Design and Validation of a Wearable "DRL-less" EEG using a Novel Fully-Reconfigurable Architecture

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***Abstract*— The conventional EEG system consists of a driven-right-leg (DRL) circuit, which prohibits modularization of the system. We propose a Lego-like connectable fully reconfigurable architecture of wearable EEG that can be easily customized and deployed at naturalistic settings for collecting neurological data. We have designed a novel Analog Front End (AFE) that eliminates the need for DRL while maintaining a comparable signal quality of EEG. We have prototyped this AFE for a single channel EEG, referred to as Smart Sensing Node (SSN), that senses brain signals and sends it to a Command Control Node (CCN) via an I^2C bus. The AFE of each SSN (referential-montage) consists of an off-the-shelf instrumentation amplifier (gain=26), an active notch filter (f_c = 60Hz), 2nd-order active Butterworth low-pass filter followed by a passive low pass filter (f_c = 47.5 Hz, gain = 1.61) and a passive high pass filter (f_c = 0.16 Hz, gain = 0.83). The filtered signals are digitized using a low-power microcontroller (MSP430F5528) with a 12-bit ADC at 512 sps, and transmitted to the CCN every 1 s at a bus rate of 100 kbps. The CCN can further transmit this data wirelessly using Bluetooth to the paired computer at a baud rate of 115.2 kbps. We have compared temporal and frequency-domain EEG signals of our system with a research-grade EEG. Results show that the proposed reconfigurable EEG captures comparable signals, and is thus promising for practical routine neurological monitoring in non-clinical settings where a flexible number of EEG channels are needed.**

I. Introduction

EEG is a non-invasive technology for recording continuous neurological data at natural environments. EEG sensors being ambulatory and lightweight can be comfortably donned for sensing brain activities unobtrusively. There have been many studies in the literature on designing wireless EEG measurement tools using commercial-off-the-shelf (COTS) components and custom-fabricating ICs [1-3]. However, there is no report on designing a modular EEG device in which sensors can be connected in a Lego-like fashion. Such modular devices are significantly important especially for monitoring patients with neurological disorders (e.g., Autism Spectrum Disorder, Alzheimer, and Epilepsy) and in emergency care conditions where the locations of EEG sensor electrodes need to suit the individual's need.

This work was partially supported by FedEx Institute of Technology Innovation Grant, Grant Number: 2013-537908.

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Conventional EEG systems can not be modularized at the sensor level because most systems are based on the driven-right-leg (DRL) circuit. The rationale of DRL circuit is to minimize the common-mode and power-line interference while data acquisition [4]. In this study, we propose a novel analog front end (AFE) design for EEG systems which will not need DRL while maintaining comparable EEG signal quality and hence sensor level modularization can be implemented. In the proposed "DRL-less" EEG paradigm, any sensor node can be connected or disconnected from the central node in a modular fashion (Lego-like).

In the conventional EEG systems, sensors are either non-reconfigurable or partially reconfigurable, e.g. Neurosky, B-Alert, Emotiv, etc. [5-7]. These sensors do not have any intelligence and only transfers the raw information. On the other hand, in the proposed EEG system, the sensors are fully-reconfigurable and scalable because each sensor is independent of other. Also, sensors are smart in order to partially process the raw signal. The distributed intelligence in the sensing nodes addresses the challenge of the data payload in this integrated sensing network. In this study, we refer these smart sensors as *Smart Sensing Node* (SSN) whereas, the central node is addressed as *Command Control Node (CCN)*. The role of CCN is to synchronize all the attached SSNs in the network and aggregate their data periodically.

The proposed scalable system is suitable for non-clinical settings with neurological patients.The proposed cost-effective monitoring system with plug-and-play sensors is fast and easy to deploy. It should be noted that this system can also be extended to any physiological sensor like ECG, temperature, pulse oximeter, etc.

