

RealTime Wireless and Wearable EEG Acquisition System

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Abstract:

Electroencephalogram (EEG) Ambulatory monitoring has been regarded as a promising tool to improve diagnosis, classification and medication prescription in patients with epilepsy and other paroxysmal diseases. This study presents the development of a wireless and wearable EEG acquisition system for ambulatory monitoring. The platform comprises 32 active dry electrodes, an analog-to-digital conversion unit with 24 bit resolution, 1 ksp/s sampling frequency per channel and a module for acquisition, processing and wireless transmission based on IGEP COM embedded system development platform under a Linux™ operative system.

The base operating system consists of two software frameworks which interact to ensure the real-time requirements of the acquired signals and parallel recording, processing and data transmission. In order to control the analog-to-digital converters and the synchronous reception of converted data, a Linux™ kernel driver was developed. It was also developed an userspace application for data saving, digital processing and wireless transmission via socket TCP-IP on a 802.11 b/g network topology. An application based on C# from .NET development environment was also developed for PC data reception and visualization.

This application consists of a TCP socket server for data reception and a graphic environment for signal's visualization. For signal plotting, it was used the open source ZedGraph library. The proposed system may operate on data streaming or event detection modes and presents feasible performance on EEG monitoring of both epileptic inpatients and outpatients.

Keywords:

EEG, epilepsy, wireless, dry-electrodes, embedded systems.

I. INTRODUCTION

The clinical gold standard for epilepsy diagnostics requires simultaneous video and electroencephalography inpatient monitoring [1]. EEG ambulatory monitoring of outpatients has been regarded as an alternative for the time consuming and expensive current approach [1-4]. EEG ambulatory monitoring also seems to be a promising tool to improve diagnosis, classification and medication prescription in patients with epilepsy and other paroxysmal diseases [5]. Although many platforms have been trying to accomplish the outpatient monitoring, some features required for an effective ambulatory system remain to be met.

Those features are described by the American Clinical Neurophysiology Society in their guidelines for systems of EEG long-term monitoring in epilepsy patients, and can be resumed into devices with the minimum number of channels between 32 and 64 to get a good spatial resolution and a minimum monitoring time of 24 hours running [6]. They also recommend the usage of event detection algorithms to improve the efficiency level of these applications. The electroencephalography (EEG) acquisition platforms have been described as typical wired systems characterized by a different number of channels, sampling frequencies per channel and by the fact that the signal processing is associated with another computing device to which it connects [7].

More recently, wireless systems have been described within the area of EEG acquisition [5, 8-13]. Usually, these systems receive the signals from the electrodes and send it to a computer mainframe for visualization and digital processing. Although wireless systems present significant improvements compared to the wired ones, such as the shielding against electromagnetic interferences and the versatility of monitoring in non-hospital environments, they still have some limitations, such as short battery life, long periods of patient preparation and the aesthetic aspect that recreates the individuals who wear them. Other technical limitations like modest signal resolution, sampling frequency, number of channels and wireless bandwidth are still holding the general implementation of wireless EEG system in clinics.

Many studies [5, 10-14] and commercial devices [9] describe wireless EEG acquisition platforms with 4 to 16 channels and high sampling frequencies. However those two characteristics rarely meet in a single device. In applications designed to monitor patients in an ambulatory setting, it becomes evident the need for more autonomous wireless systems, with the ability to read as well as to process information for critical decision making [1]. From this perspective, EEG acquisition systems should be small and lightweight enough to be wearable, have low power consumption for long-term monitoring, be computationally powerful enough to process the acquired data for online decision making and flexible enough to communicate data in every situation [15].

The system described in this study meets the necessary specifications for long-term monitoring in both ambulatory outpatient and inpatient settings of epileptic patients. Two operation modes are supported, with differentiated power consumptions: data streaming mode (more suitable for inpatient monitoring) and event detection mode. The proposed system gathers features such as: 32 dry electrode channels, 24 bits of resolution per channel, 1 kSps sampling frequency, complete data saving into SD-

card, complete wireless data stream transmission and high processing power for event detection algorithms. It can also run for 25 hours straight at maximum overload.

