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An Externally Head-Mounted Wireless Neural Recording Device for Laboratory Animal Research and Possible Human Clinical Use

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Abstract— **In this paper we present a new type of head-mounted wireless neural recording device in a highly compact package, dedicated for untethered laboratory animal research and designed for future mobile human clinical use. The device, which takes its input from an array of intracortical microelectrode arrays (MEA) has ninety-seven broadband parallel neural recording channels and was integrated on to two custom designed printed circuit boards. These house several low power, custom integrated circuits, including a preamplifier ASIC, a controller ASIC, plus two SAR ADCs, a 3-axis accelerometer, a 48MHz clock source, and a Manchester encoder. Another ultralow power RF chip supports an OOK transmitter with the center frequency tunable from 3GHz to 4GHz, mounted on a separate low loss dielectric board together with a 3V LDO, with output fed to a UWB chip antenna. The IC boards were interconnected and packaged in a polyether ether ketone (PEEK) enclosure which is compatible with both animal and human use (e.g. sterilizable). The entire system consumes 17mA from a 1.2Ahr 3.6V Li-SOCl2 1/2AA battery, which operates the device for more than 2 days. The overall system includes a custom RF receiver electronics which are designed to directly interface with any number of commercial (or custom) neural signal processors for multi-channel broadband neural recording. Bench-top measurements and *in vivo* testing of the device in rhesus macaques are presented to demonstrate the performance of the wireless neural interface.**

I. Introduction

RECORDING of neural data from a large (≈100) group of single neurons by intracortical multielectrode arrays has been a primary method for neuroscientists to investigate e.g. motor behavior in primates from the neural microcircuit dynamics operating at cellular level. Over the past decade, researchers worldwide have used this approach to gain insight into both fundamental behavioral neuroscience and applications in neuroprosthetics. Important recent results in advancing neuroprostheses have been reported in both human and non-human primates [1]-[5]. Elsewhere, multielectrode-based neural recordings have been used to examine spike train patterns in large ensembles of single neurons in persons with epilepsy [6], pointing to the possibility of early seizure detection and prevention based on diagnosis from spiking activity. As of today, while several types of broadband neural interface systems are available for animal use, only one broadband, multi-unit recording systems has been approved for human study: The NeuroPort system from Blackrock Microsystems, an FDA 510k (premarket approval) cleared device for multi-channel neural broadband recording application in human subjects [7]. This system has been used in clinical trials for the past several years in a handful of patients with spinal cord injuries and brainstem stroke [1], [2], [8], with the goal to decode motor control information from the neural activity recorded by an intracortical MEA. The decoded signals were thereafter used to control assistive devices, such as a robotic arm to demonstrate the restoration for patients of certain degree of upper limb motor capabilities. In these first and seminal neuroprostheses experiments, a cumbersome cable between was required between the patient and the system electronics. This tethered connection severely limits the mobility of the patient, is a potential safety hazard, and the associate long conductor path can compromise electrical signal quality from e.g. electromagnetic interference.

Much motivation and rationale exists, therefore, replace the cabled neural interface connection with a short-range wireless link. Over the past ten years, many wireless recording systems have been proposed and developed for animal models [9]-[13], both for non-human primates and for rodents. The "Hermes"-series of wireless head-mounted systems for primates represent a cutting edged example of these early wireless interfaces [9]-[10]. Yet, each reported system has engineering tradeoffs to meet their specific research needs, and not designed for potential human use. A notable void exists for a wireless recording device that offers both the necessary electrical functions, such as simultaneous broadband multi-channel recording, low-power, low-noise, and high data rate wireless communication, and at the same time addresses requirements for human clinical use such as patient safety, electromagnetic compatibility (EMC) safety, moisture resistance, and sterilizability.

