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Equalization for Intracortical Microstimulation Artifact Reduction

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Abstract—**We present a method for decreasing the duration of artifacts present during intra-cortical microstimulation (ICMS) recordings by using techniques developed for digital communications. We replace the traditional monophasic or biphasic current stimulation pulse with a patterned pulse stream produced by a Zero Forcing Equalizer (ZFE) filter after characterizing the artifact as a communications channel. The results find that using the ZFE stimulus has the potential to reduce artifact width by more than 70%. Considerations for the hardware implementation of the equalizer are presented.**

Keywords- Microstimulation, ICMS, Artifact, Neural Recording, LFP, ZFE, Equalization, Linearity

I - INTRODUCTION

Recent advancements in neural stimulation have given hope to patients of spinal cord injuries, Parkinson's Disease and numerous other debilitating neurological conditions. A key tool in these advancements has been Intracortical Microstimulation (ICMS), a technique for stimulating a population of neurons using electrical current. In addition to its therapeutic and reconstructive applications, ICMS allows the neuroscientists to stimulate and measure the response of neural pathways, which helps illuminate the brain's organization [1-2].

It is desirable to monitor electrical activity in the brain during and after ICMS in both the low-frequency Local Field Potential (LFP) and high-frequency Action Potentials (AP). In neural implants, this capability enables true bi-directional communication between the device and the brain. A major hurdle to the simultaneous stimulation and recording of brain activity is the artifact that occurs immediately after stimulation [2]. Figure 1 shows the measured electrical response in the dorsolateral striatum (DLS) of a rat after stimulating with a single current pulse of 40uA and 250μs duration in the primary motor cortex (M1). Notice that while the artifact is Figure 1 has a peak amplitude of 200μV, artifacts can have amplitude as large as hundreds of millivolts depending on the relative location of the stimulation and recording electrodes. Since neural signals can have amplitudes on the order of 10μV, this artifact distorts the neural recordings, rendering several milliseconds of recording data useless.

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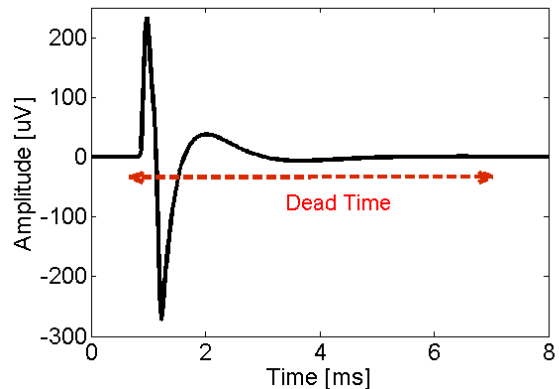*These authors contributed equally to this work.

Figure 1: An artifact resulting from a 40uA stimulus

It is desirable to minimize the amplitude and duration of the artifact, as this could uncover neural activity occurring immediately after stimulation enabling recording with high-frequency stimulation patterns and improving the performance of protocols that require close timing relationships, such as recording-triggered ICMS described in [3]. Several techniques have been proposed to this end. In [5], amplifier saturation from the stimulus artifact is identified as the major cause of signal degradation and the recording amplifier inputs are disconnected from the electrodes during stimulation using electronic switches. In [6], artifacts are removed in post-processing by fitting a function to model the artifact and subtracting it from the signal. This technique does not improve on the distortion of the recording nor decrease the dynamic range required in the recording electronics. In [7], in the context of a DBS system with fixed-frequency stimulation, a notch filter is used to suppress the artifact. Finally in [8], still in the context of DBS, a combination of electrode placement and frequency separation is used.

The technique proposed here takes a different approach; instead of coping with the artifact, it designs the system to prevent it from occurring in the first place through stimulation waveform design. As such, it can be combined with other techniques, further improving the rejection. In our approach, the neural channel is first characterized as a linear time-invariant (LTI) digital communications channel, as depicted in Figure 2. A Zero Forcing Equalizer (ZFE) is then applied on the input to reduce the dead time.

