Contents

1 Introduction to Radiowaves 1
1.1 Introduction 1
1.2 Radio Services 2
1.3 International Codes and Standards 3
1.3.1 Objectives 3
1.3.2 Class of Codes and Standards 3
1.3.3 Radio Regulations 4
1.3.4 ITU-R Recommendations 5
1.4 Basic Terms and Definitions 5
1.5 Classification of Radio Systems 6
1.5.1 Classification Based on Frequency Bands 6
1.5.2 Classification Based on Service Types 6
1.6 Radio Frequency Bands 7
1.6.1 Role of Frequency in Radiocommunications 7
1.6.2 Classification of Frequency Bands 7
1.7 Application of Frequency Bands 8
1.7.1 ELF, ULF, and VLF Bands 9
1.7.2 LF Band (30–300 kHz) 9
1.7.3 MF Band (300–3000 kHz) 9
1.7.4 HF Band (3–30 MHz) 10
1.7.5 VHF Band (30–300 MHz) 10
1.7.6 UHF Band (300–3000 MHz) 10
1.7.7 SHF Band (3–30 GHz) 10
1.7.8 EHF Band (30–300 GHz) 11
1.7.9 Micrometric and Nanometric Bands 11
1.8 Frequency Allocation 11
1.8.1 Introduction 11
1.8.2 Frequency Registration 12
1.8.3 ITU Regions for Frequency Allocation 12
1.8.4 Frequency Assignment 13

1.9 Atmosphere Layers 14
1.9.1 Troposphere Layer 15
1.9.2 Stratosphere Layer 16
1.9.3 Ionosphere Layer 16
1.9.4 Magnetosphere Layer 17
1.10 Designation of Emissions 18
1.11 Summary 19
1.12 Exercises 19

2 Basic Principles in Radiowave Propagation 23
2.1 Introduction 23
2.2 Transmission Media 24
2.2.1 Media Characteristics 24
2.2.2 Radiowave Velocity 25
2.2.3 Depth of Radiowave Penetration 26
2.3 Electromagnetic Waves 28
2.3.1 Maxwell Equations 28
2.3.2 Electromagnetic Wave Spectrum 29
2.4 Wave Equations and Spectrum 29
2.4.1 Plane Waves 29
2.4.2 Radiowave Spectrum 30
2.5 Media Effects on Radiowaves 31
2.6 Propagation Parameters 31
2.7 Radiowave Polarization 32
2.7.1 Definition of Polarization 32
2.8 Main Types of Radiowave Polarization 32
2.8.1 Basic Polarized Radiowaves 33
2.9 Radio Links 36
2.10 Free-Space Loss 37
2.10.1 Power Flux Density 37
2.10.2 Free-Space Loss 38
2.10.3 ITU-R Formulas 40
2.11 Equivalent Radiated Power 43
2.11.1 Antenna Gain 43
2.11.2 ERP and EIRP 44
2.11.3 Electric Field Intensity 44
2.12 Transmission Loss 46
2.12.1 Loss Terms in Radio Links 46
2.12.2 Basic Transmission Loss 46
2.12.3 System and Total Losses 48
2.13 Radio Ray Path and K-Factor 49
2.13.1 Curvature of Ray Path 49
2.13.2 K-Factor 51
2.14 Summary 52
2.15 Exercises 53

