
T A B L E O F C O N T E N T S

Preface	xxi
Glossary of Symbols.....	xxvii
1 Fundamentals	1
1.1 Impedance of Linear, Time-Invariant, Lumped-Element Circuits	1
1.2 Power Ratios	2
1.3 Rules of Scaling	5
1.3.1 Scaling of Physical Size	6
1.3.1.1 Scaling Inductors.....	8
1.3.1.2 Scaling Transmission-Line Dimensions.....	8
1.3.2 Power Scaling	9
1.3.3 Time Scaling	10
1.3.4 Impedance Scaling with Constant Voltage	12
1.3.5 Dielectric-Constant Scaling	14
1.3.5.1 Partially Embedded Transmission Lines.....	15
1.3.6 Magnetic Permeability Scaling	15
1.4 The Concept of Resonance	16
1.5 Extra for Experts: Maximal Linear System Response to a Digital Input	22
2 Transmission Line Parameters	29
2.1 Telegrapher's Equations	31
2.1.1 <i>So Good It Works on Barbed Wire</i>	34
2.1.2 The No-Storage Principle and Its Implications for Returning Signal Current	35
2.2 Derivation of Telegrapher's Equations	38
2.2.1 Definition of Characteristic Impedance Z_C	39
2.2.2 Changes in Characteristic Impedance	40
2.2.3 Calculation of Impedance Z_c From Parameters $R, L, G,$ And C	41
2.2.4 Definition of Propagation Coefficient γ	44
2.2.5 Calculation of Propagation Coefficient γ from Parameters $R, L, G,$ and C ...	46
2.3 Ideal Transmission Line.....	48
2.4 DC Resistance	55
2.5 DC Conductance	57

2.6	Skin Effect	58
2.6.1	What Causes the Skin Effect, and What Does It Have to Do With Skin?.....	58
2.6.2	Eddy Currents within a Conductor.....	61
2.6.3	High and Low-Frequency Approximations for Series Resistance	63
2.7	Skin-Effect Inductance.....	66
2.8	Modeling Internal Impedance	67
2.8.1	Practical Modeling of Internal Impedance	70
2.8.2	Special Issues Concerning Rectangular Conductors	73
2.9	Concentric-Ring Skin-Effect Model	75
2.9.1	<i>Modeling Skin Effect</i>	76
2.9.2	<i>Regarding Modeling Skin Effect</i>	79
2.10	Proximity Effect.....	79
2.10.1	Proximity Factor	81
2.10.2	Proximity Effect for Coaxial Cables	84
2.10.3	Proximity Effect for Microstrip and Stripline Circuits.....	85
2.10.4	Last Words on Proximity Effect	85
2.10.4.1	<i>Proximity Effect II</i>	85
2.10.4.2	<i>2-D Quasistatic Field Solvers</i>	87
2.11	Surface Roughness.....	90
2.11.1	Severity of Surface Roughness	90
2.11.2	Onset of Roughness Effect.....	91
2.11.3	Roughness of Pcb Materials.....	91
2.11.4	Controlling Roughness.....	92
2.12	Dielectric Effects	94
2.12.1	Dielectric Loss Tangent	98
2.12.2	Rule of Mixtures	99
2.12.3	Calculating the Loss Tangent for a Uniform Dielectric Mixture	101
2.12.4	Calculating the Loss Tangent When You Don't Know q	103
2.12.5	Causality and the Network Function Relations.....	105
2.12.6	Finding $ er $ to Match a Measured Loss Tangent	110
2.12.7	Kramers-Kronig Relations	114
2.12.8	Complex Magnetic Permeability.....	115
2.13	Impedance in Series with the Return Path	115
2.14	Slow-Wave Mode On-Chip	117
3	Performance Regions.....	121
3.1	Signal Propagation Model.....	121
3.1.1	Extracting Parameters for RLCG Simulators.....	127
3.2	Hierarchy of Regions	128
3.2.1	<i>A Transmission Line Is Always a Transmission Line</i>	130
3.3	Necessary Mathematics: Input Impedance and Transfer Function	132
3.4	Lumped-Element Region.....	135
3.4.1	Boundary of Lumped-Element Region	136
3.4.2	Pi Model.....	137

