Electronic Warfare Receivers and Receiving Systems

Richard A. Poisel
# Table of Contents

Preface xxi

Chapter 1 Receiving Systems and Receiving System Architectures 1
  1.1 Introduction 1
  1.2 Electronic Support Systems 2
    1.2.1 Electronic Support 2
    1.2.2 Command and Control 3
  1.3 The Electromagnetic Spectrum 4
  1.4 Receiving System Architectures 4
    1.4.1 Fundamental Receiving System Model 5
  1.5 Monitor Receivers 8
    1.5.1 Concept of the Superhet Receiver 8
  1.6 Search Receiver Architectures 10
    1.6.1 Scanning Narrowband Receiver 10
    1.6.2 Compressive Receiver 11
    1.6.3 Digital Transform Receiver 14
    1.6.4 Receiver Considerations 15
  1.7 Key System Performance Parameters 16
    1.7.1 Noise Figure 16
    1.7.2 Sensitivity 17
    1.7.3 Selectivity 17
    1.7.4 Dynamic Range 17
    1.7.5 Other Significant Parameters 17
  1.8 Spread Spectrum 18
    1.8.1 FHSS 19
    1.8.2 DSSS 19
    1.8.3 THSS 19
  1.9 Collection Management 20
    1.9.1 The Collection Management Process 20
  1.10 Concluding Remarks 22

Appendix 1.A Collection Management Process Output Products 23
  1.A.1 Asset Evaluation Worksheet 23
  1.A.2 Intelligence Synchronization Matrix 23
## Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4.8 LNA Nonlinearity Model</td>
<td>140</td>
</tr>
<tr>
<td>3.5 Noise Reduction with an Input Transformer</td>
<td>142</td>
</tr>
<tr>
<td>3.6 Band Select Filtering/Preselector Filters</td>
<td>145</td>
</tr>
<tr>
<td>3.6.1 Roofing Filters</td>
<td>146</td>
</tr>
<tr>
<td>3.7 Concluding Remarks</td>
<td>147</td>
</tr>
<tr>
<td>References</td>
<td>147</td>
</tr>
<tr>
<td>Chapter 4 Bandwidth Expansion for Small Signal Amplifiers</td>
<td>149</td>
</tr>
<tr>
<td>4.1 Introduction</td>
<td>149</td>
</tr>
<tr>
<td>4.2 Shunt Peaking</td>
<td>150</td>
</tr>
<tr>
<td>4.3 Input and Output Matching</td>
<td>153</td>
</tr>
<tr>
<td>4.3.1 Bandwidth Enhancement for Transimpedance Amplifiers</td>
<td>153</td>
</tr>
<tr>
<td>4.3.2 Limits to Bandwidth Enhancement</td>
<td>153</td>
</tr>
<tr>
<td>4.4 Lossy Matching</td>
<td>161</td>
</tr>
<tr>
<td>4.4.1 Performance Parameters</td>
<td>161</td>
</tr>
<tr>
<td>4.4.2 Practical Considerations</td>
<td>167</td>
</tr>
<tr>
<td>4.4.3 Summary</td>
<td>167</td>
</tr>
<tr>
<td>4.5 Feedback</td>
<td>167</td>
</tr>
<tr>
<td>4.5.1 Shunt-Series Feedback</td>
<td>167</td>
</tr>
<tr>
<td>4.5.2 Shunt Feedback</td>
<td>170</td>
</tr>
<tr>
<td>4.5.3 Bandwidth Extension</td>
<td>171</td>
</tr>
<tr>
<td>4.6 Balanced Amplifiers</td>
<td>172</td>
</tr>
<tr>
<td>4.6.1 Coupling</td>
<td>176</td>
</tr>
<tr>
<td>4.7 Distributed Amplifier</td>
<td>183</td>
</tr>
<tr>
<td>4.8 Concluding Remarks</td>
<td>185</td>
</tr>
<tr>
<td>References</td>
<td>186</td>
</tr>
<tr>
<td>Chapter 5 RF Mixers and Mixing</td>
<td>189</td>
</tr>
<tr>
<td>5.1 Introduction</td>
<td>189</td>
</tr>
<tr>
<td>5.2 RF Mixers</td>
<td>190</td>
</tr>
<tr>
<td>5.2.1 Introduction</td>
<td>190</td>
</tr>
<tr>
<td>5.2.2 Nonlinear Mixers</td>
<td>191</td>
</tr>
<tr>
<td>5.2.3 Analog Mixing</td>
<td>192</td>
</tr>
<tr>
<td>5.2.4 Large Signal Mixer Performance</td>
<td>193</td>
</tr>
<tr>
<td>5.2.5 Switching or Sampling Mixers</td>
<td>197</td>
</tr>
<tr>
<td>5.2.6 Some Passive Mixers</td>
<td>205</td>
</tr>
<tr>
<td>5.2.7 Some Active Mixers</td>
<td>211</td>
</tr>
<tr>
<td>5.2.8 Isolation</td>
<td>218</td>
</tr>
<tr>
<td>5.2.9 Conversion Gain</td>
<td>218</td>
</tr>
<tr>
<td>5.2.10 Mixer Noise</td>
<td>219</td>
</tr>
<tr>
<td>5.2.11 Image Reject Filtering</td>
<td>220</td>
</tr>
<tr>
<td>5.2.12 Summary</td>
<td>231</td>
</tr>
<tr>
<td>5.3 Local Oscillators</td>
<td>231</td>
</tr>
</tbody>
</table>
5.3.1 Characteristics of Feedback 233
5.3.2 Fundamental Oscillator Types 238
5.3.3 Crystal Oscillators 240
5.3.4 Microelectromechanical Oscillators 245
5.3.5 Phase Locked Loops 246
5.3.6 Frequency Synthesizers 255
5.3.7 Oscillator Phase Noise 260
5.3.8 Oscillator Stability 269
5.4 Concluding Remarks 271
References 271

