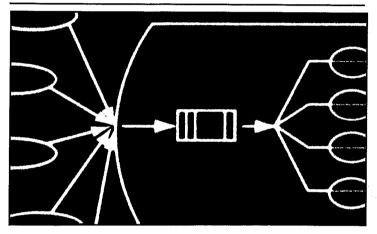
J. MEDHI



STOCHASTIC MODELS IN QUEUEING THEORY

SECOND EDITION

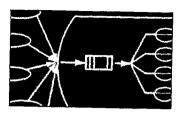


ACADEMIC PRESS

An imprint of Elsevier Science

Amsterdam Boston London New York Oxford Paris San Diego San Francisco Singapore Sydney Tokyo

Contents



Preface xv

CHAPTER

1	Sto	Stochastic Processes 1			
	1.1	Introdu	uction 1		
	1.2	Markov	Chains 2		
		1.2.1	Basic ideas 2		
		1.2.2	Classification of states and chains 4		
	1.3	Continu	ious-Time Markov Chains 14		
		1.3.1	Sojourn time 14		
			Transition density matrix or infinitesimal		
			generator 15		
		1.3.3	Limiting behavior: ergodicity 16		
		1.3.4	Transient solution 18		
		1.3.5	Alternative definition 19		
	1.4	Birth-a	nd-Death Processes 23		
		1.4.1	Special case: M/M/1 queue 25		
		1.4.1	_ · · · · · · · · · · · · · · · · · · ·		
	1.5	Poisson	Process 25		
		1.5.1	Properties of the Poisson process 28		
			Generalization of the Poisson process 29		
		1.5.3			

1.6 Randomization: Derived Markov Chains 32

Markov chain on an underlying Poisson process (or subordinated to a Poisson process)

viii	Conte	ents	
			Equivalence of the two limiting forms 33 Numerical method 34
			l Processes 35
		1.7.1	Introduction 35
		1.7.2	Residual and excess lifetimes 36
	1.8	Regene	rative Processes 37
		1.8.1	Application in queueing theory 38
	1.9		Renewal Processes and Semi-Markov
		Process Problem	
			ns 41 nces and Further Reading 46
			-
CHAPTER 2	Que	ueing	Systems: General Concepts 47
	2.1	Introdu	ection 47
		2.1.1	
			The input or arrival pattern of customers 48
		2.1.3	The pattern of service 49
			The number of servers 49
			The capacity of the system 49
			The queue discipline 49
		Vueuei	ng Processes 50
			nt and Steady-State Behavior 52
			tions of the Steady-State Distribution 53
			ieneral Relationships in Queueing Theory 54
			Arrival Process and Its Characteristics 59
		2.7.1	PASTA: Poisson arrivals see time averages 59
		2.7.2	ASTA: arrivals see time averages 62
		Refere	nces and Further Reading 62
CHAPTER 3			-Death Queueing Systems:
	Ехр	onenti	al Models 65
	3.1	Introd	uction 65
	3.2	The Sir	mple M/M/I Queue 65
		3.2.1	,
		3.2.2	
		3.2.3	1 1
	77	3.2.4	, y
	J.J		n with Limited Waiting Space: $M/1/K$ Model 77
		3.3.1	
		3.3.2	Steady-state solution 77 Expected number in the system L_{κ} 78
		0.0.2	expected number in the system LK 10

