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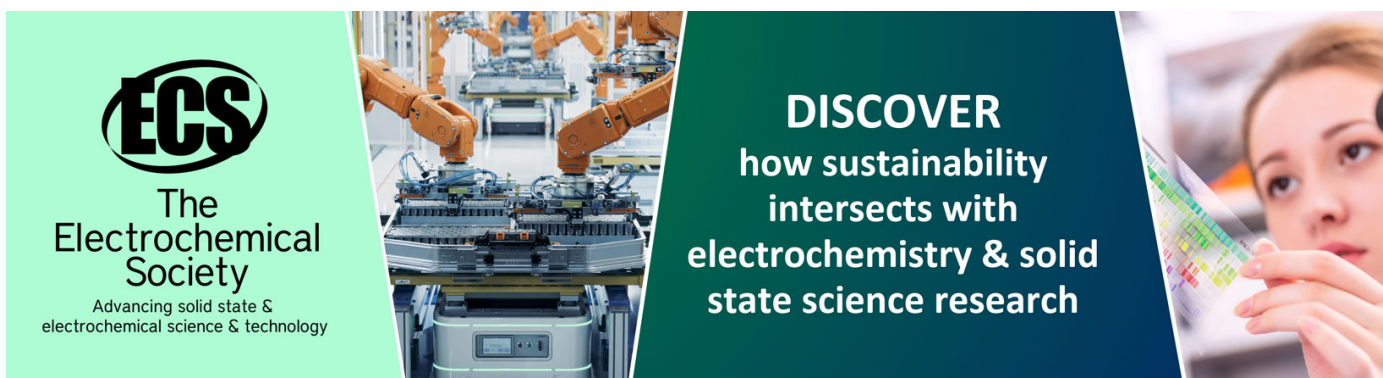
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Wearable System for Acquisition and Monitoring of Biological Signals

D J Piccinini¹, N B Andino¹, S D Ponce¹, MA Roberti¹ y N López²

¹ Analysis, Development and Biomedical Research Group, Facultad Regional San Nicolás, Universidad Tecnológica Nacional, Argentina.

² Medical Technology Cabinet, Universidad Nacional de San Juan, Argentina.

Abstract. This paper presents a modular, wearable system for acquisition and wireless transmission of biological signals. Configurable slaves for different signals (such as ECG, EMG, inertial sensors, and temperature) based in the ADS1294 Medical Analog Front End are connected to a Master, based in the CC3200 microcontroller, both from Texas Instruments. The slaves are configurable according to the specific application, providing versatility to the wearable system. The battery consumption is reduced, through a couple of Li-ion batteries and the circuit has also a battery charger. A custom made box was designed and fabricated in a 3D printer, preserving the requirements of low cost, low weight and safety recommendations.

1. Introduction

Medical technology is a key element in global problems concerning health, as it can improve the quality of life or extend it through the appropriate use and prevention. Its value is calculated not only for its economic cost but also for its impact in practice and the success of medical treatments. Due to medicine improvements, life expectancy has increased. Along with this, the caring for the elderly and people with chronic diseases, have also improved emphasizing the necessity of preventive medicine and monitoring of this patients [1, 2].

In this context, what is proposed is the development of a platform of wearable sensors for the monitoring of the health and well-being of the individuals, in a direct or remote way. The incorporation of this technology improves the quality of the elderly's life, people with cognitive or memory disorders, disabled or with motor disability, obese patients, or any other pathology that may place the user in a vulnerable situation. It also allows a continuous and non-invasive monitoring during sport practices, exposition to adverse environmental situations, and other applications in healthy individuals [3-5]. In recent years, the use of these technologies has been incorporated in entertaining and rehabilitation video games and also in augmented reality systems.

A wearable system should meet certain design conditions, such as data storage, wireless connection, efficiency in the supply, portability, versatility and capacity of pairing several sensors, among others [6].



The proposed system consists of a master module in charge of data reception and collection, synchronization and wireless transmission. This module is connected to sensors or slaves which acquire a biological signal and then process and format it adequately to send it to the master. It is important to remark that the communication between the disposals should respect the same protocol, independently of the nature of the acquired signal.