II. Hardware System Design

This section gives details of the hardware design of the proposed wearable EEG. The printed-circuit boards (PCB) for the entire system are designed using OrCAD Capture CIS (Cadence Design Sys, Inc.) and populated in the lab settings using surface mount COTS.

A. Smart Sensing Node (SSN)

The objective of the SSN is to digitize the bio-potential on the node. We have custom-designed a 4-layer PCB for single-channel referential montage based EEG. We use a low–noise instrumentation amplifier (INA 118) as the first stage of signal conditioning which amplifies the difference between two channel inputs: Ch1 and Ref (Gain =26). The signal is then notch filtered at f_c = 60 Hz with an active filter before it is passed to an active 2nd-order Butterworth low-pass filter cascaded with a passive low-pass filter for f_c = 47.5 Hz (Gain= 1.61). Further, the signal is high-pass filtered at f_c =0.16 Hz (Gain= 0.83), biased at V_{gnd} (to avoid any static offset in the circuit) and passed through a final amplification stage of the design (Gain=17.5). The theoretical differential gain of the AFE is 608 (55.6 dB). This "DRL-less" AFE design gives qualitatively comparable signals as a DRL-based EEG [8].

We have used AD8607, a dual-channel rail-to-rail input and output operational amplifier in the circuit design because of its low noise (22 nV/√Hz) and high Common Mode Rejection Ratio (CMRR) of 100 dB. The output of AFE is referred to the virtual ground (V_{gnd}) which is the mid-rail of the input voltage, V_{cc} = 3.3 V (i.e., 1.65 V). It should be noted that the SSN does not have any power supply circuit on its node, rather it is powered through the CCN which is connected via an I^{2}C bus through a 6-pin ribbon cable. Fig. 1 depicts the block diagram of the hardware configuration of the SSN. Each EEG SSN is a circular node of diameter 1.29" compared with a quarter coin diameter 0.95".

The analog brain signal is digitized by a 12-bit successive approximation register (SAR) ADC of an ultra-low power MSP430F5528 µC at 512 sps. The SSN starts sampling the signal as soon as it gets a *Start* command from the CCN via I^{2}C bus. DMA controller saves the sampled data in one of the two Mutex buffers (each 1024 bytes) based on their availability. This data is further sent upon request to the CCN through the digital I^{2}C bus at the speed of 100kbps.

B. Reference and V_{gnd} node

To implement the referential montage of EEG, a 4-layer PCB is solely designed to sense the designated reference channel signal. This reference signal is communicated to the other SSN nodes through the I^{2}C bus. In this study, the Ref node is attached on the mastoid of the subject.

In order to avoid any offset in the body, a V_{gnd} potential is separately generated and fed to the body using V_{gnd} node. Its circuit consists of a voltage divider followed by the high input impedance buffer designed with AD8607. The diameter dimensions of the reference and V_{gnd} nodes are 0.91"and 0.95" respectively.

One side of the reference, V_{gnd} and SSN nodes is soldered to the electrode connector so that these nodes can be directly snapped on the EEG electrodes attached to the scalp.

C. Command Control Node (CCN)

In comparison with SSN, the 4-layered PCB for CCN does not contain any signal conditioning unit. Rather, it has an ultra-low power, 16-bit RISC-based MSP430F5659 µC operating at 1 MHz system clock which aggregates data from all the SSNs in the network in a round-robin topology. It also contains a Class-2 Bluetooth module, Li-poly battery, power management circuitry, Tri LED, I^{2}C port connectors and Mini-USB port for charging (see Fig. 2). Apart from collecting data from SSNs, the CNN also synchronizes all attached SSNs every 1 s and sends the available data to UART at a baud rate of 115.2 kbps. At the power reset, CCN firstly scans for the attached SSNs in the network and dynamically allocates memory for each SSN data.

