Chapter 12
Signal-Adaptive Analog-to-Digital Converters for ULP Wearable and Implantable Medical Devices:
A Survey

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ABSTRACT

The mission of this chapter is to introduce the reader the recent developments in the design of ultra-Low Power ADCs for Wearable and Implantable Medical Devices (WIMDs). The focus of this chapter will be on Signal-Adaptive Successive Approximation Register (SAR) ADC architectures and their derivatives, since the majority of the ULP medical devices rely on these architectures. The proposed chapter first provides an overview of the WIMDs, and electrophysiological signals. Then, basic SAR ADCs are introduced followed by the study of adaptive SAR ADCs. The chapter concludes with a brief summary of the other prevalent ADC architecture for WIMDs, namely the Level-Crossing ADCs.

1. INTRODUCTION

There is a surge in wearable devices for physiological monitoring and treatment (Medtronic MiniMed insulin pump (Medtronic 2015), Second Sight Argus II Retinal Prosthesis (Second Sight 2015)) and for activity monitoring for healthy living (FitBit 2015). The wearable market is expected to have a 35% compound annual growth rate in the next five years (Danova 2015) and to reach to a global retail revenue of $53.2B by 2019 (Juniper Research 2014).

Similarly, implantable medical devices (IMDs) have become an indispensable option for patient monitoring and treatment, while their size has continuously shrunk. IMDs came a long way from the early pacemakers. For instance, the latest pacemakers such as Nanostim (St. Jude Medical 2015) can fit

DOI: 10.4018/978-1-5225-5484-4.ch012

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inside the heart eliminating the need for a surgical pocket, and can stimulate the heart without leads. There are over 4 million people with devices including pacemakers for managing cardiac rhythms worldwide, and 700,000 new pacemakers are implanted every year (Strickland 2013). Furthermore, modern IMDs offer new functionality for monitoring and treatment of various diseases and disorders ranging from Deep Brain Stimulation for Parkinson's disease with Medtronic ActiveRC (Medtronic 2015a) to weight loss treatment for obesity with EntroMedics Maestro System (EntroMedics 2015).

Together, Wearable/Implantable Medical Devices (WIMDs) provide exciting opportunities for significantly improving the health of the general population. On the other hand, the design and implementation of the WIMDs have unique engineering challenges.

1.1. Stringent Power Constraints for WIMDs

As the demand for achieving more functionality in smaller volume for wearable and implantable medical devices grow, the requirements for power consumption become more and more restricted. An important hurdle for the adoption of these devices is the need for large batteries or frequent battery recharging. The frequent battery recharging can easily become a hassle for the patients. More importantly, the limited battery life for implantable devices makes battery replacement surgeries a necessity. An ideal solution is to have these systems rely solely on energy harvesting to avoid the need for battery replacement or recharging, altogether. Yet, for most medical applications, there is a large gap between the energy demand and the energy that can be harvested.

A satisfactory compromise for the short-term can be wearable or implantable systems, which only require recharging infrequently, such as once a month. This extended period of use without recharging also opens the possibility of the recharging to take place only at routine visits to the physician's office. Thus, the risk of relying on the patients to recharge their own devices can be circumvented.

For making wearable and implantable devices ubiquitous, power consumption should be considered at every layer of the design. In this context, it is no longer feasible to design subsystems in isolation without intimate knowledge of the use patterns, power consumption, and capabilities of the surrounding systems. Analog-to-Digital Converters (ADCs) are a key building block in these Ultra-Low Power (ULP) systems since they dictate the accuracy and speed of the analog-to-digital conversion. As a result, ADCs also dictate the size of the resulting bit stream.

The mission of this chapter is to introduce to the reader the state-of-the-art methods, the challenges, and the opportunities of designing ultra-low power ADCs for wearable and implantable medical devices. The focus of this chapter will be on Successive Approximation Register (SAR) ADC architectures and their derivatives (e.g. adaptive SAR ADCs), since the majority of the ULP medical devices rely on these architectures. The SAR-ADC architecture is preferred for ULP implementations due to its relatively simple design, small area footprint, and high efficiency (energy/conversion). SAR ADC is a good fit for the resolution range required by the medical sensing applications. Due to the recent interest in the Level-Crossing ADCs for WIMDs, this chapter will also briefly cover the Level-Crossing ADCs and their inherent signal-adaptive behavior.

The rest of this chapter consists of 7 sections and is organized as follows. In Section 2, WIMDs are introduced. In Section 3, a summary of electrophysiological signal characteristics relevant to the current context is given. The next section introduces the SAR ADC. Section 5 provides the theoretical background for ADC power consumption. Section 6 offers a comprehensive review of the Reconfigurable and Adaptive SAR ADCs. The power consumptions of these ADC architectures are compared against a

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