Wireless Biopotential Signals Acquisition System

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***Abstract*— In this paper, we present a low power wireless system based on a MSP430 based system-on-chip for biopotential signals acquisition. The system is capable of recording up to 12 ksps from up to 4 channels with independent gain and a 1 Hz to 5 kHz bandwidth. The gain for each channel may vary from 2.5 kV/V to 68 kV/V, being able to adapt signals in a range of 20 µV to 1 mV, to be digitalized in a 12 bits ADC. The system consists of 2 modules, which communicate wirelessly with each other via a 915 MHz link, with Minimum-shift keying (MSK) modulation. The communication reaches 358 kbps of transmission rate, with less than 2% of packets lost without retransmissions, within a 5 meters range. One of the modules is wired to a PC via a USB cable, reaching 921.6 kbps of transmission rate through UART protocol. The wired module is powered through the USB port, whereas the wireless module is powered with 2 AAA batteries, lasting for more than 24 hours of operation. A Matlab toolbox was developed in order to facilitate the data storage, system configuration as well as collected data analysis.**

***Keywords*— Low power wireless data transmission; Biopotential signals acquisition; MSP430 system-on-chip.**

I. INTRODUCTION

In the last decade the study and processing of neural signals based on the possibilities opened by the evolution of microelectronics and embedded systems have significantly increased [1]. Nowadays, it can be found from the most fundamental works about the understanding of how the human brain reacts to certain neurological conditions, to applications oriented to handling specialized hardware through bioelectrical impulses [2, 3, 4 and 5].

Moreover, for the past years the interest in wireless solutions for this kind of devices has grown [6], providing more freedom of movement to the test subject hence adding all kind of new scenarios not possible with wired implementations. Besides, using wireless systems reduces the length of wires and isolates the test subject from power line, providing security and reducing interference. On the other hand, the wireless device faces the challenge of maximizing lifespan while keeping the size and weight of batteries to its minimum.

Devices that work with biopotential signals face many challenges, signals vary from 1 uV (electroencephalography) to 10 mV (electromyography), in a wide frequency spectrum (0.5 Hz to 10 kHz). This wide frequency spectrum required e.g. for acquisition of neural spikes, when coupled with the need of several channels, leads to transmit a great amount of sampled data wirelessly, while keeping low consumption.

In this paper, we describe the development of a low-power wireless system for biopotential signal acquisition based on off the shelf components. The aim of this work is to develop a system capable of acquiring those signals from a test subject (for example cats or humans), with a four channels wireless module and transmit these digitalized signals into a wired module to be collected in the PC for later analysis. This work aimed at 12 bits, 10 ksps acquisition and real-time transmission of neural signals (compatible with 5 kHz signal bandwidth, suitable for neural spike processing). This goal is a challenging one in the context of low power, off the shelf, embedded systems (e.g. the work in [6] achieves 4 ksps of 12 bits). In order to achieve this goal two modules based on an ultra-low-power system-on-chip (SoC) of the MSP430 family from Texas Instruments (TI), with integrated RF, has been built: the Remote Module kept by the test subject and the Base Module connected to a PC.

This paper is organized as follows. The proposed solution and implementation of the system are described in section II; including the hardware development, the SoC programming and GUI implementation. Experimental results and discussions are reported in section III. Finally, conclusions are presented in section IV.

II. PROPOSED SOLUTION

The developed system is depicted in Fig. 1.

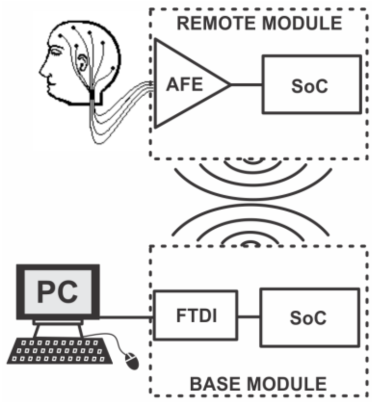

Fig. 1. High-level description of the biopotential signals acquisition system.

