Understanding Jitter and Phase Noise

A Circuits and Systems Perspective

Gain an intuitive understanding of jitter and phase noise with this authoritative guide. Leading researchers provide expert insights on a wide range of topics, from general theory and the effects of jitter on circuits and systems, to key statistical properties and numerical techniques. Using the tools provided in this book, you will learn how and when jitter and phase noise occur, their relationship with one another, how they can degrade circuit performance, and how to mitigate their effects – all in the context of the most recent research in the field. Examine the impact of jitter in key application areas, including digital circuits and systems, data converters, wirelines, and wireless systems, and learn how to simulate it using the accompanying Matlab code. Supported by additional examples and exercises online, this is a one-stop guide for graduate students and practicing engineers interested in improving the performance of modern electronic circuits and systems.

Nicola Da Dalt is Analog Engineering Manager for High-Speed Serial Interfaces at Intel Corporation, having previously worked at Telecom Italia and Infineon Technologies.

Ali Sheikholeslami is Professor in the Department of Electrical and Computer Engineering at the University of Toronto.

As we continue to push operating speeds in electronic systems, timing jitter has emerged as an increasingly important showstopper across a wide range of applications. Consequently, pushing the envelope requires a thorough understanding of jitter from its mathematical description, to its manifestation in circuits and its impact on systems. This book delivers the most comprehensive treatment of this subject to date and provides valuable content to jitter-plagued engineers at all levels of experience.

Boris Murmann, *Stanford University*

All components generate noise. They give rise to thermal and 1/f noise. All amplifiers and filters have Signal-to-Noise ratio as one of their most important specifications. In oscillators however, noise gives rise to jitter and phase noise. This is why this book is so important. It provides unique insight in the origins and the analysis of these specifications. Many applications are highlighted in the field of data converters, wireless and wireline systems, and a number of digital applications. Examples are the jitter in a CMOS inverter, in a LC oscillator, in a ring oscillator, etc. As a result this book is a necessity for all designers who have to know about noise and its performance limitations.

Willy Sansen, *KU Leuven*

Phase noise is the primary source of performance deterioration in all wireless/wireline communication systems – and yet, dedicated books have been conspicuously absent to date. We are therefore very fortunate that two real experts – Dr. Da Dalt and Professor Sheikholeslami – have finally decided to fill this gap, presenting us with what will become standard reading for anyone desirous to understand the peculiar and often elusive nature of phase noise.

Professor Pietro Andreani, *Lund University*

The rigorous mathematical description of jitter, its link to phase noise as well as its practical impact on different classes of circuits (e.g. digital, wireline, wireless, data converters) are all known as difficult and sometimes obscure topics even for experienced designers. This is the only book that I know which covers all of these subjects, providing at the same time both the intuitive understanding, the Matlab codes are particularly useful from this standpoint, and the appropriate mathematical rigour. The authors, that are two leading experts in the field, have also done a significant effort also in discussing the key findings available in both classical and more recent open literature, not just presenting their own work. I highly recommend this book.

Carlo Samori, *Politecnico di Milano*

This excellent reference provides a wealth of material to satisfy both engineers new to clocking and seasoned veterans that are experts in jitter and phase noise. The authors address all the important aspects of these critical topics and provide great insights for readers.

Samuel M Palermo, *Texas A&M University*

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To our parents,
Giuliana and Guido
Fatemeh and Hadi

Contents

Preface

This book provides a rigorous yet intuitive explanation of jitter and phase noise as they appear in electrical circuits and systems. The book is intended for graduate students and practicing engineers who wish to deepen their understanding of jitter and phase noise, and their properties, and wish to learn methods of simulating, monitoring, and mitigating jitter. It assumes basic knowledge of probability, random variables, and random processes, as taught typically at the third- or fourth-year undergraduate level, or at the graduate level, in electrical and computer engineering.