3 Radiowave Propagation in Troposphere 57
3.1 Introduction 57
3.2 Earth Atmosphere 58
3.2.1 Major Parameters 58
3.2.2 Lower Part of Troposphere 59
3.2.3 Standard Earth Atmosphere 59
3.2.4 Non-standard Atmospheric Parameters 61
3.3 Radiowave Refraction 62
3.3.1 Refractive Index of Air 63
3.3.2 Wave Path and Effective Earth Radius 64
3.4 K-Factor 64
3.4.1 Definition 64
3.4.2 Variation Range of K-Factor 65
3.4.3 The Earth Bulge 66
3.4.4 Radio Horizon 68
3.4.5 Atmospheric Duct 70
3.5 Radiowave Attenuation in Troposphere 78
3.5.1 Introduction 78
3.5.2 Rain Attenuation 78
3.5.3 Cloud and Fog Attenuation 82
3.5.4 Hail and Snow Attenuation 84
3.5.5 Aerosols 86
3.6 Radiowave Reflection 87
3.6.1 Reflection Equations 87
3.6.2 Multipath Reception 91
3.6.3 Coverage Diagram and Height Gain Curve 93
3.6.4 Fresnel Zones 96
3.6.5 Fresnel Radius Calculation 97
3.7 Radiowave Diffraction 100
3.7.1 Introduction 100
3.7.2 Diffraction Parameter 101
3.7.3 Field in Diffraction Region 102
3.7.4 Field in Interference Region 103
3.7.5 Field in the Midpath Region 105
3.8 Attenuation of Obstacles 108
3.8.1 Obstruction Loss in Diffraction Condition 108
3.8.2 Obstructed Radio Path 111
3.9 Forest and Vegetation Area 112
3.9.1 Overall Views 112
3.9.2 VHF/UHF Frequency Bands 114
3.9.3 SHF/EHF Frequency Bands 116
3.10 Summary 120
3.11 Exercises 121

4 Radiowave Propagation in Ionosphere 127
4.1 Introduction 127
4.2 Ionization in Ionosphere Layer 127
4.2.1 Ionization and Plasma State 127
4.2.2 Ionosphere Layer Classification 129
4.2.3 Ionospheric Phenomena 129
4.3 Ionospheric Communications in MF/HF Frequency Band 131
4.3.1 Radiowave Propagation in Ionosphere 131
4.3.2 Applications 132
4.3.3 Vertical Propagation in Ionosphere 133
4.3.4 Inclined Propagation of Ionospheric Waves 135
4.3.5 Optimum Usage Frequency 136
4.3.6 Long-Distance Communications 138
4.3.7 Effects of D Sub-layer and Day/Night Frequencies 140
4.3.8 Time Delay of Different Transmission Modes 140
4.3.9 Solar Effects 143
4.3.10 Geomagnetic Field Effect 144
4.4 Ionosphere Effects on Satellite Communications 145
4.4.1 Main Effects 145
4.4.2 Ionosphere Ionization 146
4.4.3 Faraday Rotation 147
4.4.4 Group Delay 148
4.4.5 Dispersion 148
4.4.6 Scintillation 150
4.4.7 Frequency Dependence of Ionospheric Effects 152
4.5 Ionosphere Reference Characteristics 153
4.5.1 Introduction 153
4.5.2 Mapping Functions 154
4.5.3 Prediction of f_0F2 and $M(3000)F2$ 156
4.5.4 Prediction of f_0E 157
4.5.5 Prediction of f_0F1 159
4.5.6 Software Programs 161
4.6 Ionosphere Main Parameters 162
4.6.1 Main Indices 162
4.6.2 Sunspot Numbers 163
4.6.3 Index Φ 164
4.7 Summary 165
4.8 Exercises 166

5 Propagation in 3 kHz to 30 MHz Band 171
5.1 Introduction 171
5.1.1 Applications 171
5.1.2 Evolution Trend 172
5.1.3 Main Considerations 172

5.2 Propagation in VLF/LF Frequency Band 173
5.2.1 Introduction 173
5.2.2 Radiowave Propagation in Seawater 173
5.2.3 Design Considerations 175
5.2.4 Submarine Vessel Radiocommunications 176
5.2.5 Propagation in the Earth Atmosphere 180
5.3 Surface Wave Propagation 181
5.3.1 Introduction 181
5.3.2 Electric Characteristics 181
5.3.3 Electric Characteristic Variation 181
5.3.4 Wave Penetration 183
5.3.5 Effective Factors in Electric Characteristics 184
5.3.6 Received Power 185
5.3.7 Vertically Polarized Waves 185
5.3.8 Horizontally Polarized Waves 187
5.3.9 ITU-R Diagrams 188
5.3.10 Mixed Paths 194
5.4 Wave Propagation in MF/HF Band 196
5.4.1 Location of the Control Points 196
5.4.2 Screening Frequency for E and F2 Layers 197
5.4.3 Propagation Modes 198
5.4.4 Wave Elevation Angle 199
5.4.5 Field Intensity of Waves 199
5.4.6 Received Power 203
5.4.7 Signal-to-Noise Ratio 204
5.4.8 Lowest Usable Frequency 205
5.4.9 Design Considerations 205
5.4.10 Wave Propagation in MF Band 209
5.5 Summary 211
5.6 Exercises 212