Equivalence of an M/M/1/K model with 3.3.3 a two-stage cyclic model

3.4	Birth-	and-Death Processes: Exponential Models 81			
3.5	The M	The M/M/ ∞ Model: Exponential Model with an Infinite			
7 /		Number of Servers 83			
3.6		odel M/M/c 84			
	3.6.2	Steady-state distribution 84			
	3.6.2				
	J.O.J				
77	J.O.4	The output process 93 /M/c/c System: Erlang Loss Model 95			
J. 1	3.7.1				
	3.7.1	Recursive algorithm 99			
	3.7.2	. •			
7 Ω		with Finite Input Source 101			
0.0	3.8.1	Steady-state distribution: $M/M/c//m (m>c)$.			
	0.0.1	Engset delay model 101			
	3 8 2	Engset loss model $M/M/c//m/(m > c)$ 106			
	3 8 3	The model $M/M/c//m$ ($m \le c$) 109			
3.9		ent Behavior 110			
4.7		Introduction 110			
		Difference-equation technique 112			
		Method of generating function 117			
	3.9.4				
	3.9.5	, ,			
3.10		nt-State Distribution of the M/M/c Model 127			
		Solution of the differential-difference			
		equations 127			
	3.10.2	Busy period of an $M/M/c$ queue 133			
	3.10.3	Transient-state distribution of the output			
		of an M/M/c queue 136			
3.11	Multich	nannel Queue with Ordered Entry 138			
	3.11.1	Two-channel model with ordered entry			
		(with finite capacity) 139			
	3.11.2	The case $M = 1$, $N = N$ 140			
	3.11.3	Particular case: $M = N = 1$ (overflow system) 142			
	3.11.4	Output process 144			
	Problen	ns and Complements 145			
	Refere	nces and Further Reading 159			
Non	-Birth	-and-Death Queueing Systems:			

CHAPTER 4 No Markovian Models 165

4.1 Introduction, 165

- The system $M/E_k/1$ The system $E_k/M/1$ 165 4.1.1
- 4.1.2 170

- 4.2.1 Markovian bulk-arrival system: M^x/M/1 174
- 4.2.2 Equivalence of M'/M/1 and $M/E_r/1$ systems 178
- 4.2.3 Waiting-time distribution in an $M^x/M/1$ queue 178
- 4.2.4 Transient-state behavior 179
- 4.2.5 The system $M^{x}/M/\infty$ 181

4.3 Queueing Models with Bulk (Batch) Service 185

- 4.3.1 The system M/M(a, b)/1 186
 - 4.3.2 Distribution of the waiting-time for the system M/M(a, b)/1 190
 - 4.3.3 Service batch-size distribution 195

4.4 M/M(a, b)/1: Transient-State Distribution 196

- 4.4.1 Steady-state solution 198
- 4.4.2 Busy-period distribution 198
- 4.5 Two-Server Model: M/M(a, b)/2 202
 - 4.5.1 Particular case: M/M(1, b)/2 204
- 4.6 The M/M(1, b)/c Model 205
 - 4.6.1 Steady-state results M/M(1, b)/c 208

Problems and Complements 210

References and Further Reading 217

CHAPTER 5 Network of Queues 221

- 5.1 Network of Markovian Queues 221
- 5.2 Channels in Series or Tandem Queues 222
 - 5.2.1 Queues in series with multiple channels at each phase 224
- 5.3 Jackson Network 226
- 5.4 Closed Markovian Network
 (Gordon and Newell Network) 233
- 5.5 Cyclic Queue 236
- 5.6 BCMP Networks 238
- 5.7 Concluding Remarks 240
 - 5.7.1 Loss networks 241

Problems and Complements 242
References and Further Reading 249

CHAPTER 6 Non-Markovian Queueing Systems 255

- 6.1 Introduction 255
- 6.2 Embedded-Markov-Chain Technique for the System with Poisson Input 256

6.3	The M	/G/1 Model: Pollaczek-Khinchin Formula 259
	6.3.1	
		epoch system size 259
	6.3.2	0
	6.3.3	•
		of an $M/G/1$ queue: supplementary
		variable technique 267
	6.3.4	1
	6.3.5	1,7
6.4 Busy Period 276		
		Introduction 276
	6.4.2	Busy-period distribution: Takács integral
		equation 277
	6.4.3	Further discussion of the busy period 279
	6.4.4	
	6.4.5	, , , , , , , , , , , , , , , , , , , ,
6.5	•	s with Finite Input Source:
		I//N System 289
6.6		with Limited Waiting Space:
		1/K System 292
6.7		/G/I Model with Bulk Arrival 295
	6.7.1	
		epochs in steady state (Pollaczek-Khinchin
		formula) 295
	6.7.2	<u> </u>
	6.7.3	
6.8		$G(\alpha, b)/1$ Model with General
		ervice 304
6.7	•	M/1 Model 306
	6.9.1 6.9.2	
	0.7.2	General time system size in steady state 309
	6.9.3	
		Expected duration of busy period
	0.7.4	and idle period 313
6.10	Multise	erver Model 314
0.10		The $M/G/\infty$ model: transient-state
	0.10.1	distribution 314
	6.10.2	The model $G/M/c$ 319
	6.10.3	The model $M/G/c$ 322
6.11	Queues	with Markovian Arrival Process 324
-	Problems and Complements 326	
		nces and Further Reading 334

