Contents

About the Authors xi

Preface xiii

Acknowledgments xv

1 Characterization of Wireless Transmitter Distortions 1
1.1 Introduction 1
1.1.1 RF Power Amplifier Nonlinearity 2
1.1.2 Inter-Modulation Distortion and Spectrum Regrowth 2
1.2 Impact of Distortions on Transmitter Performances 6
1.3 Output Power versus Input Power Characteristic 9
1.4 AM/AM and AM/PM Characteristics 10
1.5 1 dB Compression Point 12
1.6 Third and Fifth Order Intercept Points 15
1.7 Carrier to Inter-Modulation Distortion Ratio 16
1.8 Adjacent Channel Leakage Ratio 18
1.9 Error Vector Magnitude 19
References 21

2 Dynamic Nonlinear Systems 23
2.1 Classification of Nonlinear Systems 23
2.1.1 Memoryless Systems 23
2.1.2 Systems with Memory 24
2.2 Memory in Microwave Power Amplification Systems 25
2.2.1 Nonlinear Systems without Memory 25
2.2.2 Weakly Nonlinear and Quasi-Memoryless Systems 26
2.2.3 Nonlinear System with Memory 27
2.3 Baseband and Low-Pass Equivalent Signals 27

2.4	Origins and Types of Memory Effects in Power Amplification Systems	29
	2.4.1 Origins of Memory Effects	29
	2.4.2 Electrical Memory Effects	30
	2.4.3 Thermal Memory Effects	33
2.5	Volterra Series Models	38
	References	40
3	**Model Performance Evaluation**	**43**
3.1	Introduction	43
3.2	Behavioral Modeling versus Digital Predistortion	43
3.3	Time Domain Metrics	46
	3.3.1 Normalized Mean Square Error	46
	3.3.2 Memory Effects Modeling Ratio	47
3.4	Frequency Domain Metrics	48
	3.4.1 Frequency Domain Normalized Mean Square Error	48
	3.4.2 Adjacent Channel Error Power Ratio	49
	3.4.3 Weighted Error Spectrum Power Ratio	50
	3.4.4 Normalized Absolute Mean Spectrum Error	51
3.5	Static Nonlinearity Cancelation Techniques	52
	3.5.1 Static Nonlinearity Pre-Compensation Technique	52
	3.5.2 Static Nonlinearity Post-Compensation Technique	56
	3.5.3 Memory Effect Intensity	59
3.6	Discussion and Conclusion	61
	References	62
4	**Quasi-Memoryless Behavioral Models**	**63**
4.1	Introduction	63
4.2	Modeling and Simulation of Memoryless/Quasi-Memoryless Nonlinear Systems	63
4.3	Bandpass to Baseband Equivalent Transformation	67
4.4	Look-Up Table Models	69
	4.4.1 Uniformly Indexed Loop-Up Tables	69
	4.4.2 Non-Uniformly Indexed Look-Up Tables	70
4.5	Generic Nonlinear Amplifier Behavioral Model	71
4.6	Empirical Analytical Based Models	73
	4.6.1 Polar Saleh Model	73
	4.6.2 Cartesian Saleh Model	74
	4.6.3 Frequency-Dependent Saleh Model	76
	4.6.4 Ghorbani Model	76
	4.6.5 Berman and Mahle Phase Model	77
	4.6.6 Thomas–Weidner–Durrani Amplitude Model	77
	4.6.7 Limiter Model	78
	4.6.8 ARCTAN Model	79

	4.6.9	*Rapp Model*	81
	4.6.10	*White Model*	82
4.7	Power Series Models		82
	4.7.1	*Polynomial Model*	82
	4.7.2	*Bessel Function Based Model*	83
	4.7.3	*Chebyshev Series Based Model*	84
	4.7.4	*Gegenbauer Polynomials Based Model*	84
	4.7.5	*Zernike Polynomials Based Model*	85
	References		86
5	**Memory Polynomial Based Models**		**89**
5.1	Introduction		89
5.2	Generic Memory Polynomial Model Formulation		90
5.3	Memory Polynomial Model		91
5.4	Variants of the Memory Polynomial Model		91
	5.4.1	*Orthogonal Memory Polynomial Model*	91
	5.4.2	*Sparse-Delay Memory Polynomial Model*	93
	5.4.3	*Exponentially Shaped Memory Delay Profile Memory Polynomial Model*	95
	5.4.4	*Non-Uniform Memory Polynomial Model*	96
	5.4.5	*Unstructured Memory Polynomial Model*	97
5.5	Envelope Memory Polynomial Model		98
5.6	Generalized Memory Polynomial Model		101
5.7	Hybrid Memory Polynomial Model		106
5.8	Dynamic Deviation Reduction Volterra Model		108
5.9	Comparison and Discussion		111
	References		113
6	**Box-Oriented Models**		**115**
6.1	Introduction		115
6.2	Hammerstein and Wiener Models		115
	6.2.1	*Wiener Model*	116
	6.2.2	*Hammerstein Model*	117
6.3	Augmented Hammerstein and Weiner Models		118
	6.3.1	*Augmented Wiener Model*	118
	6.3.2	*Augmented Hammerstein Model*	119
6.4	Three-Box Wiener–Hammerstein Models		120
	6.4.1	*Wiener–Hammerstein Model*	120
	6.4.2	*Hammerstein–Wiener Model*	120
	6.4.3	*Feedforward Hammerstein Model*	121
6.5	Two-Box Polynomial Models		123
	6.5.1	*Models' Descriptions*	123
	6.5.2	*Identification Procedure*	124

