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A wireless microsystem with digital data compression for neural spike recording

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ABSTRACT

The paper describes a multi-channel neural spike recording system sensing and processing the action potentials (APs) detected by an electrode array implanted in the cortex of freely-behaving small laboratory animals. The core of the system is a custom integrated circuit (IC), with low-noise analog front-end interfaced to a 16 electrode array followed by a single 8-bit SAR ADC, a digital signal compression and a 400-MHz wireless transmission units. Data compression is implemented by detecting action potentials and storing up to 20 points per each spike waveform. The choice greatly improves data quality and allows single spike identification. The transmitter delivers a 1.25-Mbit/s data rate coded with a Manchester-coded frequency shift keying (MC-FSK) within a 3-MHz bandwidth. An overall power consumption of 17.2 mW makes possible to reach a transmission range larger than 20-m. The IC is mounted on a small and light printed circuit board. Two AAA batteries, set in a pack positioned on the back of the animal, power the system that can work continuously for more than 100 h.

1. Introduction

Research in electrophysiology and behavioral neuroscience are generating an increasing demand for wireless microsystems capable to record neural signals from a large number of implanted electrodes and to deliver data in real time to a remote processing unit. Moreover, these systems are seen as a step towards devices for assisting humans with disabilities [1]. However, as the number of electrodes increases a huge data throughput is generated calling for an increase of processing frequency, power and RF spectral bandwidth. To cope with this issue two design trends have been followed so far: (i) to drastically reduce the throughput, detecting just the occurrence time of action potential spikes [2]; (ii) to push the throughput to the limits, preserving the entire data content and either transmitting ultra-wide band (UWB) pulses in the 3.1–10.6 GHz with low spectral efficiency [3], or using pulse-width modulated (PWM) signals [4] to reach a better spectral efficiency at lower RF frequencies. In [4] FSK modulation at 915 MHz delivers a 5.5 Mbit/s equivalent throughput with 38 MHz spectral occupation (14% spectral efficiency). In this frame this work investigate an intermediate approach: understanding whether data compression can be improved thus making possible to preserve the information needed for single neuron identification while keeping the throughput and the bandwidth occupation limited to few MHz. In addition the transmission range was pushed well beyond the 1 m value reported in [2–4] to make possible realistic *in vivo* experiments.

2. The wireless neural spike recording system

The neural recording system (see Fig. 1) consists of four elements: a microelectrode array from Tucker–Davis Technologies [5], a headstage (inset of Fig. 1) mounting the custom recording/transmitting IC, an antenna and a backpack with the batteries. The 16 electrodes of the array are arranged in two rows of 8 electrodes each. Their 50-μm diameter is set by the size of a tungsten core and by the surrounding insulating polyimide cladding. The electrode core is small enough to make its tiny tip capturing single neuron activity.

The electrode impedance and its noise have to be carefully considered in the design of the circuit front-end. Fig. 2 shows the frequency dependence of both the impedance magnitude and the noise spectral density when the electrode is immersed in a saline solution. When a metal interacts with conductive solution, a double layer of charged molecules (i.e., the Helmholtz layer) surrounds its exposed surface. Therefore the electrode impedance shows a dominant capacitive response with a parallel resistance accounting for small leakage currents. Both values are dependent on frequency. At 1 kHz the impedance is dominated by a 4-nF capacitance, giving a magnitude of about 40 kΩ. The front-end

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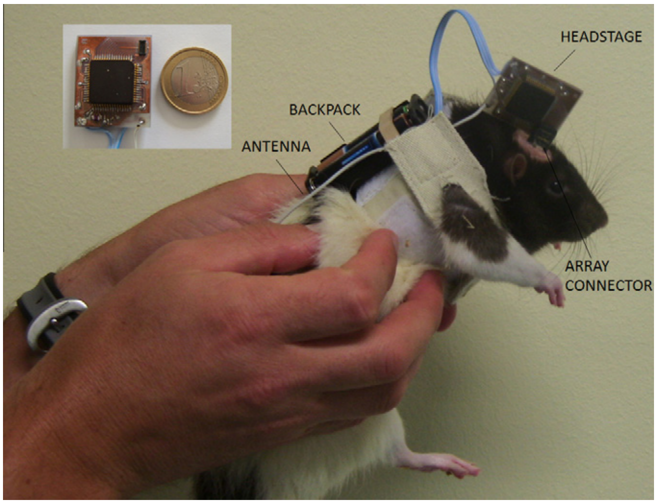

Fig. 1. The wireless neural recording system mounted on a freely-behaving rat. The detail of the headstage is shown in the inset.

amplifier should be properly designed to interface such large capacitive impedance while keeping the input-referred noise to values less than 5 μV rms over the neural spike bandwidth (i.e., 100 Hz–7 kHz). These specs, together with additional limitations set by the need for accurate digitalization and low-power wireless transmission, have guided system partitioning and forced to careful design of all the functional blocks.

