

# Contents

<b>PREFACE</b>	<b><i>xi</i></b>
<b>1 TYPICAL REAL-TIME APPLICATIONS</b>	<b>1</b>
1.1 Digital Control	2
1.2 High-Level Controls	10
1.3 Signal Processing	14
1.4 Other Real-Time Applications	19
1.5 Summary	25
<b>2 HARD VERSUS SOFT REAL-TIME SYSTEMS</b>	<b>26</b>
2.1 Jobs and Processors	26
2.2 Release Times, Deadlines, and Timing Constraints	27
2.3 Hard and Soft Timing Constraints	27
2.4 Hard Real-Time Systems	29
2.5 Soft Real-Time Systems	31
2.6 Summary	32
<b>3 A REFERENCE MODEL OF REAL-TIME SYSTEMS</b>	<b>34</b>
3.1 Processors and Resources	35
3.2 Temporal Parameters of Real-Time Workload	37
3.3 Periodic Task Model	40
3.4 Precedence Constraints and Data Dependency	42
3.5 Other Types of Dependencies	45
3.6 Functional Parameters	48
3.7 Resource Parameters of Jobs and Parameters of Resources	51
3.8 Scheduling Hierarchy	52
3.9 Summary	56
<b>4 COMMONLY USED APPROACHES TO REAL-TIME SCHEDULING</b>	<b>60</b>
4.1 Clock-Driven Approach	60
4.2 Weighted Round-Robin Approach	61

- 4.3      Priority-Driven Approach    62
- 4.4      Dynamic versus Static Systems    65
- 4.5      Effective Release Times and Deadlines    65
- 4.6      Optimality of the EDF and LST Algorithms    67
- 4.7      Nonoptimality of the EDF and the LST Algorithms    70
- 4.8      Challenges in Validating Timing Constraints  
         in Priority-Driven Systems    72
- 4.9      Off-Line versus On-Line Scheduling    77
- 4.10     Summary    81
- 4.11     Exercises    82

**5    CLOCK-DRIVEN SCHEDULING**

- 5.1      Notations and Assumptions    85
- 5.2      Static, Timer-Driven Scheduler    86
- 5.3      General Structure of Cyclic Schedules    88
- 5.4      Cyclic Executives    90
- 5.5      Improving the Average Response Time of Aperiodic Jobs    92
- 5.6      Scheduling Sporadic Jobs    96
- 5.7      Practical Considerations and Generalizations    102
- 5.8      Algorithm for Constructing Static Schedules    106
- 5.9      Pros and Cons of Clock-Driven Scheduling    111
- 5.10     Summary    113

**6    PRIORITY-DRIVEN SCHEDULING OF PERIODIC TASKS**

- 6.1      Static Assumption    116
- 6.2      Fixed-Priority versus Dynamic-Priority Algorithms    117
- 6.3      Maximum Schedulable Utilization    124
- 6.4      Optimality of the RM and DM Algorithms    129
- 6.5      A Schedulability Test for Fixed-Priority Tasks  
         with Short Response Times    130
- 6.6      Schedulability Test for Fixed-Priority Tasks with Arbitrary  
         Response Times    140
- 6.7      Sufficient Schedulability Conditions for the RM  
         and DM Algorithms    146
- 6.8      Practical Factors    159
- 6.9      Summary    179

**7    SCHEDULING APERIODIC AND SPORADIC JOBS IN  
     PRIORITY-DRIVEN SYSTEMS**

- 7.1      Assumptions and Approaches    190
- 7.2      Deferrable Servers    195
- 7.3      Sporadic Servers    204
- 7.4      Constant Utilization, Total Bandwidth, and Weighted  
         Fair-Queueing Servers    218

7.5	Slack Stealing in Deadline-Driven Systems	233
7.6	Slack Stealing in Fixed-Priority Systems	244
7.7	Scheduling of Sporadic Jobs	250
7.8	Real-Time Performance for Jobs with Soft Timing Constraints	259
7.9	A Two-Level Scheme for Integrated Scheduling	263
7.10	Summary	267
<b>8</b>	<b>RESOURCES AND RESOURCE ACCESS CONTROL</b>	<b>277</b>
8.1	Assumptions on Resources and Their Usage	277
8.2	Effects of Resource Contention and Resource Access Control	280
8.3	Nonpreemptive Critical Sections	284
8.4	Basic Priority-Inheritance Protocol	286
8.5	Basic Priority-Ceiling Protocol	290
8.6	Stack-Based, Priority-Ceiling (Ceiling-Priority) Protocol	300
8.7	Use of Priority-Ceiling Protocol in Dynamic-Priority Systems	304
8.8	Preemption-Ceiling Protocol	308
8.9	Controlling Accesses to Multiple-Unit Resources	313
8.10	Controlling Concurrent Accesses to Data Objects	317
8.11	Summary	322
<b>9</b>	<b>MULTIPROCESSOR SCHEDULING, RESOURCE ACCESS CONTROL, AND SYNCHRONIZATION</b>	<b>330</b>
9.1	Model of Multiprocessor and Distributed Systems	331
9.2	Task Assignment	339
9.3	Multiprocessor Priority-Ceiling Protocol	352
9.4	Elements of Scheduling Algorithms for End-to-End Periodic Tasks	360
9.5	Schedulability of Fixed-Priority End-to-End Periodic Tasks	371
9.6	End-to-End Tasks in Heterogeneous Systems	384
9.7	Predictability and Validation of Dynamic Multiprocessor Systems	386
9.8	Summary	387
<b>10</b>	<b>SCHEDULING FLEXIBLE COMPUTATIONS AND TASKS WITH TEMPORAL DISTANCE CONSTRAINTS</b>	<b>394</b>
10.1	Flexible Applications	395
10.2	Tasks with Temporal Distance Constraints	411
10.3	Summary	417
<b>11</b>	<b>REAL-TIME COMMUNICATION</b>	<b>420</b>
11.1	Model of Real-Time Communication	421
11.2	Priority-Based Service Disciplines for Switched Networks	429
11.3	Weighted Round-Robin Service Disciplines	445
11.4	Medium Access-Control Protocols of Broadcast Networks	453
11.5	Internet and Resource Reservation Protocols	469
11.6	Real-Time Protocol	480

## Contents

11.7	Communication in Multicomputer Systems	485
11.8	Summary	489

## **12 OPERATING SYSTEMS** **497**

12.1	Overview	498
12.2	Time Services and Scheduling Mechanisms	507
12.3	Other Basic Operating System Functions	523
12.4	Processor Reserves and Resource Kernel	534
12.5	Open System Architecture	538
12.6	Capabilities of Commercial Real-Time Operating Systems	549
12.7	Predictability of General-Purpose Operating Systems	556
12.8	Summary	564

## **APPENDIX POSIX THREAD AND REAL-TIME EXTENSIONS** **571**

## **BIBLIOGRAPHY** **577**

## **INDEX** **589**