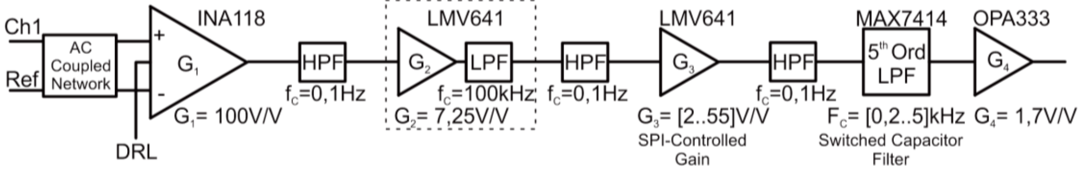

Fig. 2. Block description of a signal's path through one channels of the AFE.

The Remote Module is composed by an analog front-end stage (AFE) that is a programmable biopotential band-pass amplifier, and a SoC that implements the digitalization of up to four signals and the communication with the Base Module. The Base Module consists in a SoC symmetric to the one in the Remote Module. This SoC handles the communication between modules, and the communication to the PC via an FTDI chip that also provides the module's power supply. The GUI was developed as a toolbox in MATLAB and besides storing the data in the PC, offers a friendly interface for the user to operate the Remote Module and visualize and analyze the acquired data.

A. Analog front-end

In Fig. 2 a block diagram of one channel of the analog front-end is presented.

Signals are acquired differentially by two electrodes that enter into a balanced AC-Coupled Network circuit for differential filtering (not shown in Fig. 2) [7]. Afterwards, signals get to an instrumentation amplifier (IA), for which low noise, high gain, high input impedance and high CMRR are required. The INA118 from TI is chosen for that matter, having low noise (9 nV/√Hz) with a 2.7 V voltage supply operation capability, and retaining all the other desired features, according to the research done over sixty different IA from TI, Analog Devices, Maxim Integrated and Linear Technologies. Fig. 3 shows a summary of the most significant IAs compared. INA118's gain is set in 100 V/V by means of an external resistor.

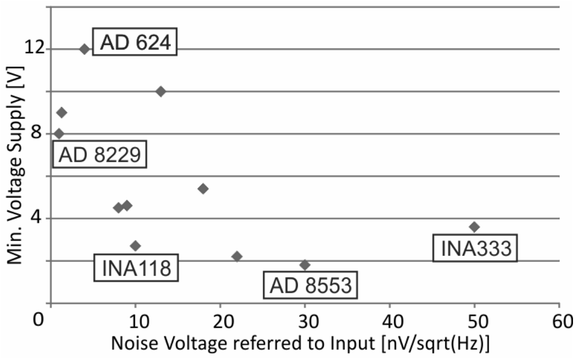

Fig. 3. IAs Noise vs. Supply Voltage comparison.

A DC restoration circuit is incorporated in the feedback loop of the INA118 as well as a Drive Right Leg (DRL) circuit [8] (not shown in Fig. 2). Both circuits were implemented with the operational amplifier (OA) OPA333 from TI. This OA was selected because of its very low consumption and very low offset voltage.

Following the differential amplification, the signal is band-pass filtered between 0.1 Hz and 100 kHz and amplified 7.25 V/V with an OA (LMV641 from TI) in a non-inverting configuration. The LMV641 is a low power, wide bandwidth OA, that offers low input referred voltage noise (14 nV/√Hz) allowing 2.7 V power supply voltage.

Further amplification corresponds to a variable amplification stage implemented with a LMV641 and controlled with a 1024 steps digital rheostat (AD5270 from Analog Devices). The AD5270 has a SPI interface, thus allowing dynamic configuration with 1% end-to-end resistor tolerance. The gain achieved in this stage can be configured by the SoC between 2 V/V and 55 V/V.