We have used 7-bit addressing mode of I^{2}C bus at 100kbps speed, according to which keeping the required I^{2}C bus capacitance, C_b=400pF into account [9], we can theoretically connect up to 39 SSNs in the network (as each SSN and CCN has C_b = 10pF). However, more SSNs can be included in the architecture by increasing the bus speed to 400 Kbps (maximum by MSP430) and also by using SSNs of sampling rate <512 sps.

D. Graphical user Interface (GUI)

A user interface has been developed for real-time data acquisition in Matlab similar to as mentioned in [8]. The GUI reads the serial port data and thereby saves CCN data in *.mat file for later use. CCN always send a packet of 1025 bytes to the UART, in which 1st byte is the Slave ID followed by 1024 bytes of SSN data. The GUI also checks if any packet is lost and notifies the user by displaying *Packet Missed* on the command window in Matlab.

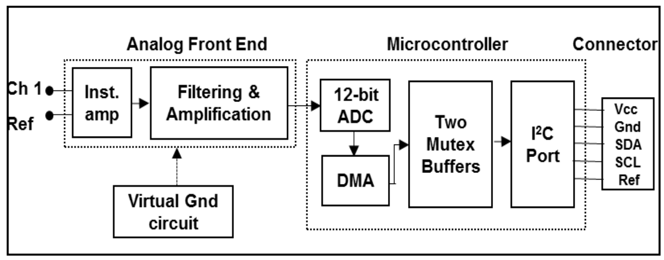

Figure 1. Block diagram of the single-channel "DRL-less" EEG SSN depicting analog and digital elements.

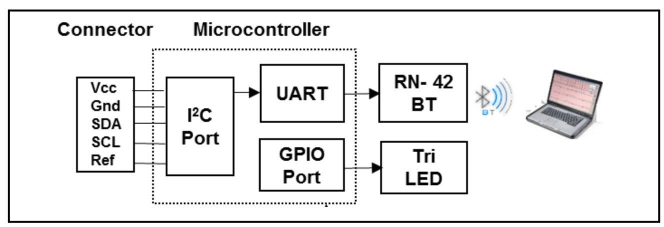

Figure 2. Block diagram of the CCN hardware with its peripherals. CCN is connected with all other nodes of the system using a 6-pin ribbon cable.

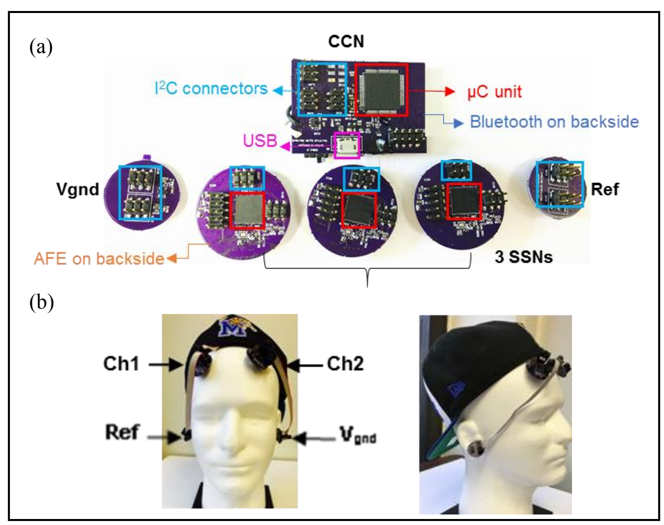

Figure 3. (a) Prototype of the EEG SSN, CCN, V_{gnd} and Reference nodes (b) Nodes deployed on a mannequin head (CCN is concealed in the cap). Channel locations can be decided at the time of deployment.

