Real-time Multi-channel Seizure Detection and Analysis Hardware

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***Abstract*—This paper presents a low power platform which performs continuous multi-channel detection and analysis of seizures for epilepsy patients. The detection unit, upon detecting a seizure, enables an analysis circuit that locally processes and transmits energy and frequency contents of the EEG data. Transmission traffic reduction of 256x is achieved by locally processing data and transmitting critical information about the EEG rather than transmitting the raw EEG data itself. Multi-channel detection is accomplished by replicating an ultra low-power single-channel detection unit 16 times, each for a distinct EEG channel. These detection units pass their output into a multi-channel detection block that, when multiple channels flag a seizure, enables the analysis circuit. The proposed detection architecture removes all false positives as opposed to the current method, in addition to reducing the detection latency by as much as 16 sec. The platform is implemented in 65 nm CMOS which contains 16 seizure detection modules with a seizure analysis unit and occupies 0.43 mm^2. When simulated at 1.3 V, the seizure detection unit runs continuously and dissipates 0.04 μW at 256 Hz. The analysis unit consumes 0.36 μW at 1.85 KHz when powered on after a seizure detection.**

I. Introduction

About 50 million people worldwide suffer from epilepsy [1], the neurological disorder characterized by seizures. The primary tool for diagnosis of an epileptic seizure is an electroencephalography (EEG) which records the brain's spontaneous electrical activity. This requires the placement of a minimum of 16 electrodes on the scalp with each electrode being interpreted as a channel. Prior work developing low power, low area seizure detection devices is limited to detection using only one channel. For real time detection, the device must be replicated for each channel, which in effect, multiplies the area and power consumption. Additionally, current devices are only capable of detection which limits the usefulness of the device in a non-clinical setting.

In this paper, we propose a portable, low power, low area device that supports 16 channels of EEG inputs and performs post detection seizure analysis. Detection of seizures is accomplished using an ultra low power circuit. To prevent false positives, multiple channels are analyzed to differentiate a seizure from random spikes in brain activitiy. Upon detection of a seizure, the device uses the EEG data to perform seizure analysis. The data is separated into different frequency bands for a neurologist to determine the type and location of the seizure [2]. To reduce power consumption, spectral analysis is only performed after the detection of a seizure. At the conclusion of post-seizure analysis, the results are transmitted to a mobile device for storage. The following sections begin by discussing previous work that leads to the proposed hardware. Then the architecture is described including results. Finally the implemented hardware is described and discussed.

II. Background

As opposed to the randomness of normal brain activity, electrical behavior captured by an EEG exhibits distinct rhythmicity at the onset of an epileptic seizure [3]. However, seizures can occur throughout the brain, so using a single electrode to detect a seizure is insufficient [4]. Figure 1 illustrates high amplitude content in channels 1 and 2 signified by the solid boxes at the beginning of the seizure. At the onset of a seizure, the energy in a particular frequency band dominates the brain activity captured by the EEG. Due to the proximity of the seizure in the brain to the electrodes, only channels 1 and 2 capture the onset of the seizure whereas channels 3 though 6 do not. For this reason in real time detection, multi-channel detection is necessary for ensuring that seizures are detected in all regions of the brain.

Previously proposed algorithms use either temporal [5] or spectral [6] analysis to detect the rhythmic oscillation. The work in [5] suggests detecting a seizure in the time domain when the amplitude crosses a threshold a specified number of times within a set time period. In [6], an FFT is used to convert to the frequency domain and then a bandpass filter is used to isolate a particular frequency band. However, spectral analysis is not commonly used for detection due to the power and area constraints of converting to the frequency domain using an FFT. Power consumption is a particular concern when the device must be powered by a portable source for a minimum of 24 hours. Prior work on seizure analysis focuses on determining the location and classification of the seizure by studying the energy at multiple frequency bands. Multiple channel analysis is used to map an image of a patient's brain activity to determine the location and classifcation of the seizure [2].