3.4.3	Taylor-Series Approximation of H (Lumped-Element Region).....	139
3.4.4	Input impedance (Lumped-Element Region).....	140
3.4.5	Transfer Function (Lumped-Element Region).....	143
3.4.6	Step Response (Lumped-Element Region)	145
3.5	RC Region.....	148
3.5.1	Boundary of RC Region.....	149
3.5.2	Input Impedance (RC Region)	151
3.5.3	Characteristic Impedance (RC Region).....	152
3.5.4	General Behavior within RC Region	153
3.5.5	Propagation Coefficient (RC Region).....	155
3.5.6	Transfer Function (RC Region)	155
3.5.6.1	Propagation Function of RC Line with Open-Circuited Load	155
3.5.6.2	Propagation Function of RC Line with Matched End Termination	156
3.5.6.3	Propagation Function of RC Line with Matched Source Termination....	156
3.5.6.4	Propagation Function of RC Line with Resistive End Termination.....	157
3.5.7	Normalized Step Response (RC Region).....	157
3.5.8	Tradeoffs Between Distance and Speed (RC Region)	159
3.5.9	Closed-Form Solution for Step Response (RC Region).....	159
3.5.10	Elmore Delay Estimation (RC Region).....	160
3.6	LC Region (Constant-Loss Region).....	166
3.6.1	Boundary of LC Region.....	166
3.6.2	Characteristic Impedance (LC Region).....	167
3.6.3	Influence of Series Resistance on TDR Measurements	169
3.6.4	Propagation Coefficient (LC Region)	173
3.6.5	Possibility of Severe Resonance within the LC Region.....	176
3.6.5.1	Alternate Interpretation of Equation [3.17].....	178
3.6.5.2	Practical Effect of Resonance	179
3.6.6	Terminating an LC Transmission Line	179
3.6.6.1	End Termination	180
3.6.6.2	Source Termination.....	181
3.6.6.3	Both-Ends Termination.....	181
3.6.6.4	Subtle Differences Between Termination Styles.....	181
3.6.6.5	Application of Termination Equations to Other Regions.....	183
3.6.7	Tradeoffs Between Distance And Speed (LC Region).....	183
3.6.8	Mixed-Mode Operation (LC and RC Regions).....	184
3.7	Skin-Effect Region.....	185
3.7.1	Boundary of Skin-Effect Region.....	185
3.7.2	Characteristic Impedance (Skin-Effect Region).....	186
3.7.3	Influence of Skin-Effect on TDR Measurement	188
3.7.4	Propagation Coefficient (Skin-Effect Region).....	189
3.7.5	Possibility of Severe Resonance within Skin-Effect Region.....	193
3.7.5.1	Subtle Differences Between Termination Styles.....	194
3.7.5.2	Application of Termination Equations to Other Regions.....	194
3.7.6	Step Response (Skin-Effect Region).....	195