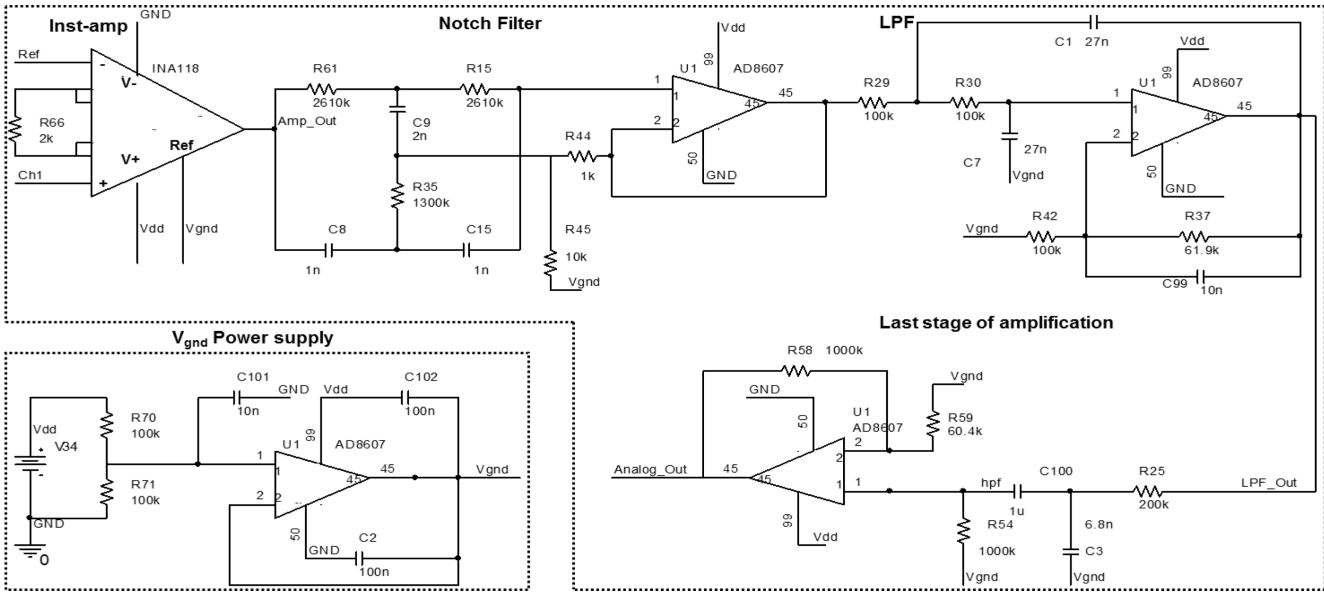

Figure 4. Schematic of DRL-less AFE of EEG SSN depicting signal conditioning circuit including inst-amp , filters and V_{gnd} power supply circuit.

III. System Validation

A. Data acquisition

For EEG data collection with the proposed system, pre-gelled disposable sensors (GS26, Bio-medical Instruments) were used. During data acquisition, active electrodes were placed on AF3 and AF4 frontal lobe locations whereas, Ref and V_{gnd} electrodes were attached to the left and right mastoid respectively. We have compared brain signals of the proposed EEG device with a Neuroscan EEG system which is widely used in medical research applications. The Institutional Review Board of the University of Memphis approved the device safety, usage and protocol for human subjects for this study (No: 2289).

Neuroscan uses SynAmps RT amplifier (Compumedics Neuroscan Ltd.) which has 64 monopolar channels with a low-noise 24-bit ADC, and high CMRR of 110 dB [10]. In this study, we only connected two channels to the amplifier. Ag/AgCl disc electrodes of the Neuroscan were placed side-by-side (<1 cm) to the GS26 electrodes on the frontal and mastoid sites. The skin of the subjects was gently abraded before data collection by rubbing the scalp with the abrasive Nuprep gel (DO Weaver and Co.). Signals were recorded in a magnetically shielded room for 50 s from two subjects at f_s=500 sps while sitting on a chair in the relaxed position. Subjects were asked to avoid any physical movement and were instructed to blink every 5 s during data acquisition.