III. Proposed Architecture

The proposed hardware supports detection and analysis of epileptic seizures using 16 EEG input channels on a single SoC. The block diagram in Fig. 2 illustrates the connectivity of the SoC to an EEG device. EEG data across the 16 channels are sampled in parallel at 256 Hz using 16 bit ADCs. The data is passed into the 16 respective seizure detection modules.

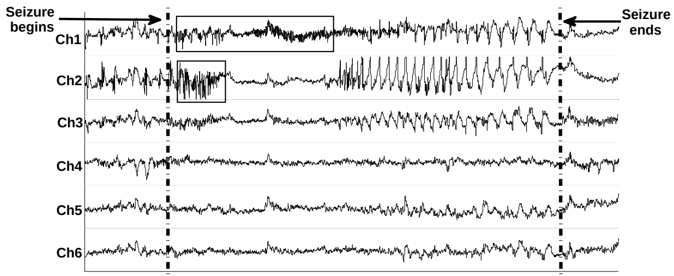


Fig. 1. EEG data on 6 channels. The detectable portion of the seizure, notated by the solid rectangles, only exists in channels 1 and 2. Multiple channel detection is therefore necessary for detecting seizures in all regions of the brain.

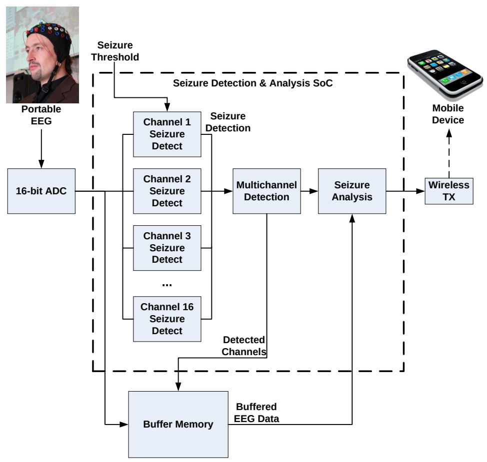


Fig. 2. Proposed multi-channel seizure detection architecture. 16 single channel detection circuits are instantiated and passed to a threshold detector to confirm a seizure. Subsequently, analysis circuitry is enabled. System validation is confirmed using EEG data from the Freiburg Center for Data Analysis and Modeling [7]

In parallel, EEG data is written to a running memory buffer for post-detection signal analysis. To minimize memory, the memory buffer records a running window of the previous 60 seconds which is the maximum calculated delay in detection as depicted in Tab. I. The 16 seizure detection modules are connected to one multi channel detection block to eliminate false positives. When a seizure is detected, the seizure analysis block is powered on to convert data to the frequency domain for spectral analysis. The results are then transmitted wirelessly to a mobile device. The proposed architecture is validated using EEG data from the Freiburg Center for Data Analysis and Modeling [7].

A. Improved Seizure Detection

The proposed seizure detection unit bases itself on a previous design [5] which is attractive both in terms of low power dissipation and small layout area as diagrammed in Fig. 3. In this paper we propose an improvement to the original architecture which suffers from high delay and high false positives. The algorithm assumes that EEG waveforms oscillate about the x-axis when, in fact, there is often a DC offset present. Since DC offset is usually inconsistent

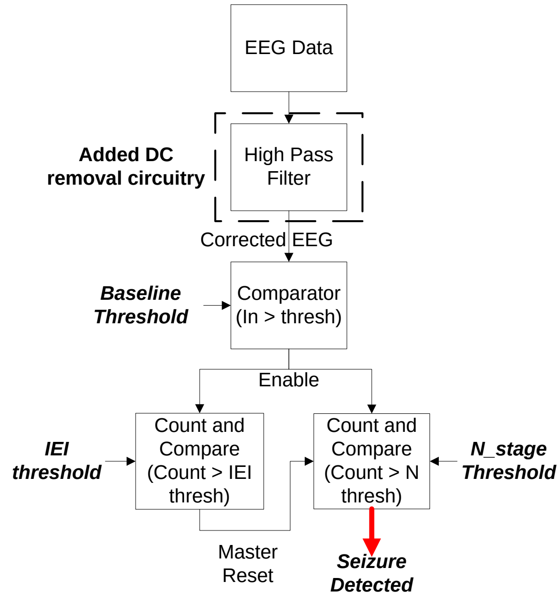


Fig. 3. Proposed single-channel seizure detection algorithm. A 4Hz high-pass filter added to remove DC component from incoming EEG signal. When the filtered EEG data surpasses the *baseline* thereshold *N* times within the *IEI time threshold*, a seizure is detected.

