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A multichannel telemetry system for single unit neural recordings

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Abstract

We present the design, testing, and evaluation of a 16 channel wearable telemetry system to facilitate multichannel single unit recordings from freely moving test subjects. Our design is comprised of (1) a 16-channel analog front end board to condition and sample signals derived from implanted neural electrodes, (2) a digital board for processing and buffering the digitized waveforms, and (3) an index-card sized 486 PC equipped with an IEEE 802.11b wireless ethernet card. Digitized data (up to 12 bits of resolution at 31.25 k samples/s per channel) is transferred to the PC and sent to a nearby host computer on a wireless local area network. Up to 12 of the 16 channels were transmitted simultaneously for sustained periods at a range of 9 m. The device measures 5.1 cm × 8.1 cm × 12.4 cm, weighs 235 g, and is powered from rechargeable lithium ion batteries with a lifespan of 45 min at maximum transmission power. The device was successfully used to record signals from awake, chronically implanted macaque and owl monkeys.

Keywords: Neural telemetry; Single unit recording; Wireless; Neural data acquisition; Portable

1. Introduction

Multichannel single unit recordings have been used to demonstrate the feasibility of building brain machine interfaces. By correlating subject movement with neural activity, researchers have been able to control primitive prosthetic limbs (Taylor et al., 2002; Wessberg et al., 2000). Progress in this area is limited by the requirement that subjects be restrained and tethered to the neural recording hardware (Nicolelis, 2001). Although wireless neural recording devices have been reported (Akin et al., 1998; Irazoqui-Pastor, 2002; Maki, 1998; Mojarradi, 2003), none are sufficient for recording multiple channels of single units in freely moving subjects. At present, inductive coil based systems either support too few channels or have too small of a transmission range. Analog systems are susceptible to transmission channel noise, which may adversely affect spike sorting (Kim and Kim, 2000). Furthermore, future on-board processing, such as spike detection and spike sorting may require algorithms better suited to the digital domain (Chandra and Optican, 1997; Hulata et al., 2002; Letelier and Weber, 2000).

We present a design for a wearable telemetry system weighing 235 g capable of transmitting up to 12 of 16 signals from implanted neural electrodes. Signals are digitized at 31.25 k samples/s per channel at eight, ten, or 12 bits of resolution, and telemetered using an IEEE 802.11b wireless ethernet card to a host computer up to 9 m away. The device has been built, characterized, and tested in vivo.

2. System design

2.1. Overview

Our system consists of a wearable telemetry unit which communicates with a stationary host computer. The telemetry unit has four main parts: (1) the analog front end (AFE), (2) the digital board, (3) the wearable computer, and (4) the battery. The AFE (described in detail elsewhere (Obeid et al., 2004) conditions and time-division multiplexes up to 16 neural signals before sampling them at 31.25 k samples/s

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per channel. Fifty digital inputs are required to control channel enables, variable gain amplifiers, and analog to digital converter timing. These controls are generated on the digital board, which also provides regulated power, frames the digitized data, and communicates with the wearable computer. The wearable computer acquires the data from the digital board, transmits it to the host computer via a IEEE 802.11 wireless network, and receives control commands from the user. The telemetry system is powered from a pair of rechargeable lithium-ion batteries. The functionality of the various parts of the telemetry system are explained below in more detail.

2.2. Digital board

The digital board consists of three main components: (1) power regulation circuitry, (2) a complex programmable logic device (CPLD), and (3) a first-in first-out (FIFO) memory. The CPLD (Fig. 1) generates both static and timing control signals. The static signals are set by the user, and are loaded into registers in the CPLD. These lines directly assert control signals on the AFE board. The timing signals coordinate the operation of the time-division multiplexer, the analog to digital converter (ADC), and the FIFO. Time is divided into *sets* of 24 periods of a 12 MHz clock, since 24 periods is the time it takes to sample and convert one channel. A priority encoder consults a channel enable list and determines whether to enable or disable the ADC for the current channel; if the ADC is disabled, the CPLD idles until the end of the 24 clock-cycle set before continuing to the next channel. Since each set takes 24/12 MHz s and each channel is processed once every 16 sets, the effective sampling rate is $1/[(24 \times 16)/12\,\text{MHz}] = 31.25$ k samples/s per channel, or one sample per 32 μs.

