Beyin-Bilgisayar Arayüzü Uygulamaları için Düşük Maliyetli Taşınabilir 4 Kanallı Kablosuz EEG Veri Toplama Sistemi

Low-Cost Portable 4-Channel Wireless EEG Data Acquisition System for BCI Applications

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***Özetçe*— Bu çalışmada, beyin-bilgisayar arayüzü (BBA) uygulamaları için düşük maliyetli taşınabilir 4 kanallı kablosuz elektroensefalografi (EEG) veri toplama sistemi geliştirilmiştir. Mevcut düşük maliyetli sistemler çoğunlukla düşük örnekleme hızları ile EEG kaydı ve izlemesi yapmaktadır ancak ileri sinyal işleme ve sinyal ortalama için yüksek örnekleme hızları gerekmektedir. Bu çalışmada, her kanal için 2000 örnek/s maksimum örnekleme hızı elde edilmiştir. Önerilen tasarım, veri toplama donanımı ve uzak alıcı modüllerinden oluşmaktadır. Veri toplama donanımı EEG sinyalini yükseltip sayısallaştırmakta ve ve kablosuz bir şekilde aktarmaktadır. Uzak alıcı ise bu veriyi toplamakta ve aynı zamanda gerçek zamanlı olarak bir bilgisayar ekranında görüntülemektedir. Tüm sistem 6.6 sm x 4.9 sm PCB üzerine monte edilmiş ve başarıyla üç farklı deneyle test edilmiştir: (i) elektrokardiyografi (EKG) kaydı (ii) alfa bandını (8-12 Hz) gözlemlemek için gözler kapalı bir şekilde EEG kaydı ve (iii) durağan-hal görsel uyarılmış potansiyel (DHGUP) gözlemlemek için bir başka EEG kaydı. Sisteme görsel uyaran donanımı ve tetikleme-işaretleme kanalı ilavesi için çalışmalara devam edilmektedir.**

Anahtar Kelimeler — EEG Veri Toplama Sistemi; Beyin-Bilgisayar Arayüzü; BBA; Kablosuz İzleme, Durağan-Hal Görsel Uyarılmış Potansitel; DHGUP; EKG.

***Abstract*— This paper puts forward a low-cost portable 4-channel wireless Electroencephalography (EEG) Acquisition system for brain-computer interface (BCI) applications. Available low-cost systems mostly aim at monitoring EEG at low sampling rates whereas higher data rates are needed for advanced processing such as signal averaging. In this study, 4-channel EEG acquisition system was developed, with maximum achievable sampling rate of 2000 samples/s for each channel is achieved. The proposed design consists of Data Acquisition (DAQ) hardware and remote receiver module. DAQ hardware amplifies and digitizes EEG and transmits it wirelessly. Remote receiver receives the data and displays the trend in real-time on computer screen. Whole system is mounted on a 6.6 cm x 4.9 cm PCB and is successfully tested in three different experiments: (i) Electrocardiography, (ECG) recording, (ii) EEG recording, with eyes closed, to observe alpha band (8-12 Hz), and (iii) EEG recording, to observe Steady State Visually Evoked Potential (SSVEP) responses. Further studies will involve addition of visual stimuli hardware and trigger-marking channel.**

Keywords — EEG Acquisition System; Brain-Computer Interface; BCI; Wireless Monitoring, Steady-State Visual Evoked Potential; SSVEP; ECG.

I. Introduction

Electroencephalography (EEG) based brain-computer interfaces (BCIs), due to their non-invasive, portable and temporal resolution properties, are widely used in the field of neural engineering [1]. BCI technology allows for making use of the brain signals, generated as a result of certain stimulus, and estimate the user's intent. Some common applications of such BCI systems include: controlling a computer cursor, real-time drowsiness detection system for drivers, recognizing the user's mental states and measuring attention levels based on the electrophysiological signals [2-5]. For such applications, portable low-cost systems are needed. Most of the low-cost systems at hand, monitor EEG signals at low sampling rates while for sophisticated handling, such as signal averaging, higher data rates are needed.