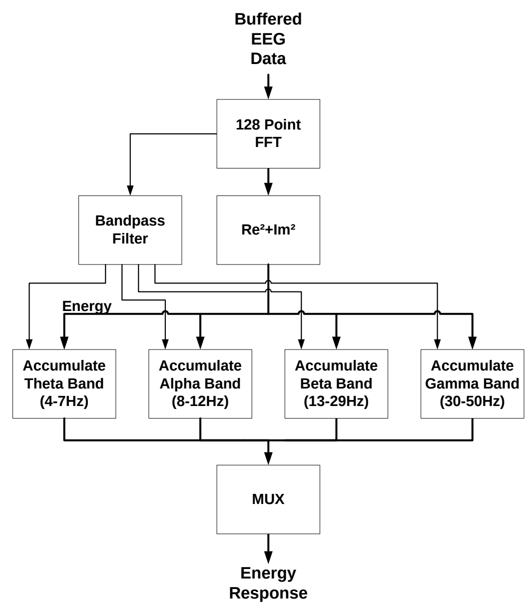


Fig. 4. Block diagram of seizure analysis enabling spectral analysis of the detected seizure

throughout the duration of a test, the additional offset results in detection delays, false positives, or false negatives. Using the original algorithm, the threshold values can be recalibrated, but it results in a tradeoff of delay or accuracy. To rid the EEG of the DC signal, the incoming EEG data is passed through a 4 Hz high pass 21-tap FIR filter. This removes any information located in the band of 0-4 Hz. Seizure detection using the original and the proposed method is shown in Fig. 5(a) and (b), respectively. The EEG data in Fig. 5(a) has a -2000 unit DC offset that interferes with the amplitude threshold, whereas the EEG data in Fig. 5 (b) is void of DC content. This results in a 9.7 second detection delay improvement. The same tests comparing the two algorithms were conducted for other patients with results in Tab. I. In all cases there was an improvement in delay and accuracy.

In order to detect a seizure, the unit must first be tuned specifically for the patient. These parameters include the *baseline* threshold, the *Inter-event-Interval*, or *IEI* threshold, and the *N-stage* threshold [5]. To fine-tune these parameters, seizure EEG data is passed through a 4 Hz high-pass filter and then analyzed. Characteristics of concern while tuning the circuit are amplitude and period. The baseline threshold is set based on the amplitude characteristics during the seizure. The IEI threshold is essentially the maximum allowed time between two amplitude violations; if this time threshold is surpassed, the N-stage counter is reset. The higher the characteristic frequency of the seizure, the lower the IEI threshold can be set to capture the seizure and disregard lower frequencies. The N-stage threshold is chosen based on the duration of the high-frequency seizure activity as opposed to normal activity. For example, high-frequency bursts may occur during normal activity but the N-stage threshold is set high enough to ignore these random bursts. Testing shows that once the circuit is initially tuned, it will detect future seizures within that patient.

B. Multi-Channel Detection

To further reduce the number of false positives, multiple EEG channels are used. The output of the seizure detection modules are connected to a multi channel detection block. When multiple EEG channels locally flag a seizure within a certain time period, a seizure is detected. This is implemented by a threshold detector and a countdown timer–small, low-power hardware. The benefit is that the multi channel block is scalable for more than the currently implemented 16 channels without significantly increasing power consumption. For testing, two channels were required to detect a seizure; when the second channel detects a seizure, the analysis circuit is enabled. Tab. I. shows the results of multi-channel detection for 6 channels of data on five patients–over 120 hours of seizure data for testing. The results illustrate the ability of the multi-channel arcuitecture to remove false positives with respect to the original single-channel unit.