Zero-Forcing Equalization is a form of linear equalization used in communication systems which applies the inverse frequency response of a channel at the stimulus in order to compensate for distortions caused by finite bandwidth in the channel. The ZFE produces a sequence that minimizes the Euclidean distance to our desired pattern at the output of the

overall system. The desired output we chose includes only initial upward and downward spikes seen in Figure 1 but with a null response in the "artifact" window. This choice reduces overall dead time and maintains charge neutrality, which prevents degradation of the stimulated tissue [2].
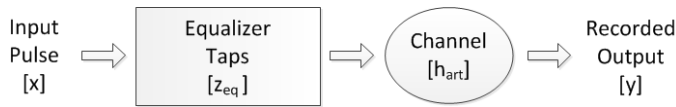

Figure 2: Equalizer block diagram

In this paper we describe initial results focusing on the mathematical framework for characterizing the channel and the demonstration of ZFE efficacy using pre-recorded ICMS data from the brain of a live rat (Sections II and III). Hardware specification for a possible implementation are determined in the final parts of Section III. Conclusions and future work are discussed in Section IV.
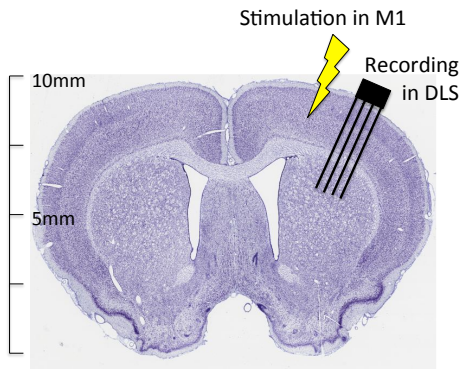
II - CHANNEL MEASUREMENTS AND MODEL

Figure 3: Stimulation and recording configuration, shown on coronal slice of rat brain from [9]

ICMS data was taken *in-vivo* from an awake, freely behaving rat. All experiments were done in accordance with the Animal Care and Use Committee at the University of California, Berkeley. To measure ICMS data and model the channel, a variable amplitude commercial stimulator A-M Systems 2100 isolated pulse stimulator is connected to an array of 16 tungsten microelectrodes located in the primary motor cortex (M1) of a live, awake rodent as depicted in Figure 3. A second array of microelectrodes is implanted in the dorsolateral striatum (DLS) and connected to a commercial multichannel acquisition processor (MAP) recording system from Plexon, Inc.

A. Characterizing the Artifact and Neural Path

250μs-long current pulses with amplitudes varying from 10μA to 60μA were used for stimulation, while neural activity was recorded at 40kHz. The analysis of the neural channel and corresponding equalizer was implemented in MATLAB. The neural channel is considered static for a given specimen during a single session of recordings. The individual artifacts are aligned according to their maxima, and then the mean offset is subtracted from the artifact by averaging the samples prior to

stimulation. Averaging across all artifacts obtained from one continuous recording of one specimen provides the most reliable estimate of the neural channel for a given electrode. The 60Hz content is considered to be noise and is removed from the recordings prior to further processing.

Artifact stability is shown in Fig. 4, which shows overlaid artifacts from 31 trials from a single recording session. The Euclidean distance between artifact vectors, an indirect measure of the channel time variance, is on average 8.4% of the artifact energy.