The next stage is a filtering stage implemented with a MAX7414 from Maxim Integrated. It is a 5th-order, low-pass Butterworth, switched-capacitor filter that allows corner frequencies from 1 Hz to 15 kHz set by an external clock, as well as admitting power supply voltages down to 2.7 V. The clock that sets the corner frequency is provided from the SoC.

Lastly, there is a low gain amplification stage implemented with an OPA333 because of its low power, low offset voltage and rail-to-rail features. It offers a 1.7 V/V gain in order to maximize the signal amplitude at the input of the analog to digital converter (ADC).

All the system, including the SoC, operates with two AAA (900 mA/h) rechargeable batteries, connected to a step-up DC/DC converter. The step-up is required because the supply voltage for many components cannot be reached with those batteries. For this purpose the MCP1640 from Microchip is employed since it offers stable output voltages of 3.3 V with input voltages as low as 0.65 V, with high efficiency. Considering the consumption of four channels and the SoC at full capacity, the system can operate at least for 24 hours.

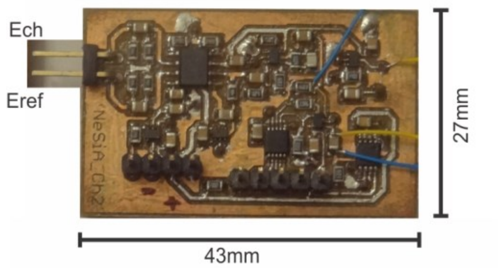

Fig. 4. Front layer of the implemented PCB for a single channel of the AFE.

The implemented PCB for a single channel of the AFE is presented in Fig. 4, along with its dimensions.

B. SoC and Communication Module

The digitalization and communication between modules is based on CC430F6137 from TI, an ultra-low-power SoC with integrated RF. In our case, among the devices included in the

SoC, we took advantage of the MSP430 microcontroller, the CC1101-based sub-1 GHz RF transceiver and the 12 bits ADC, Timers, UART and SPI peripherals. An evaluation board (EM430F6137RF900) was applied for the initial implementation, demonstrating the excellent performance of the SoC for the assigned tasks.

The four signals from each channel of the AFE are picked up by one of the 8 multiplexed inputs of the 12 bits ADC and sampled. The sampling frequency, which is configured from the GUI before starting the experiment, may vary between 10 ksps at full speed sampling (allowing 1 channel at 10 ksps, 2 channels at 5 ksps, 3 channels at 3.3 ksps and 4 channels at 2.5 ksps) to 2 ksps in a "Battery Save Mode" (4 channels, each at 0.5 ksps). In order to program the system gain and bandwidth, the SoC is connected to the SPI interface of the digital potentiometer that controls the gain (AD5270), as well as, to the clock pin of the programmable filter (MAX7414).

For the communication between modules, a packetized system was selected employing 60 bytes for data, 1 byte as counter for detection of lost packets, and 10 bytes internally added by the radio core (8 for synchronization and preamble bytes and 2 for CRC). Each sample is dispatched in 2 bytes, so each packet carries up to 30 samples. The 60 bytes are used during the Acquisition Mode for sending sampled data, and also during the Configuration Mode to send programming parameters and consult current configuration. The communication is done over a 915 MHz link, with MSK modulation and the programmed data rate is 358 kbps.

At reception in the Base Module, the packages are forwarded to the PC through the UART interface, at 921.6 kbps and converted by a FTDI chip into USB protocol.

The selection of this SoC was made on base of its low-power consumption combined with the possibility of reaching wireless data rates close to 500 kbps.

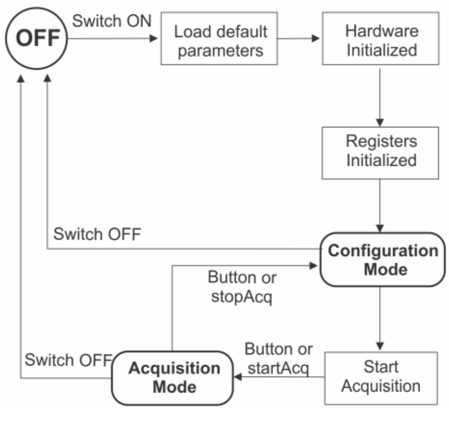

Fig. 5. High level firmware flowchart.