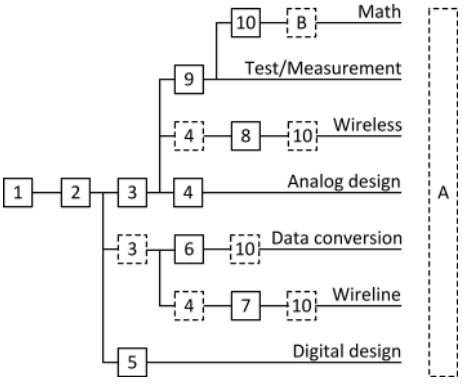
The book is organized as follows: Chapter 1 provides a qualitative overview of the book and its contents. Chapter 2 covers the basics of jitter, including formal definitions of various types of jitter and the key statistical concepts, starting from jitter mean and the standard deviation up to random and deterministic jitter. Phase noise will be first introduced in Chapter 3, and its relation to jitter and to the voltage spectrum of the clock signal will be extensively investigated. In particular, how to derive from phase noise the values of the several jitter types introduced previously will be explained. Chapter 4 is dedicated to the effects of jitter and phase noise in basic circuits and in basic building blocks such as oscillators, frequency dividers, and multipliers. Chapters 5 to 8 discuss the effects of jitter and phase noise in various circuit applications. Chapter 5 is dedicated to the effects of jitter on digital circuits, Chapter 6 to data converters, Chapter 7 to wireline, and Chapter 8 to wireless systems. More advanced topics on jitter are covered in Chapter 9, followed by numerical methods for jitter in Chapter 10. This chapter also explains how to generate jitter and phase noise, with various characteristics, for simulation purposes. The corresponding Matlab code for producing jitter is included in Appendix B.

As mentioned earlier, this book assumes the reader has a basic knowledge of random variables and random processes. However, to refresh the reader's memory of the definitions of some key terms, Appendix A simply lists these key terms along with their basic definitions.

Guidance for the Reader

The book does not require the reader to adhere strictly to the order in which the chapters appear, nor to read all of them. Its structure and the content of each chapter allow different paths to be followed, depending on the particular interests or learning objective of

the reader. The graph below summarizes the possible paths, with the solid boxes indicating strongly recommended chapters and the dashed boxes the suggested additional readings.



While Chapters 1 and 2 form the fundamentals, and thus should be read before any other chapter, the remaining chapters are relatively independent from each other. Chapter 3 introduces the concept of phase noise and its relation to jitter. Even though this chapter constitutes, together with Chapter 8, a required path to the reader active in the wireless field, its contents are relevant to a number of other application fields, among them wireline and jitter testing. For this reason the authors suggest it should be included independently of the particular focus. Chapter 4 is an important reading for analog IC designers, while Chapter 5 addresses specifically the needs of custom digital designers. The latter chapter does not require knowledge of phase noise; thus Chapter 3 could be omitted. Both Chapters 4 and 5 can be skipped by readers interested exclusively in the system or mathematical aspects of jitter and phase noise. Chapters 6 and 7 can be read directly after the first three chapters by readers interested in data converters or wireline communication systems respectively. For the reader whose interest lies in the mathematical treatment of jitter and phase noise, the first three chapters plus Chapter 9 will provide a complete path. Finally, Chapter 10 and Appendix B are suggested reading for students or engineers who want to analyze the effect of jitter and phase noise on systems of any nature by means of transient simulation. The book uses a number of terms from probability and random processes. For ease of reference, we have included these key terms and their brief definitions in Appendix A.

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In writing this book we were fortunate to receive support from numerous professors, colleagues, and friends from both academia and industry. The quality of the book was greatly improved by their innumerable suggestions, questions, and discussions. For this, we sincerely thank and are deeply indebted to Pietro Andreani (Lund University), Yunzhi (Rocky) Dong (Analog Devices), Salvatore Levantino (Politecnico di Milano), Antonio Liscidini (University of Toronto), Gabriele Manganaro (Analog Devices), Boris Murmann (Stanford University), Maurits Ortmanns (Ulm University), Samuel Palermo (Texas A&M University), Behzad Razavi (University of California, Los Angeles), Carlo Samori (Politecnico di Milano), Willy Sansen (KU Leuven), Richard Schreier (Analog Devices), Hossein Shakiba (Huawei), and John Stonick (Synopsys). To them the merit of having made this a better book. The mistakes are all ours.

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