Chapter 6 IF Amplifiers 273
6.1 Introduction 273
6.2 Amplifier Input and Output Impedances and Gain 273
6.3 RF Amplifiers 277
6.3.1 EW RF Amplifier Analysis 277
6.3.2 BJT IF Amplifiers 285
6.3.3 MOSFET High Frequency Amplifiers 286
6.3.4 Frequency Response of RF Amplifiers 287
6.3.5 Microwave Tubes 290
6.4 Transformer Coupling 291
6.5 Automatic Gain Control 293
6.5.1 Introduction 293
6.5.2 VGA Types 294
6.5.3 Loop Dynamics 296
6.5.4 Detector Types 296
6.5.5 Operating Level of Detector 299
6.6 Concluding Remarks 300
References 300

Chapter 7 IF Filters 301
7.1 Introduction 301
7.2 Filters and Signals 302
7.3 Basic Filter Types 303
7.3.1 Transfer Functions 303
7.3.2 Brick-Wall Filter 309
7.3.3 Bandpass 310
7.3.4 Notch or Bandstop 311
7.3.5 Lowpass 313
7.3.6 Highpass 314
7.3.7 All-Pass or Phase-Shift 315
7.3.8 Higher-Order Filters 316
7.4 Filter Approximations 319
### Table of Contents

7.4.1 Introduction 319  
7.4.2 Butterworth 322  
7.4.3 Chebyshev 323  
7.4.4 Bessel 327  
7.4.5 Elliptic (Cauer) 330  
7.5 Approaches to Implementing Filters 331  
7.5.1 Passive Filters 332  
7.5.2 Surface Acoustic Wave Filters 347  
7.5.3 Crystal Filters 350  
7.5.4 Ceramic RF and IF Filters 356  
7.5.5 MEMS RF Filters 359  
7.6 Concluding Remarks 362  
References 362

Chapter 8 Narrowband Receivers 363  
8.1 Introduction 363  
8.2 Superheterodyne Receivers 364  
8.2.1 Superheterodyne Receiver History 365  
8.2.2 Mixing and the Superhet Receiver 366  
8.2.3 Images in the Superhet Receiver 366  
8.2.4 IF Frequencies 366  
8.2.5 Superhet Receiver Block Diagram 368  
8.3 Homodyne (Zero-IF) Receiver 373  
8.3.1 Concept of the DCR 373  
8.3.2 Overview of DC Offsets in DCRs 375  
8.3.3 Noise in Direct Conversion Receivers 377  
8.4 Tuned Radio Frequency Receivers 378  
8.5 Concluding Remarks 380  
References 380

