The increasingly demanding performance requirements of communications systems, as well as problems posed by the continued scaling of silicon technology, present numerous challenges for the design of frequency synthesizers in modern transceivers.

This book contains everything you need to know for the efficient design of frequency synthesizers for today's communications applications. If you need to optimize performance and minimize design time, you will find this book invaluable.

Using an intuitive yet rigorous approach, the authors describe simple analytical methods for the design of phase-locked loop (PLL) frequency synthesizers using scaled silicon CMOS and bipolar technologies. The entire design process, from system-level specification to layout, is covered comprehensively. Practical design examples are included, and implementation issues are addressed.

A key problem-solving resource for practitioners in integrated-circuit design, the book will also be of interest to researchers and graduate students in electrical engineering.

Andrea Lacaita is Full Professor of Electrical Engineering at the Politecnico di Milano, Italy.

Salvatore Levantino is Assistant Professor of Electrical Engineering at the Politecnico di Milano.

Carlo Samori is Associate Professor of Electrical Engineering at the Politecnico di Milano.
Integrated Frequency Synthesizers for Wireless Systems

Andrea Lacaita, Salvatore Levantino, and Carlo Samori

Politecnico di Milano, Italy
## Contents

**Preface**  
Preface  

**Acknowledgments**  
Acknowledgments  

1 Local oscillator requirements  
1.1 AM and PM signals  
1.2 Effect of phase noise and spurs  
1.3 Frequency accuracy  
1.4 Switching speed  
1.5 References  

2 Phase-locked loops  
2.1 Basics  
2.2 PLL for frequency synthesis  
2.3 Discrete-time and non-linearity effects  
2.4 Spectral purity: spurs and phase noise  
2.5 References  

3 Fractional-\(N\) PLLs  
3.1 Beyond the integer-\(N\) approach  
3.2 Fractional-\(N\) division  
3.3 \( \Delta \Sigma \) control of division factor  
3.4 \( \Delta \Sigma \) fractional-\(N\) PLL  
3.5 References  

4 Electronic oscillators  
4.1 Introduction  
4.2 Principles of LC oscillators  
4.3 Single-transistor oscillators  
4.4 Differential oscillators  
4.5 References  

5 Noise in oscillators  
5.1 Introduction  
5.2 Linear and time-invariant model  
5.3 Noise–power trade-off and scaling issues  

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td>vii</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>viii</td>
</tr>
<tr>
<td>1 Local oscillator requirements</td>
<td>1</td>
</tr>
<tr>
<td>1.1 AM and PM signals</td>
<td>2</td>
</tr>
<tr>
<td>1.2 Effect of phase noise and spurs</td>
<td>6</td>
</tr>
<tr>
<td>1.3 Frequency accuracy</td>
<td>9</td>
</tr>
<tr>
<td>1.4 Switching speed</td>
<td>12</td>
</tr>
<tr>
<td>1.5 References</td>
<td>12</td>
</tr>
<tr>
<td>2 Phase-locked loops</td>
<td>14</td>
</tr>
<tr>
<td>2.1 Basics</td>
<td>14</td>
</tr>
<tr>
<td>2.2 PLL for frequency synthesis</td>
<td>23</td>
</tr>
<tr>
<td>2.3 Discrete-time and non-linearity effects</td>
<td>32</td>
</tr>
<tr>
<td>2.4 Spectral purity: spurs and phase noise</td>
<td>38</td>
</tr>
<tr>
<td>2.5 References</td>
<td>47</td>
</tr>
<tr>
<td>3 Fractional-(N) PLLs</td>
<td>49</td>
</tr>
<tr>
<td>3.1 Beyond the integer-(N) approach</td>
<td>49</td>
</tr>
<tr>
<td>3.2 Fractional-(N) division</td>
<td>50</td>
</tr>
<tr>
<td>3.3 ( \Delta \Sigma ) control of division factor</td>
<td>58</td>
</tr>
<tr>
<td>3.4 ( \Delta \Sigma ) fractional-(N) PLL</td>
<td>65</td>
</tr>
<tr>
<td>3.5 References</td>
<td>72</td>
</tr>
<tr>
<td>4 Electronic oscillators</td>
<td>74</td>
</tr>
<tr>
<td>4.1 Introduction</td>
<td>74</td>
</tr>
<tr>
<td>4.2 Principles of LC oscillators</td>
<td>74</td>
</tr>
<tr>
<td>4.3 Single-transistor oscillators</td>
<td>82</td>
</tr>
<tr>
<td>4.4 Differential oscillators</td>
<td>91</td>
</tr>
<tr>
<td>4.5 References</td>
<td>101</td>
</tr>
<tr>
<td>5 Noise in oscillators</td>
<td>103</td>
</tr>
<tr>
<td>5.1 Introduction</td>
<td>103</td>
</tr>
<tr>
<td>5.2 Linear and time-invariant model</td>
<td>103</td>
</tr>
<tr>
<td>5.3 Noise–power trade-off and scaling issues</td>
<td>105</td>
</tr>
</tbody>
</table>
Contents

