Contents

Foreword .................................................................................................................xiii
Preface ......................................................................................................................xvii

1. INTRODUCTION TO SYSTEM EMI AND EMC

1.1 Electronic System In An EMI Environment .................................................1
   1.1.1 System EMI: A Necessary Evil .................................................................1
   1.1.2 EMC—The Science Of Electronic System Coexistence ......................6
   1.1.3 Electronic System EMI Synthesis and Analysis ......................................14

1.2 System EMI Controlling Factors .................................................................17
   1.2.1 Basic EMI Study Approaches and Coupling Path ..............................18
   1.2.2 Meet EMI Emitters / Sensors .................................................................18
   1.2.3 What You Always Wanted to Know (But were Afraid to Ask)
       about Differential and Common Mode Transmission ............................26
   1.2.4 Meet EMI Generators / Receptors .......................................................29

1.3 Defining And Modeling EMC Performance Parameters .........................44
   1.3.1 Basic Emissions and Immunity Units ....................................................44
   1.3.2 Typical EMC Performance Models ......................................................45
   1.3.3 Elementary Source = Radiator + Generator .......................................53
   1.3.4 Electronic System as an Active Antenna Array ....................................55

1.4 EMI Suppression: the important objective of EMC .................................59
   1.4.1 EMI Mitigation Techniques .................................................................59
   1.4.2 Comparing Different EMI Suppression Techniques:
       Cable Crosstalk Example .................................................................64
2. UNDERSTANDING ELECTROMAGNETIC SHIELDING

2.1 Shielding at the EMC "Front line" .............................................................. 71
2.2 A Shield Is a Shield Is a Shield ................................................................. 73
   2.2.1 Shielding Enclosures for Electronic Products .................................... 74
   2.2.2 Cable Shielding .................................................................................. 80
   2.2.3 Architectural Shielding ...................................................................... 81
   2.2.4 "Mobile" Shielding: How Good Shield is a Taxicab ......................... 84
   2.2.5 System Shielding: Limitations of System EMI Analysis ................... 84
   2.2.6 Shielding, Grounding, and All That 'Jazz' ....................................... 85
   2.2.7 Connectors: Don't Miss the Link ....................................................... 87
   2.2.8 Importance of Shielding System Integrity: Shielding System for Electrostatic Discharge Protection .................. 89
   2.2.9 Ground Plane in Printed Circuit Board: Parallel Shielding Effect ...... 91
2.3 This Confusing World Of Electromagnetic Shielding .............................. 92
   2.3.1 What Is Electromagnetic Shielding, Anyhow? ................................. 92
   2.3.2 Do You Speak "Shieldinese"? ............................................................... 94
   2.3.3 Transmission Theory of Shielding: User Alert ................................. 96
   2.3.4 What We Have Learned and What's Missing .................................... 103
2.4 Shielding—This Is Not Very Simple ........................................................ 104
   2.4.1 A Fresh Look at a Familiar Problem ................................................ 105
   2.4.2 Transmission Line vs. Plane Wave Shielding Models ...................... 110
   2.4.3 Plane Shield / Plane Wave Model Constraints ............................... 113
2.5 A System View On Electromagnetic Shielding ....................................... 116
   2.5.1 The Roads We Take ......................................................................... 116
   2.5.2 "Parallel Bypass" Model of Energy transfer through the Shield .......... 119
   2.5.3 "Series" Model of System Electromagnetic Shielding ..................... 121
   2.5.4 Reciprocity Principle in Electromagnetic Shielding ....................... 127
2.6 So, What Is Electromagnetic Shielding, After All? ................................. 129
   2.6.1 System Definitions of Electromagnetic Shielding ............................. 129
   2.6.2 Shielding Model Generality Vs Relevancy ....................................... 130
   2.6.3 What's Next? .................................................................................... 132