The duration of the "dead time" is found by looking for the instant at which the artifact has decayed below our recording noise floor. For the artifacts in Figure 1, an average duration of 6.8ms is obtained in this manner.
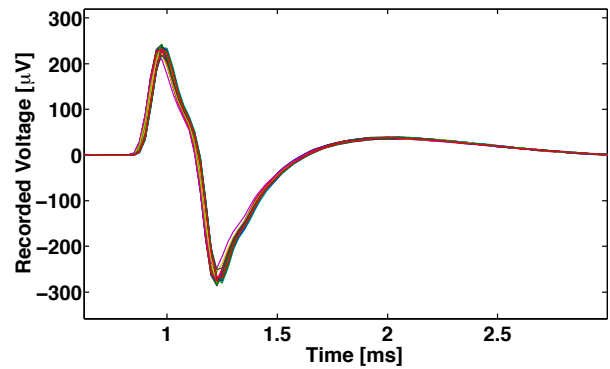

Figure 4: Overlaid stimulus artifacts from 31 trials

B. Verifying the LTI hypothesis

Applying 250μs current pulses with amplitudes varying from 10-60μA provided the data needed to analyze homogeneity. The stimulus amplitude x_1 was scaled by a factor β to produce stimulus x_2. The corresponding scaling of the artifact α was measured using vector projection analysis. If y_1 and y_2 are the responses to stimuli x_1 and x_2 respectively, then the artifact scaling factor α is determined by

$$\alpha = \frac{<y_1,y_2>}{|y_1|^2}. \tag{1}$$

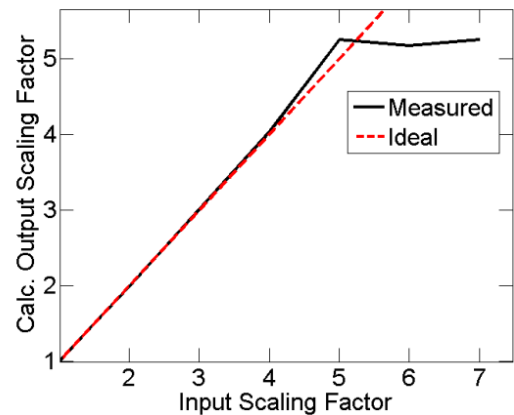If $\beta = \alpha$, then the neural path can be called homogenous.

Figure 5: Artifact homogeneity scaled w.r.t. baseline 10uA stimulus

Applying this method to the collected data results in Figure 5. Here, the 10µA is response used as the baseline. The results show that the channel is homogeneous for input current amplitudes up to approximately 50µA. At high current levels, the signal saturates due to electrochemical effects at the electrode interface. To ensure that the channel behaves in an LTI manner, we will design our ZFE to equalize a 40µA stimulus. This is verified in section III.C.

To analyze additivity, we use data collected from 15µA current pulses. A biphasic input pulse is normally applied to ensure a charge balanced stimulation [2], preventing electrode corrosion and DC voltage build up. If $x_{mon}(t)$ is a monophasic pulse, the biphasic pulse can be described by

$$x_{bi} = x_{mon}(t) - x_{mon}(t-T) \qquad (2)$$

where x_{bi} is the biphasic input, x_{mon} is monophasic input, and T represents the monophasic impulse width. If the channel is time invariant, then the response to the biphasic input would be expected to be additive, as shown in Equation (3). With y_{bi} being the artifact given a biphasic stimulus and y_{mon} being the artifact with a monophasic stimulus, an LTI channel gives

$$y_{bi} = y_{mon}(t) - y_{mon}(t-T) \qquad (3)$$

The ideal output in Equation (3) is compared with the measured biphasic output in Figure 6. The distance between ideal and measured response is within 2.3% of measured biphasic signal energy. Overall, the measured and theoretical results match sufficiently to call the channel LTI over our range of inputs.
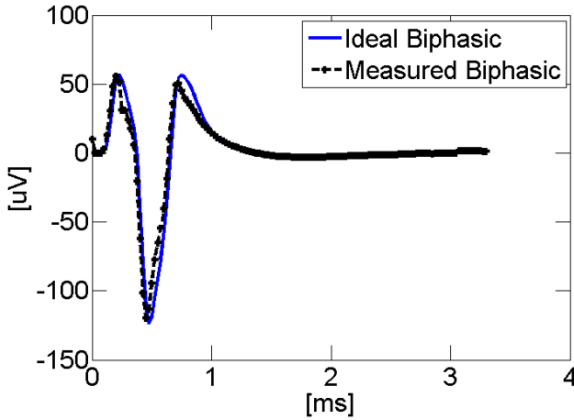