The firmware operates in two modes: a Configuration Mode and an Acquisition Mode, which are controlled from the GUI. In Fig. 5 the modes flowchart is shown. A simple scheme for mode control was applied in order to minimize the processing time devoted to this. In both modes, the Base Module works as part of the communication channel between the PC and the Remote Module, always forwarding packages from one to the other. The firmware functionality in the Remote Module depends on the operation mode. In Fig. 6 the flowchart for Configuration Mode is shown, where the implementation of the commands for: setting a new configuration (New Conf.), reading the current configuration (Get Conf.) and Start Acquisition are depicted. The commands referred to the configuration are answered by transmitting the configuration (Tx Conf). Fig. 7 shows the flowchart for the Acquisition Mode.

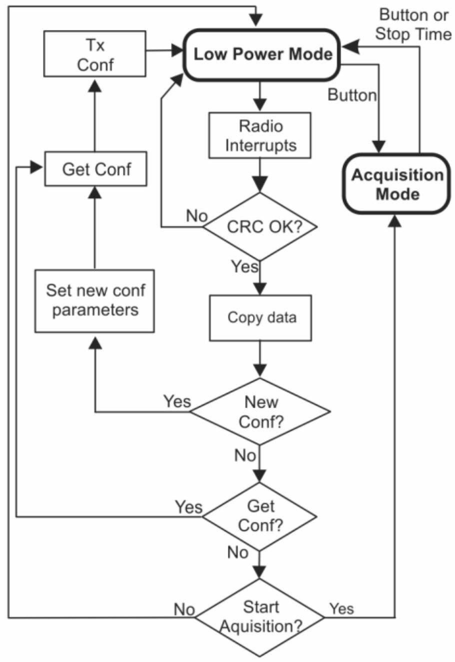

Fig. 6. Flowchart of the Configuration Mode, at the Remote Module.

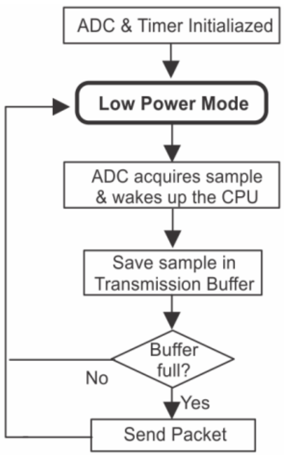

Fig. 7. Flowchart of the Acquisition Mode, at the Remote Module.

C. *Grafic user interface (GUI)*

The GUI was programmed in MATLAB® as an open toolbox and offers an easy way to operate the whole system. Once started from the main menu, six buttons give access to each of the system functionalities, as is shown in Fig. 8 A), B) and C).

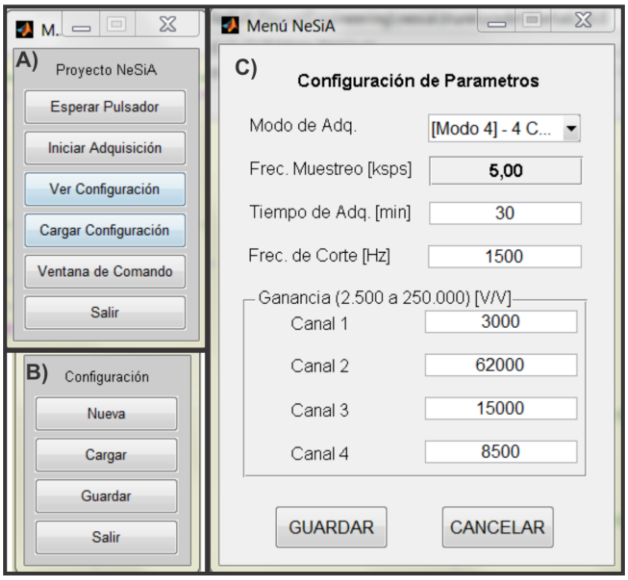

Fig. 8. A) Main menu of the GUI; B) Configuration menu of the GUI ; Change Configuration menu of the GUI.