As part of our group's overall approaches to wireless multichannel neural interfaces, we have ongoing research and development towards fully implantable neural recording devices [14]-[16], [22]. While a fully implantable device does represent a far reaching aspiration and ambition for clinical use, much basic science utility and translational benefits can

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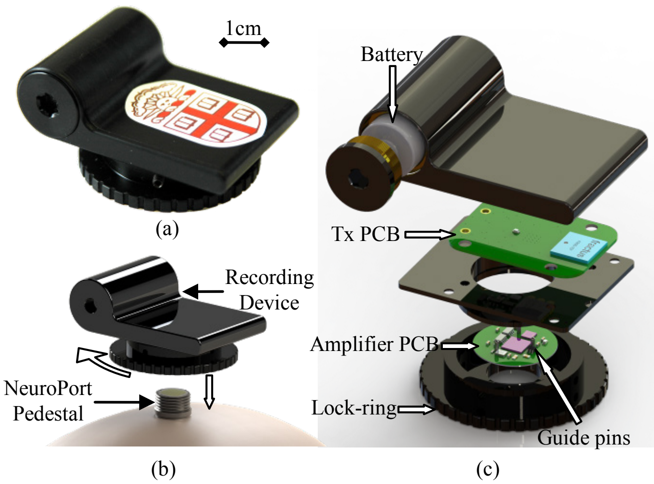


Fig. 1. (a) Photograph of the externally mounted neural recording device. (b) 3D SolidWorks model shows the attachment of the device to a NeuroPort pedestal on a human head model. (c) 3D SolidWorks model that demonstrates the gross assembly of the external-mounted wireless neural recording device.

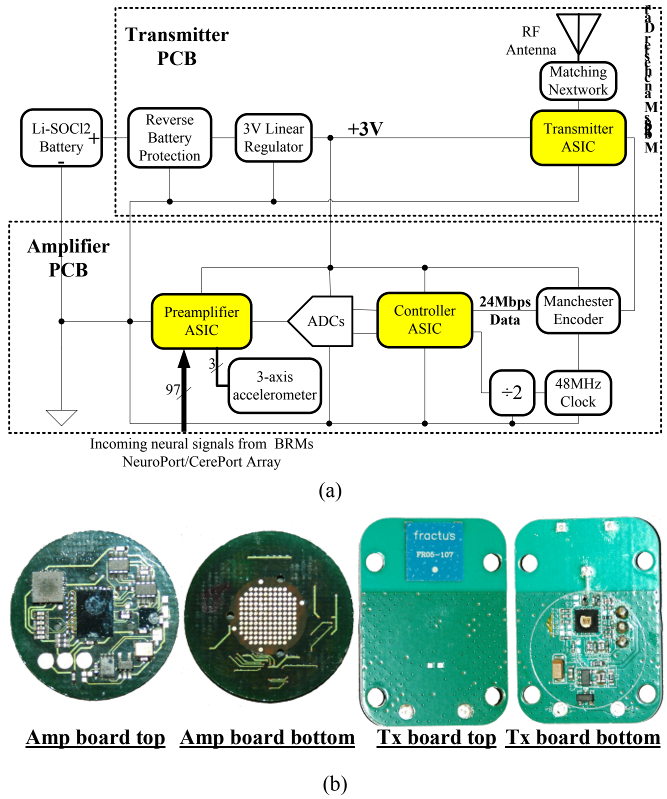


Fig. 2. Circuit block diagram (a) and photographs (b) of the amplifier board and the transmitter board for the external-mounted wireless neural recording device. The highlighted blocks in (a) refer to the custom designed ASICs; others are off-the-shelf components.

be expected from external, head-mounted devices. Therefore, we present in this paper, an externally mounted wireless neural recording device in a package that can be used in both laboratory and clinical experimentation. This device was designed to interface with the 510k approved NeuroPort MEA, as part of a potential roadmap for regulatory approval as a clinical device. Additionally, and as shown by the high performance capability of our head-mounted compact system described in this paper, the new device is expected to significantly enrich non-human primate research, such as for freely moving monkeys.

The paper is organized as follows: in Section II, the system details of the externally mounted wireless neural recording device are discussed. Section III focuses on the design of the wireless RF receiving unit. Section IV presents both bench-top and *in vivo* non-human primate results from testing the device, followed by the conclusion in Section V.