3.7.7	Tradeoffs Between Distance and Speed (Skin-Effect Region)	199
3.8	Dielectric Loss Region	200
3.8.1	Boundary of Dielectric-Loss-Limited Region	200
3.8.2	Characteristic Impedance (Dielectric-Loss-Limited Region)	202
3.8.3	Influence of Dielectric Loss on TDR Measurement	205
3.8.4	Propagation Coefficient (Dielectric-Loss-Limited Region)	206
3.8.5	Possibility of Severe Resonance within Dielectric-Loss Limited Region	210
3.8.5.1	Subtle Differences Between Termination Styles	211
3.8.5.2	Application of Termination Equations to Other Regions	211
3.8.6	Step Response (Dielectric-Loss-Limited Region)	212
3.8.7	Tradeoffs Between Distance and Speed (Dielectric-Loss Region)	216
3.9	Waveguide Dispersion Region	216
3.9.1	Boundary of Waveguide-Dispersion Region	217
3.10	Summary of Breakpoints Between Regions	218
3.11	Equivalence Principle for Transmission Media	221
3.12	Scaling Copper Transmission Media	224
3.13	Scaling Multimode Fiber-Optic Cables	229
3.14	Linear Equalization: Long Backplane Trace Example	230
3.15	Adaptive Equalization: Accelerant Networks Transceiver	234
4	Frequency-Domain Modeling	237
4.1	<i>Going Nonlinear</i>	237
4.2	Approximations to the Fourier Transform	239
4.3	Discrete Time Mapping	241
4.4	Other Limitations of the FFT	243
4.5	Normalizing the Output of an FFT Routine	243
4.5.1	Deriving the DFT Normalization Factors	244
4.6	Useful Fourier Transform-Pairs	245
4.7	Effect of Inadequate Sampling Rate	247
4.8	Implementation of Frequency-Domain Simulation	249
4.9	Embellishments	251
4.9.1	What if a Large Bulk-Transport Delay Causes the Waveform to Slide Off the end of the Time-Domain Window?	251
4.9.2	How Do I Transform an Arbitrary Data Sequence?	251
4.9.3	How Do I Shift the Time-Domain Waveforms?	252
4.9.4	What If I Want to Model a More Complicated System?	252
4.9.5	What About Differential Modeling?	252
4.10	Checking the Output of Your FFT Routine	253
5	Pcb (printed-circuit board) Traces	255
5.1	Pcb Signal Propagation	257
5.1.1	Characteristic Impedance and Delay	257
5.1.2	Resistive Effects	258
5.1.2.1	DC Resistance of Pcb Trace	258

5.1.2.2	AC Resistance of Pcb Trace	258
5.1.2.3	Calculation of Perimeter of Pcb Trace	261
5.1.2.4	Very Low Impedance Pcb Trace	262
5.1.2.5	Calculation of Skin-Effect Loss Coefficient for Pcb trace	262
5.1.2.6	<i>Popsicle-Stick Analysis</i>	262
5.1.2.7	<i>Nickel-Plated Traces</i>	266
5.1.3	Dielectric Effects	268
5.1.3.1	Estimating the Effective Dielectric Constant for a Microstrip	269
5.1.3.2	Propagation Velocity	270
5.1.3.3	Calculating the Effective Loss Tangent for a Microstrip	270
5.1.3.4	Dielectric Properties of Laminate Materials (core and prepreg)	271
5.1.3.5	<i>Variations in Dielectric Properties with Temperature</i>	275
5.1.3.6	Passivation and Soldermask	277
5.1.3.7	Dielectric Properties of Soldermask Materials	280
5.1.3.8	Calculation of Dielectric Loss Coefficient for Pcb Trace	280
5.1.4	Mixtures of Skin Effect and Dielectric Loss	281
5.1.5	Non-TEM Modes	282
5.1.5.1	<i>Strange Microstrip Modes</i>	282
5.1.5.2	Simulation of Non-TEM Behavior	286
5.2	Limits to Attainable Distance	288
5.2.1	<i>SONET Data Coding</i>	291
5.3	Pcb Noise and Interference	294
5.3.1	Pcb: Reflections	294
5.3.1.1	<i>Both Ends Termination</i>	295
5.3.1.2	Pcb: Lumped-Element Reflections	297
5.3.1.3	<i>Potholes</i>	300
5.3.1.4	Inductive Potholes	303
5.3.1.5	<i>Who's Afraid of the Big, Bad Bend?</i>	304
5.3.1.6	<i>Stubs and Vias</i>	305
5.3.1.7	<i>Parasitic Pads</i>	306
5.3.1.8	<i>How Close Is Close Enough?</i>	309
5.3.1.9	<i>Placement of End Termination</i>	312
5.3.1.10	<i>Making an Accurate Series Termination</i>	314
5.3.1.11	<i>Matching Pads</i>	315
5.3.2	Pcb Crosstalk	318
5.3.2.1	Purpose of Solid Plane Layers	318
5.3.2.2	Variations with Trace Geometry	318
5.3.2.3	Directionality	319
5.3.2.4	NEXT: Near-End or Reverse Crosstalk	320
5.3.2.5	FEXT: Far-End or Forward Crosstalk	321
5.3.2.6	Special Considerations	322
5.3.2.7	<i>Directionality of Crosstalk</i>	323
5.4	Pcb Connectors	326
5.4.1	<i>Mutual Understanding</i>	326