The data transmitted from the master module to the PC can be seen, processed and exported to specific softwares according to the user. The software should be modular to suit the sensors chosen for each application, which give versatility to the system, functioning in an interchangeable way. The proposed biologic variables to be sensed, each with its own specific acquisition and preprocessing module:

- Temperature and humidity module: it registers two temperature channels, which can be put in two body segments or in one external segment to determine the metabolic answer to adverse environmental conditions. The humidity is an important variable in the control of the body temperature, and its sensing lets us know the user's adaptation to external conditions.
- Heart rate module and pulse oximetry: with only one module both variables are registered through a LED emitter of specific frequency to the absorption of red cells or red corpuscles, which indicates the degree of oxygenation. Moreover, it allows inferring the heart rate. On one hand, this module is of vital importance in the remote monitoring of cardiac, respiratory and elderly patients. On the other hand, the module is a body activity indicator for sedentary and obese users. Finally, it is crucial for the use in sports. The placement of these sensors should be done directly on the skin, because of the operating mechanism above-named.
- Kinetics measurements module: this module has an inertial sensor IMU (Inertial Measurement Unit) that contains an accelerometer and a gyroscope. It is necessary to place the sensor on the body segment wanted to be studied, or to put an IMU in each segment. The information of each IMU module is processed to avoid singularities and both sources (accelerometer and a gyroscope) are merged through Kalman filter. It is possible to determine the established angles between them with two or more segments, what is a true articular angle stimulator. Only one IMU provides information related to the user's activity, inactivity level, waste of energy (with reference with the temperature).
- Magnetometer / GPS: this sensor is incorporated into the above-named IMU, but it will be used strictly to monitor and locate the patient. This module is particularly useful for patients with cognitive impairment, Alzheimer's disease or similar pathologies. In the case of risk patients it is vitally important if any alarm sounds, for example the heart rate. Furthermore it is used when the continuous monitoring of a user is done, to study the behavior in everyday activities. The location allows knowing the activity and surroundings that are related to each event.
- Surface electromyography module (EMG): in recent years, it has been a progress in the study of muscular behavior in rehabilitation patients through the non-invasive EMG. It is possible to use these technologies to quantitative evaluations of ergonomics, fatigue and muscular effort in repetitive and forced labor, where musculoskeletal system injuries are the main cause of disability.

The modular design and the configuration of variables that are proposed in this design allow the configuration of active sensors (minimizing the battery consumption), the selective data storage and the continuous transmission of monitoring parameters depending on the application.

In this paper, the development of the master system is presented together with one slave module to acquire signals; in this case they were used electrocardiographic (ECG) and electromyography (EMG) signals as examples.

2. Materials and Methods

The system consists of individual sensors (Slaves) that includes, in situ, a stage of preparation of the biologic signal, another of regulation and feeding filtering and an analogue digital converter. These sensors are connected to a Master board that is in charge of: controlling the communication with the Slaves, the wireless transmission to a PC and the feeding of the whole system, including the batteries charging. The connection between Slaves and Master is intended to be in a properly wired article of clothing. The data transmission from the Master is carried out through Wi-Fi using TCP/IP protocol to a personal computer in order to process and extract characteristics (Figure 1). The system gives the possibility of having the data in flat file format, facilitating the analysis and application of algorithms with any programming language or even in a simple commercial or open spreadsheet.