II. SYSTEM ARCHITECTURE

The developed system can be divided into three major functional blocks: the active dry electrodes, the analog-to-digital converter (ADC) and the central processing and transmission unit (CPTU). The EEG electrodes are connected to the ADC ADS1299 [16]. The developed software driver establishes a bidirectional communication between the ADC and the CPTU both for configuration and data acquisition. Once the acquired data arrives to the CPTU memory buffer it is processed through a digital filter and remotely transmitted to a PC by a TCP/IP wireless socket.

The currently built prototype is mounted to an acrylic cape that is placed over the individual's shoulders and correctly stabilized by 2 straps. The electrode cables exit through that structure towards the head cap allowing the free cervical spine movement (Fig. 1). The overall structure measures 130 x 110x50 mm and weighs 640 g. ADC interface and a userspace application for data saving, processing and transmission. The kernel driver uses a SPI port at 4 MHz for bidirectional communication in order to programme and read the signals converted in the ADCs. Synchronization between the ADCs and the driver is done via an interruption given from a converter signal (DRDY).

The driver also allocates two equally sized memory blocks: one is used to manage the data readings in every interruption; the other one is a mapped memory block to be used as a "shared memory buffer" with a flag to sign an event occurrence. Thus, for each interruption whose period is determined by the sampling frequency, the driver reads the converted data and sets it in the allocated memory block (Fig. 2).

Raw EEG Data Program



Fig. 1: First build prototype structure.

A. Central Processing and Transmission Unit (CPTU)

The Processing and Communications unit is composed of IGEPTM COM developmental platform embedded systems [17] that include a DM3730 microprocessor which, in turn, includes a single core ARM cortex-A8 running at 1 GHz, DSP (Digital Signal Processor), 3D graphics acceleration and 802.11 b/g wireless communication on-board. The platform runs on a high-level Preemptive Multitask Open-source Linux™ operating system (Angstrom distribution).

The main functions of this unit are:

- Acquisition data samples from the ADS1299;
- Store data conversions in an SD-card for offline analyses and backup;
- Digital Processing of the acquired data;
- Data wireless transmission by TCP/IP-socket to a PC or a mobile platform.

In order to accomplish those functions the platform runs on two software structures: the kernelspace driver for the CPTU-

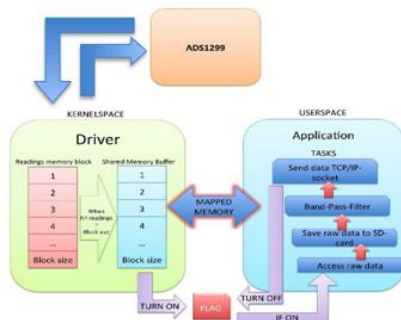


Fig. 2: Software diagram in data streaming operation mode.

Depending on the sampling frequency and the chosen time-window size to process the data, the driver saves the readings continuously in the memory block. When the number of readings reaches the size of the chosen window, the driver locks that process, copies the data into the “shared memory buffer”, turns the flag “on” and unlocks the reading process again, all in a small fraction of the sampling time period. The application, which directly accesses the same mapped memory, is constantly checking the flag status in order to copy data from the mapped memory and write them to the storage unit, as soon as the flag is ‘on’. Then, the same data is digitally filtered by a 2nd order IIR band-pass Butterworth filter and processed in a epilepsy event detection algorithm.

If there is a event detected, the data is automatically transmitted to the mainframe unit through TCP-IP Socket, else, there is no transmission and the flag is changed over to an “off” state. The platform can be configured according to various parameters, such as sampling frequency, the signal resolution, the data transmission protocol (continuous or based on a detection algorithm) and the data writing in the storage device. The system uses a wireless standard IEEE 802.11 b/g for communication to the computer mainframe in an ad-hoc or infra-structure network typology. Due to the fact that the microprocessor is based on a Preemptive Multitask Operative System (OS), not a Real Time OS, the scheduling task priorities had to be reconfigured. The kernel driver tasks (interrupt and SPI tasks) were configured with maximum priority (RT –real-time priority), while the userspace application was configured with a medium priority.