II. System Architecture

A. Overall System Concept and Circuit Block Diagram

A photograph of the design concept of externally mounted neural recording device is shown in Fig.1a. In the version for this paper, Fig.1b shows a 3D SolidWorks™ model that demonstrates the attachment of the device to the NeuroPort skull-mounted pedestal connector (by Blackrock Microsystems) – here on the human head model. (The pedestal houses a 100-pin connector to which neural signals from the brain recorded by intracortical MEAs are percutanously routed using a, insulated gold-wire bundle). For ease of interfacing our device to this specific pedestal connector, we designed the housing to include three guide pins (Fig.1c). During the wireless device attachment, these posts are press-fit into the NeuroPort pedestal which allows precise transverse alignment of the input pads on the device with those on the pedestal. The lock-ring (Fig.1c) then screws down tightly onto the pedestal to make the final vertical connections between those pads robust. The complete assembly of the device envelope is pictured in the exploded view of Fig.1c, which shows that the entire neural recording device consists of closely packed assembly three major parts: an amplifier PCB, a transmitter PCB, and a Li-$SOCl_2$ battery. The circuit block diagrams of these constituent system blocks are shown in Fig. 2 along with the images of the actual PCBs. The detailed description of each block will be discussed next.

B. Amplifier PCB

As shown in Fig.2a, the amplifier PCB integrates a custom application specific integrated circuit (ASIC) with 100 channels of preamplifiers and two analog multiplexers, a 3-axis accelerometer, two successive approximation ADCs, a controller ASIC, and a 48MHz clock source. The incoming neural signal on each channel is conditioned, amplified, and multiplexed by the custom low power preamplifier ASIC. The circuit block diagram of the preamplifier ASIC is shown in Fig.3a. It has 100 identical low-noise low-power preamplifiers arranged in a 10 by 10 array. The design of a single low power preamplifier is shown in Fig.3b, which uses a capacitive-feedback, folded cascode operational transconductance amplifier (OTA) configuration with a source follower output buffer. The closed-loop gain of the OTA is set by the ratio of the feedback voltage divider capacitors C_2 and C_3, which is 46dB = 10pF/0.05pF. A large capacitor (C_4 =6.8pF) is connected to the wells of Mp_4 and Mp_5 to minimize the effect of their parasitic capacitance on the gain of the preamplifier. The 5pF capacitor C_L across the

