A Nonlinear Signal-Specific ADC for Efficient Neural Recording

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Abstract—A bandwidth-efficient technique for nonlinearly converting analog neural signals into digital is presented to be used in implantable neural recording microsystems. It is shown that the choice of a proper nonlinear quantization function helps reduce the outgoing bit rate carrying the recorded neural data. Another major benefit of digitizing neural signals using a proper nonlinear analog-to-digital converter (ADC) is the improvement in the signal-to-noise ratio (SNR) of the signal. The 8-b nonlinear anti-logarithmic ADC reported in this paper digitizes large action potentials with 10b resolution, while quantizing the small background noise with a resolution of as low as 3b. The circuit was designed and simulated in a 0.18-um CMOS process. According to the experimental results, SNR of the neural signal increases from 5.11 before digitization to 22 after being digitized using the proposed ADC approach.

I. INTRODUCTION

Nowadays, ADCs are widely used in the industry. Usually, ADCs are designed to convert analog signals with arbitrary waveforms into digital. To convert specific signals, however, some aspects of the signal (e.g., frequency content or wave-shape) might help optimize the design of the ADC in order to achieve higher performance in terms of speed, power dissipation, or circuit complexity. Some efforts in the design of signal-specific ADCs are put on utilizing nonlinear quantization functions in order to benefit from the non-uniform distribution of input amplitude samples. One of the reasons for nonlinear quantization is to achieve non-uniform resolution along the input range. For instance, in sensory systems, one of the approaches to compensate the nonlinear characteristics of a sensor is to digitize it using a nonlinear ADC with proper nonlinearity function [1]. As another example, audio signals are sometimes digitized in communications systems along with amplitude compressing/expanding (companding). This is to increase the dynamic range for the input signal as well as to improve the signal-to-noise ratio (SNR) [2, 3].

Depending on the application and on the specific case under study, different kinds of nonlinearity functions are employed in nonlinear ADCs, including exponential function [4], logarithmic function [5], piecewise-linear approximation of logarithmic function [1, 2], square-law function [6], and non-uniform staircase [3].

From an architectural and circuit implementation viewpoint, nonlinear ADCs can be classified into two major types:

- Perhaps the most straightforward approach to realize a nonlinear ADC is to perform linear analog-to-digital conversion using a standard ADC and mapping to the nonlinear space of interest as two separate steps [7]. Nonlinear ADCs of this type are not expected to be power- or area-efficient compared to those categorized as the second type.

- In the nonlinear ADCs of the second type, the nonlinear function of interest is interfused into the analog-to-digital conversion process in such a way that the nonlinear function is embedded into the digitization process, resulting in a nonlinear quantization characteristic for the ADC [1-6]. This can significantly reduce circuit complexity, silicon area, and power dissipation of the ADC as compared to those of the first type ADCs.

In this paper, a nonlinear ADC is used to quantize neural signals in implantable neural recording microsystems. Reduced bit rate and improved signal-to-noise ratio are among the advantages of the proposed idea.

II. NONLINEAR ADC FOR NEURAL RECORDING

Typical waveshape of an intracortically-recorded extracellular neural signal is shown in Fig. 1. In a wide variety of neuroscientific and neurophysiological studies, as well as in many neuroprosthetic applications, it is the action potentials (neural spikes) that carry the useful information embedded in neural signals. In implantable neural recording microdevices, neural signals are usually digitized using linear ADCs, i.e., ADCs with linear quantization characteristics. This means that the non-useful background noise is digitized with the same resolution as the useful action potentials are. In other words, when telemetering a digitized neural signal, part of the outgoing bit-rate is wasted to carry the noise content present in the neural signal. The basic idea proposed in this paper is to digitize neural signals using an ADC with non-uniform quantization levels.