Figure 6: Biphasic Comparison for a 20uA Current Stimulus

III - EQUALIZER DESIGN

A. Algorithm

With the neural path classified as LTI, the transmit-side ZFE equalizer can be designed using well-known algorithms [4]. We realize the equalizer by modeling the channel response as auto-regressive, moving average process (ARMA), using the Steigtlitz-McBride algorithm [10] and then inverting the minimum phase portion of the resulting model. Since the data is recorded at 40 kHz, but the stimulation pulse has a 250 µs duration, impulse response data is decimated to a 4 kHz sampling rate before model fitting in order to consider the

input a single discrete-time delta function. The best results were obtained using 4-th order polynomials for both numerators and denominators of the model. Figure 7 shows the pole-zero constellation of the extracted model. Three of the model four zeros lie outside of the unit-circle and hence cannot be equalized. This lower bounds the equalized artifact length to 750µs.
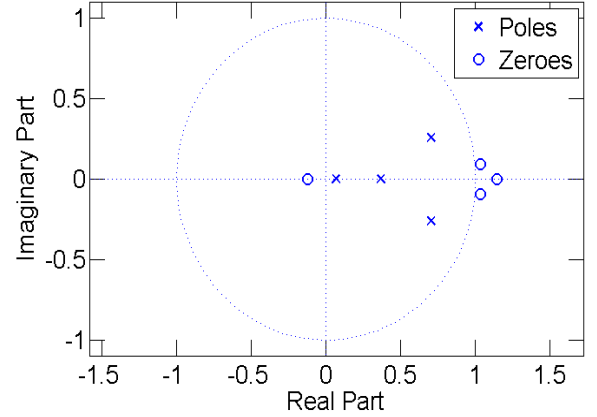

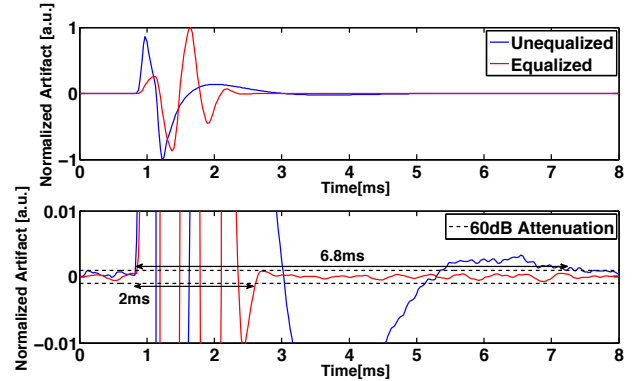**Figure 7: Pole-zero constellation for extracted model**

Figure 8: Dead time reduction through equalization: waveforms (top) and detail 60dB settling (bottom)
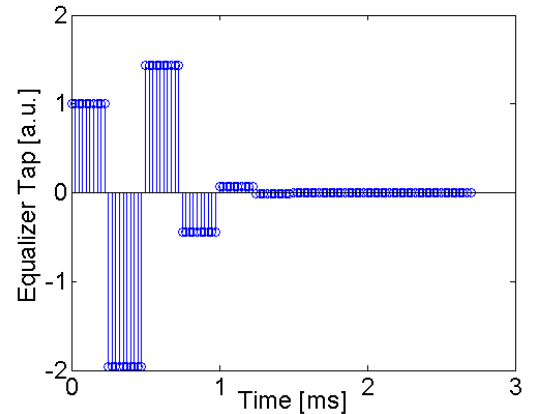

Figure 9: Output of the upsampled ZFE response

Figure 8 shows a comparison of the normalized artifact with and without equalization. We define the dead time as the delay between when stimulation is applied and when it decays to 0.1% of its peak value. A 0.1% error results in a disturbance below 1μV, and hence well below the measured noise floor of 6μVrms. Equalization improves the dead time from 6.8ms to 1.8ms, a 73% reduction. Figure 9 shows the resulting equalizer, (Z_{eq} in Figure 2) after it was up-sampled to 40kHz and processed by a zero-order hold.