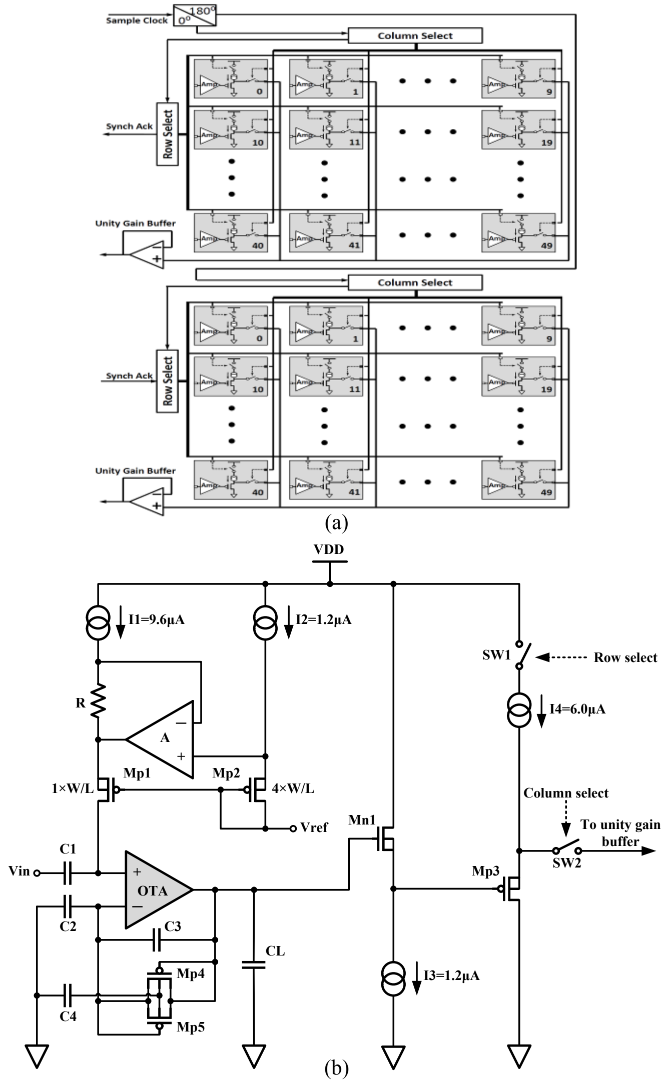


Fig. 3. (a) Circuit block diagram of the 100-channel preamplifier ASIC. (b) Schematic of the individual preamplifier.

OTA output provides the dominant pole for the OTA and sets the bandwidth of the circuit at 7.8kHz. The detailed description of the preamplifier can be found in [15].

In our design, we replaced three channels of neural inputs with the signals from a 3-axis accelerometer (ADXL327, Analog Devices), thereby giving a total of 97 neural recording channels plus three x-y-z accelerometer channels. Since the accelerometer has an output range from 0.1V to 2.8V, in order to match it to the input range of the preamplifiers, 1:1000 capacitive attenuators first attenuate these signals before they are fed into the preamplifier input. Although not highlighted further in this paper, such accelerometer signals are of important use for body tracking in neurological disease diagnoses, such as the detection and monitoring of seizures in epilepsy, or other motion analysis.

After amplification, the 100 broadband signals are multiplexed and buffered into two analog signals. Two commercial 12-bit SAR-ADCs (LTC2366, Linear Technology) running at a 24MHz clock rate digitize these analog signals to provide 20kSps/ch sampling rate. Each of the ADCs consumes 4.8mW at 3V. A controller ASIC manages the data flow between the preamplifier ASIC and the ADCs and packages the two ADCs' outputs into a single 24Mbps serial bit digital data. In order to facilitate the data and clock recovery on the RF receiver side, the 24Mbps data was Manchester-encoded into a 48Mbps data stream using commercial off-the-shelf (COTS) components: two D flip-flops (SN74AUP2G80, Texas Instruments) and a XOR gate (SN74LVC1G86, Texas Instruments). This Manchester-encoded data was then fed into the transmitter board for wireless transmission.

C. *Transmitter PCB*

The transmitter PCB, as shown in Fig.2a, integrates a custom design OOK transmitter, a 3.1GHz to 5GHz UWB chip antenna, a 3V low-dropout (LDO) regulator, and a reverse battery protection circuit. The block diagram of the newly conceived (by us), ultralow-power, dedicated transmitter ASIC is shown in Fig.4a. It consists of three major parts: a free-running voltage-controlled oscillator (VCO) with switchable capacitor array and varactor diode for wide range frequency tuning, an active Gilbert mixer with quad switches driven by baseband signals, a current-reuse power amplifier (PA) specifically designed by us for neural interface and related medical device applications which require for short-distance (1-2 meter) high efficiency wireless transmission.

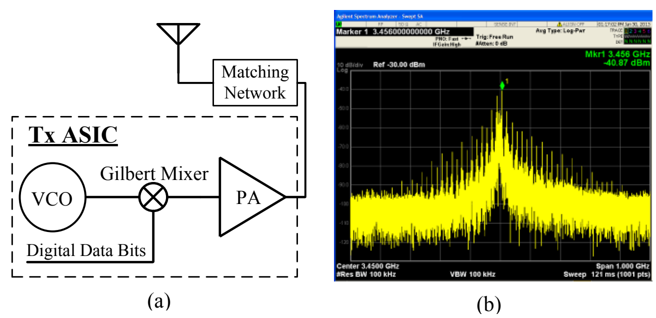
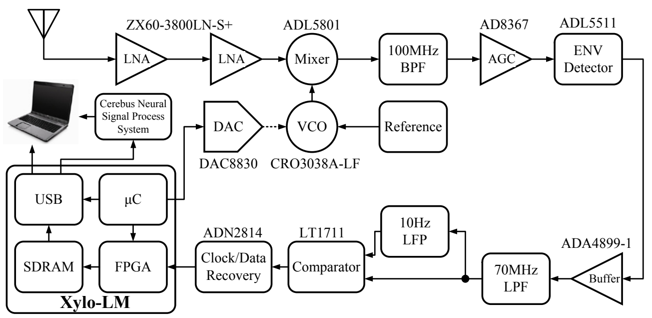


