Contents

PREFACE xv

1 Introduction 1

1.1 Examples of Multiconductor Transmission-Line Structures 4
1.2 Properties of the Transverse ElectroMagnetic (TEM) Mode of Propagation 7
1.3 Derivation of the Transmission-Line Equations for Two-Conductor Lines 13
1.3.1 Derivation from the Integral Form of Maxwell's Equation 13
1.3.2 Derivation from the Differential Form of Maxwell's Equations 21
1.3.3 Derivation from the Per-Unit-Length Equivalent Circuit 22
1.3.4 Properties of the Per-Unit-Length Parameters 24
1.4 Classification of Transmission Lines 26
1.5 Restrictions on the Applicability of the Transmission-Line Equation Formulation 30
1.5.1 Higher-Order Modes 30
1.5.1.1 The Infinite Parallel-Plate Transmission Line 30
1.5.1.2 The Coaxial Transmission Line 36
1.5.1.3 Two-Wire Lines 37
1.5.2 Transmission-Line Currents vs. Antenna Currents 37
References 40
Problems 42

2 The Multiconductor Transmission-Line Equations 46

2.1 Derivation from the Integral Form of Maxwell's Equations 46
2.2 Derivation from the Per-Unit-Length Equivalent Circuit 56

2.3 Summary of the MTL Equations 57
2.4 Properties of the Per-Unit-Length Parameter Matrices L, C, G 58
References 62
Problems 62

3 The Per-Unit-Length Parameters 64

3.1 Definitions of the Per-Unit-Length Parameter Matrices L, C, G 65
3.1.1 The Per-Unit-Length Inductance Matrix, L 65
3.1.2 The Per-Unit-Length Capacitance Matrix, C 69
3.1.3 The Per-Unit-Length Conductance Matrix, G 72
3.1.4 The Generalized Capacitance Matrix, $\mathscr{C}$ 73
3.2 Multiconductor Lines Having Conductors of Circular Cylindrical Cross Section 77
3.2.1 Fundamental Subproblems for Wires 77
3.2.1.1 Magnetic Flux Due to a Filament of Current 77
3.2.1.2 Voltage Due to a Filament of Charge 80
3.2.1.3 The Method of Images 82
3.2.2 Exact Solutions for Two-Conductor Wire Lines 83
3.2.2.1 Two Wires 83
3.2.2.2 One Wire Above an Infinite, Perfectly Conducting Plane 89
3.2.2.3 The Coaxial Cable 90
3.2.3 Wide-Separation Approximations for Wires in Homogeneous Media 92
3.2.3.1 $(n + 1)$ Wires 93
3.2.3.2 n Wires Above an Infinite, Perfectly Conducting Plane 93
3.2.3.3 n Wires Within a Perfectly Conducting Shield 96
3.2.4 Numerical Methods for the General Case 97
3.2.4.1 Applications to Inhomogeneous Dielectric Media 103
3.2.5 Computed Results: Ribbon Cables 109
3.3 Multiconductor Lines Having Conductors of Rectangular Cross Section 113
3.3.1 Method of Moments (MOM) Techniques 115
3.3.1.1 Applications to Printed Circuit Boards 124
3.3.1.2 Computed Results: Printed Circuit Boards 135
3.3.2 Finite Difference Techniques 140
3.3.3 Finite Element Techniques 146
3.4 Miscellaneous Additional Techniques 153
3.4.1 Conformal Mapping Techniques 154

3.4.2 Spectral-Domain Techniques 155
3.5 Shielded Lines 156
3.6 Incorporation of Losses; Calculation of **R**, $\mathbf{L}_i$, and **G** 157
3.6.1 Calculation of the Per-Unit-Length Conductance Matrix, **G** 158
3.6.2 Representation of Conductor Losses 161
3.6.2.1 Surface Impedance of Plane Conductors 162
3.6.2.2 Resistance and Internal Inductance of Wires 164
3.6.2.3 Internal Impedance of Rectangular Cross Section Conductors 168
3.6.2.4 Approximate Representation of Conductor Internal Impedances in the Frequency Domain 177
References 180
Problems 182