Among various BCI paradigms [6], visual evoked potential (VEP) based BCIs have received increased interest in recent years [7]. VEP based BCI systems have interface to the stimulus hardware along with the data acquisition (DAQ) and classification subsystems. A trigger-marker channel is used in addition so that averaging and other off-line processes can be done on the EEG. Features such as trigger-marker channel and high sampling rate are needed for a BCI system which use advanced paradigms such as steady-state visual evoked potential (SSVEP), code-modulated visual evoked potential (c-VEP) etc. We are specifically aiming at developing a hardware which will

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serve as a DAQ base and could be incorporated in a portable and advanced BCI system.

To this end, we have proposed a system, consisting of DAQ hardware, which collects EEG signals, digitizes, and transmits them through direct Wi-Fi link to the remote receiver. High resolution EEG chip (ADS-1299), on DAQ hardware allows detecting signals below 10 µV, making it an appropriate device for wireless health-monitoring systems. The portability and affordability of the system makes it more suitable for the practical use in research activities.

II. System Architecture

The basic scheme of our proposed design is presented in Fig.1.

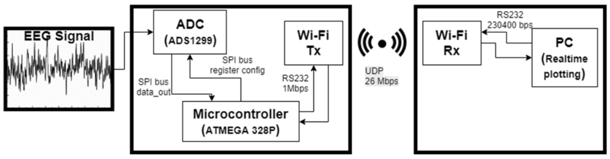

Figure. 1. Basic Scheme for Low-Cost 4-Channel EEG Acquisition System.

DAQ hardware has four subcomponents mounted on it, EEG amplifier, logic level shifter, µController and Wi-Fi Tx module. Signal from brain/source is fed to EEG chip after passing through a low pass filter with cut-off frequency of 72 kHz. Next, on-board microcontroller receives the data output by ADC module and sends it to the Wi-Fi Tx after passing it through the logic level shifter. Remote receiver consists of Wi-Fi Rx module attached to PC. After receiving the data of Wi-Fi Rx, the developed application on PC displays the data in real time. Moreover, data is simultaneously stored in a text file which can later be used for offline processing.

A. Data Acquisition (DAQ) Hardware

As previously mentioned, DAQ hardware consists of four different modules: EEG chip, µController, logic level shifter and Wi-Fi transmitter. The main component mounted on the DAQ is a 4-channel Texas Instrument's EEG chip ADS1299-4. It is a 24-bit, simultaneous-sampling delta-sigma (ΔΣ) analog-to-digital converter (ADC) with a built-in programmable gain amplifier (PGA), internal reference, and an onboard oscillator. It can operate at data rates from 250 samples/sec to 16000 samples/sec. It incorporates all commonly-required features for EEG and ECG applications. This EEG chip requires three different DC power supplies (-2.5V, 2.5V and 3.3V). On the designed Printed Circuit Board (PCB), input signal from electrodes is passed through a low pass filter and fed directly to EEG chip. Then microcontroller (ATMega328-P AU) receives the data from EEG chip via Serial Peripheral Interface (SPI) protocol at a clock rate of 8 MHz. The data sheet of ADS 1299 defines the protocol for 8 channel data out and for the 4 channel ADS chip, which we have used in our design, the format is same except the number of output bits is reduced by half. The software uploaded on microcontroller is taken from OpenBCI (an open source platform [8]), which also utilizes the same EEG chip (ADS1299), and is modified according to the need of our hardware. The detailed data output protocol is described in Fig.2.

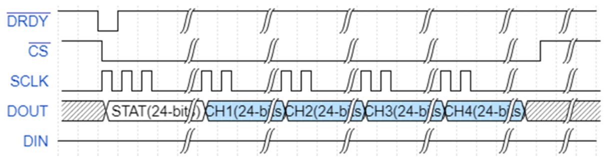

Figure. 2. SPI Bus Data Output Protocol from ADS-1299. [9]

SPI Interface of the ADS1299 has Chip Select ($\overline{CS}$) pin and Data Ready ($\overline{DRDY}$) pin functioning independently. $\overline{DRDY}$ goes high when data conversions are started and goes low when data is ready [9]. µController continuously monitors the $\overline{DRDY}$ pin and on the falling edge of $\overline{DRDY}$, µcontroller pulls down the $\overline{CS}$ pin to start the SPI communication between µcontroller and EEG chip [9]. Each time $\overline{DRDY}$ goes low, the µcontroller starts generating an 8MHz SCLK signal, as shown in Fig.2, and the device then clocks out the data on rising edge of SCLK, MSB first [9].