5.4.2	<i>Through-Hole Clearances</i>	328
5.4.3	<i>Measuring Connectors</i>	330
5.4.4	<i>Tapered Transitions</i>	332
5.4.5	<i>Straddle-Mount Connectors</i>	335
5.4.6	<i>Cable Shield Grounding</i>	336
5.5	Modeling Vias.....	338
5.5.1	Incremental Parameters of a Via.....	338
5.5.2	Three Models for a Via.....	341
5.5.3	Dangling Vias.....	343
5.5.4	Capacitance Data.....	345
5.5.4.1	Three-Layer Via Capacitance.....	345
5.5.4.2	Effect of Back-Drilling.....	346
5.5.4.3	Effect of Multiple Planes.....	347
5.5.5	Inductance Data.....	351
5.5.5.1	Through-Hole Via Inductance.....	351
5.5.5.2	Via Crosstalk.....	354
5.6	<i>The Future of On-Chip Interconnections</i>	359
6	Differential Signaling	363
6.1	Single-Ended Circuits.....	363
6.2	Two-Wire Circuits.....	368
6.3	Differential Signaling.....	370
6.4	Differential and Common-Mode Voltages and Currents.....	374
6.5	Differential and Common-Mode velocity.....	376
6.6	Common-Mode Balance.....	377
6.7	Common-Mode Range.....	378
6.8	Differential to Common-Mode Conversion.....	378
6.9	Differential Impedance.....	380
6.9.1	Relation Between Odd-Mode and Uncoupled Impedance.....	383
6.9.2	Why the Odd-Mode Impedance Is Always Less Than the Uncoupled Impedance.....	383
6.9.3	<i>Differential Reflections</i>	384
6.10	Pcb Configurations.....	385
6.10.1	<i>Differential (Microstrip) Trace Impedance</i>	386
6.10.2	Edge-Coupled Stripline.....	389
6.10.3	<i>Breaking Up a Pair</i>	397
6.10.4	Broadside-Coupled Stripline.....	399
6.11	Pcb Applications.....	404
6.11.1	Matching to an External, Balanced Differential Transmission Medium.....	404
6.11.2	Defeating ground bounce.....	405
6.11.3	Reducing EMI with Differential Signaling.....	405
6.11.4	Punching Through a Noisy Connector.....	407
6.11.4.1	<i>Differential Signaling (Through Connectors)</i>	408
6.11.5	Reducing Clock Skew.....	409

6.11.6	Reducing Local Crosstalk.....	411
6.11.7	A Good Reference about Transmission Lines.....	413
6.11.8	<i>Differential Clocks</i>	413
6.11.9	<i>Differential Termination</i>	414
6.11.10	<i>Differential U-Turn</i>	417
6.11.11	<i>Your Layout Is Skewed</i>	419
6.11.12	<i>Buying Time</i>	420
6.12	Intercabinet Applications.....	422
6.12.1	Ribbon-Style Twisted-Pair Cables.....	423
6.12.2	Immunity to Large Ground Shifts.....	424
6.12.3	Rejection of External Radio-Frequency Interference (RFI).....	426
6.12.4	Differential Receivers Have Superior Tolerance to Skin Effect and Other High-Frequency Losses.....	427
6.13	LVDS Signaling.....	429
6.13.1	Output Levels.....	429
6.13.2	Common-Mode Output.....	430
6.13.3	Common-Mode Noise Tolerance.....	430
6.13.4	Differential-Mode Noise Tolerance.....	431
6.13.5	Hysteresis.....	431
6.13.6	Impedance Control.....	432
6.13.7	Trace Radiation.....	435
6.13.8	Risetime.....	435
6.13.9	Input Capacitance.....	435
6.13.10	Skew.....	435
6.13.11	Fail-Safe.....	436
7	Generic Building-Cabling Standards	439
7.1	Generic Cabling Architecture.....	442
7.2	SNR Budgeting.....	446
7.3	Glossary of Cabling Terms.....	446
7.4	Preferred Cable Combinations.....	449
7.5	FAQ: Building-Cabling Practices.....	449
7.6	Crossover Wiring.....	451
7.7	Plenum-Rated Cables.....	452
7.8	Laying cables in an Uncooled Attic Space.....	453
7.9	FAQ: Older Cable Types.....	453
8	100-Ohm Balanced Twisted-Pair Cabling	457
8.1	UTP Signal Propagation.....	459
8.1.1	UTP Modeling.....	460
8.1.2	Adapting the Metallic-Transmission Model.....	462
8.2	UTP Transmission Example: 10BASE-T.....	465
8.3	UTP Noise and Interference.....	471
8.3.1	UTP: Far-End Reflections.....	471