In Fig. 9 a flowchart is presented with the different functionalities for the GUI.

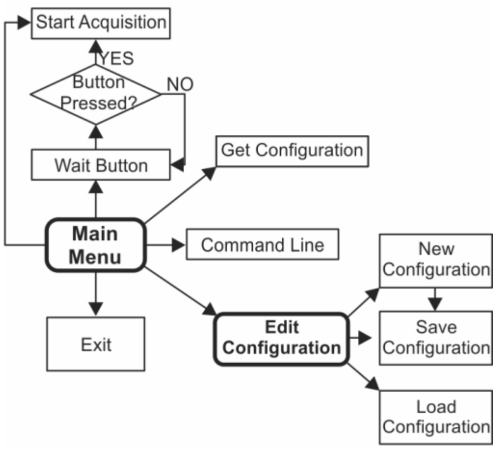

Fig. 9. Flowchart of the implemented GUI for the acquisition and configuration management of the system.

The acquisition can be started directly from the PC or the system can be commanded to wait until a button, in the Remote Module, is pressed. Once the acquisition starts, the communication between modules becomes unidirectional from the Remote Module to the Base Module, in order to take advantage of all the airtime to transmit the sampled data. To force a stop in the acquisition, the button in the Remote Module has to be pressed again. Also a time limit can be selected for the test and once reached the system automatically stops (see Fig. 8 A). The received data is stored in memory and can be saved on request. There is also the possibility to go to the command line to analyze the received data. The software can read the current configuration, send a new one, as well as edit, save and load configuration in the PC. The parameters that can be programmed in a configuration are: total gain of each independent channel; upper cutoff frequency (same for all the channels); time of acquisition and mode of operation (number of channels to be sampled and sample rate).

III. Experiments and Results

A. Experiments on the SoC and Communication Module

The number of packets sent from the Remote Module to the Base Module during the experiments for this part, was fixed to 10 thousand, in order to have an easy way to measure packet-loss rate during the acquisition. With this number of packets, it takes 60 seconds for the communication to be fulfilled. It is important to take into account that the implemented communication does not have retransmissions of packets.

Several scenarios where tested measuring an average of 10 runs for each scenario. In TABLE I these averages are reported along with the proposed scenario. These numbers indicates than in most cases the packet-loss rate is around 1%; however, it deteriorates whenever there is obstacle very close to one of the stations.

Up to 12 ksps at 358 kbps radio data rate were achieved with less than 2% packet loss at a 5 meters distance, with a transmit power of 10 dBm. Data rates of 407 kbps were tested and can be used at the cost of a higher packet-loss ratio.

TABLE I. Packet-loss ratio for different scenarios of acquisition

Modules Distance[a]	**Obstacle in the line of sight**	**Packet-Loss Ratio**
H: 1.5 m; V: 0	No	0.94%
H: 3.0 m; V: 0	No	1.19%
H: 3.0 m; V: 0	Person	1.26%
H: 4.0 m; V: 1.5 m	No	1.45%
H: 6.0 m; V: 0	No	1.29%
H: 6.0 m; V: 0	Person	1.68%
H: 6.0 m; V: 1.0 m	Thick wall of bricks	1.11%
H: 7.0 m; V: 0	No	1.09%
H: 7.0 m; V: 0	Person	1.13%
H: 7.0 m; V: 0	Person close to the Base Module (0.20m)	3.00%

[a] H means Horizontal; V means Vertical

The effective sampling and transmission ratio depends on the processing load of the SoC. While sampling up to 3 channels and transmitting them at 358 kbps radio data rate, an overall sampling rate operation of 12 ksps is reached (1 channel at 12 ksps, 2 channels at 6 ksps each or 3 channels at 4 ksps each). Acquisition and transmission of 4 channels requires slowing the sampling rate to 10 ksps (at 2.5 ksps per channel).