First, all the acquired data is stored on the internal memory of µController and then $\overline{CS}$ pin is pulled high to stop SPI communication until the next sample arrives. Secondly, data is sent to Wi-Fi Tx module via RS232 protocol at a baud rate of 1 Mbps. Experimentally, we found that ATMega328 takes about 0.1ms to transmit the data serially to Wi-Fi Tx. Wi-Fi module works on 3.3 V whereas our µController uses 5.0 V. We use logic level shifter (SN74LVCC3245ADW) between µController and Wi-Fi Tx that scales the voltages from 5V to 3.3V. An Arduino compatible ESP8266 Wi-Fi module is used as Wi-Fi Tx module. ADS1299 EEG chip outputs 3 bytes for each sample from one channel, so in total we receive 12 bytes for 4 channels which we refer to as a single-sample-dataset (SD). As soon as data reaches the Wi-Fi Tx module, this module stores the data in the internal memory and waits for the next SD coming from microcontroller. This loop works till the number of bytes stored in the buffer becomes 80 SDs which is 960 bytes. Wi-Fi Tx transmits this large-sized packet containing 80 SDs via UDP. Wireless transmission rate is about 26 Mbps with UDP transmission and for 80 SDs it takes about 0.3 ms to 0.5 ms. The maximum packet size is limited by the buffer size of Wi-Fi Tx module, which is 1440 bytes. Packet size of 960 bytes will set the data refresh rate at the receiving side to 25Hz for 2000 samples/sec and to 12.5 Hz for 1000 samples/sec. These refresh rates are acceptable for real time display of the signals. Moreover, if needed, using 400 bytes as our buffer size, at 2000 sampling rate, we can achieve the refresh rate of 60 Hz. Dimensions of the DAQ PCB are 6.6 cm x 4.9 cm and is shown in Fig.3. Our PCB requires 7.4V DC power supply; we have used Li-ion battery of 7.4V with 2200 mAh capacity. The

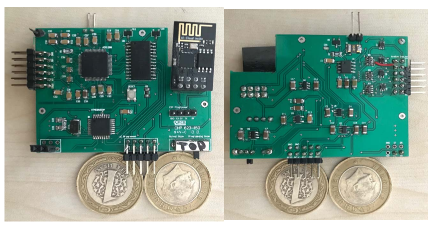

Figure. 3. Four Channel DAQ PCB.

current ratings are: 110 mA-140 mA while Wi-Fi transmission takes place. Otherwise, without Wi-Fi it takes 20 mA.

B. Remote Receiver System

The remote receiver system consists of Wi-Fi receiver and PC. NODE MCU 1.0 is used as a Wi-Fi module on the receiver system. Both the Wi-Fi modules, ESP8266 and NODE MCU 1.0 have built-in UDP and TCP stacks which makes it easier to program them. Wi-Fi receiver stores the packet in the internal memory of its internal µcontroller. At the availability of serial port from PC, this µController transmits the data via RS232 at a baud rate of 230400 bps. Dimensions of NODE MCU 1.0 are 5.6 cm x 3 cm and the module is USB powered.

An application is developed on the computer that plots the data in real-time and stores the samples in a text file for offline processing. On start-up, it sends a dollar '$' sign all the way back to µController (ATMega-328) and signal the DAQ hardware to start transmitting. This allows the user to control the DAQ hardware and synchronizes the communication between the DAQ hardware and remote receiver system. Node µController of the Wi-Fi receiver, transmits the data serially to the PC where it is stored and also is passed through the moving average filter in order to remove any DC offset before it is displayed in real-time. This is needed because the ADS chip does not have a built-in high-pass (HP) filter and it uses low amount of amplification not to saturate its amplifiers (at most a gain of 24). However, the online HP filter mentioned here is needed not to saturate the screen display. The application plots the data in a sliding-scroll mode and the screen updates every 40 ms.

III. Results and Discussion

DAQ hardware was successfully implemented and mounting of components, including EEG Chip, was done manually in our lab. Major components in our design are: ADS1299-4 ($30) [9], ATMega328-P, SN74LVCC3245ADW, ESP8266, NODE MCU 1.0 and voltage regulators/capacitors/resistors. Including the PCB manufacturing cost of $40 the total price for single system added up to $98. Our DAQ hardware is 4-channel which can be easily upgraded to 8-channel by replacing the ADS1299-4 with ADS1299-8 and it will increase the cost by $20.