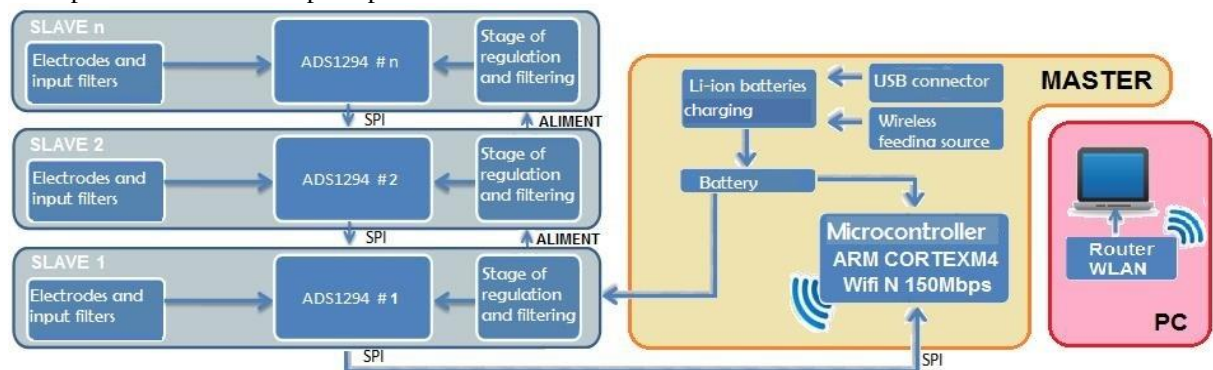


Figure 1. System block diagram

2.1. Slave Units

As it has been said before, these Slave units (color blue in figure 1) consists of one stage of low noise and high 115dB CMRR amplification of programmable gain, a multichannel delta-sigma A/D converter of 24 bits and sampling rate up to 32kSPS and low noise internal tension reference, possibility of common mode feedback through the RLD (Right-Leg Drive) circuit and SPI (Serial Peripheral Interface) digital output compatible with cascade connection of multiple disposals (Daisy Chain). All this is given for the ADS129X integrated circuit from Texas Instruments. In our case, that is, Slave module for ECG/EMG the ADS1294 model was used, which has 4 differential channels and internal clock for its digital section and delta-sigma converters. It has to be emphasized that all the family ADS129X satisfies the IEC60601 standard [7].

To feed this unit, a +3.3v unipolar unit is proposed to the digital part and a +5v unipolar tension to the analogic part. To do that, ultra-low noise linear regulators TPS7A49 from Texas Instruments are used; all recommended to analogic applications of high accuracy and precision.

The SPI bus functions at 4MHz speed (within a maximum of 20 MHz) and can add up to 41 Slaves that are directly placed on the disposable electrodes. The maximum quantity indicated is according to the SPI bus, but also limitations can exist because when the Wi-Fi router is far away from our position, the communication bandwidth is dropped.

The following equation corresponds to a calculation of the estimation of the number of Slaves connected through the SPI bus:

$$N_{\text{DEVICES}} = \frac{f_{\text{SCLK}}}{f_{\text{DR}} (N_{\text{BITS}}) (N_{\text{CHANNELS}}) + 24}$$

f_{SCLK} stands for the frequency of the ISP used, f_{DR} is the frequency of the ADC sampling, N_{BITS} is the quantity of sample bits, in this case there are 24 bits and N_{CHANNELS} corresponds to the four ADS1294 channels. The chosen configuration is 1000SPS (Samples per Second). It is possible to reach to 208 connected Slaves if using an SPI speed of 20 MHz, since the microcontroller and the ADS128X allow it, but this can result in problems in the communication originated from the length of the wires. Even though, the necessary precautions were taken into account in the moment of design the board if this or other application is required.

The Daisy Chain configuration was selected to interconnect the Slaves. The Daisy Chain share the SCLK, DIN and CS bus signals, going through each ADS1294. The DOUT line corresponding to the output data of each ADS goes into the DAISY_IN entry of the previous module, and so on, creating a continuous chain. That is to say, the minimum number of wires needed to make the communication in this way, is 5 and it is always the same. There is a START reference indicating the beginning of the conversion, however, it was decided to replace the physical signal to an OPERATION COMMAND through the SPI to avoid the use of another wire. The internal clock is also used for the internal synchronism signals, avoiding another extra wire and additional electronic components. In figure 2 the required wiring diagram is appreciated.