The proposed architecture to reduce false positives is not only to create an accurate seizure detection unit, but to dramatically reduce power consumed by the analysis circuit. The analysis circuit will only be enabled when the number of EEG channels reporting a seizure surpasses that of the threshold in the multi-channel detection block.

C. Seizure Data Analysis

After detection, the seizure data analysis module is powered on to process EEG data for transmission and future analysis by a neurologist or medical specialist as diagrammed in Fig. 4. The module consists of a 128 point FFT sampling every half second and bandpass filters to divide the frequency into four

Patient_{set}	Delay (s)		**% Improvement**	False Pos	
	Orig	Prop		Orig	Prop
1_1	n/a	5.11	∞	55	0
1_2	10.78	4.96	53.8	15	0
1_3	2.60	0.01	99.6	2	0
1_4	4.26	0.73	82.9	25	0
2_1	31.98	15.29	52.2	25	0
2_2	32.35	28.77	11.1	5	0
3_1	57.76	55.60	3.7	2	0
3_2	n/a	44.02	∞	1	0
4_1	n/a	2.30	∞	2	0
4_2	12.64	3.54	72.0	0	0
4_3	9.08	2.88	68.3	0	0
4_4	7.95	7.55	5.0	36	0
4_5	n/a	1.20	∞	4	0
5_1	6.00	3.2	46.7	0	0
5_2	8.40	2.30	72.6	0	0

TABLE I

RESULTS OF ORIGINAL VS. PROPOSED ALGORITHM. WHERE ∞ APPEARS, THIS MEANS THE ORIGINAL ALGORITHM NEVER DETECTED A SEIZURE. FOR THIS SET OF DATA, FALSE POSITIVES WERE ALWAYS ELIMINATED USING THE PROPOSED MULTI-CHANNEL ARCHITECTURE.

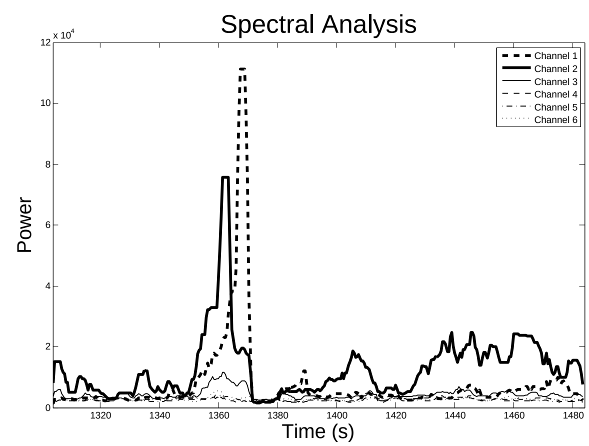
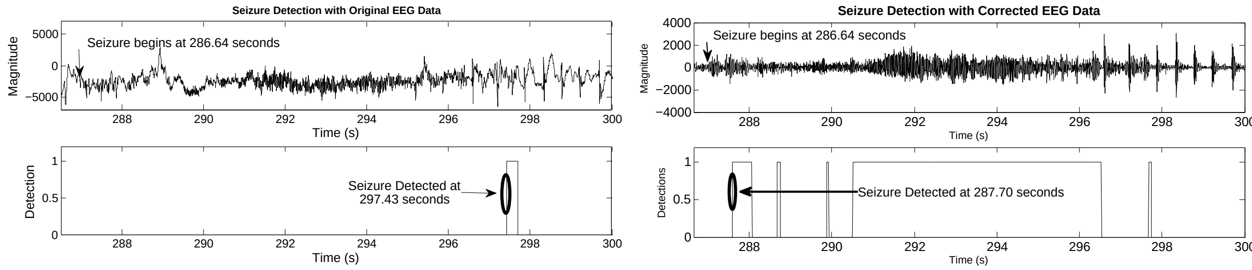


Fig. 6. Spectral Analysis from 30-50Hz frequency band during a seizure beginning at 1,304 seconds until 1,371 seconds. Channels 1 and 2 detect the seizure as evident by the high amplitude. Channels 3 through 6 do not detect the seizure.

bands; Theta band (4-7 Hz), Alpha (8-12 Hz), Beta (13-29 Hz), and Gamma (30-50 Hz). To remove imaginary components, the power is computed from the energy. A 4 point median filter is implemented to reduce random noise. This process is performed serially for all 16 channels in order to ascertain the location of the seizure. To reduce power consumption, only the band with the largest enegy is transmitted. Using the EEG Freiburg data base [7], Fig. 6 plots the spectral analysis over 6 channels over a 180 second period before, during, and after a seizure. The seizure occurs from 1,304 seconds until 1,371 seconds where the seizure is captured by channels 1 and 2.

