CMOS Time-Mode Circuits and Systems

Fundamentals and Applications

EDITED BY **FEI YUAN**

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Preface

The rapid scaling of complementary metal oxide semiconductor (CMOS) technology has resulted in the sharp increase of time resolution and the continuous decrease of voltage headroom. As a result, time-mode circuits where information is represented by the time difference between the occurrence of digital events, rather than the nodal voltages or branch currents of electric networks, offer a viable and technology-friendly means to combat scaling-induced difficulties encountered in the design of mixed-mode systems. Time-mode approaches have found a broad spectrum of applications since their inception in time-of-flight measurement several decades ago. These applications include digital storage oscillators, laser-based vehicle navigation systems, analog-to-digital data converters, signal processing, medical imaging, instrumentation, infinite and finite impulse response filters, all digital phase-locked loops, giga-bit-per-second (Gbps) serial links, and channel select filters for software-defined radio, to name a few. Various architectures and design techniques of time-mode circuits have emerged recently; a comprehensive examination of the principles of time-based signal processing and the design techniques of time-mode circuits, however, is not available. This book provides the fundamentals of time-based signal processing with an emphasis on the design techniques and applications of CMOS time-mode circuits.

Chapter 1 examines the fundamentals of time-mode circuits. The definition of time-based signal processing is provided. The characteristics of time-mode circuits are examined and compared with those of their voltage-mode and current-mode counterparts. Challenges encountered in time-based signal processing are investigated. The key building blocks of time-mode circuits are briefly examined with a detailed study of these building blocks in later chapters. The applications of time-based approaches in mixed-mode signal processing are discussed briefly.

Chapter 2 deals with voltage-to-time converters. An emphasis is given to the techniques that improve the linearity of voltage-to-time converters. Voltage-to-time converters using voltage-controlled delay units are studied, and their pros and cons are examined in detail. Voltage-to-time converters using voltage-controlled delay units and source degeneration are also investigated. Relaxation voltage-to-time converters that provide a better linearity are studied. Reference voltage-to-time converters that also exhibit a good linearity are examined. The applications of voltage-to-time converters in time-mode comparators are investigated.

Chapter 3 provides a comprehensive treatment of the principles, architectures, and design techniques of time-to-digital converters (TDCs) with an emphasis on the critical assessment of the advantages and limitations of each class of TDCs. It first provides the classification of TDCs. The key performance indicators of TDCs are then depicted. Sampling TDCs where time variables are digitized directly such as counter TDCs, delay line TDCs, TDCs with interpolation, vernier delay line TDCs, pulse-shrinking TDCs, pulse-stretching TDCs, successive approximation TDCs, flash TDCs, and pipelined TDCs are investigated in detail. Noise-shaping TDCs that suppress in-band quantization noise such as gated ring oscillator TDCs, switched ring oscillator TDCs, gated relaxation oscillator TDCs, MASH TDCs, and $\Delta\Sigma$ TDCs are studied.

Chapter 4 starts with a brief review of TDC architectures. A three-step TDC with phase interpolation is introduced to improve the resolution and reduce the power consumption and die area. The resolution of the three-step TDC with phase interpolation is improved by using a phase interpolator and a time amplifier for the improvement of the in-band phase noise when used in all-digital phase-locked loops.

Chapter 5 introduces some important performance parameters of time interval measurements. It is followed by the presentation of basic counting methods for time measurement. Interpolation methods for performance improvement are presented and analyzed in a greater detail. We show that the combination of the counter method with the interpolation of timing pulse positions within the clock period provides a very efficient method for realizing a high-precision, accurate TDC with a wide operation range. This approach combines the inherently good single-shot resolution of a short-range interpolator based on digital delay line techniques with the excellent accuracy and wide linear range of the counting method. It is shown that in a general measurement situation where the timing pulses are asynchronous with respect to the system clock, the effect of interpolator nonlinearities on the final averaged output is strongly suppressed due to the inherent averaging effect of the interpolation method. On the other hand, these nonlinearities widen the distribution of the measured single-shot results and in many cases limit the single-shot precision of the TDC. It is also pointed out that the careful synchronization of the timing signals is needed in order to get unambiguous measurement results that are free from systematic errors. Finally, two case studies show that, with the aforementioned approaches, a TDC realized in standard nonaggressive CMOS technologies can achieve a ps-level resolution and a single-shot precision better than 10 ps (sigma value) over a wide operation range of hundreds of microseconds.

Chapter 6 explores the time-mode techniques that overcome the difficulties encountered in the realization of multibit voltage-mode analog-to-digital converters. The chapter starts with the close examination of the key parameters and figure of merits that quantify the performance of analog-to-digital converters. It is followed by the detailed study of the principles and properties of multibit quantizers realized using voltage-controlled ring oscillators. Both voltage-controlled oscillator (VCO)-based phase and frequency quantizers are studied. The chapter continues with the investigation of open-loop analog-to-digital converters utilizing VCO phase and frequency quantizers. The chapter first reviews the fundamentals of $\Delta\Sigma$ modulators in closed-loop time-mode analog-to-digital converters. Time-mode $\Delta\Sigma$ modulators are then introduced, and their characteristics are investigated in detail. Time-mode $\Delta\Sigma$ modulators with VCO phase and frequency quantizers are explored. $\Delta\Sigma$ modulators with phase feedback are also examined. $\Delta\Sigma$ modulators with pulse-width modulation for linearity improvement are explored. Multistage, also known as MASH time-mode $\Delta\Sigma$ modulators, both single-rate and multirate are examined. Dynamic element matching, an effective technique to minimize the effect of the mismatch of digital-to-analog converters, is briefly studied with the inclusion of an exhaustive list of published studies on dynamic element matching. The chapter ends with the comparison of the performance of some recently reported time-mode $\Delta\Sigma$ modulators.