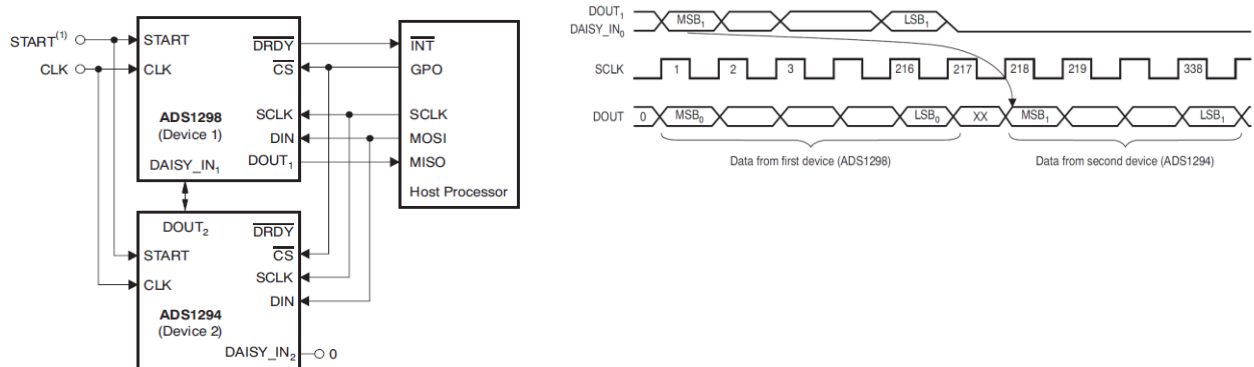


Figure 2. Multi-configuration used. **Figure**

3. Diagram of data synchronization for figure 2.

The electromagnetic interference would largely affect the system, through common mode tensions produced by the magnetic field coupling that comes from the feeding line and other sources, including fluorescent lights. For this, it is made use of a RLD circuit that senses the common mode of a set of determined electrodes and originates a negative feedback injecting the patient with an inverted common mode signal in phase [8, 9]. The reference voltage applied in this system corresponds to $+2.5V$, that is to say $(AVDD + AVSS)/2$, generated in an internal manner.

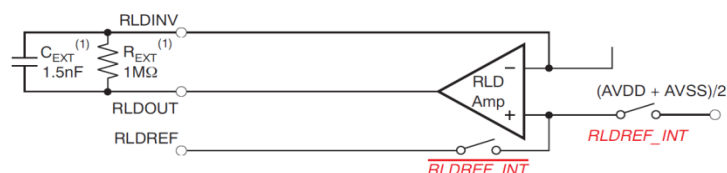


Figure 4. RLD internal block.

The producer of the front-end ADS1294 recommends the following wiring diagram for the RLD when multiple interconnected disposals are used, providing feedback through a single Slave but with all of the Slaves taking part in the average, bearing in mind the body as unipotential.

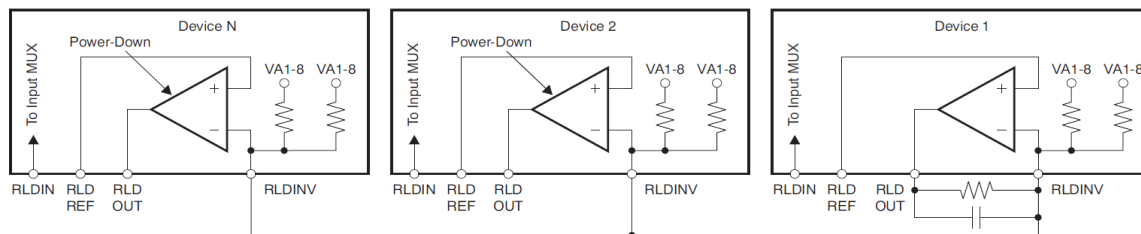


Figure 5. Connection diagram of RLD for multiple disposals.

2.2 Master Unit

The Slaves of this system are connected to a central unit or master. The microcontroller responsible for performing all the control tasks and transmission is the CC3200 of the Texas Instruments. This microcontroller corresponds to one SOC of dual core ARM CortexM4 of 32bits with floating-point, running at 80MHz and an external memory for the user program of 8 Mbit of capacity. As a remarkable characteristic of this model is a Wi-Fi connection embedded in the same module ready to be used, coordinated by a sub-processor network. It has a capacity for make transmissions of 150 Mbps under N norm and allows the user to have the possibility to use data encryption, such as AES, DES, SHA, TLS/SSL or MD5. It also has common peripherals as GPIO, PWMs, UARTs, SPI, IIC, etc. Another important characteristic of this integrated circuit is that it has certifications (FCC, IC, CE, Wi-Fi CERTIFIED) that enables the streamline of the development, economize its commercial implementation and reduce installation timings in the market. It can be appreciated in greater detail, in figure 6 the internal peripherals of the module.