6 Terrestrial Mobile Radio Propagation 217
6.1 Introduction 217
6.2 Diffraction Loss 219
6.2.1 Fresnel Zones 219
6.2.2 Basic Concepts 220
6.2.3 Diffraction of Spherical Earth 222
6.2.4 Obstacle Diffraction 226
6.2.5 Single Knife-Edge Obstacles 226
6.2.6 Single Rounded Obstacles 227
6.2.7 Double Isolated Obstacles 230
6.2.8 Multiple Isolated Obstacles 234
6.3 Propagation Environment in Mobile Radio Communications 235
6.4 Signal Level Variability 236
6.4.1 Introduction 236

6.4.2 Shadow 237
6.4.3 Location Variability 237
6.4.4 Time Variability 241
6.4.5 Location and Time Variability 241
6.4.6 Fade Margin 242
6.5 Polarization 243
6.5.1 Depolarization Effects 243
6.5.2 Polarization Diversity 244
6.6 Antenna Height 244
6.6.1 Outlines 244
6.6.2 Antenna Height Gain 245
6.6.3 Fixed Antenna Height Gain 247
6.6.4 Mobile Antenna Gain 248
6.7 Reflection and Multipath 249
6.7.1 Local Reflections 249
6.7.2 Correlation Between Main and Unwanted Signals 250
6.7.3 Multipath Fading 251
6.8 Time Delay Spread 251
6.8.1 Received Signal Time Delay 251
6.8.2 System Performance 253
6.9 Climate Effects 254
6.9.1 Index of Refraction 254
6.9.2 Climate Factors 254
6.10 Earth Effects 255
6.10.1 Seawater 256
6.10.2 Fields and Hills 256
6.11 Guided Radiowave Propagation 257
6.11.1 Radiowave Propagation in Tunnels 258
6.11.2 Leaky Feeders 259
6.11.3 Air Duct 259
6.12 Mobility Effects 260
6.12.1 Surrounded Areas 260
6.12.2 Body Loss 260
6.13 Media Conditions 260
6.13.1 Introduction 260
6.13.2 Main Factors 261
6.13.3 Received Power Equation 262
6.14 Received Signal Level 265
6.14.1 Introduction 265
6.14.2 Link Power Budget Equation 265
6.15 Area Coverage Prediction Models 268
6.15.1 Introduction 268
6.15.2 Classification of Models 268
6.15.3 Model Limitations 269

6.16 Basic Models 269
6.16.1 Theoretical Model 269
6.16.2 Simple Empirical Model 270
6.17 Applied Models 272
6.17.1 Bullington Model 272
6.17.2 Hata Model 274
6.17.3 COST 231-Hata Model 276
6.17.4 Lee Model 277
6.18 Summary 280
6.19 Exercises 281

7 Line-of-Sight Propagation 291
7.1 Introduction 291
7.1.1 Propagation Environment 291
7.1.2 Main Factors 292
7.1.3 Frequency Bands 292
7.2 Ray Trajectory 293
7.2.1 Radius of Radio Path Curvature 293
7.2.2 K-Factor 295
7.2.3 Earth Atmosphere 297
7.2.4 Typical Values of K-Factor 298
7.2.5 Radio Path Profiles 299
7.3 Terrestrial Obstacles 302
7.3.1 Obstacle Types 302
7.3.2 Fresnel Radius 303
7.3.3 Diffraction Loss 303
7.4 Radio Path Clearance 305
7.4.1 Single-Antenna Criterion 305
7.4.2 Two-Antenna Space Diversity Criterion 306
7.4.3 Three-Antenna Space Diversity Configuration 306
7.4.4 Minimum Antenna Height 307
7.4.5 Single-Antenna Height 307
7.4.6 Antenna Space Diversity 307
7.4.7 Optimum Antenna Height 308
7.4.8 Antenna Around Clearance 309
7.5 Propagation Loss in LOS Radio Links 311
7.5.1 Communication Equation 311
7.5.2 Propagation Loss 313
7.5.3 Precipitation Loss 314
7.5.4 Cross-Polarization Discrimination, XPD 319
7.5.5 Antenna to Air Coupling Loss 322
7.6 Design Criteria 322
7.6.1 Hypothetical Reference Circuit 323
7.6.2 Grade of the System 323
7.6.3 Availability and Unavailability Criteria 324