B. Signal pre-processing and analysis

For one-to-one comparison with the proposed system, signals from Neuroscan were up-sampled at 512 sps and digitally filtered at 0.16-47 Hz using the Curry 7 Neuroimaging suite. As most of the useful information in EEG is band limited to <40 Hz, we further applied a low-pass filter at 40 Hz and notch filter at 60 Hz on both systems' signals in Matlab. To find a correlation between the two time-series in the time-frequency domain, we computed wavelet coherence (WCO) using *wcoher* (in Matlab) as:

$$WCO = \frac{\left|S(P_x^*(a,b)P_y(a,b))\right|^2}{S(\left|P_x(a,b)\right|^2)S(\left|P_y(a,b)\right|^2)} \quad (1)$$

where $P_x(a,b)$ and $P_y(a,b)$ are the continuous wavelet transforms of signals x and y at scale a & position b, S is the smoothing operator in time & scale and superscript * is the complex conjugate.

IV. Experimental Results

The AFE of the custom-designed EEG system has been functionally verified in the lab and in-vitro settings. Some of the technical specifications are tabulated in Table I. Power consumption is also evaluated for this wearable EEG. Independently, CCN consumes an average current of 3.41mA without any SSN, 5.83 mA with 1 SSN, and 11.6 mA with 2 SSNs. Thus, when powered with an 800 mAh Li-poly battery, the system can work continuously up to 69 hrs. with 2 SSNs in the network. Fig. 3 depicts the deployed sensing nodes on the human subject, whereas complete schematic of the AFE for EEG SSN is shown in Fig. 4. Common mode gain of the system at 60 Hz is measured as 0.06 for the test input (refer Fig 5, DC bias is removed). For the measured differential gain of 190 corresponding to a representative $3mV_{p\text{-}p}$ input at 60 Hz, CMRR is obtained as $20\log_{10}(190/0.06)$= 70 dB.

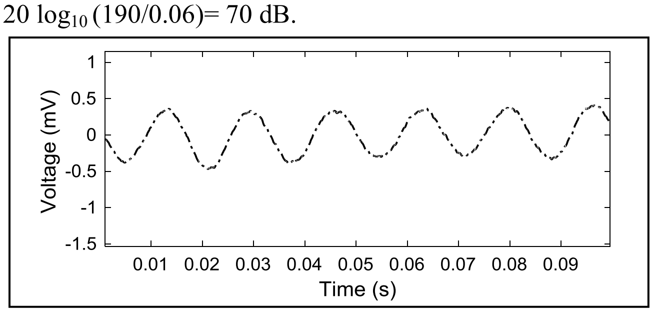

Figure 5. Common-mode response to a test sine input , V_{in}= 100 $mV_{p\text{-}p}$ at 60 Hz (Ch1 and Ref channels were tied together for the measurement).

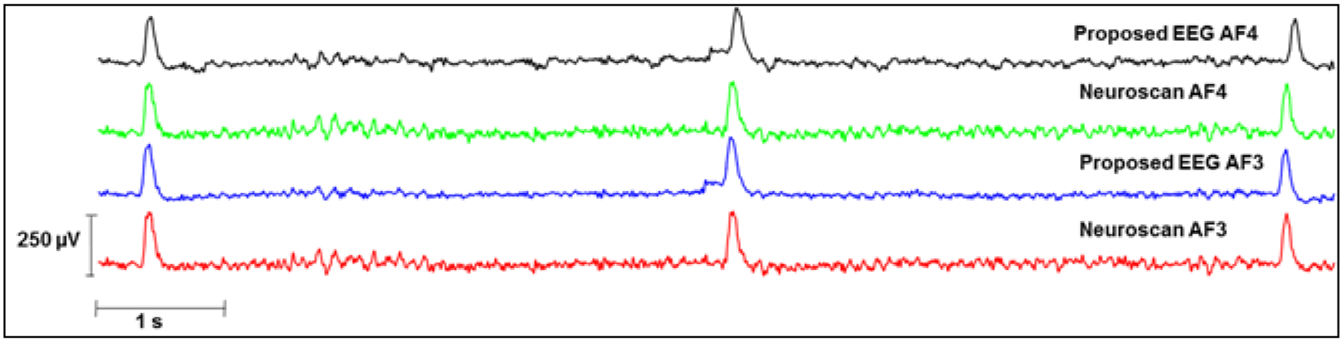

Figure 6. A section of the real-time EEG signal from the Neuroscan and the proposed EEG from AF3 and AF4 locations of Subject 1 for around 10 s.