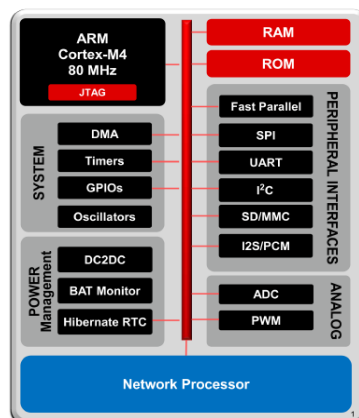


Figure 6. Peripherals conforming the CC3200 module.

Through this plaque, two media are controlled, on one hand a Wi-Fi communication, on the other hand, a SPI bus. The Master sends wirelessly the data of the acquisition through the TCP/IP protocol. The serial peripheral interface or SPI bus is a communication standard to control the transference of information between diverse integral circuits, in this case, between the slave sensors and the master unit.

The complete system functions with a pair of Li-ion batteries, for electric reasons, this is the only way of operating. These batteries are charged using the MAX1555 integral circuit of Maxim Integrated, which allows the charge with energy that comes from a USB connector or a DC source. As an innovative approach, it was used a wireless feeding source suitable to the Qi specification, BQ541013B integrated circuit of Texas Instruments, designed for portable systems. This stage consists of a transmitter and a receiver that through the beginning of electromagnetic

induction allows charging the batteries mentioned above. This source gives a capacity of 5W to 5 volts output power.

It can be seen in figure 1 that the Master part is represented by an orange color, consisting on the stages named above. Moreover, it can be observed in figure 10, the physical implementation of the system.

2.2. Firmware

The firmware of the Master unit was programmed in C language, using the Code Composer Studio software distributed freely by the producer of the integrated circuit, Texas Instruments. It has been decided that the system would be composed of varied tasks in the same operating system in real time, TI RTOS, running in the microcontroller of the module. Even though, if the producer does not give examples of the Wi-Fi interface applications under this operating system, the Wi-Fi communication has been manipulated and all the other segments that make the communication, as sockets TCP/IP, Smart Link, etc. In figure 7, the firmware diagram for the Master is presented in detail.

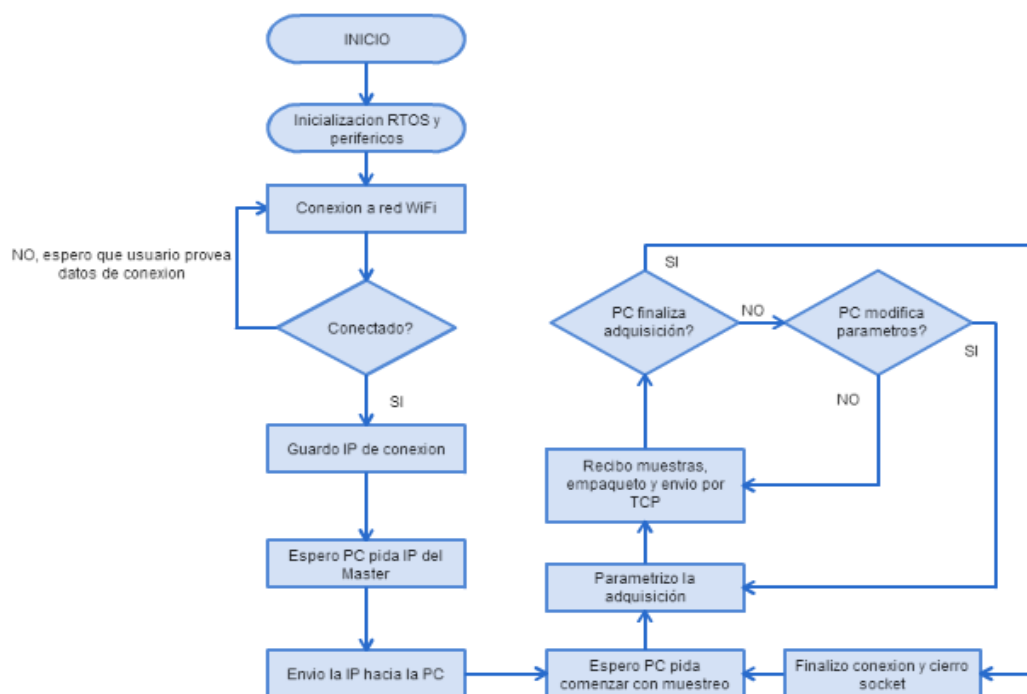


Figure 7.Diagram of the Master state.