Chapter 9 Compressive Receivers 381  
9.1 Introduction 381  
9.2 Compressive Receiver Configurations 381  
9.2.1 C-M-C and M-C-M Configurations 383  
9.3 Fundamentals of CxRx Operation 384  
9.3.1 The M(s)-C(l)-M Arrangement 385  
9.4 Dispersive Delay Lines 387  
9.4.1 Limitations of Practical SAW Devices 389  
9.5 M-C CxRx Operation 390  
9.5.1 Swept Local Oscillator 393  
9.5.2 Frequency Resolution 395  
9.5.3 Frequency Accuracy 397  
9.5.4 Sensitivity and Compression Time 397
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5.5</td>
<td>Simultaneous Signal Detection</td>
<td>399</td>
</tr>
<tr>
<td>9.5.6</td>
<td>CxRx Response</td>
<td>399</td>
</tr>
<tr>
<td>9.6</td>
<td>The C-M-C Chirp Transform Arrangement</td>
<td>406</td>
</tr>
<tr>
<td>9.7</td>
<td>Concluding Remarks</td>
<td>407</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>408</td>
</tr>
<tr>
<td>10.1</td>
<td>Introduction</td>
<td>409</td>
</tr>
<tr>
<td>10.2</td>
<td>Digital Receiver Architectures</td>
<td>410</td>
</tr>
<tr>
<td>10.2.1</td>
<td>Narrowband Digital Receiver</td>
<td>410</td>
</tr>
<tr>
<td>10.2.2</td>
<td>Digital RF Architecture</td>
<td>412</td>
</tr>
<tr>
<td>10.2.3</td>
<td>IF Sampling Topology</td>
<td>412</td>
</tr>
<tr>
<td>10.2.4</td>
<td>Electronic Warfare Digital Receiver</td>
<td>413</td>
</tr>
<tr>
<td>10.3</td>
<td>Digital Receiver Technology Drivers</td>
<td>414</td>
</tr>
<tr>
<td>10.3.1</td>
<td>Analog-to-Digital Converter</td>
<td>414</td>
</tr>
<tr>
<td>10.3.2</td>
<td>Digital Signal Processor</td>
<td>414</td>
</tr>
<tr>
<td>10.4</td>
<td>Elementary Introduction to RF/IF Digital Signal Processing</td>
<td>415</td>
</tr>
<tr>
<td>10.4.1</td>
<td>Frequency-Domain Ambiguity</td>
<td>416</td>
</tr>
<tr>
<td>10.4.2</td>
<td>Quadrature Signals</td>
<td>418</td>
</tr>
<tr>
<td>10.4.3</td>
<td>Summary</td>
<td>424</td>
</tr>
<tr>
<td>10.5</td>
<td>Digital EW Receivers</td>
<td>424</td>
</tr>
<tr>
<td>10.5.1</td>
<td>Introduction</td>
<td>424</td>
</tr>
<tr>
<td>10.5.2</td>
<td>Single-Signal versus Multisignal</td>
<td>425</td>
</tr>
<tr>
<td>10.5.3</td>
<td>Benefits of Implementing a Digital Receiver</td>
<td>425</td>
</tr>
<tr>
<td>10.5.4</td>
<td>Receiver Performance Expectations</td>
<td>430</td>
</tr>
<tr>
<td>10.5.5</td>
<td>Available Noise Power</td>
<td>430</td>
</tr>
<tr>
<td>10.5.6</td>
<td>Cascaded Noise Figure</td>
<td>431</td>
</tr>
<tr>
<td>10.5.7</td>
<td>Noise Figures and ADCs</td>
<td>432</td>
</tr>
<tr>
<td>10.5.8</td>
<td>Conversion Gain and Sensitivity</td>
<td>433</td>
</tr>
<tr>
<td>10.5.9</td>
<td>ADC Spurious Signals and Dither</td>
<td>435</td>
</tr>
<tr>
<td>10.5.10</td>
<td>Third-Order Intercept Point</td>
<td>437</td>
</tr>
<tr>
<td>10.5.11</td>
<td>ADC Clock Jitter</td>
<td>438</td>
</tr>
<tr>
<td>10.5.12</td>
<td>Phase Noise</td>
<td>440</td>
</tr>
<tr>
<td>10.5.13</td>
<td>Summary</td>
<td>441</td>
</tr>
<tr>
<td>10.6</td>
<td>Gain and Phase Imbalance</td>
<td>442</td>
</tr>
<tr>
<td>10.7</td>
<td>Concluding Remarks</td>
<td>443</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>444</td>
</tr>
<tr>
<td>11.1</td>
<td>Introduction</td>
<td>445</td>
</tr>
<tr>
<td>11.2</td>
<td>Wideband Receivers</td>
<td>446</td>
</tr>
<tr>
<td>11.2.1</td>
<td>Channelized</td>
<td>448</td>
</tr>
<tr>
<td>11.3</td>
<td>Sampling Methods and Analog Filtering</td>
<td>448</td>
</tr>
</tbody>
</table>

