Contents

1 Introduction to IP Traffic 1
1.1 TCP/IP Architecture Model 1
1.1.1 Physical Layer 3
1.1.2 Data Link Layer 4
1.1.3 Network Layer 5
1.1.4 Transport Layer 5
1.1.5 Application Layer 8
1.2 Aspects of IP Modeling 9
1.2.1 Levels of Modeling 10
1.2.2 Traffic Relations 13
1.2.3 Asymmetry in IP Traffic 17
1.2.4 Temporal Behavior 17
1.2.5 Network Topology 18
1.3 Quality of Service 19
1.3.1 Best Effort Traffic 19
1.3.2 Time Sensitive Data Traffic 20
1.3.3 Overprovisioning 20
1.3.4 Prioritization 21
1.4 Why Traditional Models Fail 22

2 Classical Traffic Theory 29
2.1 Introduction to Traffic Theory 29
2.1.1 Basic Examples 29
2.1.2 Basic Processes and Kendall Notation 32
2.1.3 Basic Properties of Exponential Distributions 33
2.2 Kolmogorov Equation 34
2.2.1 State Probability 36
2.2.2 Stationary State Equation 37
2.3 Transition Processes 38
2.4 Pure Markov Systems M/M/n 40
2.4.1 Loss Systems M/M/n 40

2.4.2 Queueing Systems M/M/n 44
2.4.3 Application to Teletraffic 52
2.5 Special Traffic Models 58
2.5.1 Loss Systems M/M/∞ 58
2.5.2 Queueing Systems of Engset 58
2.5.3 Queueing Loss Systems 59
2.6 Renewal Processes 60
2.6.1 Definitions and Concepts 60
2.6.2 Bounds for the Renewal Function 65
2.6.3 Recurrence Time 66
2.6.4 Asymptotic Behavior 68
2.6.5 Stationary Renewal Processes 70
2.6.6 Random Sum Processes 71
2.7 General Poisson Arrival and Serving Systems M/G/n 73
2.7.1 Markov Chains and Embedded Systems 73
2.7.2 General Loss Systems M/G/n 73
2.7.3 Queueing Systems M/G/n 74
2.7.4 Heavy-Tail Serving Time Distribution 80
2.7.5 Application of M/G/1 Models to IP Traffic 95
2.7.6 Markov Serving Times Models GI/M/1 102
2.8 General Serving Systems GI/G/n 107
2.8.1 Loss Systems 107
2.8.2 The Time-Discrete Queueing System GI/G/1 109
2.8.3 GI/G/1 Time Discrete Queueing System with Limitation 117
2.9 Network Models 122
2.9.1 Jackson's Network 122
2.9.2 Systems with Priorities 130
2.9.3 Systems with Impatient Demands 131
2.9.4 Conservation Laws Model 133
2.9.5 Packet Loss and Velocity Functions on Transmission Lines 134
2.9.6 Riemann Solvers 141
2.9.7 Stochastic Velocities and Density Functions 146
2.10 Matrix-Analytical Methods 148
2.10.1 Phase Distribution 148
2.10.2 Examples for Different Phase Distributions 153
2.10.3 Markovian Arrival Processes 156
2.10.4 Queueing Systems MAP/G/1 161
2.10.5 Application to IP Traffic 173

3 Mathematical Modeling of IP-based Traffic 181
3.1 Scalefree Traffic Observation 181
3.1.1 Motivation and Concept 181
3.1.2 Self-Similarity 183
3.2 Self-Similar Processes 184

3.2.1 Definition and Basic Properties 184
3.2.2 Fractional Brownian Motion 190
3.2.3 α-stable Processes 194
3.3 Long-Range Dependence 202
3.3.1 Definition and Concepts 203
3.3.2 Fractional Brownian Motion and Fractional Brownian Noise 207
3.3.3 Farima Time Series 211
3.3.4 Fractional Brownian Motion and IP Traffic – the Norros Approach 218
3.4 Influence of Heavy-Tail Distributions on Long-Range Dependence 226
3.4.1 General Central Limit Theorem 226
3.4.2 Heavy-Tail Distributions in M/G/∞ Models 233
3.4.3 Heavy-Tail Distributions in On-Off Models 235
3.4.4 Aggregated Traffic 240
3.5 Models for Time Sensitive Traffic 245
3.5.1 Multiscale Fractional Brownian Motion 245
3.5.2 Norros Models for Differentiating Traffic 249
3.6 Fractional Lévy Motion in IP-based Network Traffic 259
3.6.1 Description of the Model 259
3.6.2 Calibration of a Fractional Lévy Motion Model 260
3.7 Fractional Ornstein-Uhlenbeck Processes and Telecom Processes 261
3.7.1 Description of the Model 261
3.7.2 Fractional Ornstein-Uhlenbeck Gaussian Processes 262
3.7.3 Telecom Processes 263
3.7.4 Representations of Telecom Processes 263
3.7.5 Application of Telecom Processes 265
3.8 Multifractal Models and the Influence of Small Scales 267
3.8.1 Multifractal Brownian Motion 267
3.8.2 Wavelet-Based Multifractal Models 270
3.8.3 Characteristics of Multifractal Models 280
3.8.4 Multifractal Formalism 292
3.8.5 Construction of Cascades 296
3.8.6 Multifractals, Self-Similarity and Long-Range Dependence 308
3.9 Summary of Models for IP Traffic 316

4 Statistical Estimators 321
4.1 Parameter Estimation 321
4.1.1 Unbiased Estimators 322
4.1.2 Linear Regression 329
4.1.3 Estimation of the Heavy-Tail Exponent α 335
4.1.4 Maximum Likelihood Method 344

4.2 Estimators of Hurst Exponent in IP Traffic 349
4.2.1 Absolute Value Method (AVM) 349
4.2.2 Variance Method 352
4.2.3 Variance of Residuals 354
4.2.4 R/S Method 356
4.2.5 Log Periodogram – Local and Global 359
4.2.6 Maximum Likelihood and Whittle Estimator 363
4.2.7 Wavelet Analysis 368
4.2.8 Quadratic Variation 378
4.2.9 Remarks on Estimators 379

5 Performance of IP: Waiting Queues and Optimization 383
5.1 Queueing of IP Traffic for Perturbation with Long-Range Dependence Processes 383
5.1.1 Waiting Queues for Models with Fractional Brownian Motion 384
5.1.2 Queueing in Multiscaling FBM 392
5.1.3 Fractional Lévy Motion and Queueing in IP Traffic Modeling 395
5.1.4 Queueing Theory and Performance for Multifractal Brownian Motion 405
5.2 Queueing in Multifractal Traffic 411
5.2.1 Queueing in Multifractal Tree Models 411
5.2.2 Queueing Formula 417
5.3 Traffic Optimization 423
5.3.1 Mixed Traffic 423
5.3.2 Optimization of Network Flows 424
5.3.3 Rate Control: Shadow Prices and Proportional Fairness 435
5.3.4 Optimization for Stochastic Perturbation 442
5.3.5 Optimization of Network Flows Using an Utility Approach 449

References 465

Index 479