The digitized data is passed serially from the ADC to the CPLD, where it is organized into bytes and stored in the FIFO. In order to reduce the data bandwidth, the user may opt to drop either two or four bits of the 12 generated by the ADC. In these cases, the eight most significant bits are written to the FIFO while the remaining bits are stored in a temporary register; when this register accumulates eight bits, it is moved to the FIFO and then cleared. Up to 24 ms of data are stored in the FIFO before being transferred to the wearable computer's parallel port; a handshake timing module in the CPLD negotiates this transfer.

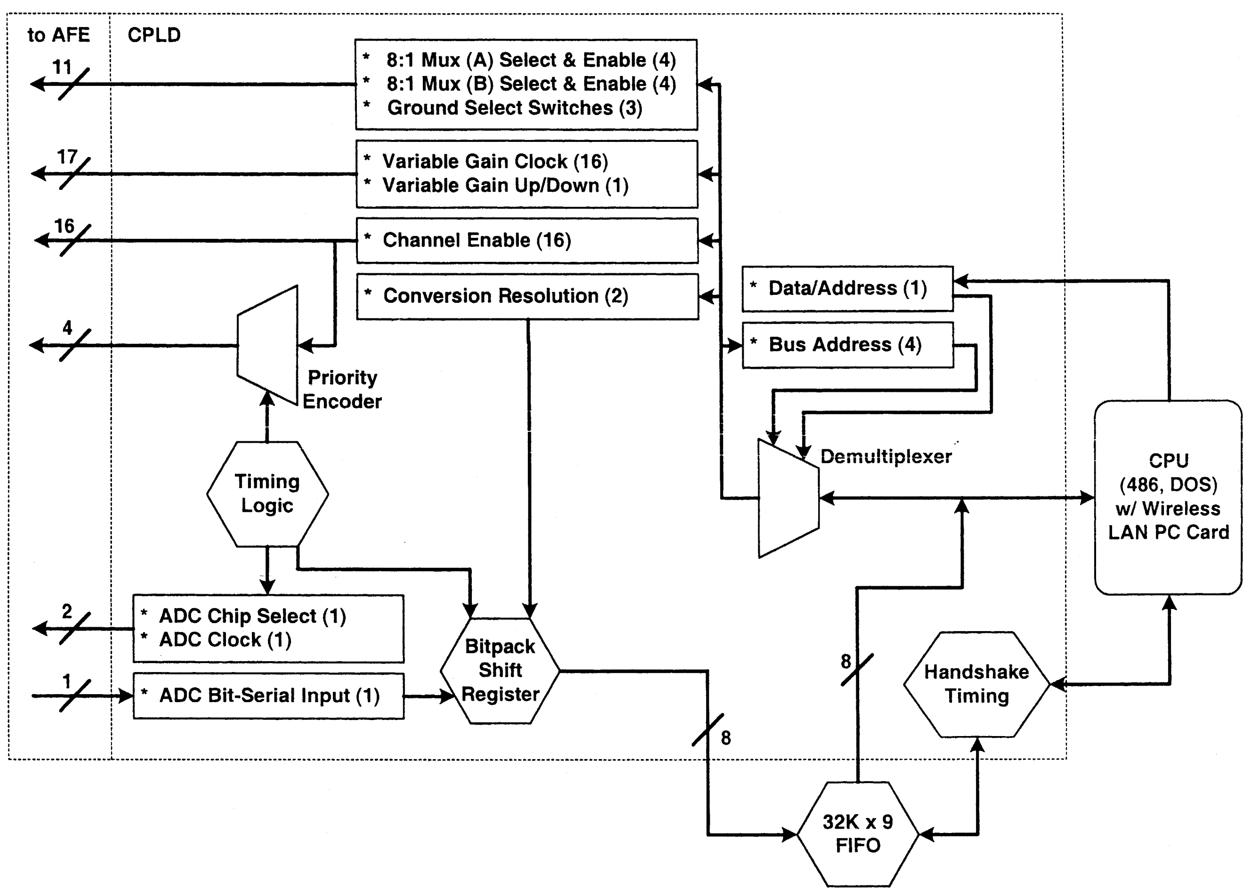

Fig. 1. Control signals on the digital board are generated by a CPLD. The CPLD generates timing signals for the AFE's time division multiplexer and analog to digital converter. It also has registers for static control signals, such as channel enables and ground select settings. The CPLD receives user commands via the wearable PC.