B. Analog-to-Digital Conversion

Four Sigma-Delta Texas™ ADS1299 [16] performed the analog-to-digital conversion. This component was chosen due to its low power and specific design for EEG application features. The ADC features 8 channels with 24 bits resolution, sampling frequencies from 250 sps to 1 ksp/s, instrumentation amplifier with

CMRR of -110 dB, Programmable Gain Amplifier (PGA) of 1 to 24, Driven-Right-Leg (DRL) input, input noise of 1 μ Vpp (70 Hz BW) and low power consumption of 5 mW/Channel. All ADS1299 configurations, such as sampling rate, PGA, reference, DRL properties, lead-off detection, and others, are accessible through its 25 registers. Through the SPI protocol, the ADCs were programmed to a 1 kSps sampling rate, PGA of 1, internal reference of about $\frac{1}{2}$ VCC, and the DRL was switched on. The 4 ADCs were connected in cascade mode, sharing the same DRL input. The ADC amplitude bandwidth was of about $\pm \frac{1}{2}$ VCC (from -2.5 to 2.5 V). In continuous reading mode, the ADS1299 provides an output signal timer interrupt (DRDY-Data Ready), which allows the synchronization with the CPTU unit.

C. Active Dry Electrodes

The active dry electrodes were assembled in two parts: the mechanical interface with the scalp and the signal conditioning circuit. The electrode contact with the scalp is established by 64 Phosphor-Bronze Gold plated pins with 0.8 mm diameter, 5 mm length and 2.54 mm spacing. In the other top of this structure a snap button (male type) was soldered in order to interface with the cap. The electrode also includes an active part, i.e. the electronic circuit for signal conditioning. The circuit is composed of a simple buffer using TLC272 [18] precision op-amp which offers high input impedance (1012 Ω) and low noise function.

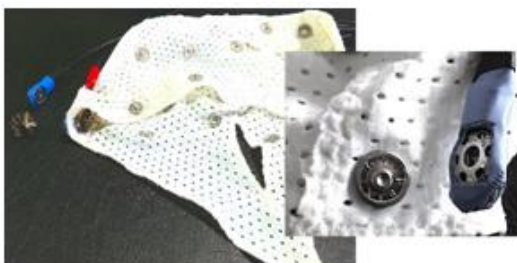


Fig. 3: Active dry electrode and cap.

This way, on one side there is the electronic circuit and, on the other, a snap button (female type) for coupling with the cap.

The cap is made of an elastic fabric and has an electrode organization and location according to the standard 10-20. At each electrode position, the cap has two snap buttons: a female type snap button that holds the pins that establish contact with the skin; and a male type snap button that holds the signal conditioning electronic circuit in place (Fig. 3).

III. RESULTS AND DISCUSSION

The presented platform was tested in terms of driver and application performance, throughput communication, power consumption and overall system functionality.

A. Performance of Embedded System

The kernelspace driver performance related to the real-time tasks (reading data from the ADCs at each interruption) was measured in 2 different task priorities configuration modes due to the specificity of the operative system. In a default priority configuration, the module spends a minimum of 427 μ s and a maximum of 1221 μ s to read 768 bits (32 Channels x 24 bits) at each interruption. In the real-time task priority configuration, the same process takes a minimum of 427 μ s and a maximum of 458 μ s. The minimum and maximum time the driver needs to copy a set of data with 1 second length from the “readings memory buffer” to the “shared memory buffer” is of 122 μ s and 244 μ s respectively.

Overall, at the maximum overload, the driver spends a minimum time of 549 μ s and a maximum of 702 μ s to accomplish all the tasks. This timeframe window is very important and reflects the impact of real-time constraints (configuration of priority task scheduling) on a non-real time operative system. The access time of the userspace application to the “shared memory buffer” was of about 275 μ s. The read/write speed of the SD-card displayed 470 Mbps and took 1.4 ms to save 768 kb (1 second of data). The digital signal processing took about 67 ms to apply the 2nd order recursive band-pass-filter (0,5-40 Hz) to all the 32 signals.

