A 64-channel wireless EEG recording system for wearable applications

Martín Causa, Franco La Paz, Santiago Radi, Juan P. Oliver, Leonardo Steinfeld and Julián Oreggioni.

***Abstract*— A wireless 64-channel EEG (Electroencephalography) recording system for wearable applications is presented. The aim of this system is to allow the patient to move freely for a reasonable time in a short distance environment, in order to extend the field of application of traditional electroencephalography studies. The system consists of a wireless module located in the patient and a user interface that runs on a PC (Personal Computer). The wireless module is responsible for acquiring EEG signals (amplify, filter and digitize), processing and sending them wirelessly to the PC.**

The system is capable of acquiring up to 64 EEG signals and 6 synchronism signals for more than 24 hours, with a programmable sampling frequency between 100 Hz and 10 kHz. The system supports four types of system configuration (1, 4, 21 or 64 channels), with a programmable bandpass filter where high-pass frequency can vary between 0.1 Hz and 500 Hz and the low-pass frequency can vary between 100 Hz and 20 kHz. The analog front-end has an input impedance of $1.3 G\Omega$, an input-referred noise of $2.4\ \mu V_{rms}$ and a common mode rejection ratio of 82 dB. The maximum distance measured between the wireless module and the PC was 12 meters.

I. Introduction

The advance of neuroscience and electronics in recent years has made it possible to develop wireless devices for recording EEG signals in a diverse range of applications outside the medical clinic. For instance, fatigue monitoring [1], mind-controlled video games [2], market research [3], among others. This makes it feasible to imagine the development of new EEG (Electroencephalography) devices for a large number of novel applications.

A wireless 64-channel EEG recording system for wearable applications is presented. The aim of our work is to allow the patient to move freely for a reasonable time (about 1 day) within a short distance (about ten of meters), in order to extend the field of application of traditional EEG. This work is part of a bigger project that consist of implementing a compression algorithm [4] in the recording system presented here.

There were and there are multiple efforts in this direction. For example [5], [6] present systems that attain very low power consumptions using very specialized custom hardware, and at the expense of other features we designed for, such as transmission range, robust and secure transmission protocols and mobility, among others. On the other hand, there are works such as [7] where a system based on standard hardware is presented, and there are several commercial systems [8]–[11]. A comparison of the latter with our proposal is presented at the end of this work.

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II. Wireless EEG recording system

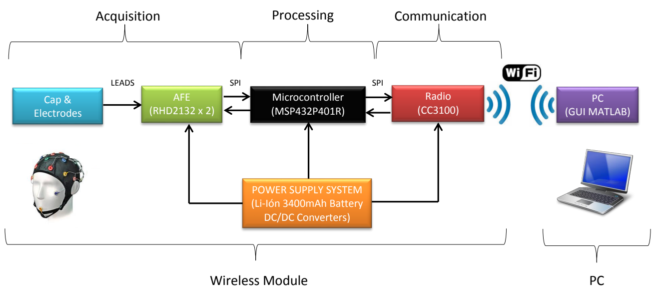

Fig. 1. Block diagram of the proposed system.

The proposed solution, depicted in Fig. 1, consists of a wireless module located in the patient and a graphical user interface (GUI) that runs on a PC (Personal Computer). The wireless module is composed of four blocks. The first block implement the EEG signal acquisition, the second one is in charge of the data processing and the third one is responsible for the wireless communication with the PC. Finally, a power supply system block that comprises a 3400 mAh 3.7 V Li-ion rechargeable battery and two dc/dc converters. One linear dc/dc converter power the analog part of the system and one switched dc/dc converter power the rest of the wireless module. The output of both dc/dc converters is $V_{DD} = 3.3\ V$.

At the beginning of the test the user selects the desired system configuration, which implies setting the high-pass (f_{HP}) and low-pass (f_{LP}) frequency, the sampling frequency (f_S), the number of channels to be sampled (N_C, that can be selected from four predefined standard electrode arrangement: 1, 4, 21 or 64 channels) and the number of synchronism channels (N_S, up to 6). The synchronism channels allow to record the reaction to a stimulus synchronized with the EEG signals (for example the pressing of a button in front of a visual stimulus to analyze the reaction time). Next, the user gives the command to start in the GUI and the EEG test begins. The data acquisition block samples $N_C + N_S$ channels every $T_S = 1/f_S$ and sends them (via a Serial Peripheral Interface, SPI) to the data processing block, which in turn processes the data and sends them (via SPI) to the data communication block. Finally, this block sends the acquired data (via WiFi) to the PC, where the user can view them in real time.

