

Gabriel Vasilescu

Electronic Noise and Interfering Signals

Principles and Applications

With 385 Figures and 58 Tables

 Springer

Contents

| | | |
|----------|--|----|
| 1 | Introduction | 1 |
| 1.1 | Noise Definitions | 1 |
| 1.1.1 | Traditional Definitions | 1 |
| 1.1.2 | Definitions Pertinent to Particular Fields | 3 |
| 1.2 | Overview | 4 |
| 1.2.1 | Intrinsic Noise | 4 |
| 1.2.2 | Extrinsic Noise | 5 |
| 1.3 | Comparing Intrinsic and Extrinsic Noise | 5 |
| 1.3.1 | General Properties | 5 |
| 1.3.2 | Bandwidth | 6 |
| 1.3.3 | Amplitude | 6 |
| 1.3.4 | Noise Calculation | 6 |
| 1.3.5 | Low-Noise Design | 7 |
| 1.3.6 | Noise Immunity | 7 |
| 1.4 | Why Is Noise a Concern? | 8 |
| 1.4.1 | Noise in Communication Systems | 9 |
| 1.4.2 | Noise in Industrial Applications | 10 |
| 1.4.3 | Benefits of Noise | 11 |
| 1.4.4 | Conclusion | 12 |

Part I Intrinsic Noise

| | | |
|----------|--|----|
| 2 | Fundamental Concepts | 15 |
| 2.1 | Introduction | 15 |
| 2.2 | Fluctuations: Signal Theory Approach | 16 |
| 2.2.1 | Average Value | 17 |
| 2.2.2 | Mean Square Value | 18 |
| 2.2.3 | Form Factor | 20 |
| 2.2.4 | Peak Factor | 20 |
| 2.2.5 | Correlation | 20 |

| | | |
|----------|---|-----------|
| 2.3 | Fluctuations: Probabilistic Approach | 23 |
| 2.3.1 | One Random Variable | 23 |
| 2.3.2 | Two Random Variables | 29 |
| 2.3.3 | Energy and Power Spectra | 33 |
| 2.3.4 | Fourier Analysis of Fluctuations | 35 |
| 2.3.5 | Correlation Matrix | 39 |
| 3 | Physical Noise Sources | 45 |
| 3.1 | Introduction | 45 |
| 3.2 | Noise Sources | 46 |
| 3.2.1 | Thermal Noise | 46 |
| 3.2.2 | Diffusion Noise | 51 |
| 3.2.3 | Shot Noise | 52 |
| 3.2.4 | Quantum Noise | 56 |
| 3.2.5 | Generation-Recombination Noise (G-R Noise) | 58 |
| 3.2.6 | 1/f Noise (Flicker Noise or Excess Noise) | 60 |
| 3.2.7 | Popcorn (Burst) Noise | 64 |
| 3.2.8 | Avalanche Noise | 65 |
| 3.3 | Conclusion | 67 |
| 4 | Noise Parameters | 69 |
| 4.1 | Introduction | 69 |
| 4.2 | Definitions Concerning Electrical Power and Bandwidth | 70 |
| 4.2.1 | Normalized Power | 70 |
| 4.2.2 | Various Definitions of Power | 72 |
| 4.2.3 | Available Power and Available Power Gain | 74 |
| 4.2.4 | Exchangeable Power and Exchangeable Power Gain | 77 |
| 4.2.5 | Various Gain Definitions | 79 |
| 4.2.6 | Noise Bandwidth | 80 |
| 4.3 | Noise Parameters of Linear One-Ports (Spot Values) | 83 |
| 4.3.1 | Equivalent Noise Resistance | 83 |
| 4.3.2 | Equivalent Noise Current | 85 |
| 4.3.3 | Noise Temperature | 85 |
| 4.3.4 | Noise Ratio | 87 |
| 4.3.5 | Noise Equivalent Power (NEP) | 88 |
| 4.3.6 | Signal-to-Noise Ratio (S/N Ratio) | 88 |
| 4.4 | Noise Parameters of Linear One-Ports (Average Values) | 89 |
| 4.5 | Noise Parameters of Linear Two-Ports (Spot Values) | 89 |
| 4.5.1 | Equivalent Input Noise | 89 |
| 4.5.2 | Signal-to-Noise Ratio | 91 |
| 4.5.3 | Input Noise Temperature | 92 |
| 4.5.4 | Operating Noise Temperature | 96 |
| 4.5.5 | Effective Noise Temperature | 97 |
| 4.5.6 | Noise Factor (Noise Figure) | 97 |
| 4.5.7 | Operating Noise Factor | 103 |