Chapter 11 Sampling and Analog-to-Digital Converters 445

11.1 Introduction 445

11.2 Wideband Receivers 446

11.2.1 Channelized 448

11.3 Sampling Methods and Analog Filtering 448
11.3.1 Nyquist Sampling 449  
11.3.2 Bandpass Sampling 453  
11.4 Effects of Quantization Noise, Distortion, and Receiver Noise 458  
  11.4.1 Introduction 458  
  11.4.2 ADC Transfer Function 459  
  11.4.3 Input-Referenced Noise 459  
  11.4.4 Theoretical Signal-to-Noise Ratio 460  
  11.4.5 Practical Specifications for Real ADCs 461  
  11.4.6 ADC Noises 461  
  11.4.7 Spurious-Free Dynamic Range 472  
  11.4.8 Noise Power Ratio 475  
11.5 Flash ADC 476  
  11.5.1 Flash ADC Architecture 477  
  11.5.2 Sparkle Codes 478  
  11.5.3 Metastability 478  
  11.5.4 Input Signal Frequency Dependence 478  
11.6 Sigma-Delta ADCs 479  
  11.6.1 Introduction 479  
  11.6.2 Σ-Δ ADC Operation 480  
  11.6.3 Higher Order Loop Considerations 484  
  11.6.4 Multibit Sigma-Delta Converters 486  
  11.6.5 Bandpass Sigma-Delta Converters 486  
11.7 Flash ADC versus Other ADC Architectures 487  
  11.7.1 Flash versus SAR ADCs 487  
  11.7.2 Flash versus Pipelined ADCs 488  
  11.7.3 Flash versus Integrating ADCs 489  
  11.7.4 Flash versus Sigma-Delta ADCs 489  
  11.7.5 Flash ADC Architectural Tradeoffs 490  
  11.7.6 Flash Converter Characteristics 492  
  11.7.7 Summary 492  
11.8 Other Sampling and ADC Considerations 492  
  11.8.1 Ease of ADC Implementation 492  
  11.8.2 Linearity 492  
  11.8.3 Power Consumption, Circuit Complexity, Chip Area, and Reconfigurability 493  
11.9 Concluding Remarks 493  
References 494

Chapter 12 Digital Filtering 497  
12.1 Introduction 497  
  12.1.1 Advantages of Using Digital Filters 498  
  12.1.2 Disadvantages of Digital Filters 499  
12.2 Operation of Digital Filters 500
12.3 Simple Digital Filters 501
  12.3.1 Order of a Digital Filter 503
  12.3.2 Digital Filter Coefficients 503
12.4 Recursive and Nonrecursive Filters 505
  12.4.1 Impulse Response 505
  12.4.2 Lowpass FIR Filter 507
  12.4.3 Order of an IIR Filter 509
  12.4.4 Example of a Recursive Filter 510
  12.4.5 Coefficients of IIR Digital Filters 511
12.5 The Transfer Function of a Digital Filter 512
  12.5.1 The Frequency Response of Digital Filters 515
12.6 Multirate Processing of Bandpass and I/Q Signals 517
  12.6.1 Decimation or Downsampling with Complex Signals 518
  12.6.2 Interpolation or Upsampling with Complex Signals 518
  12.6.3 Efficient Polyphase Structures 518
12.7 Hilbert Transform and Delay 526
  12.7.1 Filtering Effect of the Delay Processing 528
12.8 Concluding Remarks 534
References 535

