front-end module were digitized using a 16 bit parallel A/D (LTC 1853, Linear Technologies Corp., CA, USA) at 80kHz total sampling frequency. A detailed circuit diagram of the digital section is shown in Fig. 3.

The operation of the digital transmitter section could be explained as follows: first the FIFOs were reset and then as the A/D clocked, output parallel data latched into the FIFOs. Since each of the FIFOs had 4Kbit x 9 capacities, as 2Kbit x 9 filled into each FIFO, the *Half-Full* signal went active low. This *Half-Full* signal was used as a start sign in the Digi embedded module. The module then enabled the SPI *Chip Select* signal and clocked the SPI port at 2.3MHz. Using the *Chip Select* signal and the SPI *Clock* signal, the counters and hex inverters generated the FIFO *Read* signal and the shift register *Shift/Load* signal. A delay of about 74nsec was required between the FIFO *Read* and the shift register *Load* signal and this delay was generated using Hex inverters. Data was read from the FIFOs and loaded onto the shift register, serialized and collected at the SPI *Receive* pin on the Digi Connect EM embedded Ethernet module. The module was programmed to collect 4Kbytes of data (2Kbytes from each FIFO) in one packet and time-stamp the packet. A four-byte packet identifier header was added to the packets before transmitting the packets on the Ethernet port using UDP. Figs. 4, 5 show the timing diagrams of the A/D and the digital section.

An important consideration in the design of the system is that the rate at which the SPI data is transferred to the Digi Connect EM module has to be greater than the rate at which half of the FIFO fills up. The minimum speed to clock the SPI port of the module is 16 bits x 80kHz sampling rate = 1.28MHz SPI clock speed. But this speed assumes zero delay in the module as it sequentially picks up packets from the FIFO. Because of software execution delays at the module, there would be data loss. For loss-less transmission, the clock speed of the SPI port of the Digi Connect EM module should account for delays that occur as one packet of data is processed through the different stages of the module before the module is ready to receive the next packet. Hence, we clocked the SPI port of the module at 2.3MHz. This speed assured seamless flow of data between the FIFO and the module. According to the Digi Connect EM datasheet, the serial ports could be clocked as fast as 4MHz, but this was not explored. The 80kHz clock for the A/D was generated using a square wave oscillator (LTC1799, Linear Technologies, USA).

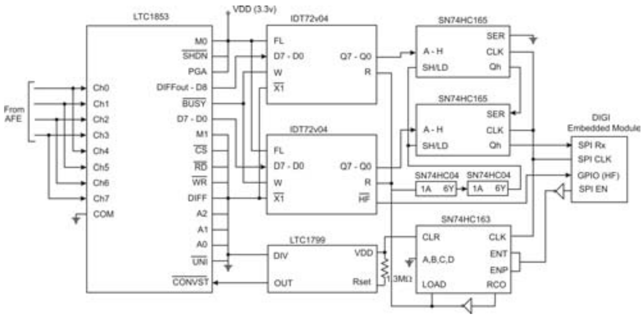

Fig. 3. Circuit diagram of the digital section of the transmitter showing the A/D, FIFOs, Shift Registers, Sampling Clock generator and the SPI port of the Digi Embedded Module.

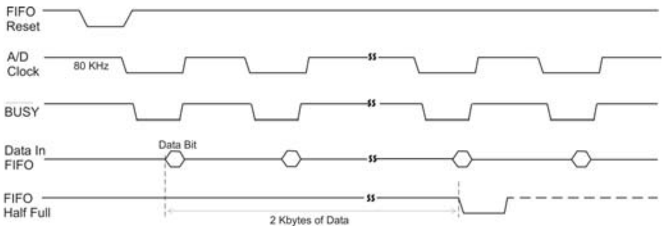

Fig. 4. Timing diagram showing A/D and FIFO operation.

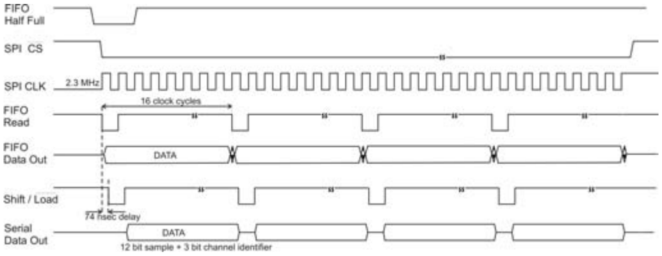

Fig. 5. Timing diagram showing data being loaded into the SPI port of the Digi module.

