Contents

Preface xv

List of Abbreviations xvii

List of Figures xix

List of Tables xxvii

Acknowledgements xxix

1 Introduction 1

1.1 Nonlinearity in Wireless Communication Systems 1

1.1.1 Power Amplifiers 2

1.1.2 Low-Noise Amplifiers (LNAs) 4

1.1.3 Mixers 6

1.2 Nonlinear Distortion in Wireless Systems 6

1.2.1 Adjacent-Channel Interference 8

1.2.2 Modulation Quality and Degradation of System Performance 9

1.2.3 Receiver Desensitization and Cross-Modulation 11

1.3 Modeling and Simulation of Nonlinear Systems 12

1.3.1 Modeling and Simulation in Engineering 12

1.3.2 Modeling and Simulation for Communication System Design 14

1.3.3 Behavioral Modeling of Nonlinear Systems 15

1.3.4 Simulation of Nonlinear Circuits 16

1.4 Organization of the Book 19

1.5 Summary 20

2 Wireless Communication Systems, Standards and Signal Models 21

2.1 Wireless System Architecture 21

2.1.1 RF Transmitter Architectures 23

2.1.2 Receiver Architecture 26

2.2 Digital Signal Processing in Wireless Systems 30

2.2.1 Digital Modulation 31

2.2.2 Pulse Shaping 37
4.3 Complex Baseband Analysis of Nonlinear Systems with Memory
   4.3.1 Volterra Series 94
   4.3.2 Single-Frequency Volterra Models 95
   4.3.3 Wiener-Hammerstein Model 96

4.4 Complex Envelope Analysis with Multiple Bandpass Signals
   4.4.1 Volterra Series 97
   4.4.2 Single-Frequency Volterra Models 99
   4.4.3 Wiener-Hammerstein Model 100
   4.4.4 Multi-Input Single-Output Nonlinear Model 103
   4.4.5 Memoryless Nonlinearity-Power-Series Model 104

4.5 Examples—Response of Power-Series Model to Multiple Signals
   4.5.1 Single Tone 107
   4.5.2 Two-Tone Signal 107
   4.5.3 Single-Bandpass Signal 108
   4.5.4 Two-Bandpass Signals 108
   4.5.5 Single Tone and a Bandpass Signal 109
   4.5.6 Multisines 110
   4.5.7 Multisine Analysis Using the Generalized Power-Series Model 111

4.6 Summary 111

5 Nonlinear Transformation of Random Signals 113

5.1 Preliminaries 114
5.2 Linear Systems with Stochastic Inputs 114
   5.2.1 White Noise 115
   5.2.2 Gaussian Processes 116
5.3 Response of a Nonlinear System to a Random Input Signal 116
   5.3.1 Power-Series Model 116
   5.3.2 Wiener–Hammerstein Models 118

5.4 Response of Nonlinear Systems to Gaussian Inputs 119
   5.4.1 Limiter Model 120
   5.4.2 Memoryless Power-Series Model 123

5.5 Response of Nonlinear Systems to Multiple Random Signals 123
   5.5.1 Power-Series Model 124
   5.5.2 Wiener–Hammerstein Model 126

5.6 Response of Nonlinear Systems to a Random Signal and a Sinusoid 128

5.7 Summary 129

6 Nonlinear Distortion 131

6.1 Identification of Nonlinear Distortion in Digital Wireless Systems 132
6.2 Orthogonalization of the Behavioral Model 134
   6.2.1 Orthogonalization of the Volterra Series Model 136
   6.2.2 Orthogonalization of Wiener Model 137
   6.2.3 Orthogonalization of the Power-Series Model 139