8.3.2	UTP: Near-End Reflections	475
8.3.2.1	UTP: (Structural) Return Loss	477
8.3.2.2	Modeling Structural Return Loss	480
8.3.3	UTP: Hybrid Circuits	481
8.3.4	UTP: Near-End Crosstalk	487
8.3.5	UTP: Alien crosstalk	490
8.3.6	UTP: Far-End Crosstalk	490
8.3.7	Power sum NEXT and ELFEXT	493
8.3.8	UTP: Radio-Frequency Interference	493
8.3.9	UTP: Radiation	496
8.4	UTP Connectors	497
8.5	Issues with Screening	501
8.6	Category-3 UTP at Elevated Temperature	502
9	150-Ohm STP-A Cabling	505
9.1	150-Ω STP-A Signal Propagation	506
9.2	150-Ω STP-A Noise and Interference	506
9.3	150-Ω STP-A: Skew	507
9.4	150-Ω STP-A: Radiation and Safety	508
9.5	150-Ω STP-A: Comparison with UTP	509
9.6	150-Ω STP-A Connectors	509
10	Coaxial Cabling	513
10.1	Coaxial Signal Propagation	515
10.1.1	Stranded Center-Conductors	522
10.1.2	<i>Why 50 Ohms?</i>	523
10.1.3	<i>50-Ohm Mailbag</i>	526
10.2	Coaxial Cable Noise and Interference	528
10.2.1	Coax: Far-End Reflected Noise	528
10.2.2	Coax: Radio Frequency Interference	529
10.2.3	Coax: Radiation	529
10.2.4	Coaxial Cable: Safety Issues	530
10.3	Coaxial Cable Connectors	532
11	Fiber-Optic Cabling	537
11.1	Making Glass Fiber	538
11.2	Finished Core Specifications	539
11.3	Cabling the Fiber	541
11.4	Wavelengths of Operation	543
11.5	Multimode Glass Fiber-Optic Cabling	544
11.5.1	Multimode Signal Propagation	546
11.5.2	Why Is Graded-Index Fiber Better than Step-Index?	551
11.5.3	Standards for Multimode Fiber	552
11.5.4	What Considerations Govern the Use of 50-micron Fiber?	554