A. Data acquisition block

The data acquisition block comprises electrodes, a cap, an analog front-end (AFE), and an analog-to-digital converter (ADC). Dry electrodes from Cognionics were used: Flex Sensor to acquire through hair and Drypad Sensor to acquire in skin. The AFE and ADC were implemented using two off-the-shelf RHD2132 chips from Intan Technologies. Each RHD2132 chip is in charge of acquire, amplify, digitize and transmit via a SPI up to 32 channels at 30 ksps each. The RHD2132 chip features an input impedance of 1.3 $G\Omega$, a common mode rejection ratio (CMRR) of 82 dB, low input referred noise ($2.4\mu V_{\mathrm{rms}}$), programmable bandwidth and low power operation. For instance, the high-pass frequency can be set between 0.1 Hz and 500 Hz and the low-pass frequency can vary from 100 Hz to 20 kHz. In addition, the total current consumption of the two chips to acquire 64 channels at 500 sps/ch is 1.8 mA and at 1 ksps/ch it is 2.1 mA.

A four-layer Printed Circuit Board (PCB) supporting the RHD2132 chips and the dc/dc converters was designed and fabricated. The top and bottom layers of this PCB (first and fourth layers) were used for signal routing. The second layer was a ground plane and the third layer was a V_{DD} plane.

B. Data processing block

The data processing block is based on the MSP432P401R microcontroller (MCU) from Texas Instruments. This MCU is a 32-bit ARM Cortex-M4F microcontroller with a maximum clock frequency of 48 MHz, with 256 kB of Flash and 64 kB of RAM memory. This chip features a typical power consumption of 4.6 mA in Active Mode and offers several modes of low-power operation, called Sleep Mode, where its power consumption can be as low as hundreds of nanoamperes. In addition, this MCU includes a rich set of peripherals including several SPI ports and timers.

The main functions of the MCU embedded software are: receive the sampled data from the RHD2132 chips, process this data and forward them to the WiFi radio module. In addition, the MCU is responsible for parsing commands received from the PC.

A round-robin with interrupts architecture is adopted, where interrupt service routines (ISR) are extensively used to exchange (transmit and receive) data, and keep the MCU in Sleep Mode while no processing is needed. The ISR in turn use flags to signal in the main loop whether extra processing is needed. If no further processing is needed, the MCU is put in Sleep Mode.

The MCU acts as master in the SPI communication with the RHD2132 chips and the WiFi radio module. MCU activates the chip select signal ($\overline{CS}$) to select the chip and provides the clock frequency (CLK). Two different SPI ports of the MCU are used to communicate with the RHD2132 chips. Firstly, to parallelize the data flow, and also to configure the two chips separately. An additional SPI port is used to communicate the MCU with the WiFi radio module.

Two MCU timers are used. One is employed to set the sampling frequency f_S. When this timer expire, the MCU triggers a new acquisition by strobing commands to the RHD2132 chips according to the system configuration and stores the received data into an input buffer. The second timer is used to periodically poll the WiFi radio module input buffer to check for incoming commands from the PC.

C. Data communication block

The data communication block is implemented with a WiFi radio module based on the CC3100 chip from Texas Instruments. The WiFi radio module sends the acquired data to the PC, receive commands from the PC as well as exchange configuration parameters. The SimpleLink library provided by the vendor (Texas Instruments) is used to communicate with the WiFi radio module.

The communication technology was selected considering the system requirements, specially maximum data rate, power consumption and communication range to ensure connectivity within the required area. The maximum effective throughput required by our application correspond to acquiring all channels ($N_C = 64$, $N_S = 6$) at the highest data sample rate ($f_S = 1kHz$) and with the maximum resolution (16 bits per sample), resulting in 1120 kbps.

WiFi was chosen, which despite of being a technology with relative high power consumption, it meets our requirements and gives us the chance to scale. In addition, WiFi is widely adopted enabling an almost straightforward integration. The application was build over TCP since it provides a reliable data stream.