4 Frequency-Domain Analysis 186

4.1 The MTL Equations for Sinusoidal Steady-State Excitation 186
4.2 Solutions for Two-Conductor Lines 189
4.3 General Solution for an $(n + 1)$-Conductor Line 194
4.3.1 Analogy of the MTL Equations to the State-Variable Equations 195
4.3.2 Decoupling the MTL Equations by Similarity Transformations 200
4.3.3 Characterizing the Line as a $2n$ Port with the Chain Parameter Matrix 205
4.3.4 Properties of the Chain Parameter Matrix 206
4.3.5 Incorporating the Terminal Conditions 209
4.3.5.1 The Generalized Thévenin Equivalent 210
4.3.5.2 The Generalized Norton Equivalent 213
4.3.5.3 Mixed Representations 214
4.3.6 Approximating Nonuniform Lines 216
4.4 Solution for Line Categories 219
4.4.1 Perfect Conductors in Homogeneous Media 220
4.4.2 Lossy Conductors in Homogeneous Media 222
4.4.3 Perfect Conductors in Inhomogeneous Media 224
4.4.4 The General Case: Lossy Conductors in Lossy Inhomogeneous Media 225
4.4.5 Cyclic Symmetric Structures 225
4.5 Lumped-Circuit Iterative Approximate Characterizations 231
4.6 Alternative $2n$-Port Characterizations 234
4.7 Power and the Reflection Coefficient Matrix 236
4.8 Computed Results 238

4.8.1 Ribbon Cables 239
4.8.2 Printed Circuit Boards 241
References 246
Problems 246

5 Time-Domain Analysis 252

5.1 Two-Conductor Lossless Lines 253
5.1.1 Graphical Solutions 257
5.1.2 The Method of Characteristics (Branin's Method) 266
5.1.3 The Bergeron Diagram 270
5.2 Multiconductor Lossless Lines 275
5.2.1 Decoupling the MTL Equations 277
5.2.1.1 Lossless Lines in Homogeneous Media 279
5.2.1.2 Lossless Lines in Inhomogeneous Media 280
5.2.1.3 Incorporating the Terminal Conditions via the SPICE Program 283
5.2.2 Extension of Branin's Method to Lossless Multiconductor Lines in Homogeneous Media 288
5.2.3 Time-Domain to Frequency-Domain Transformations 292
5.2.4 Lumped-Circuit Iterative Approximate Characterizations 295
5.2.5 Finite Difference–Time Domain (FDTD) Methods 295
5.2.6 Computed Results 309
5.2.6.1 Ribbon Cable 311
5.2.6.2 Printed Circuit Board 317
5.3 Incorporation of Losses 320
5.3.1 Two-Conductor Lossy Lines 323
5.3.1.1 Lumped-Circuit Approximate Characterizations 324
5.3.1.2 Time-Domain to Frequency-Domain Transformations 325
5.3.1.3 Finite Difference–Time Domain (FDTD) Methods 326
5.3.1.4 Direct Solution via Inversion of the Laplace Transform 334
5.3.1.5 Time-Domain Characterization of the Line as a Two Port 337
5.3.2 Multiconductor Lines 343
5.3.3 Computed Results 347
5.3.3.1 Ribbon Cable 348
5.3.3.2 Printed Circuit Board 351
References 351
Problems 354

6 Literal (Symbolic) Solutions for Three-Conductor Lines 359

6.1 Frequency-Domain Solution 363
6.1.1 Inductive and Capacitive Coupling 367
6.1.2 Common-Impedance Coupling 369
6.2 Time-Domain Solution 371
6.2.1 Explicit Solution 373
6.2.2 Weakly Coupled Lines 375
6.2.3 Inductive and Capacitive Coupling 378
6.2.4 Common-Impedance Coupling 382
6.3 Computed Results 383
6.3.1 A Three-Wire Ribbon Cable 383
6.3.2 A Three-Conductor Printed Circuit Board 388
References 393
Problems 394