7.6.4 Quality Criterion 326
7.6.5 Performance Criterion 326
7.7 Fading of the Received Signal 327
7.7.1 Permanent Attenuations 327
7.7.2 Occasional Attenuations 328
7.7.3 Fading 328
7.7.4 Multipath 329
7.7.5 Overreach Reception 332
7.7.6 Fading Occurrence Probability 334
7.7.7 New ITU-R Method 337
7.8 Outage Time 344
7.8.1 Introduction 344
7.8.2 Fade Margin 344
7.8.3 Link Outage Time 345
7.8.4 Fade Margin Calculation 347
7.9 Design Considerations 348
7.9.1 Design Criteria 348
7.9.2 Radio Site Selection 349
7.9.3 Foundations and Earthling Network 349
7.9.4 Climate 350
7.9.5 Radio Path Inclination 350
7.9.6 Zigzag Path 350
7.9.7 Path Length 351
7.9.8 Antenna Around Clearance 351
7.9.9 Radio Sources 351
7.9.10 Precipitation 352
7.9.11 Improvement Techniques 352
7.9.12 Technical Calculations 352
7.10 Summary 353
7.11 Exercises 354

8 Propagation in Guided Media 361
8.1 Introduction 361
8.2 RF Leaky Cable 361
8.3 Waveguides 363
8.3.1 TE Modes 364
8.3.2 TM Modes 367
8.4 Fiber Optic Cable 369
8.4.1 Introduction 369
8.4.2 FOC Band and Windows 370
8.4.3 Applications in Telecommunications 372
8.4.4 Propagation Principles in FOC 376
8.4.5 Main Parameters 379
8.4.6 Limiting Factors in FOC Networks 381
8.4.7 FOC Standards 385
8.4.8 FOC Telecom Networks 385

8.4.9 FOC Link Calculations 388
8.4.10 Mechanical and Civil Considerations 397
8.5 Summary 398
8.6 Exercises 398

9 Selected Topics in Radiowave Propagation 403
9.1 Scope 403
9.2 Optical Radio Links 404
9.2.1 Introduction 404
9.2.2 Main Atmospheric Effects 405
9.2.3 Atmospheric Absorption 405
9.2.4 Atmospheric Scattering 406
9.2.5 Scintillation 408
9.2.6 Atmospheric Precipitation 409
9.2.7 Aerosol Absorption 412
9.2.8 Ambient Sunlight Effect 413
9.2.9 Visibility 414
9.3 Optical Radio Link Design 415
9.3.1 Design Calculations 415
9.3.2 FSO Link Design 421
9.4 Radiowave Propagation in 20–375 THz 424
9.4.1 Main Effects of Atmosphere 424
9.4.2 Absorption 425
9.4.3 Scattering 425
9.4.4 Turbulence 427

APPENDIX 429

A Logarithmic System of Units 429
A.1 Introduction 429
A.2 Definition 429
A.3 Basic Formulas 430
A.4 Common Logarithmic Quantities 430
A.5 Principles of Logarithmic System of Units 431
A.6 Advantages of Logarithmic System of Units 432

B ITU-R Recommendations P-Series 435

C ITU-R-Based Terms and Definitions Related to Propagation in Non-ionized Media (P-310) 441
C.1 Vocabulary of Terms Used in Radio Propagation in Non-ionized Media 441

Bibliography 447

Index 451