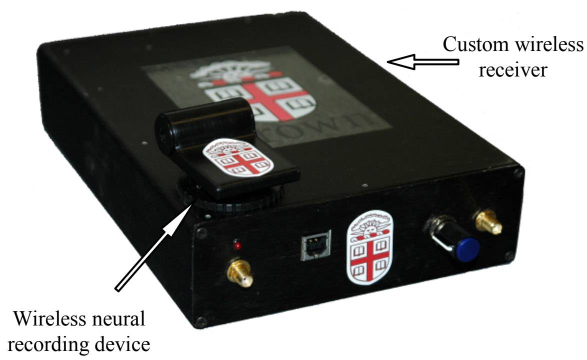
Fig. 4. (a) Circuit block diagram of the OOK transmitter ASIC. (b) The OOK signal spectrum of the device received at 1m distance with a 10dBi planar antenna.

III. Wireless Receiver

A compact, portable module was developed for receiving the RF data, with a flexible capability to route the signals to subsequent neural process electronics for decoding and assistive device control. The system block diagram of the superheterodyne receiver and its image (along with the head-mounted neural recording device for scale) are shown in Fig.5a and Fig.5b. The incoming 3.5GHz OOK signal was received by a 3.2GHz-3.8GHz 10dBi planar dual polarized antenna (PA-333810-NF, FT-RF, Taiwan). This signal, as shown in Fig.4b, was first amplified by two 24dB gain low noise amplifiers (LNAs) with a noise figure (NF) of 0.9dB, and was then down-converted to a 150MHz intermediate frequency (IF) signal by a 3.65GHz local oscillator (LO). After amplitude stabilization by an automatic-gain-control block, the IF signal was fed into an envelope detector that has two envelope filters with 70MHz cutoff frequencies set by external capacitors. Eventually, the baseband signal was restored, from which the digital data and clock were extracted using a data/clock recovery chip (ADN2814, Analog Devices). The recovered data was then forwarded to an FPGA and repackaged into 16-bit samples, which get buffered through an 8MB SDRAM and sent to a PC via USB 2.0 for further processing and visualization. The receiver also offers a second data path that directly interfaces here with the commercial Cerebus Neural Signal Processing system (Blackrock Microsystems), as shown in Fig.5a with parts numbers for each block. (The receiver electronics are flexible for design of interfaces to any number of other digital neural processing schemes and computing electronics).



(a)

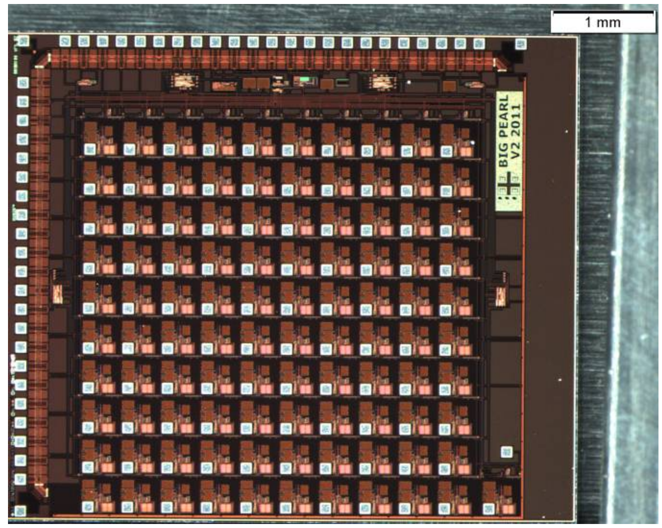


(b)

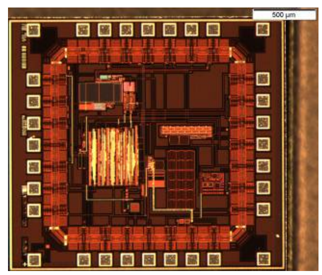
Fig. 5. (a) Circuit block diagram of the custom wireless receiver. (b) Photograph of the custom wireless receiver, shown along the externally head-mounted wireless neural recording device.