CHAPTER 7 Queues with General Arrival Time and Service-Time Distributions 339

7.1		G/1 Queue with General Arrivorvice-Time Distributions 339	
	7.1.1	Lindley's integral equation	341

- 7.1.2 Laplace transform of W
- 7.1.3 Generalization of the Pollaczek-Khinchin transform formula 346

7.2 Mean and Variance of Waiting Time W 348

- Mean of W (single-server queue) 7.2.1 348
- 7.2.2 Variance of W351
- 7.2.3 Multiserver queues: approximation of mean waiting time 353

7.3 Queues with Batch Arrivals $G^{(x)}/G/1$ 356

7.4 The Output Process of a G/G/1 System 358

- 7.4.1 Particular case 359
- 7.4.2 Output process of a G/G/c system 360

7.5 Some Bounds for the G/G/1 System 360

- 7.5.1 Bound for E(I)360
- Bounds for E(W)7.5.2

Problems and Complements 368

References and Further Reading 371

CHAPTER 8 Miscellaneous Topics 375

8.1 Heavy-Traffic Approximation for Waiting-Time Distribution 375

- 8.1.1 Kingman's heavy-traffic approximation for a G/G/1 queue 375
- Empirical extension of the M/G/1 heavy-traffic 8.1.2 approximation 379
- 8.1.3 G/M/c queue in heavy traffic 381

8.2 Brownian Motion Process 383

- 8.2.1 Introduction 383
- 8.2.2 Asymptotic queue-length distribution 386
- 8.2.3 Diffusion approximation for a G/G/1 queue 389
- 8.2.4 Virtual delay for the G/G/1 system
- 8.2.5 Approach through an absorbing barrier with instantaneous return
- 8.2.6 Diffusion approximation for a G/G/c queue: state-dependent diffusion equation

	8.2.7	Diffusion approximation for an $M/G/c$ model 396
	8.2.8	Concluding remarks 397
8.3	Queue	ing Systems with Vacations 398
	8.3.1	Introduction 398
	8.3.2	
	8.3.3	Poisson input queue with vacations:
		[exhaustive-service] queue-length
		distribution 399
	8.3.4	Poisson input queue with vacations:
		waiting-time distribution 404
	8.3.5	M/G/1 system with vacations:
		nonexhaustive service 406
	8.3.6	Limited service system: $M/G/1-V_m$ model 407
	8.3.7	Gated service system: $M/G/1-V_m$ model 408
	8.3.8	M/G/1/K queue with multiple vacations 412
	8.3.9	Mean value analysis through heuristic
		treatment 416
8.4	Design	and Control of Queues 423
8.5	Retrial	Queueing System 427
	8.5.1	Retrial queues: model description 427
	8.5.2	Single-server model: M/M/1 retrial queue 429
	8.5.3	M/G/1 retrial queue 432
	8.5.4	Multiserver models 436
	8.5.5	Model with finite orbit size 439
	8.5.6	Other retrial queue models 440
8.6		nce of a New Trend in Teletraffic Theory 441
	8.6.1	Introduction 441
	8.6.2	Heavy-tail distributions 442
	8.6.3	M/G/1 with heavy-tailed service time 445
	8.6.4	Pareto mixture of exponential (PME)
		distribution 445
	8.6.5	Gamma mixture of Pareto (GMP) distribution 447
	8.6.6	Beta mixture of exponential (BME)
		distribution 450
	8.6.7	A class of heavy-tail distributions 452
	8.6.8	Long-range dependence 454
		ns and Complements 455
	Referen	ces and Further Reading 461

Appendix 469 Index 477