6.3 Autocorrelation Function and Spectral Analysis of the Orthogonalized Model 140
8.8 Simulation of System Performance in MATLAB®
  8.8.1 BER
  8.8.2 Scatter Plots
  8.8.3 Eye Diagrams
8.9 Generation of Communications Signals in MATLAB®
  8.9.1 Narrowband Gaussian Noise
  8.9.2 OFDM Signals
  8.9.3 DS-SS Signals
  8.9.4 Multisine Signals
8.10 Example
8.11 Random Signal Generation in Simulink®
  8.11.1 Random Data Sources
  8.11.2 Random Noise Generators
  8.11.3 Sequence Generators
8.12 Digital Modulation in Simulink®
8.13 Simulation of System Performance in Simulink®
  8.13.1 Example 1: Random Sources and Modulation
  8.13.2 Example 2: CDMA Transmitter
  8.13.3 Simulation of Wireless Standards in Simulink®
8.14 Summary
9 Simulation of Nonlinear Systems in MATLAB®
  9.1 Generation of Nonlinearity in MATLAB®
    9.1.1 Memoryless Nonlinearity
    9.1.2 Nonlinearity with Memory
  9.2 Fitting a Nonlinear Model to Measured Data
    9.2.1 Fitting a Memoryless Polynomial Model to Measured Data
    9.2.2 Fitting a Three-Box Model to Measured Data
    9.2.3 Fitting a Memory Polynomial Model to a Simulated Nonlinearity
  9.3 Autocorrelation and Spectrum Estimation
    9.3.1 Estimation of the Autocorrelation Function
    9.3.2 Plotting the Signal Spectrum
    9.3.3 Power Measurements from a PSD
  9.4 Spectrum of the Output of a Memoryless Nonlinearity
    9.4.1 Single Channel
    9.4.2 Two Channels
  9.5 Spectrum of the Output of a Nonlinearity with Memory
    9.5.1 Three-Box Model
    9.5.2 Memory Polynomial Model
  9.6 Spectrum of Orthogonalized Nonlinear Model
  9.7 Estimation of System Metrics from Simulated Spectra
    9.7.1 Signal-to-Noise and Distortion Ratio (SNDR)
    9.7.2 EVM
    9.7.3 ACPR
  9.8 Simulation of Probability of Error
9.9 Simulation of Noise-to-Power Ratio 268
9.10 Simulation of Nonlinear Noise Figure 271
9.11 Summary 278

10 Simulation of Nonlinear Systems in Simulink® 279
10.1 RF Impairments in Simulink® 280
10.1.1 Communications Blockset 280
10.1.2 The RF Blockset 280
10.2 Nonlinear Amplifier Mathematical Models in Simulink® 283
10.2.1 The “Memoryless Nonlinearity” Block—Communications Blockset 283
10.2.2 Cubic Polynomial Model 284
10.2.3 Hyperbolic Tangent Model 284
10.2.4 Saleh Model 285
10.2.5 Ghorbani Model 285
10.2.6 Rapp Model 285
10.2.7 Example 286
10.2.8 The “Amplifier” Block—The RF Blockset 286
10.3 Nonlinear Amplifier Physical Models in Simulink® 289
10.3.1 “General Amplifier” Block 290
10.3.2 “S-Parameter Amplifier” Block 296
10.4 Measurements of Distortion and System Metrics 297
10.4.1 Adjacent-Channel Distortion 297
10.4.2 In-Band Distortion 297
10.4.3 Signal-to-Noise and Distortion Ratio 300
10.4.4 Error Vector Magnitude 300
10.5 Example: Performance of Digital Modulation with Nonlinearity 301
10.6 Simulation of Noise-to-Power Ratio 302
10.7 Simulation of Noise Figure in Nonlinear Systems 304
10.8 Summary 306

Appendix A Basics of Signal and System Analysis 307
A.1 Signals 308
A.2 Systems 308

Appendix B Random Signal Analysis 311
B.1 Random Variables 312
B.1.1 Examples of Random Variables 312
B.1.2 Functions of Random Variables 312
B.1.3 Expectation 313
B.1.4 Moments 314
B.2 Two Random Variables 314
B.2.1 Independence 315
B.2.2 Joint Statistics 315
B.3 Multiple Random Variables 316
B.4 Complex Random Variables 317
B.5 Gaussian Random Variables 318