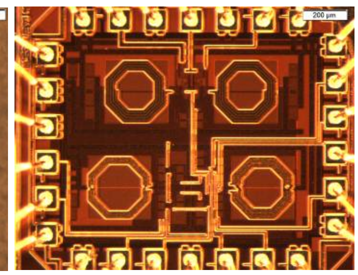
IV. Wireless System Measurement Results

Before describing the wireless neural system interface bench-top testing and in vivo nonhuman primate experiments, a short note about fabrication of the compact head-mounted device: The 100-Ch preamplifier (Fig.6a) and controller (Fig.6b) ASICs were fabricated in the ON-semiconductor 0.5µm 3M2P standard CMOS process and measure 5.2×4.9mm^2 and 2×2mm^2, respectively. The transmitter ASIC (Fig.6c) was fabricated in the IBM 7WL 0.18µm SiGe BiCMOS process and measures 1.6×1.35mm^2. The amplifier board was fabricated using a standard FR4 material. The transmitter board was fabricated using Rogers 4003 low dielectric loss, high frequency circuit material for RF signal transmission. The electronics on the amplifier PCB and



(a)





(b) (c)

Fig. 6. Microphotographs of the 100-channel preamplifier ASIC (a), the controller ASIC (b), and the OOK transmitter ASIC (c).

transmitter PCB along with the battery are encased in a 52mm×44mm×30mm polyether ether ketone (PEEK) enclosure and weights 46.1g in total, with the battery included.

A. Bench-top Testing

The externally mounted wireless neural recording device was tested on bench using a neural spike simulator (Blackrock Microsystems), which can deliver artificial neural spikes in a well-defined pattern repetitively to its 100 pads on the pedestal. The inputs of our device were connected to the simulator outputs through the lock-ring/pedestal mechanism

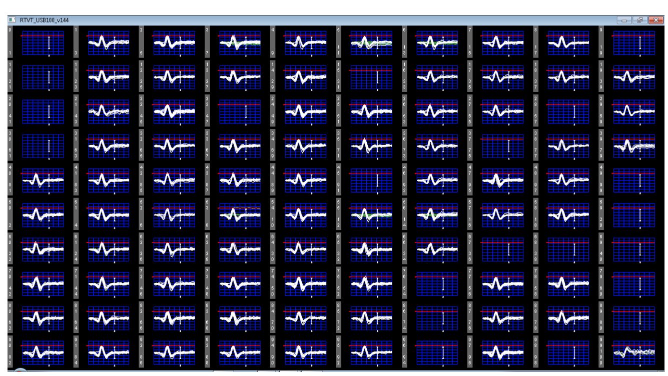


Fig. 7. Wireless recorded artificial neural spikes using the external mounted neural recording device.

described in Section II. The receiver antenna was placed 1 meter away from the device and the recorded artificial neural signals are visualized and stored by a custom visualization (RTVT) program through the USB2.0 interface or through the commercial Cerebus Neural Signal Processing system. Fig. 7 shows the recorded waveforms on the RTVT program. A summary of the measured performance of the system is shown in Table I. As a comparison, Table II lists the specifications of the proposed system along with those of the state-of-the-art wireless neural recording systems. We suggest that the aggregate performance (including compact size and battery lifetime) as well as the custom electronics embedded in the head-mounted wireless module exceed anything that has been reported in the published literature – even for animal use only.