Regarding the signal sampling in the ADC of the Remote Module, signals of different frequency and amplitude were injected directly into the ADC and transmitted. Then the recovered signals were analyzed in the PC, and the Fast Fourier Transform (FFT) was run to recover the principal frequency component. These results show that the received signal is a very accurate approximation of the injected signal. In the Fig. 10A, there is an example of the recovered signal and it’s FFT in Fig. 10B.

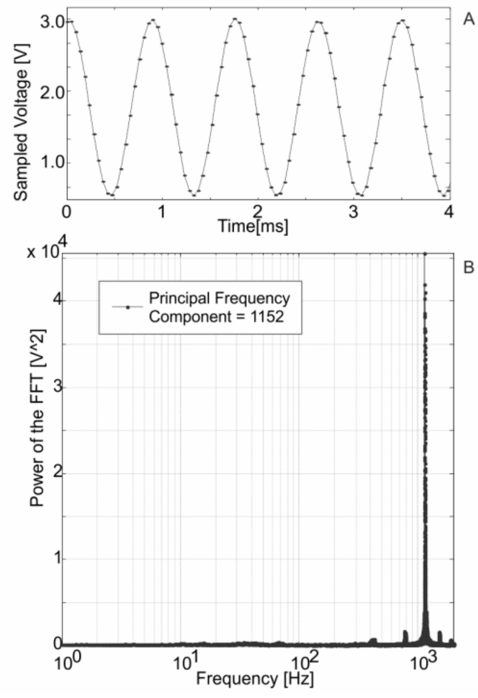

Fig. 10. Example of a signal acquired by our system. (a) Acquired signal injected directly into the ADC of the SoC; (b) FFT of the acquired signal.

B. Experiments on the AFE

The AFE provided the expected gain and bandwidth and a measured CMRR of more than 100 dB, allowing measurements in the signal range from 20 uV to 1 mV peak-to-peak amplitudes. Noise and consumption measurements are pending.

Last but not least, it is important to remark that because of the transmission power chosen for the communication, and the fact that the AFE is positioned close to the antenna, given the modules reduced size, a severe interference in the acquired signals was observed while acquiring with the system from end to end. This was produced by a bad isolation of the AFE, and for that reason is of great importance to have this into account at the moment of building the final hardware. At the time, this problem was mitigated but not fully solved, being one of the milestones for future developments for this work.

IV. Conclusions

It was possible to design and manufacture a very small AFE for one channel (43 mm x 27 mm), capable of acquiring and adapting signals ranging from 20 µV to 1 mV peak-to-peak with a CMRR of more than 100 dB. The firmware implemented is capable of acquiring four different signals with a maximum overall sampling rate of up to 12 ksps, encoded in 12 bits and transmit them wirelessly, running on a CC430F6137 SoC based development kit. This wireless communication is implemented at 915 MHz, with MSK modulation with 358 ksps programmed radio data rate with a packet loss of less than 2% at 10 dBm transmit power and 5 m distance. This firmware is also capable of controlling the gain and the upper cutoff frequency of the AFE, and implements a “Battery Save Mode” for acquiring four signals at 0.5 ksps sampling rate.

A Base Module was designed and built, capable of receiving signals acquired in the Remote Module and relay them to the PC´s USB interface, at a rate of 921.6 kbps using a FTDI chip.

A friendly GUI was developed in Matlab in order to control and configure the Remote Module, and furthermore, the experiment taking place.

Future developments for the hardware will focus in the integration of the remote module in a single board, substituting the antenna with a PCB antenna and the improvement of the shielding of the AFE against RF interference. Regarding the firmware, the line of work continues trying to upgrade the throughput of the system and the maximum sampling rate. For the GUI it would be desirable to develop an option for real time visualization of the acquired signals.

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