Chapter 13 Digital Demodulation 537
13.1 Introduction 537
13.2 Digital I/Q Demodulation 537
  13.2.1 Introduction 537
  13.2.2 I/Q Demodulation 538
13.3 Direct IF Digital Demodulator 540
  13.3.1 Digital Signal Processing without the Digital Signal Processor 540
  13.3.2 I/Q Sampling 541
  13.3.3 Vector Representation 548
  13.3.4 Undersampling 548
13.4 Direct IF-Processing Elements 548
  13.4.1 A/D Converter/IF Sampler 549
  13.4.2 Digital IF Sample to I/Q Vector Conversion 549
  13.4.3 I/Q Vector to Phase Conversion 551
  13.4.4 Vector Magnitude: AM Detection 552
  13.4.5 Summary 552
13.5 I/Q Imbalance Compensation 553
  13.5.1 Baseband Signal Model for Digital Imbalance Compensation 553
  13.5.2 Adaptive Interference Cancellation (IC)-Based Compensation 555
  13.5.3 Summary 555
# Table of Contents

13.5.4 Verification and Validation 556  
13.6 Concluding Remarks 558  
References 558

Chapter 14 Digital-to-Analog Converters 561  
14.1 Introduction 561  
14.2 Digital-to-Analog Converter Architectures 562  
14.2.1 DAC Transfer Function 562  
14.2.2 String DAC 563  
14.2.3 Fully Decoded DACs 567  
14.2.4 Time Reference Divider 573  
14.2.5 Oversampling DACs 574  
14.2.6 Sigma-Delta DACs 575  
14.2.7 Current-to-Voltage Converters 576  
14.3 Error Sources in DACs 578  
14.3.1 Static Error Sources 578  
14.3.2 Dynamic Error Sources 580  
14.4 Reconstruction Filters 585  
14.5 Concluding Remarks 586  
Appendix 14.A Semiconductor Current Sources and Switches 588  
14.A.1 Semiconductor Current Sources 588  
14.A.2 Semiconductor Switches 589  
14.A.3 Transistors as Current Source and Switch 590  
References 590

Chapter 15 Direct Digital Converters 593  
15.1 Introduction 593  
15.2 Digital Receivers 593  
15.3 Digital Downconverters 598  
15.3.1 Introduction 598  
15.3.2 Digital Downconverters 600  
15.4 Polyphase Filter Banks 610  
15.4.1 Introduction 610  
15.4.2 Polyphase Bandwidth, Spectral Spacing, and Output Sample Rates 611  
15.4.3 Computational Complexity 612  
15.5 Concluding Remarks 614  
Appendix 15.A Direct Digital Synthesis 615  
15.A.1 Phase Truncation 615  
15.A.2 Direct Digital Synthesis 616  
References 619

Chapter 16 Spread Spectrum Techniques 621
Chapter 18 Receivers for Frequency Hopped Spread Spectrum Intercept