3. TRANSFER PARAMETERS OF ELECTROMAGNETIC SHIELDS AND ENCLOSURES

3.1 Figure of Merit of electromagnetic Shield Performance .......................... 133
   3.1.1 Transfer Impedance - Shield Transfer Parameter of Choice ............ 133
   3.1.2 Universal Set of Shield Transfer Parameters: from Cables to Small and Large Products to Architectural Constructions ........................................... 137
   3.1.3 Finding EMI Voltage: A Union of Field and Circuit Theories .......... 143
3.2 Thin Homogeneous Solid Shield Performance ........................................ 149
   3.2.1 Current and Field Distribution in Homogeneous Metallic Tube - Coaxial Cable Shield / Outer Conductor .............. 149
3.2.2 Thin Homogeneous Solid Current-Carrying Plane or "Other" Shield Shapes Have Identical to Cylindrical Shield Field Distribution ....155
3.2.3 Transfer Parameters of Thin Solid Homogeneous Shields ..........156
3.2.4 Thin Homogeneous Solid Shield Performance Analysis ..........163
3.3 A "Second Look" At Transfer Parameters .........................................................172
  3.3.1 Circuit Theory/Reactive Near Field Nature of Transfer Parameters ..........................................172
  3.3.2 Shielding "from Currents" vs Shielding "from Fields" ..........173
  3.3.3 The Role of Coupling in Shield Transfer Function ..........174
  3.3.4 High Frequency Current Return Path in the Shield Mainly Follows the Direct Path ..........180
3.4 Practical Non-Uniform Shields ..............................................................182
  3.4.1 The "Troubling World" of Shield Non-Uniformities ..........182
  3.4.2 Spiral Shields ..........................................................................................185
  3.4.3 Shields with a "Longitudinal" Seam and/or Electromagnetic Gasket ........................................191
  3.4.4 Foil Shields: Effects of Seam and Overlap ..........195
  3.4.5 Mesh Shields .........................................................................................205
3.5 Braided Shield ..........................................................................................................................209
  3.5.1 Geometry and Design Parameters of Braided Shield ..........209
  3.5.2 Physical Processes in Braided Shield: Noah’s Ark of Shielding Problems ..........10
  3.5.3 Engineering Model of Braided Shield ..........214
  3.5.4 Braided Shield Performance ..........219
3.6 Multilayer Shields ..............................................................................................220
  3.6.1 Multilayer Homogeneous Shields ..........221
  3.6.2 Multilayer Nonhomogeneous Shield Performance ..........228
  3.6.3 Calculating “Derivative” Shields ..........240

4. EMI ENVIRONMENT AND ELECTROMAGNETIC COUPLING IN SHIELDING

4.1 Defining Shielding Coupling ........................................................................245
  4.1.1 Shielding To Decouple And Coupling To Shield ..........245
  4.1.2 Electromagnetic Environment and Coupling in Shielding Model ..........246
4.2 A Roadmap To Shielding Coupling Mechanisms: EMI Signal Propagation Regimes ..................................................................................................................252
  4.2.1 A Roadmap to Roadmap: Maxwell’s Equations and Coupling Mechanisms ..........252
  4.2.2 Signal Propagation Media Parameters ..........253
  4.2.3 Role of Time Variations: Solid Homogeneous Shield in a Wide Frequency Band ..........254
  4.2.4 Coupling Regimes in Conductors and Dielectrics ..........256
4.2.5 “Electrical Geometry” in Near-Zone / Far-Zone Radiating Fields
4.2.6 Shielding Coupling / Propagation Regimes: Summary
4.3 Induction Field Coupling
4.3.1 Static and Stationary Field EMI Environment and Coupling
4.3.2 Quasi-Stationary Field Coupling
4.4 Crosstalk EMI Environment and Coupling
4.4.1 Crosstalk Interactions
4.4.2 Transverse Reactive Field Environment and Coupling
4.4.3 Common Impedance (Galvanic) Coupling
4.4.4 Coupling via Third Circuit
4.4.5 Coupling Between Shielded or Coaxial Lines
4.4.6 Crosstalk Coupling Between Balanced vs Unbalanced Lines: Common and Differential Mode Regimes
4.4.7 Crosstalk Coupling Reduction Techniques
4.5 EMI Environment And Shielding Coupling In Radiating Fields
4.5.1 Problems and Strategies
4.5.2 Radiating EMI Environment: Time and Space Domain Complications
4.5.3 How Do Radiating Fields Couple?
4.5.4 Antenna Currents and Radiation Resistance of Lines and Shields
4.5.5 Aperture Coupling in Radiation Field
4.6 Transient Response of Shielding