The wireless transmission time to communicate the 768 kb in ad-hoc topology took about 70 ms in comparison to the 300 ms achieved with infra-structure topology (using a router – D-Link™ DIR-655) or 290 ms using an Android™ smartphone in AP mode – Samsung™ Galaxy Note II. Approximately, the data throughput of 11 Mbps in ad-hoc mode, 2,6 Mbps in infra-structure mode through router and 2,7 Mbps in infra-structure mode through smartphone were achieved. The system took an overall time of about 150 ms to access, save, process and transmit an entire 1 second block of EEG data.

The power consumption of the proposed platform was also measured. Acquiring and saving data to an SD-card with WiFi turned off spends about 250 mAh. When the wireless feature is turned on, the consumption increases up to 500 mAh. As expected, the WiFi communication module is the most expensive part. Therefore, two 6600 mAh lithium ion polymer batteries are used to power the proposed platform during 52,8 hours (WiFi off) or 26,4 hours (WiFi on).

B. EEG data Acquisition

EEG signal streaming on PC is accomplished through a.NET framework application that was developed in C# programming language (Fig. 4). The opensource ZedGraph library was also used for signal plotting [19]. This library allows the configuration of virtually all plot parameters and is based on a UserControl structure. The developed application provides a TCP-IP socket server that establishes a connection to the client on a selected port.

Once the connection is established and the data transmitted, the application begins to plot the signals in a graphical window. The developed application also provides online digital filtering and Fast Fourier Transform application. It provides the configuration of the number of channels to be displayed and the ability to save data into a file. Two classes were created in order to implement digital filters and Fourier Transform.

Based on the 2nd order Butterworth topology, digital filters can be configured in band-pass, low-pass and high-pass mode. In which regards Fourier Transform, a class was created in order to display the power spectrum of the transformed signals. A set of EEG signals was acquired according to 2 different well-known conditions: alpha wave replacement and clenching jaw artifact. In Fig. 4, a square wave test signal is applied on the 32 acquisition channels.



Fig. 4: PC Software developed for display of data streaming.

EEG recordings were evaluated through a alfa-wave replacement phenomenon [20]. The alpha rhythm appears on occipital regions of the scalp when the eyes are closed, and disappears when the eyes are opened [20]. In this experiment, two bipolar dry electrodes were selected on the scalp of the subject, on the Cz and O1 positions, forming an EEG channel (Fig. 5). As it can be seen on Fig. 5, the platform acquired the two ocular events (opening and closing the eyes), and the alpha wave between them.

Besides alpha rhythm and ocular artifacts, facial muscular artifacts (e.g. chewing movement) are often present as EEG sources of interference. In Fig. 6, a clenching jaw artifact was detected. In order to measure the input noise of the system, the ADS1299 differential inputs were short-circuited and a noise amplitude of about 3.1 μ Vpp was measured.

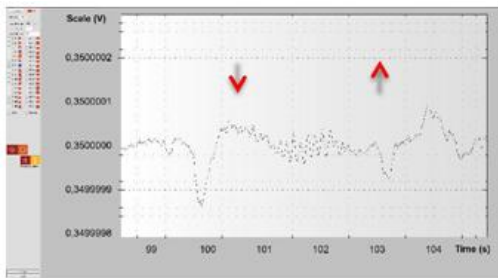


Fig. 5: Alfa rhythm during the eyes-closed and eyes-open conditions.

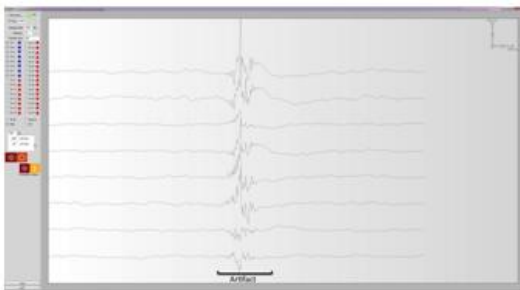


Fig. 6: Clenching jaw artifact.