11.5.5	Multimode Optical Performance Budget	555
11.5.5.1	Multimode Dispersion Budget	555
11.5.5.2	Multimode Attenuation Budget	566
11.5.6	Jitter	568
11.5.7	Multimode Fiber-Optic Noise and Interference	570
11.5.8	Multimode Fiber Safety	571
11.5.9	Multimode Fiber with Laser Source	571
11.5.10	VCSEL Diodes	573
11.5.11	Multimode Fiber-Optic Connectors	575
11.6	Single-Mode Fiber-Optic Cabling	576
11.6.1	Single-Mode Signal Propagation	577
11.6.2	Single-Mode Fiber-Optic Noise and Interference	578
11.6.3	Single-Mode Fiber Safety	578
11.6.4	Single-Mode Fiber-Optic Connectors	578
12	Clock Distribution	579
12.1	<i>Extra Fries, Please</i>	582
12.2	Arithmetic of Clock Skew	584
12.3	Clock Repeaters	589
12.3.1	Active Skew Correction	593
12.3.2	Zero-Delay Clock Repeaters	594
12.3.3	Compensating for Line Length	595
12.4	Stripline vs. Microstrip Delay	596
12.5	Importance of Terminating Clock Lines	599
12.6	Effect of Clock Receiver Thresholds	601
12.7	Effect of Split Termination	602
12.8	Intentional Delay Adjustments	605
12.8.1	Fixed Delay	605
12.8.2	Adjustable Delays	607
12.8.3	Automatically Programmable Delays	609
12.8.4	<i>Serpentine Delays</i>	610
12.8.5	Switchback Coupling	612
12.9	Driving Multiple Loads with Source Termination	616
12.9.1	<i>To Tee or Not To Tee</i>	619
12.9.2	<i>Driving Two Loads</i>	625
12.10	Daisy-Chain Clock Distribution	627
12.10.1	Case Study of Daisy-Chained Clock	629
12.11	<i>The Jitters</i>	634
12.11.1	When Clock Jitter Matters	636
12.11.1.1	Clock Jitter Rarely Matters within the Boundaries of a Synchronous State Machine	636
12.11.1.2	Clock Jitter Propagation	636
12.11.1.3	Variance of the Tracking Error	640
12.11.1.4	Clock Jitter in FIFO-Based Architectures	643

12.11.1.5	What Causes Jitter.....	644
12.11.1.6	Random and Deterministic Jitter.....	645
12.11.2	Measuring Clock Jitter.....	648
12.11.2.1	<i>Jitter Measurement</i>	651
12.11.2.2	<i>Jitter and Phase Noise</i>	654
12.12	Power Supply Filtering for Clock Sources, Repeaters, and PLL Circuits... 656	
12.12.1	<i>Healthy Power</i>	659
12.12.2	<i>Clean Power</i>	661
12.13	<i>Intentional Clock Modulation</i>	663
12.13.1	<i>Signal Integrity Mailbag</i>	665
12.13.2	<i>Jitter-Free Clocks</i>	667
12.14	Reduced-Voltage Signaling.....	668
12.15	Controlling Crosstalk on Clock Lines.....	669
12.16	<i>Reducing Emissions</i>	670
13	Time-Domain Simulation Tools and Methods.....	673
13.1	<i>Ringin g in a New Era</i>	673
13.2	Signal Integrity Simulation Process.....	674
13.2.1	How Much Modeling Do You Need?.....	676
13.2.2	What Happens After Parameter Extraction?.....	676
13.2.3	A Word of Caution.....	677
13.3	The Underlying Simulation Engine.....	678
13.3.1	Evolving Forward.....	680
13.3.2	Pitfalls of SPICE-Like Algorithms.....	680
13.3.3	Transmission Lines.....	682
13.3.4	Interpreting Your Results.....	684
13.3.5	Using SPICE Intelligently.....	685
13.4	<i>IBIS (I/O Buffer Information Specification)</i>	685
13.4.1	What Is IBIS?.....	686
13.4.2	Who Created IBIS?.....	686
13.4.3	What Is Good About IBIS?.....	687
13.4.4	What's Wrong with IBIS?.....	687
13.4.5	What You Can Do to Help.....	688
13.5	<i>IBIS: History and Future Direction</i>	689
13.5.1	IBIS Historical Overview.....	689
13.5.2	Comparison to SPICE.....	690
13.5.3	Future Directions.....	690
13.6	IBIS: Issues with Interpolation.....	691
13.7	IBIS: Issues with SSO Noise.....	695
13.8	Nature of EMC Work.....	697
13.8.1	<i>EMC Simulation</i>	698
13.9	<i>Power and Ground Resonance</i>	699
	Collected References.....	703

Points to Remember.....	710
Appendix A - Building a Signal Integrity Department.....	731
Appendix B - Calculation of Loss Slope.....	733
Appendix C - Two-Port Analysis.....	735
Simple Cases Involving Transmission Lines.....	737
Fully Configured Transmission Line.....	739
Complicated Configurations.....	741
Appendix D - Accuracy of Pi Model.....	743
Pi-Model Operated in the LC Region.....	745
Appendix E - erf().....	747
Index.....	749