2.3. Wearable computer

Telemetry is handled by a wearable computer (1.9 cm × 7.3 cm × 9.2 cm, 77 g, 486 BASE/CORE, Compulab, Haifa, Israel) fitted with an IEEE 802.11b wireless ethernet PCMCIA card (PC4800, Cisco Systems, San Jose, CA). The wearable computer, based on a 66 MHz 486 AMD processor, runs custom software under DOS to control data acquisition and wireless communication. A pair of custom-made 6 in. RF cables are used to offset the antenna of wireless ethernet card, reducing the proximity of the radiated electromagnetic power (100 mW) from the AFE. The host computer can accept the data through a wireless access point or through another radio card.

During a typical recording session, two network sockets are opened between the host and the wearable computer. A TCP/IP socket is used to send user commands from the host to the wearable, while a UDP socket transmits the data. Because it has less overhead than TCP/IP and lacks error checking, the UDP protocol is better suited for high bandwidth data transmissions. The wearable PC inserts an eight bit counter into each data packet to detect lost data, although there is no means for recovery or retransmission.

2.4. Power supply

The system is powered from a pair of rechargeable lithium ion batteries (UBC383562, Ultralife). They have a capacity of 1200 mAh at an average of 3.7 V and measure 7.6 mm × 35 mm × 62 mm. The battery plugs into the digital board, and a pair of DC to DC converters (MAX1701, Maxim IC, Sunnyvale, CA) produce power supply voltages of 3.3 and 5.0 V. The 3.3 V supply powers the FIFO and CPLD, and both supplies are used to power the wearable computer and the AFE. Table 1 shows the overall power utilization for the telemetry system. The expected battery lifespan is (1200 mAh × 3.7 V)/4.0 W, or approximately 67 min.

2.5. User interface

The user communicates with the telemetry system through a host computer with a wireless interface. A custom software package allows the user to specify the active channels, the gain setting for each channel, the reference channels, and the ADC resolution. These preferences are transmitted to the wearable computer using the TCP/IP protocol, and are relayed to the CPLD where they are stored in the appropriate registers. The user also uses this interface to specify how the received data is stored and displayed on the host computer.

Table 1
Breakdown of the predicted noise consumption for each of the major components of the wearable telemetry system

Component	Power consumption
AFE	130 mW
Wearable PC	1.31 W
Radio card	2.45 W
CPLD	29 mW
FIFO	116 mW
Total	4.0 W

The wearable PC and wireless radio card consume 94% of the power.

Table 2
Number of bits exceeding the noise floor (worst case)

Variable gain (0–31)	Number of bits exceeding noise (predicted)	Number of bits exceeding noise (measured)
0	8.8	9.4
7	6.7	8.1
15	5.7	7.2
23	5.2	6.7
31	4.8	6.3

3. Results

The wearable telemetry unit was built and tested. The bill of materials, schematics, and software are available, http://dukebme.duke.edu/backpack. The digital board measured 5.6 cm × 8.1 cm. The completed telemetry unit, including battery, measured 5.1 cm × 8.1 cm × 12.4 cm and weighed 235 g. Without the battery, the unit measured 3.5 cm × 8.1 cm × 12.4 cm and weighed 195 g.

The system achieved sustained data transfers of 12 of the 16 input channels in the eight-bit resolution mode. The maximum number of channels at ten and 12 bits of resolution was nine and eight, respectively. The lifespan of the battery was 45 min at the maximum data rate, and the range was 9 m. The range was measured in a normal laboratory setting with no precautions taken to limit multipath reflections or electromagnetic interference. The latency through the telemetry system from the input of the AFE to the input of the FIFO was 680 μs.

The number of bits exceeding the background noise level (Table 2) was found to exceed the worst case predictions based on the input referred noise of the AFE (1.1 μV_{rms}). Since the measured values exceed the predictions based on the AFE noise, it is inferred that no significant digital switching noise from the digital board is added to the neural data.

The device was tested in vivo with one rhesus macaque (*Macaca mulatta*) and one owl monkey (*Aotus nancymae*), both with multiple cortical implants of microwire bundles. The subjects were confined in a restraining chair during the tests. The telemetry unit was attached to the restraining chair and connected to the implanted electrodes using a commercial headstage (HST/8o50-G20-GR, Plexon Inc., Dallas, TX) and a short flexible cable (Parlex, Methuen, MA). Figs. 2 and 3 show sets of simultaneously recorded data from each subject. The gains for the different channels were set individually prior to data collection.