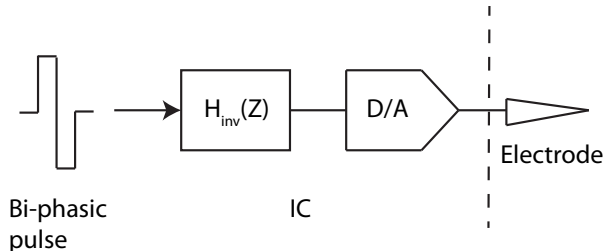### B. Hardware Implementation Considerations

Figure 10: Stimulator architecture

Since the equalizer is intended for use in an implanted microsystem in which power consumption is critical, we investigated the effect of equalizer order and coefficient precision on dead-time reduction, in order to obtain a low-complexity, low-power design. We focus this exploration on the digitally intensive architecture shown in Figure 10. A bi-phasic pulse is used as the stimulus to ensure charge neutrality. The stimulus is passed through a ZFE filter and a digital-to-analog converter (D/A) to produce and drive the required output currents.

The effect of model order on the dead time is shown in Figure 11, where numerator and denominator order are kept equal for each data point. Using a 4th order model is optimal, as significantly longer dead time is obtained for even N=3 in this case. Using N=5 results in over-fitting and instability.

The effect of coefficient precision in the digital filter is shown in Figure 12, showing that a 6-bit implementation is sufficient. Simulations also indicate that a 10-bit resolution is required for the final D/A converter.
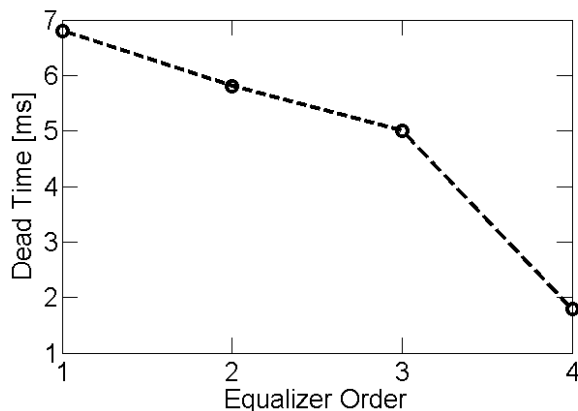

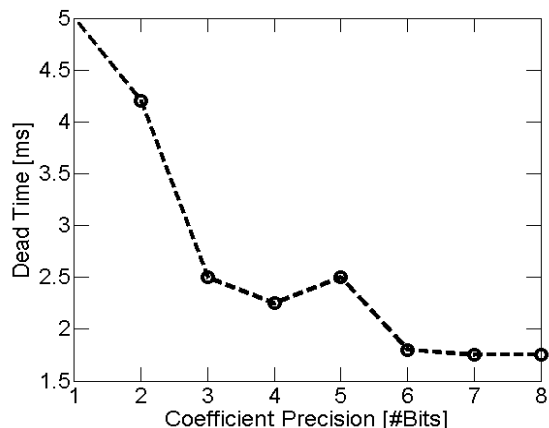**Figure 11: Dead time as a function of ARMA model order**

Figure 12: Coefficient precision vs. Equalized Dead Time

IV - CONCLUSIONS

We show the potential of zero-forcing equalization to shorten the length of the ICMS artifact and recover underlying information. Our experiment shows a reduction in dead time by over 73% over biphasic pulses. This algorithm can be combined with other artifact-reduction techniques ([5],[8]). We show that this technique has modest sensitivity to component precision and is hence amenable to a low-power integrated implementation.

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