TABLE I
MEASURED PERFORMANCE OF THE EXTERNAL-MOUNTED WIRELESS NEURAL RECORDING DEVICE

Number of channel	97 neural recording + 3 accelerometer
Preamplifier gain, bandwidth, and input referred noise	200 (46dB), 1 Hz(tunable) ~ 7.8 kHz, 2.83μV_{rms}
Preamplifier ASIC process, size, and power dissipation	On-Semi 0.5μm, 5.2×4.9mm^2, 6mW@3V
Controller ASIC process, size, and power dissipation	On-Semi 0.5μm, 2×2mm^2, 1mW@3V
Transmitter ASIC process, size, and power dissipation	IBM 7WL 0.18μm, 1.6×1.35mm^2, 15mW@3V
System resolution and sampling rate	12 bits for all channels, 20 kSps/Ch
Data encoding	Manchester (48Mbps)
Tx frequency and output power	-1.6dBm@3.5 GHz (tunable from 3-4GHz)
Receiver Sensitivity	10^{-8}BER@-77.7dBm (48Mbps)
Battery and battery life	1.2Ah 1/2AA Li-$SOCl_2$ battery, >48hrs
Total power dissipation	51mW @3V
Dimension	52mm×44mm×30mm
Total weight of the system	46.1g (8.7g for the battery, 33.8g for the package)

TABLE II
COMPARISON OF STATE-OF-THE-ART WIRELESS NEURAL RECORDING SYSTEMS.

Ref	Type	Mode Tested	Amp BW (Hz)	Noise (μV_{rms})	Res (Bits)	S/ch (kSps)	# Ch	Data rate (Mbps)	Power (mW)	Size (mm)	Tx
(Chae, et al., 2009) [18]	Chip	Bench	0.1, 200-2.2k configurable	4.9	6-9	2	128	90	6	8.8×7.2	UWB
(Harrison, et al., 2009) [10]	Chip	Bench	250-5k	5.0	10	15	100	0.345	10	5.4×4.7	902/928 FSK
(Shahrokhi, et al., 2010) [19]	Chip	Bench	10-5k	6.08	8	14	128	n.a.	9.33(Rec. +Stim.)	3.4×2.5	n.a.
(Gao, et al., 2012) [9]	Chip	Bench	<1-10k, 280-10k	2.2	10	31.25	96	30	30(IC+Tx + FPGA)	5×5(IC)	UWB (separate IC, to be integrated)
(Greenwald, et al., 2010) [17]	External	Rodent	n.a.-8.2k	1.94	10	16	16	0.256(IC) 1 (UWB)	15.84	24000mm^3	UWB
(Miranda, et al., 2010) [10]	External	Primate 3month	<1-4.5k	5.0	12	30	32	24	142	38×38×51	3.7/4.1GHz FSK
(Yin, et al., 2010) [12]	External	Rodent	1-8.8k configurable	4.9	8	20	32	2.56	5.6	n.a.	898/926MHz FSK
(Szuts, et al., 2011) [13]	External	Rodent 1hr	10-4.5k configurable	3.64	Analog	20	64	10	645	n.a.	2.38GHz FM
(Sodagar, et al., 2009) [20]	External	Guinea Pig	<100-10k configurable	8.87	8	7.8	64	2	14.4	14.4×15.5	70 – 200MHz OOK
(Rizk, et al., 2009)[11]	Implanted	Sheep 3hrs	n.a.	7	12	31.25	96	n.a.	2000	50×40×15	916.5 MHz ASK
(Rouse, et al., 2011)[21]	Implanted	Primates	DC-500 configurable	1(5Hz band)	n.a.	n.a	4	0.0117	0.04	n.a.	175kHz
(Borton, et al, 2013)[22]	Implanted	Swine & Primate >14 months	0.1-7.8k configurable	8.05/ 2.83	12	20	100	48 Manchester encoded	90.6	52×46×11	3.2/3.8 GHz FSK
This work	**External**	**Primate**	**0.1-7.8k configurable**	**2.83**	**12**	**20**	**97+3 Accel.**	**48 Manchester encoded**	**51**	**52×44×30**	**3.5 GHz OOK**