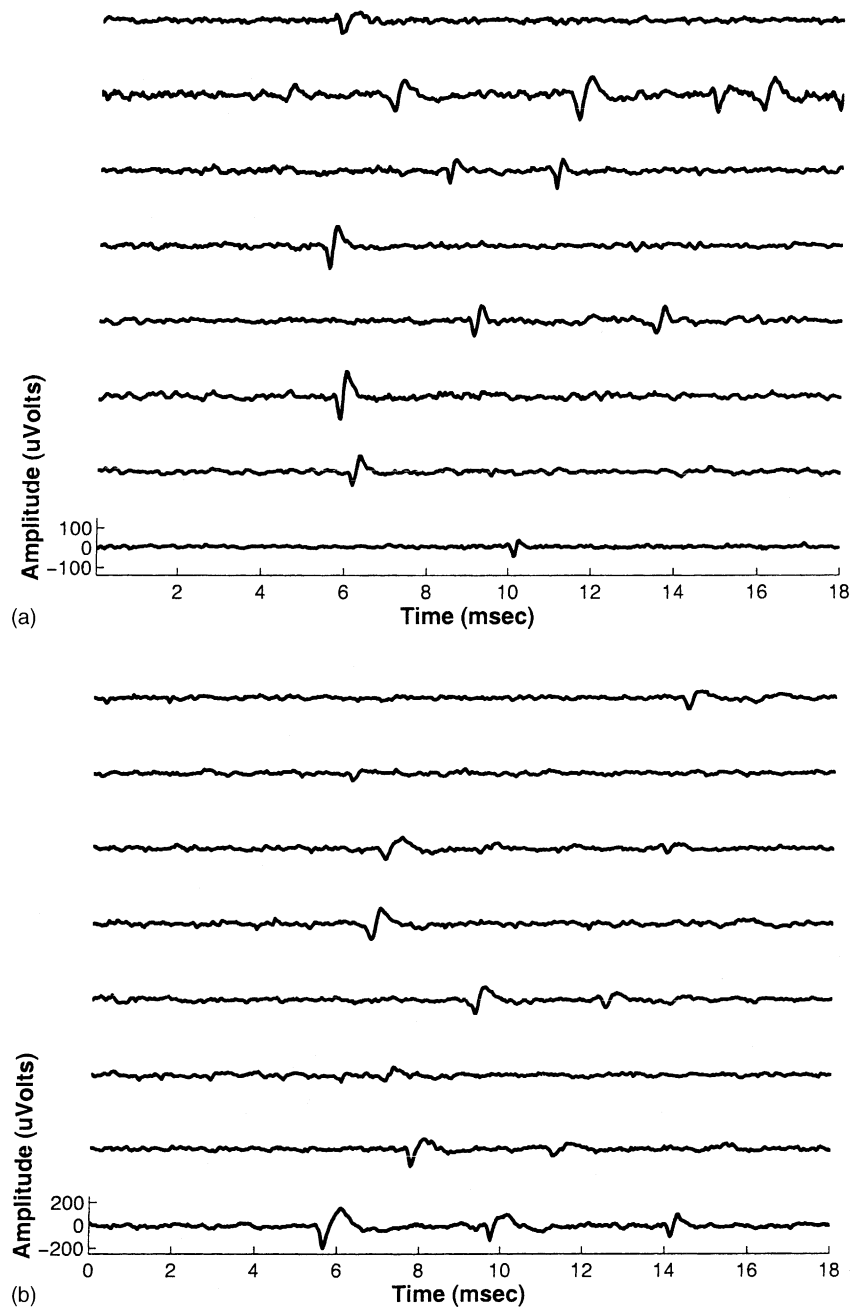

Fig. 2. Continuous signals acquired simultaneously from (a) a macaque and (b) an owl monkey demonstrate the functionality of our system in actual biological systems.

4. Discussion

4.1. System considerations

Our telemetry system is highly versatile, and may be configured in both software and hardware. Software changes in the CPLD could alter the sampling rate, the channel selection procedures, and the ADC resolution. Different batteries may be used depending on size/weight and lifespan requirements.

4.2. Digital design

Digitizing the data provides two major benefits. Firstly, digitized data is well suited to the type of on-board signal processing which will likely be incorporated in the future. Algorithms for procedures, such as spike detection and spike sorting will be easier to implement and more versatile in the digital domain. The second benefit of the digital approach is in the telemetry. Digital telemetry provides immunity to transmission channel noise, and will ultimately re-