Chapter 7 describes $\Delta\Sigma$ converters that adopt time-mode signal processing techniques. A key advantage of time-mode $\Delta\Sigma$ converters is that they are realized using digital circuits and process information in the form of time-difference intervals. As a consequence of using digital circuits, this technique benefits from low-voltage operation without concern for reduced signal swings, sensitivities to thermal noise effects, or switching noise sensitivity. Recently, several studies on time-mode $\Delta\Sigma$ converters are conducted showing that such methodology has high potential in low-voltage design. The noise-shaping behavior demonstrated by this technique can be implemented and extended in various ways, including voltage-controlled delay unit or gated-ring-oscillator-based implementations of TM $\Delta\Sigma$ converters. In this chapter, after a brief review of $\Delta\Sigma$ ADC specifications, the different architectures of TM $\Delta\Sigma$ converters that have been recently proposed are examined.

Chapter 8 covers the fundamentals of all-digital phase-locked loops. The chapter starts with a close examination of the drawbacks of charge-pump phase-locked loops. It is followed by a detailed examination of the phase noise of phase-locked loops. The basic configuration of all-digital phase-locked loops is then studied. An investigation of digitally controlled oscillators is followed. The phase noise of all-digital phase-locked loops is studied. The chapter ends with a brief examination of all-digital frequency synthesizers.

Chapter 9 outlines the general concepts related to time-mode signal processing and some of its state-of-the-art applications. These provide a very good alternative to conventional techniques, which suffer from problems such as linearity and accuracy limitations among others. The ultimate goal of this chapter is to arrive at all-digital time-domain circuits that can be synthesized using existing digital computer-aided design tools and to make the design process fully automated in contrast to its conventional analog counterpart.

Chapter 10 studies time-mode-integrated temperature sensors. Both relaxation oscillator temperature sensors and ring oscillator temperature sensors are investigated. Temperature sensors that utilize TDCs are also studied. It further investigates digital set point temperature sensors. The chapter ends with a comparison of the performance of some recently reported time-mode temperature sensors.

The book provides a comprehensive treatment of the principles and design techniques of CMOS time-mode circuits. Readers are assumed to have a fundamental knowledge of electrical networks, semiconductor devices, CMOS analog and digital integrated circuits, feedback systems, signals and systems, and communication systems. As time-mode circuits and systems are still a domain of active research, new architectures and implementations continue to emerge. The book by no means attempts to provide a complete collection of time-mode circuits and systems; it rather provides the fundamentals of time-based signal processing and the design techniques of CMOS time-mode circuits and systems and, therefore, is intended to serve as a source for those who are interested in time-based signal processing to explore further in this exciting field of research. A rich collection of recently published work on time-mode circuits and systems is provided at the end of each chapter so that readers can seek further information on the subjects covered in the book.

Although an immense amount of effort was made in the preparation of the manuscript, flaws and errors might exist due to erring human nature and time constraints. Suggestions and corrections from readers are gratefully appreciated by the editors and authors.

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Editors

Dr. Fei Yuan earned his BEng in electrical engineering from Shandong University, Jinan, Shandong, China, in 1985, and MASc in chemical engineering and PhD in electrical engineering from the University of Waterloo, Canada, in 1995 and 1999, respectively. He was a lecturer in the Department of Electrical Engineering, Changzhou Institute of Technology, Jiangsu, China, during 1985–1989. In 1989, he was a visiting professor at Humber College of Applied Arts and Technology, Toronto, Ontario, Canada, and Lambton College of Applied Arts and Technology, Sarnia, Ontario, Canada. He worked with Paton Controls Limited, Sarnia, Ontario, Canada, as a controls engineer during 1989–1994. Since 1999, he has been with the Department of Electrical and Computer Engineering, Ryerson University, Ontario, Canada, where he is currently a professor and the chair. Dr. Yuan is the author of *CMOS Current-Mode Circuits for Data Communications* (Springer, 2007), *CMOS Active Inductors and Transformers: Principle, Implementation, and Applications* (Springer, 2008), and *CMOS Circuits for Passive Wireless Microsystems* (Springer, 2010) and the principal coauthor of *Computer Methods for Analysis of Mixed-Mode Switching Circuits* (Kluwer Academic, 2004). In addition, he has authored/coauthored approximately 200 research papers in refereed journals and conference proceedings. Dr. Yuan was awarded a postgraduate scholarship by Natural Science and Engineering Research Council of Canada during 1997–1998, the Teaching Excellence Award by Changzhou Institute of Technology in 1988, and the Dean's Research Excellence Award and the Ryerson Research Chair Award in 2004 and 2005, respectively, by Ryerson University. Dr. Yuan is a registered professional engineer in the province of Ontario, Canada. He can be reached at fyuan@ryerson.ca.

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