To use the Wi-Fi connection, the bookshops provided by the producer were used, configuring it as a client in the Wi-Fi connection. The module has the ability of storing profiles for different Wi-Fi networks. When turned on, it will search for nearby networks and will connect to that of the strongest signal, used and stored in a previous occasion. In case of not having stored networks, or if the device is been used for the first time, or with the presence of networks having been detected, any of them has been connected preciously, the module will be waiting for the user's indication of what network choose. This can be done with a Smartphone through the application "Wi-Fi Starter" that is distributed freely by the Texas Instruments.

2.4. Data Reception

To begin acquiring the samples, first of all the PC, through Wi-Fi, will indicate the Master how to set-up the ADC ADS1294 of each Slave. However, it should previously know the IP address that the Wi-Fi network provided to the Master before. This can be solved assigning a fixed IP address in the Master, which is not recommended because it will only work with that address and Wi-Fi

connection, being a bit inflexible. The following may be the possible solution: to the PC sends an UDP (*User Datagram Protocol*) packet by the Wi-Fi connection directed to a well-known port of each Master, with the word “Discovery” in a Broadcast way, that is, it sends to all of the devices connected to the network.

The Master unit receives this packet, together with an IP address of the PC that is interested in start a connection, and responds to this packet with another one having its IP address. In this way, when this answer returns, the PC would have been informed of which IP address corresponds to the Master unit and the communication starts. After that, the ADS1294 should be set with the parameters as sampling frequency, internal reference tension, the status of each channel, programmable gain of each channel, RLD uses, etc. the sample reception from the ADC is done without interruptions to the sample frequency established by the user. Each sample is received by the Master of each Slave, and is sent to the PC through TCP (*Transmission Control Protocol*) to guarantee the order and delivery of the packets.

2.5. Hardware design

The printed circuit boards are designed with free or lite tools. In our case, the software KiCAD was used for the Slaves (figure 8), and in its Lite version, the software Eagle for the Master (figure 9). The designed technology adopted was SMD. For welding the chips CC3200 and BQ51013B it was needed to turn to companies of surface mount. In figure 10, it can be seen all the boards finished with the main components welded, ready for the first tests.

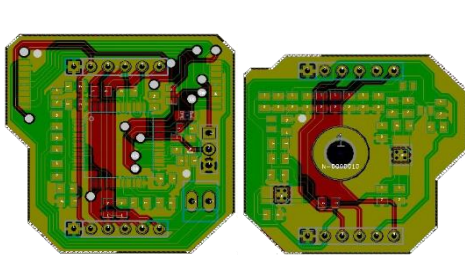


Figure 8. Design and SLAVE boards manufacture.

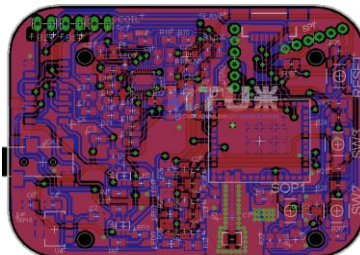


Figure 9. Design showing both layers of the MASTER board

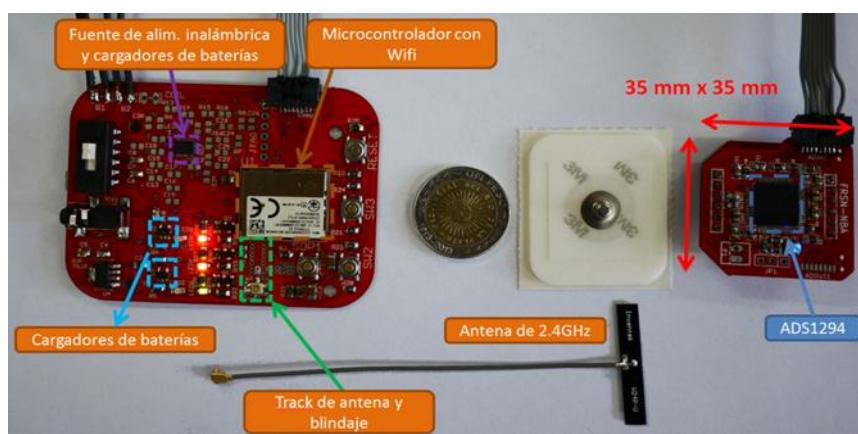


Figure 10. Finished base kit ready for the first tests.