D. User interface

The software on the PC side runs an application and the corresponding GUI, which allows the user to perform an EEG test. The software was developed in Matlab and is in charge of configuring the wireless module, storing the received data and displaying them in real time. The GUI allows the user to configure: high-pass and low-pass frequency of all channels, the system sampling frequency, the number of channels to be sampled and the number of synchronism channels.

When the user starts the application, it tries to establish a connection to the wireless module, loads the default system configuration and shows the main menu. The user may modify the system configuration selecting new parameter values. Then it sends the new configuration to the wireless module, followed by a command to get the current configuration to verify that the wireless module received it correctly. Finally it shows a new window that allows the user to perform the EEG test (visualize the data and so on).

E. Installation

Fig. 2 shows how the system is mounted on the body of the patient. The electrodes attached to the head are connected directly to a case fixed on the patient's neck (left), or through an extension cable if the case is attached to the patient's waist (right).

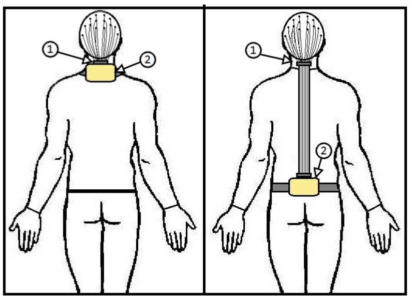

Fig. 2. Installation of the system in the patient. References: (1) electrodes connection (left: directly, right: though an extension cable), (2) electronic case (yellow box).

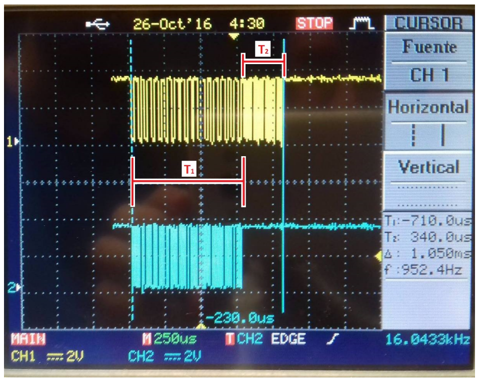

Fig. 3. Parallel configuration. Above (in yellow): $\overline{CS}$ of AFE1. Below (in sky-blue): $\overline{CS}$ of AFE0.

III. System Test

This section shows and analyzes the results of the several test performed to the proposed system.

A. Wireless communication

The system requirements imposes a minimum throughput for the payload data of 1120 kbps (see Subsection II-C). The maximum measured data throughput, at 12 m of distance between the wireless module and the router, was 5480 kbps. Although the data throughput was not measured for distances greater than 12 meters, the system has the potential to operate in a greater range.

B. Acquisition timing

In order to start an acquisition the MCU must establish a communication with both RDH2132 chips, which we will call AFE0 and AFE1. Two possible configurations were analyzed: request all channels to AFE0 first, and then all channels to AFE1 (serial configuration); or, request all channels in parallel to both chips (parallel configuration).

The measured acquisition time for 64 channels ($N_C = 64$ and $N_S = 0$) in the serial configuration was 1.03 ms, and in the parallel configuration was 1.05 ms. Although at first glance it is expected that the parallel configuration would be faster, since there is only one processor, it can not attend to both interruptions at the same time, and it attends first the interruption of the AFE0 because it has higher priority. It can be observed in Fig. 3 that during T_1 both SPI buses are active in interleaved form, but AFE0 is more busy because it has higher priority, and ends before. Then, during T_2 only AFE1 is attended until it finished its remaining channels.

Due to this similarity between the serial and parallel configuration delays, it is decided to use the serial one, since it allows a simpler and more controlled management of the embedded software.

C. System Tests

1) Maximum sampling frequency vs. number of channels: The maximum frequency f_S for which the system works without data losses for different system configurations was measured carrying out a 10-minute test. The Table I shows the recorded frequency values.

TABLE I
Maximum sampling frequency.

N_C	N_S	$f_{S_{max}}$ (Hz)
64	0	800
64	6	730
21	0	2160
21	6	1690
4	0	5970
4	6	3380
1	0	10300

The main limitation on the maximum attainable frequency is given by the time of acquisition of a *run* (*run* refers to the sampling of $N_C + N_S$ channels, the data of a *run* correspond to the same instant of time). For almost all system configurations it is used more than 90% of the time to acquire samples, leaving less than 10% to perform other tasks, mainly sending packages to the WiFi radio module. Therefore, a reduction of the acquisition time of a *run* would improve the maximum frequency currently reached by the system.