IV. CMOS IMPLEMENTATION AND RESULTS

The multi-channel seizure detection and analysis platform is implemented in 65 nm CMOS technology with a nominal supply voltage of 1.2 V (max. at 1.3 V). We use a standard-cell RTL to GDSII flow using synthesis and automatic place and



(a) Detection of a seizure using original architecture

(b) Detection of a seizure using proposed architecture

Fig. 5. Detection delay is improved by 9.7s using the proposed architecture. Note the -2000 unit DC offset in the EEG data for the current architecture and the 0 unit DC offset in the EEG data for the proposed architecture.

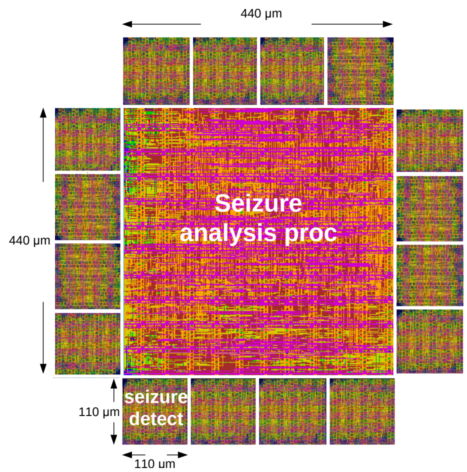


Fig. 7. Post layout view of the proposed multi-channel seizure detection and analysis hardware

	This work	
	Detection	Analysis
Technology	65 nm	
Logic utilization	96%	92%
Area per block (mm^2)	0.01	0.19
Total area (mm^2)	0.43	
Performance (KHz)	0.256	1.85
Power (uW)	0.04	0.36
Current (nA)	2.15	282

TABLE II
IMPLEMENTATION SUMMARY FOR THE PROPOSED MULTI-CHANNEL SEIZURE DETECTION AND ANALYSIS PLATFORM

route. The hardware was developed using Verilog to describe the architecture, synthesized with Synopsys Design Compiler, and placed and routed using Cadence SOC Encounter. The chip layout of the proposed hardware is shown in Fig. 7. Table II summarizes the post-layout results. The chip contains 16 seizure detection blocks with the seizure analysis block in the center. Each seizure detection block occupies 0.012 mm^2 and the seizure analysis block occupies 0.19 mm^2 which results in a total area of 0.43 mm^2. The device dissipates 10.9 nW/KHz for a single channel seizure detection and 198 nW/KHz for seizure analysis of all four frequency bands. Note that the seizure analysis circuit is only powered on when a seizure is detected. Our investigation of patient seizures in [7], indicates that the longest seizure lasts approximately 3 minutes, with a worst case of 5 seizures per day. Thus, assuming the 16 seizure detection blocks run continuously, the device can consume on average 0.04 μW.

V. CONCLUSION

This paper presents the design and implementation of a real time multi-channel seizure detection and analysis hardware. The ultra low power multi-channel detection circuit removes the false positives and seizure detection latency that existed on the original algorithm. In order to detect a seizure, the unit must first be tuned specifically for the patient, once tuned the circuit can detect future seizures for the patient. The seizure analysis operates only upon the detection of seizure and transmits important seizure data such as frequency and energy components of four different frequency bands. This results in transmission traffic reduction of 256x per seizure rather than transmitting raw EEG data. The platform integrates 16 channel seizure detection units and a seizure analysis module. It occupies 0.43 mm^2 and consumes 0.04 μW at 1.3 V and 65 nm CMOS.

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