5. SHielding EFFECTIVENESS FOR EMI PROTECTION
5.1 The Technical Bottom Line of Shielding Performance
5.2 Shielding effectiveness in Static and Stationary Fields
5.2.1 Problems of Statics
5.2.2 Electrostatic Shielding
5.2.3 Magnetostatic Shielding
5.2.4 Non-Conductive Statics Shielding
5.2.5 Complexities and Specifics of Static Shield Design
5.3 Shielding For Crosstalk Protection: From Mils To Miles
5.3.1 “Compensation” Shielding from Low-Frequency Crosstalk
5.3.2 Crosstalk between Shielded Lines in a Wide Frequency Band
5.3.3 Shielding for Crosstalk Protection in Printed Circuit Boards and Integrated Circuits
5.3.4 Crosstalk in Coaxial and Shielded Transmission Lines
5.4 Shielding In Radiating Fields
5.4.1 Shielding from Radiation vs Shielding from Crosstalk
5.4.2 Deterministic vs Statistical Nature of EMI Environment: Indoor Propagation of PCS Signal
5.5 From Transfer Impedance to Shielding Effectiveness and Crosstalk Attenuation ...........................................369
5.6 EMC And Shielding Performance Of Typical Electronic Cables ...........................................374
5.7 Ground Planes And Radiation: From EMC Test Site To PCB ...........................................378
5.8 Shielding Enclosures For Radiating Field Protection ...........................................386
  5.8.1 Critical Parameters of Shielding Enclosures ...........................................387
  5.8.2 Radiated EMI Environment Issues ...........................................387
  5.8.3 Radio Wave Penetration Through Apertures, Seams, and Slots: Navigating Through Literature ...........................................394
  5.8.4 “Mobile” Shielding Enclosures ...........................................404
5.9 Wireless Product Shielding ...........................................410

6. SHIELDING MEASUREMENT TECHNIQUES AND APPARATUS: THE TOOLS OF THE TRADE

6.1 The proof of the shielding ...........................................417
  6.1.1 Measurement Objectives ...........................................417
  6.1.2 Test Space Environment ...........................................419
  6.1.3 Shielding Measurement Rationale ...........................................421
  6.1.4 Roadmap to Shielding Measurements ...........................................426
6.2 Global System Shielding Effectiveness Measurements ...........................................426
  6.2.1 System Shielding Effectiveness Measurements in RF Radiating Fields ...........................................426
  6.2.2 System Measurements in Magnetostatic Fields ...........................................433
  6.2.3 Near Field RF and Microwave Measurements ...........................................434
6.3 Shielding Assembly Measurements ...........................................434
  6.3.1 Specifics of Shielding Assembly Measurements ...........................................434
  6.3.2 Shielding Assembly Measurements in Radiating and Magnetostatic Fields ...........................................435
  6.3.3 Antenna Current Measurements ...........................................438
  6.3.4 Shielding Effectiveness via Crosstalk Measurements ...........................................443
6.4 Transfer Impedance and Capacitive Coupling Impedance Measurements ...........................................445
  6.4.1 Coaxial Structures: Is There a Sextaxial in the Cards? ...........................................445
  6.4.2 Terminated Triaxial ...........................................455
  6.4.3 Line Injection Shielding Effectiveness Measurements ...........................................461
6.5 Testing shielding system elements ...........................................464
  6.5.1 Shielding Enclosures and Building Structures ...........................................464
  6.5.2 How to Test Shielded Cables and Connectors? ...........................................470
  6.5.3 Testing Shielding Materials ...........................................471
  6.5.4 Electromagnetic Gasket Test Specifics ...........................................478
6.6 Testing in Time Domain ...........................................479
6.7 Test Result Correlation And Interpretation ...........................................482
  6.7.1 “Apples and Oranges” ...........................................482
  6.7.2 Validating Test Procedures ...........................................487
7. SHIELDING ENGINEERING