2) Battery run-time measurements: The wireless module was powered with a 3400 mAh Li-ion rechargeable battery. A test with this parameters: $N_C = 64$, $N_S = 0$ and $f_S = 770\ Hz$, was left running until the battery could not maintain the minimum voltage required by the RHD2132 chips ($3.2\ V$). The test lasted 24 hours and 22 minutes.

3) Full-system test: At the inputs of the AFE, known signals were injected for different system configurations all with an amplitude of $10\ mV_{PP}$, and choosing $f_{LP} = 20\ kHz$ and $f_{HP} = 0.1\ Hz$, and compared with the registered data.

In Fig. 4 the signal is within the amplifier band-pass and an attenuation of 3.7% is observed (the amplitude of the signal is $9.63\ mV_{PP}$). This small attenuation can be explained by the fact that the input signal amplitude equals the maximum input linear range of the AFE, which is $10\ mV_{PP}$.

In the Fig. 5 a sawtooth with a damping at the ends is observed, this is due to the action of the filter in the AFE.

Fig. 6 presents an actual EEG test performed with our system.

IV. Conclusions

The wireless EEG recording system developed is capable of acquiring up to 64 EEG signals and 6 synchronization

TABLE II

COMPARISON WITH COMMERCIAL EEG WIRELESS RECORDING SYSTEMS (DATA EXTRACTED FROM [12]).

System	Our system	Nicolet	g.Mobilab+	eego rt	HD-72	NIRS-EEG
Number of channels	64	64	8	64	64	8
Weight (grams)	270	800	360	500	350	800
Autonomy (hours)	24	12-24	25-100	5	6	33
Effective data rate per channel (samples/s)	770	4k	256	2k	500	320
Input-referred noise	2.4μVrms	2μV_{PP}	-	1μVrms	0.7μVrms	-
Communication protocol	WiFi	WiFi	Bluetooth 2.0	WiFi	Bluetooth	Bluetooth
Manufacturer	-	Natus	g.tec	ANT Neuro	Cognionics	-
Reference	-	[8]	[9]	[10]	[11]	[7]

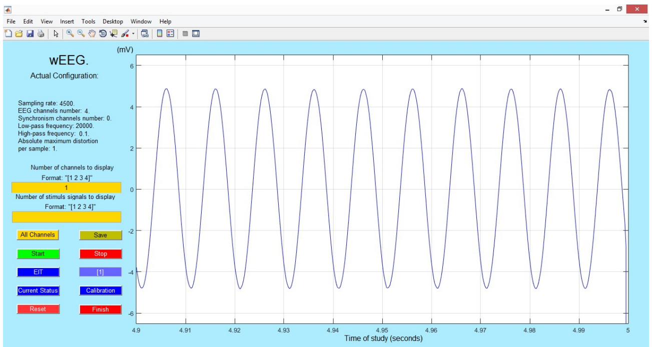

Fig. 4. Input: sinusoid of 100 Hz.

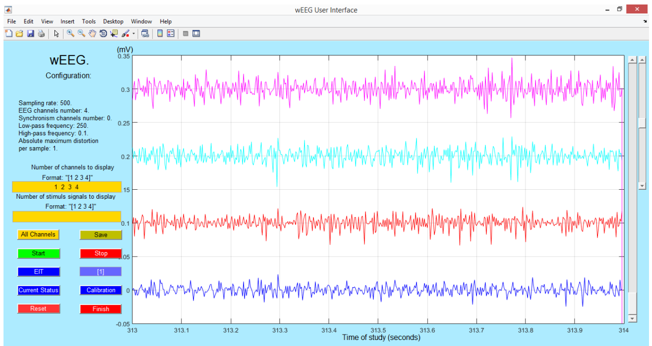

Fig. 6. EEG test performed with our system.