III. EXPERIMENTAL RESULTS

The system was powered using a 9v battery. Two stable supplies (±3.3V and 5V) were generated using a buck regulator (MIC4680, Micrel Inc., CA, USA). The output of the Ethernet port of the module was tied to a D-Link Wireless 802.11b/g pocket router (DWL-G730 AP, D-link Systems Inc., CA, USA), configured as an Access Point, to transmit the wireless neural data to a laptop with a standard Cisco Aironet 802.11b wireless PCMCIA card (Cisco Systems Inc., CA, USA). The receiver consisted of a laptop with an 802.11b wireless card ran a custom C code that accepted data from the 802.11b port and translated it to the resulting analog waveform. The packet numbers were used to timestamp the data.

The system would consume far less power and weight if instead of the Digi Connect-EM and the D-link Access Point, the pin-compatible Digi Connect Wi-EM [20] were to be used. The Connect Wi-EM can accept data in the SPI port and transmit 802.11b wireless data. This underlines the advantage of using a standard protocol like IEEE802.11b for transmission of data. As technology improves and market demands increase, companies often compete with one another to develop products with increased functionality and features. For example, a few years ago, the system reported in [14] used a 486 PC with a PCMCIA wireless 802.11b card to transmit neural data, but currently there are devices like the Connect EM and the Wi-EM which can do the s similar processing at a fraction of the power, weight and size. With the projected usage of the 802.11b technology in the market [21], it would be safe to predict that in the future, even more efficient and smaller modules would be available. At the time of writing this paper, the Connect Wi-EM was under production but not yet available.

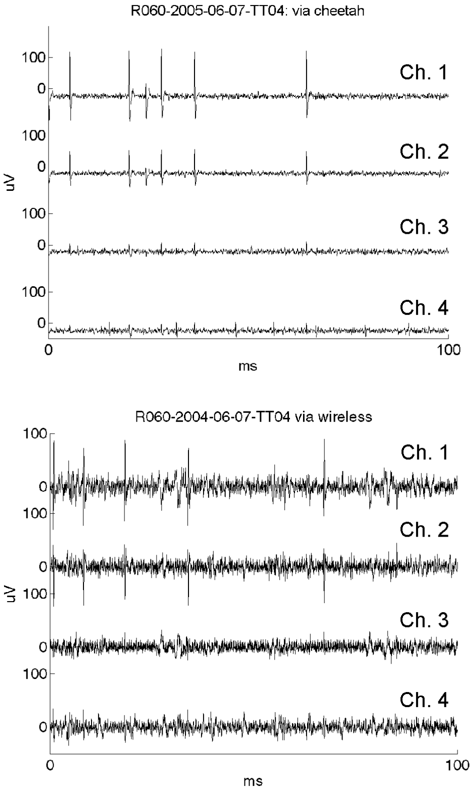

Fig. 7 (top): 100ms snapshot of 4-channels of real neural data acquired using a commercial system from a tetrode implanted in the ventral striatum of an awake & behaving rat;(bottom): 100ms snapshot of 4-channels of real neural data acquired using the wireless system.

Fig. 7 shows the actual tetrode recordings using a commercial Cheetah neural data acquisition system (Neuralynx Inc., AZ, USA) as well as the recordings from the wireless system. Although the wireless recording seems noisier, no special arrangements were made to reduce the ambient noise and the recording was taken in an open lab environment. The Cheetah recording was taken in a Faraday cage where the ground pin of the animal was tied to the ground of the recording system and the cage to reduce the noise. Also, in contrast to the wireless system sampling each channel at 20kHz, the Cheetah system samples the neural channels at 32kHz each to further reduce the noise.

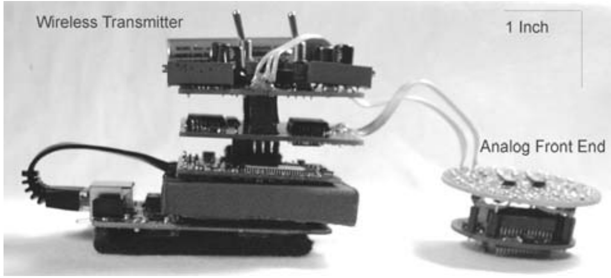

Fig. 8. Photograph showing the complete wireless recording system.

IV. CONCLUSIONS

In this paper, we described the design of a complete 4-channel wireless digital neural recording system using off-the-shelf components and protocols. The design uses commercially available IC's for analog and digital conditioning of the signals and the SPI port of a Digi Connect EM embedded microprocessor module to process data for wireless transmission using IEEE 802.11b protocol. The wireless system was successfully used to record signals from a function generator as well as neural data from a tetrode implanted in the ventral striatum of an awake & behaving rat.

The bottlenecks in realizing a wireless recording system with many more channels lie in the speeds of the serial SPI port and the wireless bandwidth. The bandwidth challenge is being addressed by the computer and telecommunication industry. For example, modules operating at IEEE 802.11g and faster Ultra Wide Band (UWB) technologies are gradually making headways in the market. Embedded processor board manufacturers like Digi International, Lantronix (CA, USA) and DPAC Technologies (CA, USA) are also continuously working to offer wireless modules with faster serial ports The algorithm used to design the system described in this paper could be used to increase the number of channels as faster modules become available.