18.1 Introduction

18.1.1 Signal Detection

18.2 Optimal Receivers for Frequency Hopped Spread Spectrum Interception

18.3 Detection of Frequency Hopped Spread Spectrum Signals with Filter Bank Combiners

18.4 Scanning Superhet for Frequency Hopped Spread Spectrum Target Detection

18.5 Compressive Receivers for Frequency Hopped Spread Spectrum Interception

18.6 Concluding Remarks

References

Chapter 19 Receivers for Time Hopped Spread Spectrum Intercept

19.1 Introduction

19.2 Detecting UWB Signals

19.2.1 Modulations

19.2.2 Required SNR Measure of Effectiveness

19.2.3 Ratio of Distance-Measure of Effectiveness

19.3 Concluding Remarks

References

Chapter 20 Direction Finding Receivers
20.1 Introduction 733
20.2 Direction of Arrival 734
20.3 Direction Finding Techniques Overview 735
   20.3.1 The Adcock Array and the Watson-Watt System 735
   20.3.2 PseudoDoppler Direction Finding System Overview 744
   20.3.3 Phase Interferometer System Overview 747
20.4 Error Sources in Direction Finding Systems 749
   20.4.1 Polarization-Induced Error 749
   20.4.2 DF Errors Caused by Incoherent Wave Interference 750
   20.4.3 DF Errors Caused by Coherent Wave Interference (Multipath) 751
   20.4.4 Modulation 752
   20.4.5 Physical Antenna Arrangement 752
   20.4.6 Receiver Noise 752
   20.4.7 Amplitude Matching and Phase Tracking 752
   20.4.8 Antenna Element Interaction 753
   20.4.9 Antenna Height above Ground 755
20.5 Adcock/Watson-Watt (Four-Element Adcock) 756
   20.5.1 Natural Direction Finding Error of the Adcock 759
   20.5.2 Adcock Direction Finding Errors Caused by Reflections (Coherent Wave Interference) 760
   20.5.3 Adcock Incoherent Interference 761
   20.5.4 Adcock Polarization Error 762
   20.5.5 Adcock/Watson-Watt Errors Due to Receiver Noise 762
   20.5.6 Amplitude Matching with Adcock Direction Finding 763
   20.5.7 Phase Errors with the Adcock Direction Finding 763
   20.5.8 Adcock/Watson-Watt Modulation-Induced Errors 764
   20.5.9 Interaction of the Adcock Antenna Elements 765
   20.5.10 Geometrical Errors of the Adcock Antenna 765
20.6 PseudoDoppler Systems 766
   20.6.1 Output Harmonics 768
   20.6.2 Other Receiver Implications 769
   20.6.3 Polarization-Induced Errors 769
   20.6.4 Doppler Coherent Wave Interference 770
   20.6.5 Doppler Incoherent Interference 770
   20.6.6 Doppler Errors due to Receiver Noise 770
   20.6.7 Tracking and Matching for Doppler Direction Finding 771
   20.6.8 Direction Finding Errors Caused by the Group Delay of the Doppler Direction Finding Receiver 771
   20.6.9 Doppler Direction Finding Errors Caused by Modulation 772
   20.6.10 Interaction of the Doppler Antenna Elements 773
   20.6.11 Geometrical Errors of the Doppler Antenna 774
20.7 Phase Interferometers 775
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.7.1</td>
<td>Four-Element Interferometer</td>
<td>779</td>
</tr>
<tr>
<td>20.7.2</td>
<td>Modulation-Induced Errors</td>
<td>783</td>
</tr>
<tr>
<td>20.7.3</td>
<td>Tracking Imbalance-Induced Errors</td>
<td>783</td>
</tr>
<tr>
<td>20.7.4</td>
<td>Polarization Induced-Errors</td>
<td>784</td>
</tr>
<tr>
<td>20.7.5</td>
<td>Antenna Interaction-Induced Errors</td>
<td>784</td>
</tr>
<tr>
<td>20.7.6</td>
<td>Geometrical Misplacement-Induced Errors</td>
<td>784</td>
</tr>
<tr>
<td>20.7.7</td>
<td>Coherent Interference</td>
<td>784</td>
</tr>
<tr>
<td>20.7.8</td>
<td>Incoherent Interference</td>
<td>785</td>
</tr>
<tr>
<td>20.8</td>
<td>Dual Channel Compressive Receivers for Direction Finding</td>
<td>785</td>
</tr>
<tr>
<td>20.8.1</td>
<td>Phase Processor</td>
<td>785</td>
</tr>
<tr>
<td>20.8.2</td>
<td>Phase Measurements</td>
<td>787</td>
</tr>
<tr>
<td>20.8.3</td>
<td>Butler Matrix</td>
<td>787</td>
</tr>
<tr>
<td>20.8.4</td>
<td>Receiver Implications</td>
<td>788</td>
</tr>
<tr>
<td>20.9</td>
<td>Concluding Remarks</td>
<td>789</td>
</tr>
<tr>
<td>Appendix 20.A</td>
<td>RMS and RSS in Error Analysis</td>
<td>790</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>791</td>
</tr>
</tbody>
</table>

List of Acronyms

About the Author

Index