A detailed description of the custom IC, fabricated in 0.35-μm technology can be found in [6]. Fig. 2 shows for comparison the input-referred noise spectral density of a front-end amplifier. The result has been achieved by properly sizing the input transistors to reduce their 1/f noise and by biasing them in sub-threshold regime to minimize the current consumption. After proper amplification the input channels are multiplexed and delivered to an 8-bit analog to digital converter. Conversion is then followed by a digital spike processing unit. The module detects action potential waveforms by threshold crossing. After each crossing 20 samples of the channel signal are recorded in a 2-kbit SRAM adding the corresponding channel address and the timing stamp. The size and the scan frequency of the SRAM were chosen based on Monte Carlo simulations to ensure that less than 0.1% spikes are missed at 50-spike/s average firing rate over all input channels. The bit stream is then completed by adding service bits reaching a final rate of 1.25 Mbit/s. The transmitter consists of a voltage controlled oscillator (VCO) inserted in a phase locked loop (PLL) and directly modulated by the digital data. A Manchester-coded frequency shift keying (MC-FSK) modulation with low modulation index was adopted to squeeze spectrum occupation into a 3-MHz bandwidth. The transmitter is completed by an open-drain class-AB power-amplifier, able to deliver an output power of 0 dBm with an efficiency of 12% to a 50-Ω load. The antenna is a quarter-wavelength whip antenna (see Fig. 1) made with a piece of wire about 17-cm long, easily placed along the back of the rat.

3. Experimental characterization, *in vivo* test and data quality validation

The overall power consumption of the chip is 17.2 mW. 60% of power is due to the PA, and was intended to reach enough transmission range not to pose issues during '*in vivo*' experiments. The receiver was built with off-the-shelf components to achieve a maximum sensitivity (about −73 dBm for a BER of 10^{-5}). Fig. 3 shows the power received by a monopole quarter-wavelength antenna as a function of the distance from the transmitting unit in free space. Note that the power decreases as the square of the range reaching the RX sensitivity floor at about 30 m, well beyond what needed to assure reliable reception in a laboratory.

A comparison with the energy efficiency of other neural wireless systems may be elaborated by taking into account that these have a transmission range of about 1 m. The presented system guarantees a 1-m range even with 30 dBm less irradiated power. At this level the power dissipation of the PA becomes negligible with respect to the other stage and leading to a power budget of 6.7 mW for 64 input channels. This value corresponds to about 105 μW/ch. that compares well with the 135, 47 and 220 μW results reported for the systems described in [2–4], respectively.

Before testing the system in a *in vivo* experiment, the quality of the signals from the implanted electrodes was analyzed using a commercial acquisition system recording the raw signals and noise from the 16 channels. The recorded traces featured a noise of about 10 μV rms on all channels. The measured noise is slightly larger than the electrode noise measured in a saline solution, due to

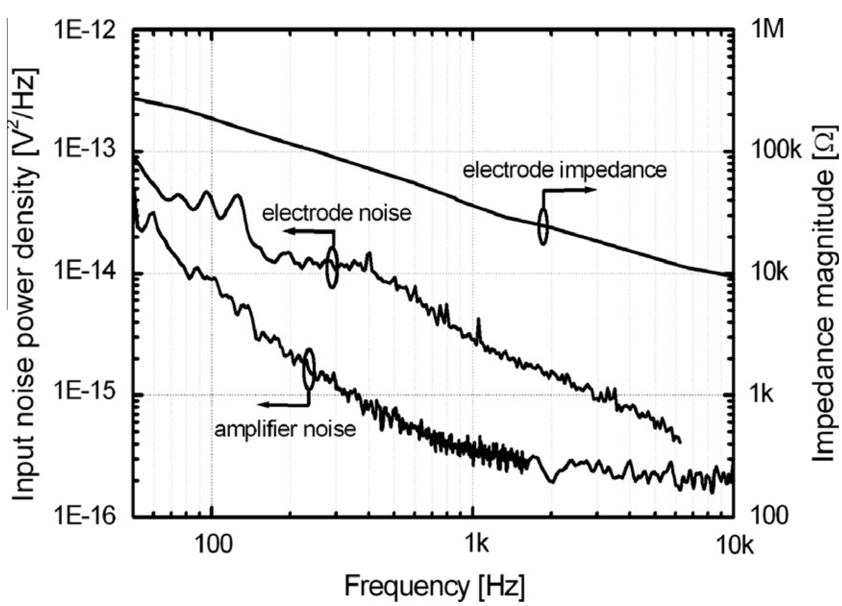

Fig. 2. Amplifier and electrode input-referred noise and magnitude of the micro-wire electrode impedance vs. frequency.