7.1 System Approach to Shielding Engineering ................................................. 491
   7.1.1 Shielding Engineering Problems .................................................. 491
   7.1.2 To Shield or Not to Shield: the First and the Last Questions ............... 495
   7.1.3 “Black Box” Model of Product and System Shielding .......................... 497

7.2 Methods and Techniques for Shielding Design .............................................. 505
   7.2.1 Basic Shielding Design Principles ............................................. 505
   7.2.2 Design by Constraints .............................................................. 506
   7.2.3 Optimal Design ........................................................................ 508

7.3 Cable Shielding Design for EMC Performance .............................................. 509
   7.3.1 Local Problems of Boundary Design ............................................. 509
   7.3.2 Local Optimization .................................................................... 515
   7.3.3 Global Braid Optimization by Cost Criterion ................................. 519

7.4 Shielding Enclosure Design for EMC Performance ........................................ 525
   7.4.1 Shielding Enclosure Design Issues .............................................. 525
   7.4.2 Aperture vs Cavity Resonances .................................................... 527
   7.4.3 Shielded Cabinets, Frames, and Shelves ....................................... 530
   7.4.4 Shielding Enclosure “Hardware” ................................................... 537

7.5 Transmission Effects in Shielding Circuit .................................................... 543

7.6 Shielding System Grounding, Termination, And Partition ............................ 546
   7.6.1 What Is Grounding Really About: Myth and Reality ......................... 546
   7.6.2 To Ground or Not To Ground? ...................................................... 550
   7.6.3 Challenges of Shielded Cable Assembly ....................................... 556
   7.6.4 Shielding and Ground Loops ....................................................... 565
   7.6.5 Shielding and Grounding System Topology and Partition .................. 571
   7.6.6 Designing Shielding System ....................................................... 574

7.7 Shielding Performance Stability and Reliability .......................................... 575
   7.7.1 Electromagnetic Shield in Physical Environment ............................... 575
   7.7.2 Environmental Stability and Aging of Electromagnetic Shielding ....... 577
   7.7.3 Effect of Manufacturing Tolerances on the Shield Performance Variability ......................................................... 582
   7.7.4 Sneaky Problem of a “Rusty Bolt”: Intermodulation ......................... 587

8. THIS BRAVE NEW OLD WORLD OF ELECTROMAGNETIC SHIELDING

8.1 Shielding Unlimited .............................................................................. 589
8.2 Leaky Shielding ................................................................................. 590
8.3 “Plastic” Shielding ............................................................................ 594
8.4 Ferromagnetic Absorptive Shielding ..................................................... 600
8.5 Superconductive Shields .................................................................... 604
8.6 Chiral Shields .................................................................................... 607
8.7 “Moving Up” The Frequency Spectrum .............................................. 614
8.8 Shielding From High Voltage Discharge ........................................616
8.9 Shielding "On-demand" ...............................................................618

Epilogue .........................................................................................620

9 APPENDIX: Selected Topics In Electromagnetics And Circuit Theory

A.1 "He Who Would Search For Pearls, Must Dive Below" .....................621
A.2 Maxwell’s Equations survival kit .......................................................622
  A.2.1 Differential Form of Maxwell’s Equations .................................622
  A.2.2 Integral Form of Maxwell’s Equations .......................................631
A.3 Poynting Vector and Poynting Theorem ........................................633
A.4 Circuit Theory survival kit ............................................................634
  A.4.1 Lumped-Element Networks .......................................................634
  A.4.2 Reciprocity Theorem ...............................................................636
  A.4.3 Differential Equations of a Transmission Line ..........................638
A.5 Analogy Between Wave Propagation In Transmission Lines And Free
  Space .................................................................................................639
A.6 Numerical Techniques: Are We There Yet? ..................................645

Bibliography .....................................................................................649

Index ..................................................................................................677