

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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NICOLA DA DALT
Intel Corporation

ALI SHEIKHOESLAMI
University of Toronto

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**To our parents,
Giuliana and Guido
FatemeH and Hadi**

Contents

	<i>Preface</i>	page xiii
	<i>Acknowledgments</i>	xv
1	Introduction to Jitter	1
	1.1 What Is Clock Jitter?	1
	1.1.1 Period Jitter	2
	1.1.2 Absolute Jitter	3
	1.1.3 Intentional Jitter	4
	1.2 What Is Data Jitter?	5
	1.2.1 Eye Diagram	5
	1.2.2 Random Versus Deterministic Jitter	7
	1.3 Jitter in Measuring Time	8
	1.4 Jitter in a Ring Oscillator	10
	1.4.1 Jitter in Delay of a CMOS Inverter	10
	1.4.2 Modeling Jitter of the Ring Oscillator	12
	1.5 Jitter in Electronic Systems	12
2	Basics of Jitter	15
	2.1 General Jitter Terminology and Definitions	15
	2.1.1 Absolute Jitter	17
	2.1.2 Relative Jitter	18
	2.1.3 Period Jitter	18
	2.1.4 <i>N</i> -Period Jitter	20
	2.1.5 Other Jitter Definitions	21
	2.1.6 Summary of Jitter Definitions and Their Relationships	25
	2.2 Statistics on Jitter	25
	2.2.1 Histograms and Probability Density Functions	27
	2.2.2 Jitter Mean	31
	2.2.3 Jitter Median	31
	2.2.4 Jitter Standard Deviation and Variance	32
	2.2.5 Jitter Peak and Peak-Peak	32
	2.2.6 Taxonomy of Jitter Based on PDF	35
	2.2.7 Combination of Jitter Components	37

	2.2.8	Jitter Decomposition	39
	2.2.9	Total Jitter and Probability of Error	40
3		Jitter and Phase Noise	43
	3.1	Basic Relationship Between Jitter and Excess Phase	43
	3.1.1	Excess Phase and Absolute Jitter in the Time Domain	43
	3.1.2	Excess Phase and Absolute Jitter in the Frequency Domain	45
	3.1.3	Voltage to Excess Phase Transformations: Random Noise	46
	3.1.4	Voltage to Excess Phase Transformations: Modulation	49
	3.1.5	Definition of Phase Noise	51
	3.2	From Phase Noise to Jitter	52
	3.2.1	Absolute Jitter	52
	3.2.2	N -Period and Period Jitter	59
	3.3	Spectral Spurious Tones and Jitter	65
	3.4	Superposition of Different Spectral Components	66
	3.5	Summary of Mathematical Relationships Between Jitter and Phase Noise	68
4		Jitter and Phase Noise in Circuits	69
	4.1	Jitter in Basic Circuits	69
	4.1.1	Noisy Current Charging a Capacitor	69
	4.1.2	Jitter of a CMOS Inverter	72
	4.1.3	Jitter of a CMOS Differential Stage	74
	4.2	Jitter in Oscillators	77
	4.2.1	Ring Oscillators	77
	4.2.2	Relaxation Oscillators	78
	4.3	Phase Noise in Oscillators	80
	4.3.1	Leeson's Model	80
	4.3.2	Oscillator Figure of Merit	83
	4.3.3	LC Oscillators	84
	4.3.4	Crystal and Other Oscillators	86
	4.4	Linear Time-Variant Analysis	90
	4.4.1	The Impulse Sensitivity Function	90
	4.4.2	Application to Ring Oscillators	93
	4.4.3	The ISF of an LC Tank	94
	4.4.4	A General Result on Leeson's Noise Factor F for LC Oscillators	96
	4.4.5	Application to Some Common LC Oscillator Topologies	98
	4.5	Comparison of Best Achievable FOM	101
	4.6	A Note on Flicker Noise	103
	4.7	Ideal Frequency Divider	104
	4.8	Ideal Frequency Multiplier	108
5		Effects of Jitter in Synchronous Digital Circuits	111
	5.1	Edge-Triggered Synchronous Design	111

5.2	Gated Clock, Divided Clock, Enabled Systems	114
5.3	Multicycle Paths	116
5.4	Latch-Based Synchronous Design	117
6	Effects of Jitter on Data Converters	121
6.1	Effects of Jitter on Current DACs	121
6.1.1	Background	121
6.1.2	Non-Return-to-Zero (NRZ) IDAC	121
6.1.3	NRZ IDAC Followed by a Linear Filter	124
6.1.4	NRZ IDAC Followed by an Integrating Capacitor	126
6.1.5	Return-to-Zero IDAC	127
6.2	Effects of Jitter on Nyquist Data Converters	128
6.2.1	Background	128
6.2.2	ADC Timing Error	129
6.2.3	Design Considerations	133
6.3	Effects of Timing Skew in Time-Interleaved ADCs	133
6.3.1	Background	134
6.3.2	Effects of Timing Skew	134
6.3.3	Alternative Approach	136
6.3.4	Design Considerations	137
6.4	Effects of Jitter on Continuous-Time $\Delta\Sigma$ Modulators	139
6.4.1	Background	139
6.4.2	Effects of Flash ADC Timing Error on SNR	141
6.4.3	Effects of DAC Timing Error on SNR	141
7	Effects of Jitter in Wireline Applications	143
7.1	Basic Concepts in Wireline Signaling	143
7.2	Jitter in Analog CDR	145
7.2.1	Linear Model of the CDR	145
7.2.2	Jitter Transfer	146
7.2.3	Jitter Generation	150
7.2.4	Jitter Tolerance	151
7.3	Effect of Jitter on Bang-Bang CDR	155
7.3.1	Background	155
7.3.2	Effect of Jitter on BB-PD Gain	157
7.3.3	Added Jitter due to BB-PD	158
7.3.4	Effect of Jitter on BB-CDR Stability	159
7.4	Jitter in the Received Eye	160
7.5	Jitter Amplification by Passive Channels	161
7.6	Jitter Monitoring and Mitigation	163
7.6.1	Eye-Opening Monitor	164
7.6.2	Relative Jitter Measurement	166
7.6.3	Absolute Jitter Measurement	168
7.7	Intentional Jitter	171