B. *In Vivo Testing*

In vivo validation on the functionality of the device was carried out in two rhesus macaque monkeys (OT and SP). At the time of the recording using our wireless device, both animals ha an MEA intracortical array implanted in the primary motor cortex, M1 (for OT) and ventral premotor cortex, PMv (for SP), for approximately 3 months and 1 year, respectively. During each of the typical half an hour recording sessions, the animals were restricted in a chair with head fixed and trained to perform a center-out reaching task. The device was then attached to the NeuroPort pedestal on the animal's head, also co-implanted earlier through a surgical procedure. The 10dBi RF receiving antenna was placed above the animal's head in the rig. We took actual recordings usually for 10 to 20 minutes. The neural spikes extracted from a 1 minute sample of recorded data from both monkeys are shown in Fig.8. In both cases, more than fifty channels show clearly identifiable neural spikes. Such data is being presently used to analyze neural circuit dynamics and correlate this with specific animal task and/or behavior.

V. CONCLUSION

We have presented in this paper the implementation of an externally head-mounted, highly compact wireless broadband neural recording device that was dedicated to interface with a 510k approved NeuroPort array device for human clinical applications. The system architecture and circuit diagram have been describe in detail in this paper, and includes custom ultralow-power microelectronic circuits, including a high performance RF ASIC chip. Among its unique features, our device is scalable to neural data transmission up to estimated 200 Mbps and is thus able to accommodate several micrelectrode arrays, whether intracortical, subdural, or other.

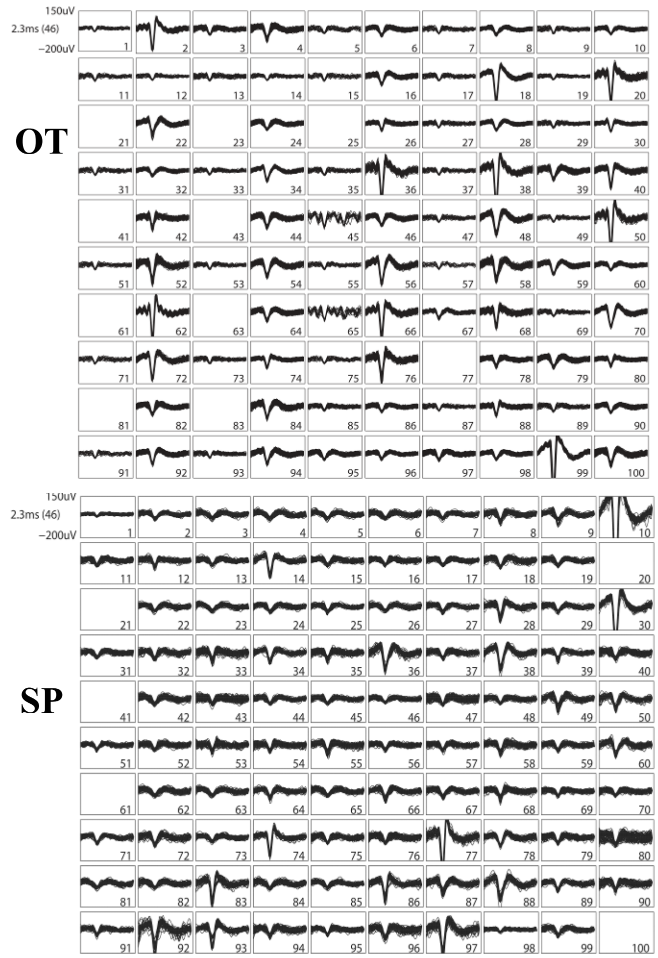


Fig. 8. Sampling of *in vivo* recorded neural action potential from two rhesus macaque monkeys: OT (top) and SP (bottom). Note: the accelerometer channels are not shown in this data of animals sitting in chair.

The bench top and *in vivo* measurement results are presented to demonstrate the full functionality of the device in non-human primates and ready to use by the animal research community. As part of the roadmap for translation to clinical applications, the device is currently undergoing a broad range of safety validation protocols.

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