C. Comparison With State-of-The-Art Platforms

Other studies have been applying different wireless communication protocols (Table 1) [5, 9-13]. These systems provide 16 channels or less, typically less than 24 bits resolution per channel and sampling frequencies of less than 1000 SPS. Additionally, these systems can rarely operate with the maximum number of channels and the maximum sampling frequency simultaneously, since the highest number of channels usually implies a lower sampling frequency, in compliance with the available transmission bandwidth. Usually platforms use microcontrollers (ARM cortex M3 [13], or proprietary architectures such as MSP430 or Atmega [10-12]) with low clock speed and low power consumption [5, 9-11, 13]. Although ambulatory systems should have low power consumption, the computational requirements for local data processing (such as digital signal processing and decision making algorithms) should meet a high processing power feature. Clocks at low frequency (from 16 MHz to 168 MHz) spend most of their processing time on reading and transmitting data.

The wireless modules used on these platforms communicate through Serial UART or SPI. The baud-rate of serial UART interface modules is usually limited to 115200 bps. SPI interface modules often provide shorter memory buffers than the transmission requirements of the proposed platform. The implications of inadequate clock and interface transmission speed constitute major limitations for EEG acquisition platforms with high resolution, sampling frequency and number of channels.

**TABLE I
SPECIFICATION COMPARISON
BETWEEN STATE-OF-THE-ART EEG
PLATFORMS AND THE PROPOSED
PLATFORM**

Platform	Proposed Platform	Bonma et al [5]	Bojarski et al [9]	Duan et al [10]	Miyang et al [11]	Liu et al [12]	Liu et al [13]	Proposed System [14]
Number of Channels	32	8	8	8	16	4	3	8
Sampling Frequency (Hz)	256-1000	190-1800	100-400	250-500	512	250	256	256
Resolution (bits)	16-24	11	11	16-24	24	8	11	16
Electrode Type	Active dry	Passive dry	Ag/AgCl adhesive	Ag/AgCl adhesive	Wet gel	Passive dry	Passive dry	Wet gel
Communication Technology	WiFi	Standa 2.4 GHz	ZigBee IEEE 802.15.4	Radio-Frequency Transceiver	WiFi IEEE 802.11 g	Bluetooth	Bluetooth	2.4 to 2.8 GHz IEEE 802.11g
Platform Technology	COTS	ASIC	COTS	COTS	COTS	COTS	COTS	-
Processor	STM32F103	MSP430	ATmega1280	ARM11763	STM32F103	ARM11763	ARM11763	-
Clock Frequency	1.0MHz	1.8MHz	1.8MHz	100MHz	72MHz	100MHz	100MHz	-
Power Consumption	100mA	4.3mA	100mA	22mA	80mA	400mA	12mA	40mA
Power Consumption (transmission)	0.2mA/50	17mA/50	0.7mA/50	0.1mA/50	0.01mA/50	0.01mA/50	0.01mA/50	0.01mA/50
OS	Linux	-	-	-	-	-	-	-
OS (kernel)	Linux	-	-	-	-	-	-	-
OS (user space)	Linux	-	-	-	-	-	-	-
OS (kernel)	Linux	-	-	-	-	-	-	-
OS (user space)	Linux	-	-	-	-	-	-	-
OS (kernel)	Linux	-	-	-	-	-	-	-
OS (user space)	Linux	-	-	-	-	-	-	-

Multitask Preemptive OS architecture is another critical feature of the proposed platform, considering the proposed functionality: to read data from 32 channels; save it to the storage unit; submit data to a decision making algorithm; and transmit either data or decisions wirelessly. The OS' multitasking feature, can accomplish all the processes with a more optimized time sharing task management [21]. Despite Preemptive Multitasking architecture is well suited to time consuming applications, the data sampling must be accomplished with highly precise frequency. For that purpose, the developed kernel driver and SPI kernel driver scheduling priorities had to be reprogrammed to real-time mode. In this new arrangement, the data readings had always maximum priority in the time-sharing of kernel task management, leaving the rest of the time available for the other purposes such as data processing, saving and transmission.