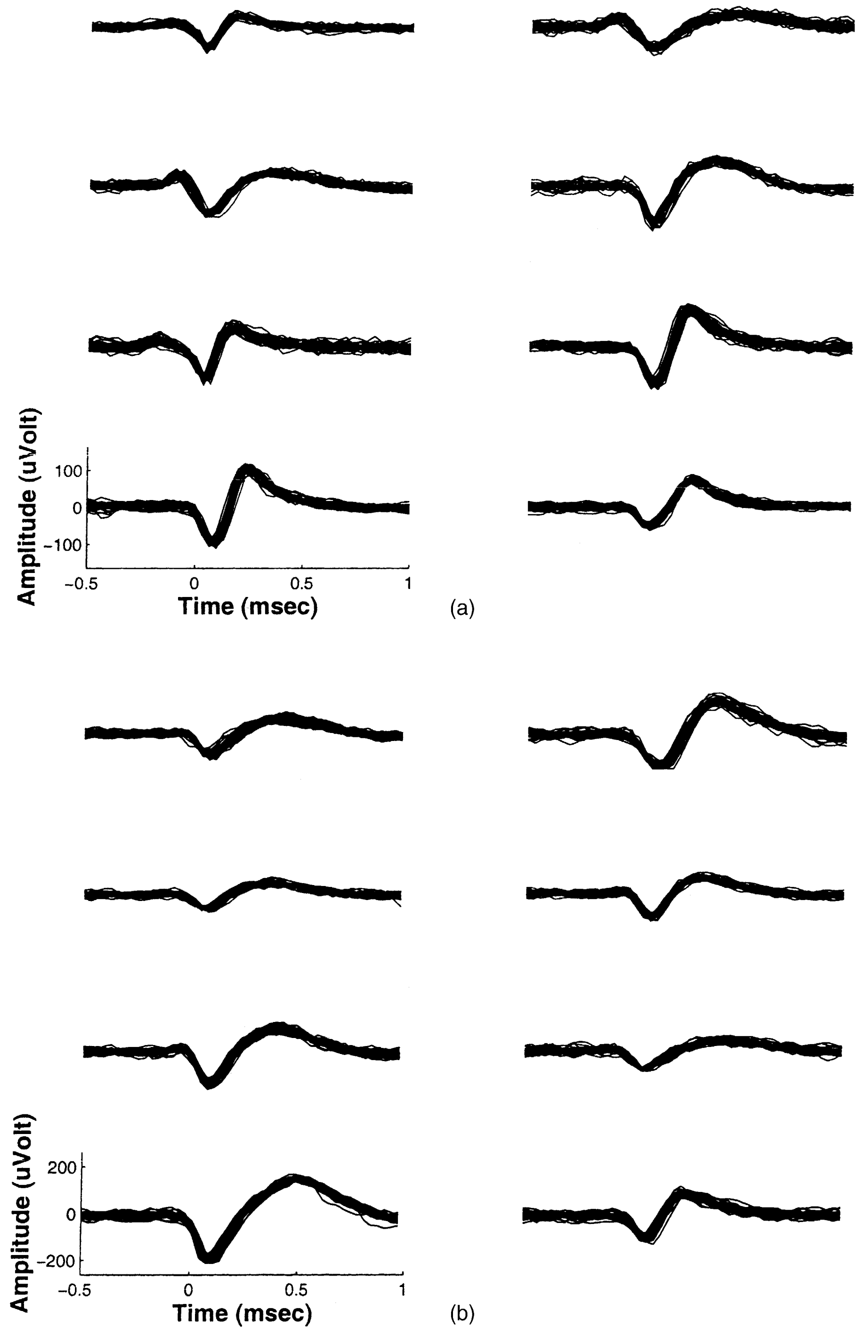

Fig. 3. Sorted action potentials derived from simultaneously acquired data from (a) a macaque and (b) an owl monkey. Signals were sorted after data collection using offline spike sorter (Plexon, Inc.).

sult in lower bit-error rates. Furthermore, the digital telemetry hardware may easily be be replaced with a standalone wireless module (such as Bluetooth® (Morrow, 2000) or Ultrawideband (Barrett, 2001)) depending on system requirements, such as battery life and transmission range.

4.3. Latency

This system was developed as part of a real-time neural prosthesis, where data latency can cause delays in command execution (Donoghue, 2002). The latency of our system is 680 μs, measured from the analog input through the FIFO input. The latency after the FIFO is software dependent; for our configuration, the delay from FIFO input to output ranged from 100 μ to 50 ms depending on the number of active channels, the ADC resolution, and the location of a particular sample within its respective packet. The maximum delay through the FIFO can be reduced in software by reducing the number of bytes stored in the FIFO before transmission. However, the effects of such a reduction on the system throughput have not been measured.