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REFERENCES

[1] G. Buzsaki, "Large scale recording of neuronal ensembles", *Nature Neuroscience*, vol. 7, no. 5, pp. 446-451, May 2004.

[2] J. P. Donoghue, "Connecting cortex to machines: recent advances in brain interfaces", *Nat. Neurosci. Supplement,* vol. 5, pp. 1085–1088, November 2002.

[3] P. R. Kennedy, M.T. Kirby, M. M. Moore, B. King, A. Mallory, "Computer control using human intracortical local field potentials", *IEEE Trans. Neural Systems and Rehab. Engineering*, vol. 12, no. 3, pp. 198–202, June 2000.

[4] K. D. Wise, D.J. Anderson, J.F. Hetke, D.R. Kipke, K. Najafi, "Wireless implantable microsystems: high-density electronic interfaces to the nervous system", *Proc. IEEE*, vol. 92, no. 1, pp. 76 – 97, January 2004.

[5] T. Akin, K. Najafi, and R. Bradley, "A wireless implantable multichannel digital neural recording system for a micromachined sieve electrode," *IEEE J. Solid-State Circuits*, vol. 33, no. 1, pp. 109-118, January 1998.

[6] A. Nieder, "Miniature stereo radio transmitter for simultaneous recording of multiple single-neuron signals from behaving owls," *J. Neuroscience Methods,* vol. 101, pp. 157-164, September 2000.

[7] M. Modarreszadeh and R. N. Schmidt, "Wireless, 32-channel, EEG and epilepsy monitoring system," *Proc. 19th Annual International Conference of the IEEE Engineering in Medicine and Biology Society,* Oct 30 - Nov 2, 1997, pp. 1157-1160.

[8] S. Takeuchi, I. Shimoyama, "A radio-telemetry system with a shape memory alloy microelectrode for neural recording of freely moving insects," *IEEE Trans. Biomedical Engineering*, vol. 51, no. 1, pp. 133 – 137, January 2004.

[9] Y. Hao, K. Najafi, "Circuitry for a wireless microsystem for neural recording microprobes," in *Proc. 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 25-28 Oct., 2001, vol. 1, pp. 761 – 764.

[10] P. Irazoqui-Pastor, I. Mody, J.W. Judy, "Transcutaneous RF-powered neural recording device," in *Proc. 24th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Houston, TX, 2002, vol. 3, pp. 2105 - 2106.

[11] P. Irazoqui-Pastor, I. Mody, J.W. Judy, "In-vivo EEG recording using a wireless implantable neural transceiver," in *Proc. 1st International IEEE EMBS Conference on Neural Engineering*, March 20-22, 2003, pp. 622 – 625

[12] P. Mohseni, K. Najafi, "Wireless multichannel biopotential recording using an integrated FM telemetry circuit," in *Proc. 26th Annual International Conference of the Engineering in Medicine and Biology Society*, 2004, pp. 4083 – 4086.

[13] N. M. Neihart, R.R. Harrison, "A low-power FM transmitter for use in neural recording applications," in *Proc. 26th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2004, pp. 2117 – 2120.

[14] I. Obeid, M. Nicolelis, P. Wolf P, "A Multichannel Telemetry System for Single Unit Neural Recordings", *J Neuroscience Methods*, vol. 133, no.1-2, pp. 33-38, February 2004.

[15] S. Farshchi, P.H. Nuyujukian, A. Pesterev, I. Mody, J.W. Judy, "A TinyOS-Based Wireless Neural Sensing, Archiving, and Hosting System," in *Proc. 2nd International IEEE EMBS Conference on Neural Engineering*, March 16-19, 2005, pp. 671 – 674.

[16] FDA website - http://www.fda.gov/cdrh/dtvalert.html

[17] D. L. Rollins, C.R. Killingsworth, G.P. Walcott, R.K. Justice, R.E. Ideker, W.M. Smith,"A telemetry system for the study of spontaneous cardiac arrhythmias," *IEEE Trans. Biomedical Engineering*, vol. 47, no. 7, pp. 887- 892, July 2000.

[18] K. Najafi, K.D. Wise, "An implantable multielectrode array with on-chip signal processing," *IEEE J. Solid-State Circuits*, vol. 21, no. 6, pp. 1035-1044, December 1986.

[19] L. P. Huelsman, "*Active and Passive Analog Filter Design*", Mc-Graw Hill Inc., 1993.

[20] Digi International – www.digi.com

[21] http://news.com.com/2010-7351-5153319.html