| | | |
|----------|---|------------|
| 4.5.8 | Extended Noise Factor | 104 |
| 4.5.9 | Noise Measure | 105 |
| 4.6 | Average Values of Two-Port Noise Parameters | 107 |
| 4.7 | Noise of a Linear Multiport | 108 |
| 4.7.1 | Output Noise Power | 108 |
| 4.7.2 | Input Noise Temperature | 109 |
| 4.7.3 | Operating Noise Temperature | 110 |
| 4.8 | Conclusion | 110 |
| 5 | Noise Analysis of Linear Circuits | 113 |
| 5.1 | Introduction | 113 |
| 5.2 | Noise Models of One-Port Circuits | 114 |
| 5.2.1 | One-Port at Uniform Temperature | 115 |
| 5.2.2 | One-Port at Different Temperatures | 119 |
| 5.2.3 | Conclusion | 121 |
| 5.3 | Time Domain Analysis of Noisy Two-Ports | 121 |
| 5.3.1 | Background | 121 |
| 5.3.2 | Noisy Two-Port | 124 |
| 5.3.3 | Model of Rothe and Dahlke | 125 |
| 5.3.4 | Basic Relationships Among Noise Parameters | 129 |
| 5.4 | Correlation Matrices | 134 |
| 5.4.1 | Linear Two-Port Circuits | 134 |
| 5.4.2 | Linear Multiport Circuits | 140 |
| 5.5 | Conclusion | 142 |
| 6 | Frequency Domain Noise Analysis of Linear Multiports | 143 |
| 6.1 | Introduction | 143 |
| 6.2 | Method of Hillbrand and Russer | 144 |
| 6.2.1 | Description | 144 |
| 6.2.2 | Noise Parameters of an Attenuating Pad | 146 |
| 6.2.3 | Collection of Elementary Passive Circuits | 149 |
| 6.3 | Noise Analysis of Linear Multiport Circuits | 152 |
| 6.4 | Algorithm | 156 |
| 6.5 | Example | 158 |
| 6.5.1 | FET Microwave Amplifier | 158 |
| 6.5.2 | Concluding Remark | 161 |
| 7 | Noise Models of Electronic Devices | 163 |
| 7.1 | Resistor Noise | 163 |
| 7.2 | Capacitor Noise | 169 |
| 7.3 | Inductor Noise | 171 |
| 7.4 | Noise in Junction Diodes | 172 |
| 7.4.1 | Ideal PN Junctions | 172 |
| 7.4.2 | Forward-Biased Diodes | 174 |
| 7.4.3 | Reverse-Biased Diodes | 176 |

| | | |
|--------|--|-----|
| 7.4.4 | PSPICE Model | 177 |
| 7.5 | Battery Noise | 177 |
| 7.6 | Noise in Bipolar Transistors | 178 |
| 7.6.1 | Preliminary Remarks | 179 |
| 7.6.2 | Physical Aspects of Noise | 180 |
| 7.6.3 | Nielsen's Model | 184 |
| 7.6.4 | Hawkins's Model | 186 |
| 7.6.5 | Model of Motchenbacher and Fitchen | 188 |
| 7.6.6 | Fukui Model | 191 |
| 7.6.7 | Model of Voinescu et al. | 195 |
| 7.6.8 | PSPICE Model | 196 |
| 7.6.9 | Conclusion | 198 |
| 7.6.10 | Noise in Heterojunction Bipolar Transistors (HBTs) | 199 |
| 7.7 | Noise of Junction Field Effect Transistors (JFETs) | 202 |
| 7.7.1 | Background | 202 |
| 7.7.2 | Noise Mechanisms | 206 |
| 7.7.3 | Van der Ziel Model | 208 |
| 7.7.4 | Robinson Model | 209 |
| 7.7.5 | Ambrozy Model | 210 |
| 7.7.6 | Bruncke Model | 210 |
| 7.7.7 | PSPICE Model | 212 |
| 7.7.8 | Conclusion | 212 |
| 7.8 | Noise in MOS Transistors | 213 |
| 7.8.1 | Introduction | 213 |
| 7.8.2 | PSPICE Model | 214 |
| 7.8.3 | Model of Nicollini, Pancini, and Pernici | 216 |
| 7.8.4 | Model of Wang, Hellums, and Sodini | 217 |
| 7.8.5 | Lee's Scalable Model | 218 |
| 7.8.6 | Conclusion | 219 |
| 7.9 | Noise of MESFET Transistors | 219 |
| 7.9.1 | Introduction | 219 |
| 7.9.2 | Physical Aspects | 220 |
| 7.9.3 | Bächtold Model | 222 |
| 7.9.4 | Model of Pucel, Haus, and Stutz | 223 |
| 7.9.5 | Fukui Model | 226 |
| 7.9.6 | Podell Model | 228 |
| 7.9.7 | Heinrich Model | 230 |
| 7.9.8 | Model of Escotte and Mollier | 233 |
| 7.9.9 | HSPICE Model | 234 |
| 7.9.10 | Conclusion | 235 |
| 7.10 | Noise of HEMT Transistors | 236 |
| 7.10.1 | Introduction | 236 |
| 7.10.2 | Cappy Model | 239 |
| 7.10.3 | Pospieszalski Model | 240 |
| 7.10.4 | Model of Hickson, Gardner, and Paul | 243 |

| | | |
|--------|--|-----|
| 7.10.5 | Model of Klepser, Bergamaschi, Schefer, Diskus, Patrick, and Bächtold | 245 |
| 7.10.6 | Conclusion | 247 |
| 7.11 | Noise in Operational Amplifiers | 249 |