In comparison to other systems previously reported and presented in Table 1 [5, 9-11, 13], the proposed system consumes more power, due to the implementation of a more expensive communication protocol. Although other platforms consume less energy, they also provide fewer channels, less signal resolution and lower sampling rates, which renders in a data package much smaller than the data package transmitted by the proposed platform. The features of high channel density, high signal resolution, high sampling rate and high processing features required for clinical applications such as epilepsy monitoring and sleep studies motivated the selection of an 802.11 g communications infrastructure, even when considering the power consumption limitations. In order to fairly compare these different platforms, considering their different technological approaches, the power consumption per bit transmitted should be assessed.

The developed platform presents one of the lowest power consumptions (0,2 nA/bit). The possibility to locally process data through an event detection algorithm is also a new feature from this platform, because most platforms depend on another processing unit (like a PC or mobile phone) to process data in real-time [5, 9-11, 13]. Lin et al [14] adopted a different approach, by using two processors, one for real-time signal's acquisition, that transmits data through Bluetooth to a second processor that receives the data and detects drowsiness states. Although this platform is presented as local processing data unit, it replaces the usual external processor (e.g. PC) by a less powerful microprocessor couple to the acquisition processor.

In studies of epilepsy or sleeping disorders, a high number of channels, high resolution (at least 16 bits) and high sampling rates (at least 1000 SPS) are often required [2, 6]. In applications such as long-term monitoring of epileptic patients, the EEG acquisition platform must read the EEG data for periods as long as 24 hours continuously.

Since long-term monitoring produces large amounts of data in streaming mode, an event detection algorithm is mandatory. The transmission of selected EEG segments with identified epileptic-like activity allows the reduction of bandwidth and power consumption requirements (the details of the event detection algorithm will be published elsewhere). Considering that the frequency of epileptic events is variable among subjects, it may be variable from day-to-day for each subject and the events are usually sparse and may last from few seconds to 5-6 minutes [20], the overall power consumption in a real-life scenario, in event detection operation mode, will likely be lower than the consumption presented herein, since the WiFi transmitter will be in sleeping state for long periods.

In other applications such as neurofeedback, neuromarketing or lower channel density, sampling resolution are required which enables the proposed platform to use Bluetooth transmission protocol instead of WiFi for data streaming and thus, to decrease the power consumption from 500 mAh to 200 mAh. Finally, the results showed that the proposed system seems to be feasible and able to satisfy the initially established requirements of a wireless and wearable EEG acquisition platform for ambulatory monitoring.

IV. CONCLUSION

The proposed system incorporates 32 dry electrodes, Linux™ embedded kernel and userspace programming and wireless transmission techniques.

The platform is based on a single core ARM microprocessor that interfaces with 4 sigma-delta ADCs with 24 bits resolution and 1 kSPS sampling rate. Once the data arrives to the processing unit, it is saved in SD-card, processed through an event detection algorithm and sent by 802.11g TCP/IP-socket protocol with minimum delay. Although the proposed monitoring system shows a higher power consumption in data streaming mode when compared to others already reported, it also provides higher channel density with more signal resolution and state-

of-the-art sampling rate, which establishes an interesting tradeoff between power consumption and system flexibility. Beyond all the novel characteristics above, the system has also the ability to operate in event detection mode by processing data in real-time with an event detection algorithm. The development of monitoring platforms, such as the one proposed, challenges the traditional usage of microcontrollers to interface with the ADCs and implement low level hardware operations. Currently, the powerful ARM processors running embedded operating systems can be programmed with real-time constraints at the kernel level to control hardware, while maintaining their parallel processing abilities in high level software applications for event detection algorithms. The proposed platform seems able to efficiently monitor epileptic patients both in inpatient and outpatient ambulatory setups.

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