5.4 Time-variant models 108
5.5 Application to some practical cases 116
5.6 Additional issues in low-phase-noise design 131
5.7 References 131

6 Reactive components in oscillators 133
   6.1 Introduction 133
   6.2 Integrated inductors 133
   6.3 Inductor topologies 141
   6.4 Integrated varactors 146
   6.5 Switched tuning 153
   6.6 References 155

7 Noise up-conversion in VCOs 157
   7.1 Introduction 157
   7.2 Tuning curve and sensitivity coefficients 157
   7.3 Noise up-conversion from varactors 161
   7.4 Topologies and methods to minimize for up-conversion 166
   7.5 Other mechanisms of noise up-conversion 175
   7.6 References 180

8 Frequency division 182
   8.1 Introduction 182
   8.2 Digital frequency dividers 182
   8.3 Programmable dividers 188
   8.4 Dual-modulus prescalers 193
   8.5 Circuit implementation 198
   8.6 Noise in digital dividers 204
   8.7 References 209

9 Phase comparison 211
   9.1 Introduction 211
   9.2 Phase comparison path 211
   9.3 Phase/frequency detectors 214
   9.4 Charge pump 224
   9.5 Phase-detection noise 229
   9.6 References 234

Index 236
The phase-locked loop (PLL) concept is about 70 years old and a wealth of literature is already available on the subject. Someone may therefore ask why another book about PLLs. The first reason is related to the specific application considered here, namely the silicon integration of frequency synthesizers. Classical texts do not deal in depth with issues related to the design of frequency synthesizers in modern transceivers. In particular, the design guidelines and the performance of some important building blocks and their impact on the whole system are sometimes barely mentioned. The attempt, here, has been instead to provide a broad description of the most typical circuit topologies of voltage-controlled oscillators, frequency dividers and phase and frequency detectors, and to discuss their performance in terms of power consumption, phase noise, spurs, and so forth. A chapter is also devoted to integrated passive components, such as varactors and inductors, since the ability to optimize their performance judiciously is becoming a key skill required of the RF designer.

The second reason is that the book attempts to provide an alternative approach to PLL theory and design. After years of research and study on the subject, the authors propose an analysis methodology that is both rigorous and intuitive. The ability to simplify the picture and to address schematically the impact of complex, often non-linear, effects is a fundamental skill of any good engineer. The PLL is a good training example for the designer. In this respect, the book provides many examples of models, starting from a schematic and simplified description of the circuit operation and then leading to estimates, which are compared with simulation results. These examples are intended not only to provide a deeper insight into complex and intriguing effects, but also to encourage students and young analogue designers to keep exercising the ability to figure out the consequences of technical choices before performing circuit simulations.

The book starts with three chapters addressing the PLL as a system. Chapter 1 points out the typical requirements of the frequency synthesizer in RF systems. Chapter 2 covers some PLL basics. It does not deal with the whole PLL theory, which is analyzed in depth in many classical books. The chapter highlights only the concepts needed for understanding the subsequent topics. Chapter 3 finally analyzes fractional-division PLLs, which are seldom discussed in other texts.

Chapters 4 to 9 are then devoted to discussing in detail the design issues related to the PLL building blocks. Chapters 4 to 7 deal with voltage-controlled oscillators and their practical implementations in bipolar and CMOS technologies, including resonator design and layout. Chapters 8 and 9 are focused on the design of programmable dividers and phase-comparison circuits, including issues related to non-linearities.
The research activity behind this book has been in progress for more than ten years. It was made possible thanks to the financial support provided by the Italian Ministry of Universities and Research and by industry. In this respect, many thanks go to Mario Paparo of STMicroelectronics (Catania, Italy), Maurizio Pagani of Ericsson Lab (Vimodrone, Italy), and to Mihai Banu of the (formerly) Silicon Circuit Research Department of Bell Laboratories (Murray Hill, NJ), for their strong support.

The authors are indebted to all their past graduate students, Mr Francesco Villa, Dr Alfio Zanchi, Dr Andrea Bonfanti, Dr Luca Romanò, Dr Stefano Pellerano, Dr Marco Milani and Dr Luigi Panseri, who shared the excitement of this research and contributed to most of the understanding reported in the following pages. The authors are also extremely grateful to their current Ph.D. students, Paolo Madoglio and Marco Zanuso, who worked out the examples and the simulations, providing critical revisions of the text. Clearly, only the authors are responsible for any errors that may still be present.