TABLE I. SPECIFICATIONS OF THE PROPOSED EEG

No. of channels	Flexible (reconfigurable between 1 to 39)
Bandwidth	0.16- 47.5 Hz, notch filter at 60 Hz
Sampling rate	512 sps with 12-bit SAR ADC
Dynamic range	5500 μV_{pp} (input referred)
Linearity	55.20 dB
Common-mode rejection	70 dB (at 60 Hz)

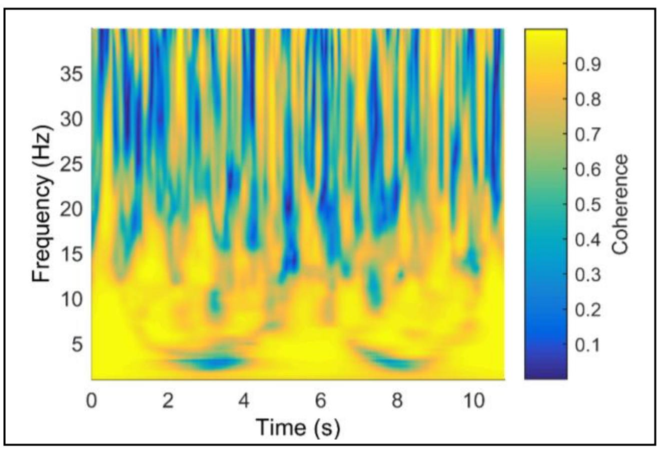

Figure 7. Wavelet coherence measured on EEG signals of two devices from AF3 location of Subject 1.

Signal patterns, as well as sensitivity to eye-blinks of the proposed EEG were found to be very similar to Neuroscan for both subjects/channels. For instance, arbitrary temporal signals of Subject 1 from both devices (AF3 and AF4 channels) for 10s duration are shown in Fig. 6. Eye-blinks in the signals can be observed after every 5 s (as per the protocol). Wavelet coherence measure plotted in Fig. 7 depicts a very high correlation (>0.9) between the signals especially in delta (1-4 Hz), theta (4-7 Hz), alpha (8-13 Hz) and beta (14-20 Hz) bands. These bands are crucial for cognitive load monitoring, attention-related processing, and other BCI applications. There is relatively lesser correlation (up to 0.7) found in high beta (20-30 Hz) band, which might be because of the different analog filtering characteristics of these devices. These results validate the functionality of the proposed "DRL-less" EEG using the novel fully-reconfigurable architecture.

V. CONCLUSION

In this study, we designed and developed prototypes of smart EEG sensing nodes (SSN) using a fully-reconfigurable architecture. In comparison with the conventional EEG systems, the unique AFE of the proposed system does not need DRL circuit and thus allows a flexible number of SSNs to be connected in a Lego-like fashion with the command control node (CCN). Each EEG SSN has a single-channel referential montage based AFE, which samples the brain signals at 512 sps and sends the data to CCN via an I^2C bus at 100 kbps. CCN periodically scans for the attached SSNs, allocates memory if any new SSN is found, aggregates SSNs data and sends the data wirelessly to the paired device at a baud rate of 115.2 kbps. Compared to the existing systems, proposed system is modular, scalable, and can adapt to at least 39 SSNs in the network (in the present set-up) without redesign of the hardware. We further compared EEG signals of the proposed system with a research-graded EEG from AF3 and AF4 locations. Results show that the proposed DRL-less EEG has a potential to be used for unobtrusive neurological monitoring in non-clinical settings.

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