7 Incident-Field Excitation of the Line 395

7.1 Derivation of the MTL Equations for Incident-Field Excitation 395
7.1.1 Equivalence of Source Representations 402
7.2 Frequency-Domain Solutions 405
7.2.1 Solution of the MTL Equations 406
7.2.1.1 Simplified Forms of the Excitations 407
7.2.2 Incorporation of the Terminal Conditions 410
7.2.2.1 Lossless Lines in Homogeneous Media 413
7.2.3 Lumped-Circuit Iterative Approximate Characterizations 415
7.2.4 Uniform Plane-Wave Excitation of the Line 416
7.2.5 Two-Conductor Lines 423
7.2.5.1 Uniform Plane-Wave Excitation of the Line 425
7.2.5.2 Special Cases 426
7.2.5.3 One Conductor Above a Ground Plane 429
7.2.5.4 Electrically Short Lines 433
7.2.6 Computed Results 435
7.2.6.1 Comparison with Predictions of the Method of Moments Codes 435
7.2.6.2 A Three-Wire Line in an Incident Uniform Plane Wave 440
7.3 Time-Domain Solutions 444
7.3.1 Two-Conductor Lossless Lines 446
7.3.1.1 The General Solution via the Method of Characteristics 446

7.3.1.2 The General Solution via the Frequency Domain 448
7.3.1.3 Uniform Plane-Wave Excitation of the Line 453
7.3.1.4 Electrically Short Lines 459
7.3.1.5 A SPICE Equivalent Circuit 460
7.3.1.6 Computed Results 463
7.3.2 Multiconductor Lines 466
7.3.2.1 Decoupling the MTL Equations 467
7.3.2.2 A SPICE Equivalent Circuit 470
7.3.2.3 Lumped-Circuit Iterative Approximate Characterizations 475
7.3.2.4 Time-Domain to Frequency-Domain Transformations 475
7.3.2.5 Finite Difference-Time Domain Methods 477
7.3.2.6 Computed Results 480
References 486
Problems 487

8 Transmission-Line Networks 489

8.1 Representation with the SPICE Model 492
8.2 Representation with Lumped-Circuit Iterative Models 492
8.3 Representation via the Admittance or Impedance Parameters 494
8.4 Representation with the BLT Equations 508
8.5 Direct Time-Domain Solutions in terms of Traveling Waves 517
References 522
Problems 523

Publications by the Author Concerning Transmission Lines 525

Appendix A Description of Computer Software 531

A.1 Programs for Calculation of the Per-Unit-Length Parameters 532
A.1.1 Wide-Separation Approximations for Wires: **WIDESEP.FOR** 533
A.1.2 Ribbon Cables: **RIBBON.FOR** 536
A.1.3 Printed Circuit Boards: **PCB.FOR, PCBGAL.FOR** 539
A.1.4 Coupled Microstrip Structures: **MSTRP.FOR, MSTRPGAL.FOR** 541
A.2 Frequency-Domain Analysis 542
A.2.1 General: **MTL.FOR** 542
A.3 Time-Domain Analysis 543

A.3.1 Time-Domain to Frequency-Domain Transformation: **TIMEFREQ.FOR** 543
A.3.2 Branin's Method Extended to Multiconductor Lines: **BRANIN.FOR** 544
A.3.3 Finite Difference–Time Domain Method: **FINDIF.FOR** 544
A.3.4 Finite Difference–Time Domain Method: **FDTDLOSS.FOR** 544
A.4 SPICE/PSPICE Subcircuit Generation Programs 545
A.4.1 General Solution, Lossless Lines: **SPICEMTL.FOR** 545
A.4.2 Lumped-pi Circuit, Lossless Lines: **SPICELPI.FOR** 545
A.4.3 Inductive-Capacitive Coupling Model: **SPICELC.FOR** 547
A.5 Incident Field Excitation 547
A.5.1 Frequency-Domain Program: **INCIDENT.FOR** 547
A.5.2 SPICE/PSPICE Subcircuit Model: **SPICEINC.FOR** 548
A.5.3 Finite Difference–Time Domain (FDTD) Model: **FDTDINC.FOR** 550
References 551

INDEX 553