6.6 Three-Box Polynomial Models 124
6.6.1 Parallel Three-Blocks Model: PLUME Model 124
6.6.2 Three Layered Biased Memory Polynomial Model 125
6.6.3 Rational Function Model for Amplifiers 127
6.7 Polynomial Based Model with I/Q and DC Impairments 128
6.7.1 Parallel Hammerstein (PH) Based Model for the Alleviation of Various Imperfections in Direct Conversion Transmitters 129
6.7.2 Two-Box Model with I/Q and DC Impairments 129
References 130

7 Neural Network Based Models 133
7.1 Introduction 133
7.2 Basics of Neural Networks 133
7.3 Neural Networks Architecture for Modeling of Complex Static Systems 137
7.3.1 Single-Input Single-Output Feedforward Neural Network (SISO-FFNN) 137
7.3.2 Dual-Input Dual-Output Feedforward Neural Network (DIDO-FFNN) 138
7.3.3 Dual-Input Dual-Output Coupled Cartesian Based Neural Network (DIDO-CC-NN) 139
7.4 Neural Networks Architecture for Modeling of Complex Dynamic Systems 140
7.4.1 Complex Time-Delay Recurrent Neural Network (CTDRNN) 141
7.4.2 Complex Time-Delay Neural Network (CTDNN) 142
7.4.3 Real Valued Time-Delay Recurrent Neural Network (RVTDRNN) 142
7.4.4 Real Valued Time-Delay Neural Network (RVTDNN) 144
7.5 Training Algorithms 147
7.6 Conclusion 150
References 151

8 Characterization and Identification Techniques 153
8.1 Introduction 153
8.2 Test Signals for Power Amplifier and Transmitter Characterization 155
8.2.1 Characterization Using Continuous Wave Signals 155
8.2.2 Characterization Using Two-Tone Signals 156
8.2.3 Characterization Using Multi-Tone Signals 157
8.2.4 Characterization Using Modulated Signals 158
8.2.5 Characterization Using Synthetic Modulated Signals 160
8.2.6 Discussion: Impact of Test Signal on the Measured AM/AM and AM/PM Characteristics 160

8.3 Data De-Embedding in Modulated Signal Based Characterization 163
8.4 Identification Techniques 170
8.4.1 Moving Average Techniques 170
8.4.2 Model Coefficient Extraction Techniques 172
8.5 Robustness of System Identification Algorithms 179
8.5.1 The LS Algorithm 179
8.5.2 The LMS Algorithm 179
8.5.3 The RLS Algorithm 180
8.6 Conclusions 181
References 181

9 Baseband Digital Predistortion 185
9.1 The Predistortion Concept 185
9.2 Adaptive Digital Predistortion 188
9.2.1 Closed Loop Adaptive Digital Predistorters 188
9.2.2 Open Loop Adaptive Digital Predistorters 189
9.3 The Predistorter's Power Range in Indirect Learning Architectures 191
9.3.1 Constant Peak Power Technique 193
9.3.2 Constant Average Power Technique 193
9.3.3 Synergetic CFR and DPD Technique 194
9.4 Small Signal Gain Normalization 194
9.5 Digital Predistortion Implementations 201
9.5.1 Baseband Digital Predistortion 201
9.5.2 RF Digital Predistortion 204
9.6 The Bandwidth and Power Scalable Digital Predistortion Technique 205
9.7 Summary 206
References 207

10 Advanced Modeling and Digital Predistortion 209
10.1 Joint Quadrature Impairment and Nonlinear Distortion Compensation Using Multi-Input DPD 209
10.1.1 Modeling of Quadrature Modulator Imperfections 210
10.1.2 Dual-Input Polynomial Model for Memoryless Joint Modeling of Quadrature Imbalance and PA Distortions 211
10.1.3 Dual-Input Memory Polynomial for Joint Modeling of Quadrature Imbalance and PA Distortions Including Memory Effects 212
10.1.4 Dual-Branch Parallel Hammerstein Model for Joint Modeling of Quadrature Imbalance and PA Distortions with Memory 213
10.1.5 Dual-Conjugate-Input Memory Polynomial for Joint Modeling of Quadrature Imbalance and PA Distortions Including Memory Effects 216

10.2 Modeling and Linearization of Nonlinear MIMO Systems 216
10.2.1 Impairments in MIMO Systems 216
10.2.2 Crossover Polynomial Model for MIMO Transmitters 221
10.2.3 Dual-Input Nonlinear Polynomial Model for MIMO Transmitters 222
10.2.4 MIMO Transmitters Nonlinear Multi-Variable Polynomial Model 223
10.3 Modeling and Linearization of Dual-Band Transmitters 227
10.3.1 Generalization of the Polynomial Model to the Dual-Band Case 228
10.3.2 Two-Dimensional (2-D) Memory Polynomial Model for Dual-Band Transmitters 230
10.3.3 Phase-Aligned Multi-band Volterra DPD 231
10.4 Application of MIMO and Dual-Band Models in Digital Predistortion 235
10.4.1 Linearization of MIMO Systems with Nonlinear Crosstalk 236
10.4.2 Linearization of Concurrent Dual-Band Transmitters Using a 2-D Memory Polynomial Model 238
10.4.3 Linearization of Concurrent Tri-Band Transmitters Using 3-D Phase-Aligned Volterra Model 240
References 242

Index **247**