Part II Interfering Signals

| | | |
|-----------|--|------------|
| 8 | External Noise | 255 |
| 8.1 | External Noise Sources | 256 |
| 8.1.1 | Natural Noise Sources | 256 |
| 8.1.2 | Man-Made Noise Sources | 260 |
| 8.2 | Glossary of Terms | 265 |
| 8.3 | Interference Problem | 267 |
| 8.4 | Coupling Paths | 268 |
| 8.4.1 | Methods of Noise Coupling | 269 |
| 8.4.2 | Coupling Modes | 273 |
| 9 | Interference Reduction Methods | 279 |
| 9.1 | Electromagnetic Shielding | 279 |
| 9.1.1 | Background | 279 |
| 9.1.2 | Circuit Shielding | 286 |
| 9.1.3 | Estimating Shielding Effectiveness | 289 |
| 9.1.4 | Performance Degradation | 290 |
| 9.1.5 | Conclusion | 295 |
| 9.2 | Filtering and Balancing | 295 |
| 9.2.1 | Filtering Interfering Signals | 296 |
| 9.2.2 | Balanced Circuits | 299 |
| 9.3 | Grounding and Bonding | 301 |
| 9.3.1 | Equipment Grounding | 301 |
| 9.3.2 | Noise Related to Grounding | 306 |
| 9.3.3 | Miscellaneous | 308 |
| 9.4 | Proper Use of Cables | 309 |
| 10 | Methods of Reducing Emission of Interfering Signals | 315 |
| 10.1 | Disturbances Associated with Mains Distribution | 316 |
| 10.2 | Noise Arising from DC Power Supplies | 320 |
| 10.2.1 | DC Power Supplies with Full-Wave Rectifiers | 320 |
| 10.2.2 | Voltage Regulators | 322 |
| 10.2.3 | Ungrounded (Floating) Power Supplies | 324 |
| 10.2.4 | Switching-Mode Power Supplies | 325 |
| 10.2.5 | Ripple Filtering | 326 |
| 10.3 | Noise Generated by Mechanical Contact Switching | 327 |
| 10.3.1 | Gas Discharge | 328 |
| 10.3.2 | Arc Discharge | 328 |

| | | |
|-----------|---|------------|
| 10.4 | Noise Emitted by Digital Circuits | 332 |
| 10.4.1 | Introduction | 332 |
| 10.4.2 | Inductive Noise | 334 |
| 10.4.3 | Noise Related to Clock Radiation | 336 |
| 10.4.4 | Reflections Due to Mismatch on the Lines | 338 |
| 10.4.5 | Abrupt Demand for DC Supply Current | 339 |
| 10.5 | Transformer Noise | 340 |
| 10.5.1 | Noise Sources | 340 |
| 10.5.2 | Solutions to Reduce Noise Coupling | 341 |
| 10.6 | Noise Due to Electrostatic Discharge | 343 |
| 10.6.1 | Accumulation of Electrostatic Charge | 344 |
| 10.6.2 | Discharge Phase | 347 |
| 10.6.3 | Prevention and Control | 349 |
| 11 | Interconnection Modeling and Crosstalk | 351 |
| 11.1 | Introduction | 351 |
| 11.2 | Interconnect Modeling | 352 |
| 11.2.1 | Interconnect Resistance | 353 |
| 11.2.2 | Mutual Capacitance and Mutual Inductance | 354 |
| 11.2.3 | Capacitance Estimation | 358 |
| 11.2.4 | Inductance Estimation | 361 |
| 11.2.5 | Modeling a Multiconductor Line | 364 |
| 11.2.6 | Modeling a Trace on a Printed Circuit Board | 366 |
| 11.3 | Crosstalk | 370 |
| 11.3.1 | Basic Concepts | 370 |
| 11.3.2 | Crosstalk Due to Dominant Capacitive Coupling | 371 |
| 11.3.3 | Crosstalk Due to Dominant Inductive Coupling | 373 |
| 11.3.4 | Crosstalk Due to Electromagnetic Coupling | 375 |
| 11.4 | Interconnect Optimization | 380 |
| 11.4.1 | Layout and Printed Circuit Board | 380 |
| 11.4.2 | Managing PCB Optimization | 381 |
| 11.4.3 | Coupling Effects in VLSI Design | 385 |
| 12 | Methods of Increasing Immunity to Interfering Signals | 389 |
| 12.1 | Balancing | 389 |
| 12.2 | Filtering | 393 |
| 12.2.1 | Decoupling Filters | 393 |
| 12.2.2 | Filtering of Wires and Cables | 396 |
| 12.3 | Grounding | 398 |
| 12.4 | Practical Advice on Reducing Noise and Interference at the Circuit Level | 402 |
| 12.4.1 | Interference Control | 403 |
| 12.4.2 | Guidelines for Circuit Design | 404 |
| 12.5 | Increasing System Immunity to Interference: Bluetooth Approach | 408 |