Our design was first tested with synthetic data from the signal generator (SRS-DS345). Signal was fed to all the four channels and to test the low amplitude signals we used voltage divider before feeding it to the DAQ hardware. Fig.4 shows the real-time DAQ of 10 mVp sinusoidal inputs and the system was tested for the amplitudes as low as 5 µV. In Fig.4, we can see that DC offset is eliminated from all the channels in real-time. We have also tested the system with square and saw-tooth waveforms and observed that samples are not missed.

We designed three experiments to ensure that the system performs ECG and EEG DAQ with the sampling rate of 2000 samples/sec. For all of the three experiments, we did an offline analysis on the recorded data using MATLAB. Using 1-35 Hz off-line band-pass (BP) filter, we removed the low frequency and mains interference.

First, using wet passive electrodes we recorded ECG for 30 seconds. Three electrodes were used, two on the right and left shoulders and the reference electrode was connected to the left

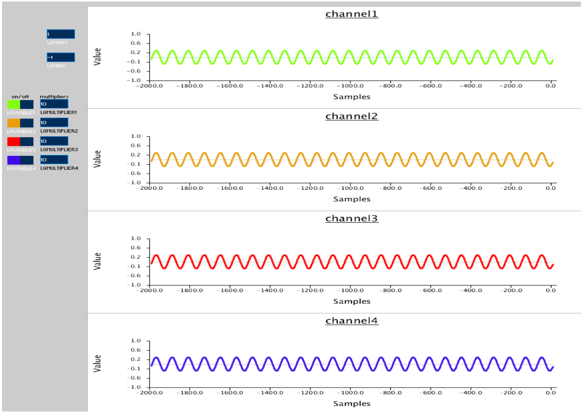

Figure. 4. Real time recording of sinusoid wave at 1000 samples/s sampling rate. Waveform generator was used to feed the signal of 30 mVp and 12.5 Hz. Note the reference in this case was connected to the PCB ground.

leg. Fig.5 shows the recorded raw ECG signal and the filtered ECG signal from channel 3. We obtained satisfying results and in Fig.5 we can see all the waves (PQRST) in ECG signal and raw ECG shows the 50 Hz interference which is not significant to affect our signal. Since the system is isolated and powered by DC battery the 50 Hz interference is minimal which is further eliminated in off-line processing.

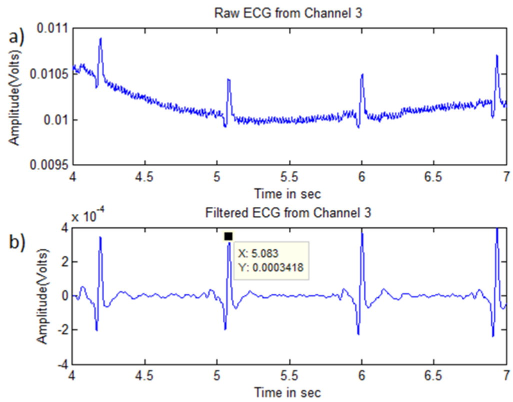

Figure. 5. ECG recordings obtained from channel 3. (a) Raw ECG data. (b) 1-35 Hz Band-pass filtered ECG data. Here, the graphs only show the data between 4th and 7th seconds of 30 seconds recording.

For the EEG experiments OpenBCI's cyton headset along with the dry electrodes were used. The EEG was recorded from electrode sites that corresponded to O1, Oz, and O2. Fig.6 shows the setup for EEG experiments.

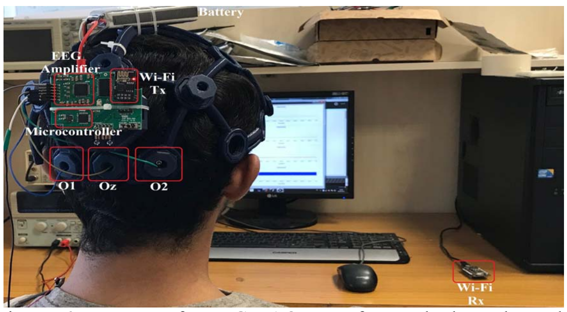

Figure. 6. Test setup for EEG DAQ. Data from only three electrode sites: O1, Oz and O2 was acquired.