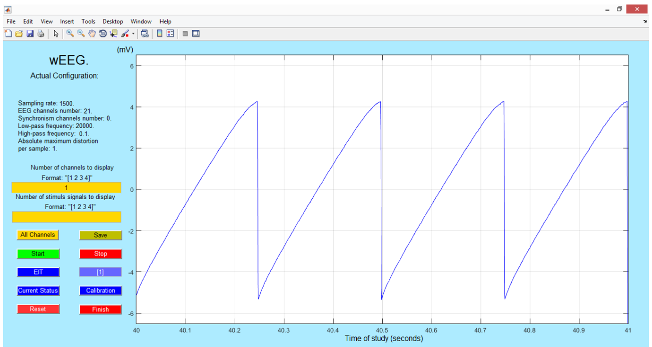

Fig. 5. Input: sawtooth of 4 Hz.

signals, with a programmable sampling frequency between 100 Hz and 10 kHz, and with an autonomy of more than 24 hours. The system supports four types of system configuration (1, 4, 21 or 64 channels), with a programmable bandpass filter where high-pass frequency can vary between 0.1 Hz and 500 Hz and the low-pass frequency can vary between 100 Hz and 20 kHz. The analog front-end has an input impedance of 1.3 $G\Omega$, an input-referred noise of 2.4 μV_{rms} and a CMRR of 82 dB. The maximum distance measured between the wireless module and the PC was 12 meters (but the system has the potential to operate in a greater range).

Table II shows a comparison between our system and some available commercial EEG recording devices. It is observed that our system compares favorably, being the only solution that offers the acquisition of 64 channels with an autonomy greater than 24 hours.

REFERENCES

[1] Smartcap, "Life: where fatigue is the problem, Life is the solution." http://www.smartcaptech.com/life-smart-cap/, Oct 2017. [On line].

[2] Uncle Milton Industries, "THE FORCE TRAINER II: HOLOGRAM EXPERIENCE." http://starwarsscience.com/product/the-force-trainer-ii-hologram-experience/, Nov 2017. [On line].

[3] Neurosky, "EEG Biosensors." http://neurosky.com/biosensors/eeg-sensor/, Nov 2017. [On line].

[4] G. Dufort, F. Favaro, F. Lecumberry, A. Martin, J. P. Oliver, J. Oreggioni, I. Ramirez, G. Seroussi, and L. Steinfeld, "Wearable EEG via lossless compression," in *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pp. 1995–1998, Aug 2016.

[5] S. D. Pascoli, D. Puntin, A. Pinciaroli, E. Balaban, and M. Pompeiano, "Design and implementation of a wireless in-ovo EEG/EMG recorder," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 7, pp. 832–840, Dec 2013.

[6] Y. Zhang, F. Zhang, Y. Shakhsheer, J. D. Silver, A. Klinefelter, M. Nagaraju, J. Boley, J. Pandey, A. Shrivastava, E. J. Carlson, A. Wood, B. H. Calhoun, and B. P. Otis, "A batteryless 19 μW MICS/ISM-band energy harvesting body sensor node SoC for ExG applications," *IEEE Journal of Solid-State Circuits*, vol. 48, pp. 199–213, Jan 2013.

[7] M. Sawan, M. T. Salam, J. L. Lan, A. Kassab, S. Gélinas, P. Vannasing, F. Lesage, M. Lassonde, and D. K. Nguyen, "Wireless recording systems: From non-invasive EEG-NIRS to invasive EEG devices," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 7, pp. 186–195, April 2013.

[8] Natus Medical Inc., "Nicolet EEG wireless amplifier. Rev 05." https://photos.medwrench.com/equipmentmanuals/5989-3568.pdf, Oct 2017. [On line].

[9] g.tec, *Advanced biosignal acquisition, processing and analysis. Product catalogue*, ch. g.MOBIlab: wireless biosignal acquisition system in your pocket, pp. 25–28. Oct 2017. [On line].

[10] ANT Neuro, "eego rt: high-density EEG solution with real-time data access.." http://www.ant-neuro.com/sites/default/files/150112_older_eego_rt_A4.pdf, Oct 2017. [On line].

[11] Cognionics, "72-Channel dry EEG Headset system, (HD-72)." http://www.cognionics.com/index.php/products/hd-eeg-systems/72-channel-system, Oct 2017. [On line].

[12] J. Oreggioni, A. A. Caputi, and F. Silveira, "Biopotential monitoring," *In Press. Encyclopedia of Biomedical Engineering. Elsevier's Biomedical Sciences Reference Module*, 2018.