x	Contents	
	7.7.1 Jitter Injection for Improved Linearity	171
	7.7.2 Jitter Injection for Jitter Measurement	172
8	Phase Noise in Wireless Applications	174
	8.1 Basics of Wireless Transceivers	174
	8.1.1 Blockers in Wireless Receivers	175
	8.1.2 Noise Figure	176
	8.1.3 Receiver Sensitivity	176
	8.2 Examples of Phase Noise Requirements for the Transmitter VCO	177
	8.3 Reciprocal Mixing at the Receiver	179
9	Advanced Concepts on Jitter and Phase Noise	183
	9.1 A General Method to Convert Phase Noise to Jitter	183
	9.2 Confidence Intervals of Statistical Parameters	184
	9.2.1 Confidence Interval on the Jitter Mean	186
	9.2.2 Confidence Interval on the Jitter Variance and Standard Deviation	188
	9.2.3 Confidence Interval on the Jitter Peak and Peak-Peak Values	191
	9.3 Estimators for Frequency Stability	193
	9.3.1 Basic Concepts	194
	9.3.2 Allan Deviation (ADEV)	195
	9.3.3 Relation Between Allan Deviation and Jitter	195
	9.3.4 Relation Between Allan Deviation and Phase Noise	197
	9.3.5 Modified Allan Deviation (MDEV) and Time Deviation (TDEV)	199
	9.4 An Overview of Flicker Noise	200
	9.5 Lorentian Spectrum of Oscillator Phase Noise	205
10	Numerical Methods	207
	10.1 Numeric Generation of Jitter with Given Phase Noise Profiles	207
	10.1.1 Generation of Jitter Samples with Flat Phase Noise Profile	208
	10.1.2 Generation of Jitter Samples with Low-Pass, High-Pass, or Band-Pass Phase Noise Profiles	208
	10.1.3 Generation of Jitter Samples with $1/f^2$ Phase Noise Profile	208
	10.1.4 Generation of Jitter Samples with $1/f$ and $1/f^3$ Phase Noise Profiles	209
	10.1.5 Generation of Jitter Samples with More Complex Phase Noise Profiles	211
	10.2 Computation of Jitter from Vector of Time Instants	211
	10.3 Computation of Phase Noise Plot from Jitter Samples	214
	10.4 Algorithms for Tail Fitting	214
Appendix A	Review of Random Variables and Processes	220
	A.1 Random Variables	220
	A.1.1 Definition	220
	A.1.2 Distribution and Density Functions	221

A.1.3	Expectation	221
A.1.4	Mean, Variance, and Higher-Order Moments	222
A.1.5	Two Random Variables	223
A.1.6	Independent Random Variables	223
A.1.7	Expectation of a Function of Two Random Variables	224
A.1.8	Correlation and Covariance	224
A.2	Random Processes	225
A.2.1	Definition	225
A.2.2	Classification of Random Processes	225
A.2.3	Mean, Autocorrelation, and Autocovariance	225
A.2.4	Stationary Processes	226
A.2.5	Wide-Sense Cyclostationary Processes	227
A.2.6	Gaussian Processes	227
A.2.7	Power Spectral Density and the Wiener–Khinchin Theorem	227
A.2.8	Engineering Definitions of the Power Spectral Density	228
A.2.9	The Physical Meaning of the Power Spectral Density	230
A.2.10	Random Processes and Linear Systems	231
A.2.11	Ergodicity	232
Appendix B	Matlab Code for Jitter Generation and Analysis	233
B.1	Generation of Jitter	233
B.1.1	Flat Phase Noise Profile	233
B.1.2	Low-Pass, High-Pass, or Band-Pass Phase Noise Profiles	233
B.1.3	$1/f^2$ Phase Noise Profile	234
B.1.4	$1/f$ Phase Noise Profiles	234
B.1.5	$1/f^3$ Phase Noise Profiles	235
B.1.6	More Complex Phase Noise Profiles	236
B.2	Analysis of Jitter	237
B.3	Tail Fitting	239
	<i>Bibliography</i>	242
	<i>Index</i>	249

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Nicola Da Dalt , Ali Sheikholeslami
Frontmatter
[More Information](#)

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.

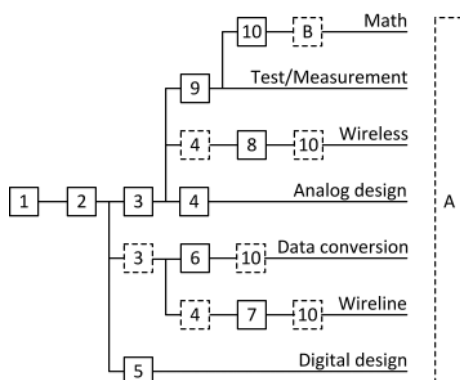
The book is organized as follows: Chapter 1 provides a qualitative overview of the book and its contents. Chapter 2 covers the basics of jitter, including formal definitions of various types of jitter and the key statistical concepts, starting from jitter mean and the standard deviation up to random 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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