Trading detection accuracy for battery autonomy in a wearable seizure-detection device

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***Abstract* — Experimental devices aiming at real-time detection and suppression of epileptic-seizure events in live subjects already exist. However, to guarantee high detection accuracy, existing approaches employ high-accuracy detection filters that overlook the incurred energy costs, thus leading to unrealistic solutions for low-power implementations. In this short paper, we capitalize on the approximate nature of the seizure-detection phenomenon and propose an energy-efficient scheme for embedded, seizure-detection devices with trivial impact on detection accuracy. For a 1% reduction in filter detection accuracy we achieve a 3.7x increase in device-battery lifetime.**

Keywords — epilepsy; seizure suppression; wavelet; FIR filter coefficients; energy; battery autonomy; approximate computing

I. Introduction

Absence (*petit mal*) seizures are a common form of epilepsy characterized by brief loss of conscience. While originally focusing on detecting such seizures, several studies have shown the feasibility of closed-loop epilepsy suppression by using electrical or optogenetic stimulation of various parts of the central nervous system [1] [2]. These systems apply stimulation when ictal activity is detected in electroencephalogram (EEG) or electrocorticogram (ECoG) recordings.

Our prior work [3] has demonstrated a wearable (generally, low-power) device that can achieve real-time seizure suppression through electrical or optical stimulation on the brain cortex on live mice, scoring high detection rates at low detection delays (i.e. within 1 sec from seizure onset). The morphology of an ictal event and the suppressing stimulation applied by the device are illustrated in Figure 1(a). The device employs a properly tuned, complex Morlet wavelet filter along with an adaptive-threshold strategy for seizure discrimination. The wavelet is implemented as a Finite-Impulse-Response (FIR) filter the impulse response of which is shown in Figure 1(b). To keep design complexity low and respect the real-time requirements, a truncated version of the filter coefficients shown in the figure is being used. The coefficient selection – along with other design choices (such as the thresholding policy) – directly affects the detection quality but also the performance and energy expenditure of the system.

Existing approaches have focused on maximizing detection accuracy which calls for complex filters with large sets of coefficients. We have found that such large sets not only increase detection delay but also incur disproportionally large energy costs. Given that detection of seizures is intrinsically an imprecise science, in this short paper we explore simplifications of the ideal wavelet that impact detection quality minimally while yielding significant energy savings and, thus, device autonomy.

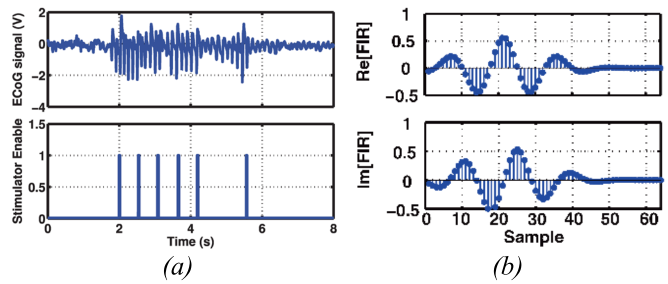

Figure 1 -- (a) Top: Typical seizures as captured in an ECoG recording. Bottom: Device suppression stimulation output. (b) Wavelet filter (real and imaginary coefficients) used to detect seizure patterns.

II. Related Work

Prior work has shown that FIR filters may obtain significant energy savings through approximate computing, while minimizing the impact on filter performance. Existing work has focused mostly on speech-recognition and image-processing applications, reducing energy consumption by over 50% by dynamically scaling the filter-order [4], bit-precision or voltage [5]. In this paper, we demonstrate that approximate computing may play a significant role in the lifetime of wearable, mission-critical devices for biomedical applications. This is particularly relevant for implantable microelectronic devices.

III. Experimental Setup

For the purposes of this experiment, a miniature, fault-tolerant, RISC-style core called SiMS has been employed which has been repeatedly used in the past for deploying implantable medical applications [6]. The core and assorted instruction and data memories run at 20 MHz frequency and exhibit a typical, average power consumption of 1,079 μW. The filter with tunable number of coefficients has been implemented in C code and has been compiled for the SiMS core with O2-level optimizations. For characterizing the accuracy of filters in the field of seizure detection, the *Average-Detection-Rate* (ADR) is widely used and is defined as the arithmetic mean of the filter sensitivity and specificity; thus:

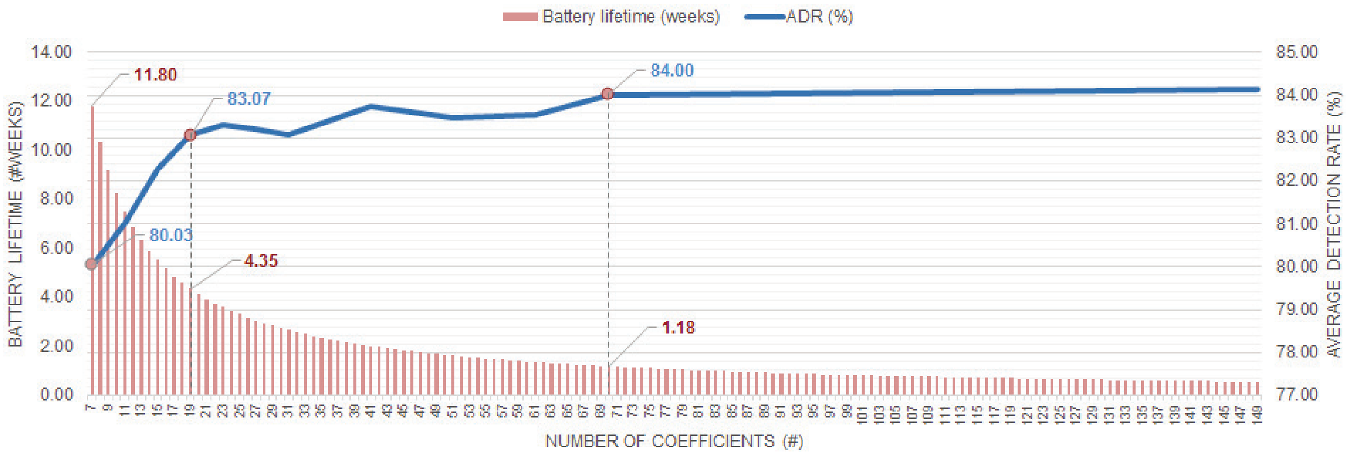

Figure 2 -- Combined chart depicting the Average Detection Rate (%) of the wavelet [right y-axis] and the respectively achieved battery autonomy levels of the seizure-suppression device in weeks (#) [left y-axis].

$$\text{ADR} = \frac{sensitivity + specificity}{2}$$

Sensitivity is defined as the percentage of successfully detected seizures and specificity as the percentage of correctly classified inter-ictal intervals [3]. For quantifying the achievable battery lifetime of a seizure-suppression device – and without loss of generality – a battery capacity of 100 mWatt-hours has been selected.

IV. Evaluation

For various coefficient sizes the filter has been fine-tuned and instantiated with the objective (in this work) of maximizing the ADR. In Figure 2, the ADR has been plotted for coefficient sets ranging from 7 to 149. It can be readily observed that – with increasing coefficient sizes – the ADR achieved by the detector saturates at a maximum of 84.12%.

However, this comes at a steep increase in energy expenditure, since the calculation of more coefficients results in longer execution times in SiMS and, subsequently, in a drastic increase in battery drain. To illustrate this phenomenon, Figure 2 illustrates in bar-chart form the total battery lifetime of the device (in weeks) as a function of employed coefficient size. Lifetime visibly drops with increasing coefficient sizes.

As observed in many other physical phenomena, the non-linear relation between gained benefit (here: ADR) and expended cost (here: autonomy) permits us to handle the application as an approximate-computing case. We can see from the figure that for a near-maximum ADR of 84%, a net battery lifetime of 1.18 weeks is being achieved. By allowing for a trivial ~1% drop in ADR (83.07%), the battery lifetime almost quadruples (3.69x) allowing 4.35 weeks of device autonomy. In the case that a slightly more aggressive reduction in the ADR is permitted (say to 80.03%), device autonomy increases by 21.46x. Of course, what is tolerable in ADR reductions depends highly on the biomedical experiment at hand. In this particular case of seizure detection, our experiments with live animals have shown that, at least for ADR reductions of 1% or less, no adverse effects are noticed in the animals (i.e. no statistically significant increase in un-suppressed seizures is measured).

V. Conclusions

In this short paper we have presented an intriguing application of approximate computing on the subject matter of seizure detection and suppression in live animals. Based on conservative measures, current experiments reveal a 3.7x increase in wearable-device autonomy at no observable penalty for living test animals. What is more, this technique can be dynamically applied in online systems as an adaptive policy. Future work involves extending it to other facets of the seizure-suppression problem, such as detection delay and asymmetric selection of filter coefficients.

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