In the second experiment, we have tried to observe a robust and a well-known EEG component, the alpha band (8-12 Hz). For this purpose, we asked the subject to close his/her eyes and recorded corresponding brain activity for 15 seconds from the occipital lobe where the brain signals in alpha band are strongly observed [10]. Fig. 7 shows EEG signal recorded from channel 1 and its power spectral density estimation. As it can be seen from the Fig. 7, there are clear high-valued components in the 8-12 Hz band in the spectrum which corresponds to alpha band.

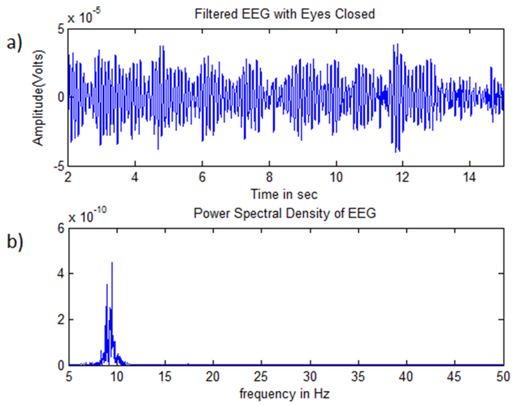

Figure. 7. EEG recordings obtained from channel 1. (a) 1-35 Hz Band-pass filtered EEG data. (b) Power spectral density estimation showing the greater peaks in the alpha band (8-12 Hz). Reference in this case was connected to the left earlobe. Here, the graphs only show the data for 2nd and 15th seconds of 17 seconds recording.

Among the BCI paradigms, steady state visually evoked potential (SSVEP) is the easiest to record and observe. In the third experiment we have recorded SSVEP responses for 15 seconds using different frequencies. As a light source we used a crude setup, an Android application called StrobeLight, which generates the flash with varying frequencies. Since we are not using a trigger-marker channel as yet, we process the recorded signals after the two seconds of the first flash. Fig. 8, shows EEG signal recorded from channel 1 for 16 Hz flash rate. For 16 Hz experiment, we can see the harmonic frequency at 32 Hz. The spectrum clearly depicts a component at exactly the same frequency as the applied stimulus.

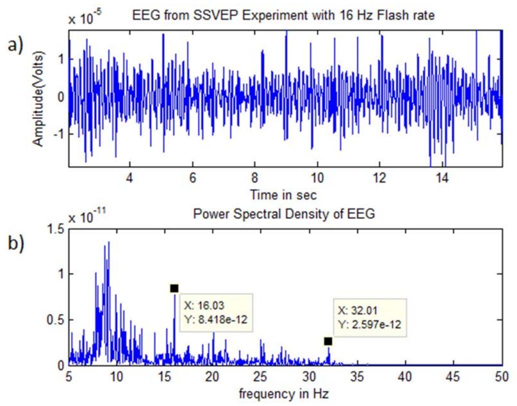

Figure. 8. EEG recordings (a) 1-35 Hz Band-pass filtered EEG data. (b) Power spectral density estimation showing the peak at the 16 Hz and its harmonic peak at 32. Here, the graphs only show the data for 2nd and 15th seconds of 17 seconds recording.

IV. Conclusion

The proposed design of real-time wireless EEG DAQ system was succesfully implemented and tested in lab. Due to small size of the DAQ hardware, it can be embedded into a headset or the locally available headcaps for recording EEG. DAQ hardware transmits the data using Wi-Fi module to the remote receiver. Remote receiver displays the data in real-time and records the text file which can be used for off-line processing. The hardware is lightwetight, portable and gives about 10 hours of runtime by using a 2200 mAh Li-Ion battery. This design can be used as a subsystem, data acquiring unit, for different BCI applications. Our 4-channel system can be easily upgraded to 8-channel without increasing the production cost. Moreover, we can use one of the channels for the trigger-marker purposes, which will make the averaging possible. We tested our hardware by acquiring ECG and different EEG recordings. The EEG module is now ready to be incorporated in a full-blown BCI system. To this end, work in near future will cover a portable and isolated visual stimulus module, an isolated stimulus-marker facility and software for classification and decision making.

Acknowledgement

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