4.4. Bandwidth

Our system transmits neural signals in their entirety, without isolating single units or action potentials. This allows for faithful transmission of subthreshold depolarizations and hyperpolarizations that may be important indicators of synapse behavior (Covey, 2000). However, if single units are detected and spike sorted before transmission, the data rate could be decreased by at least one order of magnitude (depending on signal quality and detector efficiency), thus increasing the allowable number of channels over to over 100 (Moxon et al., 2001). The number of channels could be increased further by using multiple wearable telemetry units on the same subject; the IEEE 802.11b standard allows for multiple devices to operate in close proximity.

4.5. Multipath

Multipath echoes can adversely affect the signal quality of any wireless transmission network (Rappaport, 1996). In our system, excessive multipath may cause data packets to be missed during transmission. Since UDP network sockets do not retransmit missed packets, any such data will be permanently lost. Our device was tested in vivo in a standard animal laboratory setting that was not optimized to reduce multipath reflection surfaces, and was able to transmit 12 channels at a range of 9 m without any lost data. Multipath effects could possibly be mitigated by transmitting the data via a TCP socket that would retransmit lost packets. However, this would increase overhead and would reduce the maximum number of transmission channels.

5. Conclusion

A multichannel neural telemetry system capable of continuously transmitting 12 of 16 channels has been demonstrated. The system architecture is flexible and may be modified to accommodate new radio technologies or enhanced neural signal processing techniques.

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References

Akin T, Najafi K, Bradley R. A wireless implantable multichannel digital neural recording system for a micromachined sieve electrode. IEEE J Solid State Circuits 1998;33(1):109–18.

Barrett TW. History of ultra wideband communications and radar. Part I. UWB communications, Microwave J 2001.

Chandra R, Optican LM. Detection, classification, and superposition resolution of action potentials in multiunit single-channel recordings by an on-line real-time neural network. IEEE Trans Biomed Eng 1997;44(5):403–12.

Covey E. Neural population coding and auditory temporal pattern analysis. Physiol Behav 2000;69:211–30.

Donoghue JP. Connecting cortex to machines: recent advances in brain interfaces. Nat Neurosci Suppl 2002;5.

Hulata E, Segev R, Ben-Jacob E. A method for spike sorting and detection based on wavelet packets and Shannon's mutual information. J Neurosci Methods 2002;117:1–12.

Irazoqui-Pastor P, Mody I, Judy JW. Transcutaneous rf-powered neural recording device. In Proceedings of the Second Joint EMBS/BMES Conference. TX: Houston;2002.

Kim K, Kim S. Neural spike sorting under nearly 0 dB signal-to-noise ratio using nonlinear energy operator and artificial neural-network classifier. IEEE Trans Biomed Eng 2000;47(10):1406–11.

Letelier JC, Weber PP. Spike sorting based on discrete wavelet transform coefficients. J Neurosci Methods 2000;101(2):93–106.

Maki H, Yonezawa Y, Harada E, Ninomiya I. An implantable telemetry system powered by a capacitor having high capacitance. In Proceedings of the 20th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, vol. 4; 1998. p. 1943–6.

Mojarradi M, Binkley D, Blalock B, Anderson R, Ulshoefer N, Johnson T, et al. A miniaturized neuroprosthesis suitable for implantation into the brain. IEEE Trans Neural Syst Rehabil Eng 2003;11(3):38–42.

Morrow R. Connecting with a bluetooth piconet. In Proceedings of the Fall Wireless Symposium/Portable By Design Conference and Exhibition. IL: Chicago;2000.

Moxon KA, Morizio JC, Chapin JK, Nicolelis MA, Wolf P. Designing a brain-machine interface for neuroprosthetic control. In Chapin, JK, Moxon, KA, editors. Neural prostheses for restoration of sensory and motor function. Boca Raton (FL): CRC Press; 2001.

Nicolelis MAL. Actions from thoughts. Nature 2001;409:403–7.

Obeid I, Nicolelis MAL, Wolf PD. A low power multichannel analog front end for portable neural signal recordings. J Neurosci Methods 2004;133:27–32.

Rappaport TS. Wireless communications: principles and practice. Prentice Hall (NJ): Upper Saddle River; 1996.

Taylor DM, Helms Tillery SI, Schwartz AB. Direct coritcal control of 3D neuroprosthetic devices. Science 2002;296:1829–32.

Wessberg J, Stambaugh CR, Kralik JD, Beck PD, Laubach M, Chapin JK, et al. Real-time prediction of hand trajectory by ensembles of cortical neurons in primates. Nature 2000;408(6810):361–5.