As a final comment regarding the boards, the design has been thought to be done in two layers with PTH in FR-4 material with 1mm thickness. The most critical part of the Master board has been the design of the connection to the antenna, which must meet requirements of impedance adaptation; the calculation was verified with KiCAD (Figure 11). In figure 10, it can be seen also the additional shield with PTH holes around the course to the connector of the antenna.

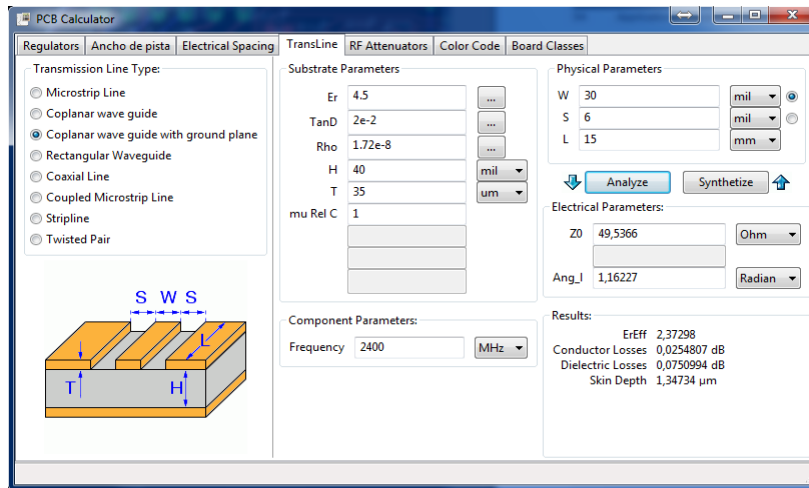


Figure 11. Calculation of the course for the antenna connector.

Lastly, the cabinet design has been performed with the use of a 3D software (figure 12), which is currently in the stage of production. A 3D printer or another conventional method of the industry dedicated to this subject is needed.



Figure 12. Prototype 3D model of the Master custom made box.

3. Results

3.1. Equipment evaluation

Before connecting the circuit with volunteers, each block was proved separately and then the complete system of ECG/EMG was proved making an acquisition of a real electrocardiogram. The performance was evaluated through the measure of its parameters and its practical use in the laboratory. A user interface that allows visualizing the signal in real time and the possibility of exporting the data for a later analysis was developed. In figure 13, it is showed the acquisition of the ECG signal.

The noise voltage equivalent to the entry was measured. If the entries are shorted out, an interpretation of the noise voltage of the ADS1294 is obtained. To a set gain configuration in 3,

an ECG signal is injected. Its bandwidth is of 100Hz and is a result of a reading that enables us to establish that all the noise to the entry is low, of some $2\mu V_{RMS}$.

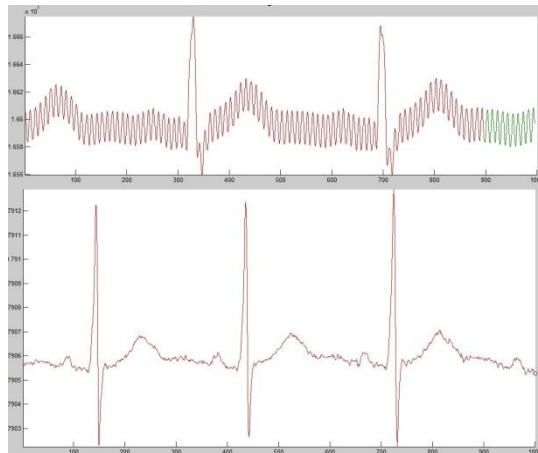


Figure 13. Capture of an analogic acquisition of the ACG signal. RLD (PD) verification.

