Nonlinear Signal-Specific ADC for Efficient Neural Recording in Brain-Machine Interfaces

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Abstract—A nonlinear ADC dedicated to the digitization of neural signals in implantable brain-machine interfaces is presented. Benefitting from an exponential quantization function, effective resolution of the proposed ADC in the digitization of action potentials is almost 2 bits more than its physical number of bits. Hence, it is shown in this paper 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 the proposed signal-specific ADC is the considerable reduction in the background noise of the neural signal. The 8-b exponential ADC reported in this paper digitizes large action potentials with maximum resolution of 10.5 bits, while quantizing the small background noise is performed with a resolution of as low as 3 bits. Fully-integrated version of the circuit was designed and fabricated in a 0.18-μm CMOS process, occupying 0.036 mm² silicon area. Designed based on a two-step successive-approximation register ADC architecture, the proposed ADC employs a piecewise-linear approximation of the target exponential function for quantization. Operating at a sampling frequency of 25 kS/s (typical for intra-cortical neural recording) and with a supply voltage of 1.8 V, the entire chip, including the ADC and reference circuits, dissipates 87.2 μW. According to the experiments, Noise-Content-Reduction Ratio (NCRR) of the ADC is 41.1 dB.

Index Terms—A/D converters, brain-machine interfaces, implantable biomedical microsystems, nonlinear ADCs.

I. INTRODUCTION

The need for simultaneously recording neural signals from hundreds of channels in implantable neural recording microsystems is essential in both neuroscientific research and neuroprosthetic applications. Advances in microtechnology over the past few decades have enabled designers to develop implantable microsystems for high-density recording of neural signals. To be fully implantable, a microsystem needs to wirelessly interface with the outside world in order to bidirectionally communicate with and receive power from an external host. Physical size, power consumption, and data communication bandwidth are among the main concerns in the design of such devices [1].

To overcome bandwidth limitation in the wireless telemetry of the recorded neural data, a wide variety of data reduction techniques has been reported. These techniques range from signal processing approaches such as the discrete wavelet transform [2]–[4] and Walsh-Hadamard transform [5] to spike detection [6], [7] and spike sorting techniques [8]. Although it is believed that approaches such as spike detection and spike sorting are informative enough in neuroprosthetic applications [9], in some other applications, namely neuroscientific studies, they are not preferred because of the loss of important information, e.g., spike wave shape they cause. Signal-processing techniques, on the other hand, have been successful from the standpoint of data compression, but they suffer from not-so-efficient circuit implementation in terms of silicon area and power dissipation [10], especially when the number of recording channels increases.

To benefit from the advantages associated with digital signal processing and also digital data communication (over their analog counterparts), it is usual in the design of neural recording devices to convert neural signals into digital. As a result, analog-to-digital converters (ADCs) are known as one of the key building blocks in such devices [6], [7], [11]–[13]. 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 waveshape) might help optimize the design of the ADC in order to achieve higher performance in terms of speed, power dissipation, or circuit complexity. Recently, some ideas in the design of signal-specific ADCs have been developed based on non-uniform sampling of certain signals in order to put more focus on where more information is concentrated in the time domain [14]–[16]. Other efforts are also put on utilizing nonlinear quantization functions in order to focus more on where more information is concentrated in the amplitude domain. For instance, in sensory systems, one of the approaches to compensate nonlinear characteristics of a sensor is to digitize the signal it provides using a nonlinear ADC (NLADC) with proper nonlinearity function [17]. Depending on the application and on the specific case under study, different kinds of nonlinearity functions are employed in nonlinear ADCs.

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