Part III Case Studies

| | | |
|-----------|--|-----|
| 13 | Low-Noise Circuit Design | 413 |
| 13.1 | Introduction | 413 |
| 13.2 | Low-Noise Design Techniques for Low-Frequency Circuits | 415 |
| 13.2.1 | Rules of Low-Noise Design | 415 |
| 13.2.2 | Noise Performance of Amplifiers | 417 |
| 13.2.3 | Noise Matching with a Coupling Transformer | 424 |
| 13.2.4 | Noise Matching by Paralleling Input Devices | 426 |
| 13.2.5 | Selection of Active Devices | 428 |
| 13.2.6 | Feedback | 430 |
| 13.2.7 | Application 1: Sensor and Its Preamplifier | 434 |
| 13.2.8 | Application 2: Dolby Noise Reduction System | 437 |
| 13.3 | Low-Noise Design Techniques for Microwave Circuits | 439 |
| 14 | Noise Performance Measurement | 443 |
| 14.1 | Noise Sources | 443 |
| 14.1.1 | Introduction | 443 |
| 14.1.2 | Case Studies | 444 |
| 14.2 | Noise Power Measurement | 451 |
| 14.2.1 | Introduction | 451 |
| 14.2.2 | Case Studies | 451 |
| 14.3 | Two-Port Noise Performance Measurement | 457 |
| 14.3.1 | Introduction | 457 |
| 14.3.2 | Case Studies | 457 |
| 14.4 | Miscellaneous | 468 |
| 14.4.1 | Passive Circuits | 468 |
| 14.4.2 | Impedances at Unequal Temperatures | 476 |
| 14.4.3 | Low-Frequency Amplifier | 482 |
| 15 | Noise in Sensing Circuits | 485 |
| 15.1 | Preamplifiers | 485 |
| 15.1.1 | Underlying Principles | 485 |
| 15.1.2 | Case Studies | 487 |
| 15.2 | Sensing Circuits | 504 |
| 15.2.1 | Underlying Principles | 504 |
| 15.2.2 | Case Studies | 505 |
| 15.3 | Circuits with Operational Amplifiers | 515 |
| 16 | Noise in Communication Systems | 535 |
| 16.1 | Attenuators | 535 |
| 16.1.1 | Underlying Principles | 535 |
| 16.1.2 | Case Studies | 535 |
| 16.2 | Multistage Amplifiers | 542 |

XVIII Contents

| | | |
|-----------|---|------------|
| 16.3 | Low-Noise Input Stages | 549 |
| 16.4 | Receivers | 553 |
| 16.4.1 | Background | 553 |
| 16.4.2 | Case Studies | 554 |
| 16.5 | Space Communication Systems | 567 |
| 16.5.1 | Background | 567 |
| 16.5.2 | Case Studies | 572 |
| 17 | Computer-Aided Noise Analysis | 583 |
| 17.1 | Noise Simulation with PSPICE | 584 |
| 17.1.1 | SPICE – An Overview | 584 |
| 17.1.2 | Noise Analysis | 592 |
| 17.1.3 | Simulation Techniques | 592 |
| 17.1.4 | Case Studies | 597 |
| 17.2 | Noise Simulation with NOF | 621 |
| 17.2.1 | NOF – An Overview | 621 |
| 17.2.2 | Case Studies | 623 |
| 18 | Protection Against Interfering Signals | 629 |
| 18.1 | Techniques to Reduce Interference | 629 |
| 18.1.1 | Shielding | 629 |
| 18.1.2 | Filtering | 640 |
| 18.1.3 | Grounding | 648 |
| 18.2 | Interconnect Modeling | 654 |
| 18.2.1 | Evaluation of Stray Elements Associated with Interconnects | 654 |
| 18.2.2 | Crosstalk | 663 |
| 18.3 | Interfering Signals | 669 |
| 18.3.1 | Transducers and Associated Circuits | 669 |
| 18.3.2 | Logic Circuits | 677 |
| 18.3.3 | Contact Protection | 684 |
| | References | 689 |
| | Appendix | 703 |
| | Index | 705 |