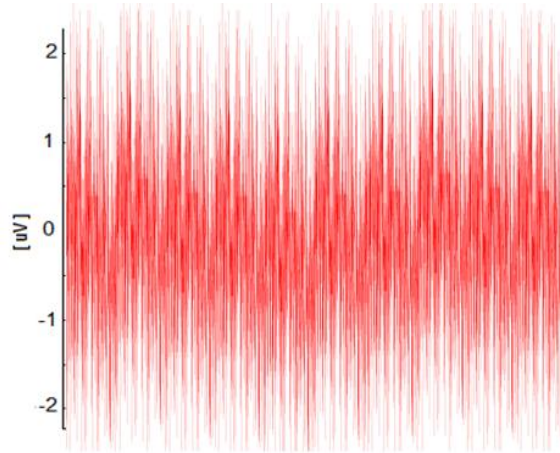


Figure 14. Interpretation of noise voltage in the entries during 10 seconds.

In the area of wireless communication with the PC it is very important that the bandwidth must be the as much as possible to guarantee the proper functioning of all the system. For that reason, two designs of implementation were compared:

- Board A: Evaluation board of the CC3200 microcontroller, commercialized by Texas Instruments. It uses an antenna mounted on board like a chip model 316M245001, which manufacturer is TaiyoYuden.
- Board B: Own designed board, commented through this entire document, and with an antenna that is not mounted on board, using a U.FL connector for radiofrequencies.

The highest bandwidths for each Board are compared, placing these 18 meter of distance from the Wi-Fi router. The analysis is done with the open **iPerf3** application.

```
C:\>iperf.exe -s -i 1 -t 100
Server listening on TCP port 5001
TCP window size: 63.0 KByte (default)
[ 41] local 172.20.20.44 port 5001 connected with
[ ID] Interval      Transfer    Bandwidth
[ 41] 2.0- 3.0 sec    1.96 MBytes 16.4 Mbits/sec
[ 41] 3.0- 4.0 sec    1.96 MBytes 16.4 Mbits/sec
[ 41] 4.0- 5.0 sec    1.94 MBytes 16.3 Mbits/sec
[ 41] 5.0- 6.0 sec    1.83 MBytes 15.3 Mbits/sec
[ 41] 6.0- 7.0 sec    1.77 MBytes 14.8 Mbits/sec
[ 41] 7.0- 8.0 sec    1.97 MBytes 16.5 Mbits/sec
[ 41] 8.0- 9.0 sec    1.94 MBytes 16.3 Mbits/sec
```

Figure 15. Measurement of bandwidth for board B.

```
C:\>iperf.exe -s -i 1 -t 100
Server listening on TCP port 5001
TCP window size: 63.0 KByte (default)
[ 41] local 172.20.20.44 port 5001 connected with
[ ID] Interval      Transfer    Bandwidth
[ 41] 2.0- 3.0 sec    0.77 MBytes 6.5 Mbits/sec
[ 41] 3.0- 4.0 sec    0.76 MBytes 6.4 Mbits/sec
[ 41] 4.0- 5.0 sec    0.69 MBytes 5.8 Mbits/sec
[ 41] 5.0- 6.0 sec    0.63 MBytes 5.3 Mbits/sec
[ 41] 6.0- 7.0 sec    0.57 MBytes 4.8 Mbits/sec
[ 41] 7.0- 8.0 sec    0.79 MBytes 6.6 Mbits/sec
[ 41] 8.0- 9.0 sec    0.75 MBytes 6.3 Mbits/sec
```

Figure 16. Measurement of bandwidth for board A.

As a final comment, it can be said that all the entire system is small and with low weight, making it wearable and portable. With an approximate consumption of 270mA when transmitting connected to a Slave and all the leds on. This consumption allows an autonomy of a bit more than 3,5 hours with Li-ion batteries of 1000 mAh. Previously these batteries are fully charged in 1,3 hours, loosing efficiency because of the use in the last years in other projects.

4. Conclusions

The design implemented in Master/Slave enables the reduction of the size in the stage of acquisition of biological signals, what allows a projection of a future system integrated to the clothing of the user.

The preliminary obtained results are promising in terms of similar size to a humid electrode, robustness in the wireless transmission and reliability in data reception and processing. Now, the design of dry electrodes for the acquisition is being developed with the aim of lower the noise and improves the system portability.

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