

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Motivation . . . . .	1
1.2	Embedded System Trends . . . . .	2
1.2.1	Market Trends . . . . .	3
1.2.2	Technology Trends . . . . .	6
1.3	Development of Embedded Real-Time Systems . . . . .	9
1.3.1	Specification and Implementation Phase . . . . .	11
1.3.2	Integration and Verification Phase . . . . .	12
1.4	Integration Challenges . . . . .	13
1.4.1	Multicore Integration Challenges . . . . .	14
1.5	Tackling the Integration Challenges . . . . .	15
1.5.1	Traditional Approaches . . . . .	16
1.5.2	Time-Orthogonalization of Resources . . . . .	16
1.5.3	Formal Performance Analysis . . . . .	18
1.6	Summary and Contributions . . . . .	22
1.6.1	Summary and Problem Statement . . . . .	22
1.6.2	Contributions . . . . .	23
1.7	Outline . . . . .	24
<b>2</b>	<b>Compositional Performance Analysis of Systems with Shared Resources</b>	<b>27</b>
2.1	Related Work . . . . .	28
2.2	Modeling of Real-Time Systems . . . . .	29
2.2.1	System Model . . . . .	30
2.2.2	Analysis Baseline . . . . .	31
2.3	Analysis Decomposition . . . . .	32
2.4	A Self-Contained Set of Analysis Functions For Multiprocessor Systems	36
2.4.1	Dependencies between Analysis Functions . . . . .	39
2.5	Analysis Composition . . . . .	40
2.5.1	Finding a Conservative Set of Parameter Values . . . . .	40
2.5.2	Finding a Consistent Set of Parameter Values . . . . .	42
2.5.3	Solving Analysis Dependencies with Fixed-Point Theory . . . . .	45
2.5.4	Conditions for Analysis Functions . . . . .	46
2.5.5	Speed of Convergence . . . . .	48
2.6	Summary . . . . .	48

<b>3</b>	<b>Timing Analysis with General Load Event Models</b>	<b>51</b>
3.1	Introduction . . . . .	51
3.2	Modeling the Timing of Events . . . . .	52
3.3	Properties of the Generalized Load Event Model . . . . .	54
3.3.1	General Load Event Models form a Complete Partial Order . . . . .	55
3.3.2	Reconstruction of Incomplete Event Stream Information . . . . .	56
3.4	Resource Models . . . . .	57
3.4.1	Task Response Time . . . . .	58
3.4.2	Continuous Service Bounds . . . . .	59
3.4.3	State-Based Resource Models . . . . .	61
3.4.4	The Need for a new Model . . . . .	62
3.5	Multiple Event Busy Time Model . . . . .	62
3.5.1	Deriving a Task's Worst-Case Response Time from its Multiple Event Busy Time . . . . .	64
3.5.2	Application to Static Priority Preemptive Scheduling . . . . .	64
3.5.3	Application to Time-Driven Scheduling . . . . .	65
3.5.4	Alternative Methods for Deriving the Busy Time Function . . . . .	66
3.6	Deriving Output Event Models . . . . .	69
3.6.1	Derivation of Minimum Event Distances . . . . .	69
3.6.2	Derivation of Maximum Event Distances . . . . .	75
3.6.3	Monotonicity with Respect to Input Parameters . . . . .	75
3.7	Experimental Evaluation . . . . .	78
3.8	Conclusion . . . . .	80
<b>4</b>	<b>Pipelined Path Latency</b>	<b>81</b>
4.1	Introduction . . . . .	81
4.1.1	Example . . . . .	82
4.1.2	Related Work . . . . .	84
4.2	Recursive Path Latency Computation . . . . .	85
4.2.1	Definitions . . . . .	85
4.2.2	Computing the Path Latency . . . . .	86
4.2.3	Reconciling Worst-Case Latency with Long-Term Throughput . . . . .	88
4.3	Fork and Join Application Topologies . . . . .	89
4.3.1	Multiple Outputs . . . . .	89
4.3.2	Multiple Inputs . . . . .	90
4.4	Cyclic Dependencies . . . . .	92
4.4.1	Non-functional Cyclic Dependencies . . . . .	92
4.4.2	Functional Cycles . . . . .	93
4.5	Experimental Evaluation . . . . .	97
4.6	Conclusion . . . . .	99

<b>5</b>	<b>Shared Resource Request Bounds</b>	<b>101</b>
5.1	Recapitulation of the Analysis Procedure . . . . .	101
5.2	Related Work . . . . .	102
5.3	Introduction . . . . .	105
5.4	Modeling Refinement . . . . .	106
5.4.1	Extended Task Model . . . . .	106
5.4.2	Capturing the Timing of Shared Resource Requests . . . . .	108
5.5	Deriving Bounds on the Shared Resource Requests . . . . .	109
5.5.1	Remote Operations Initiated by a Single Task Instance . . . . .	109
5.5.2	Multiple Instances of the Same Task . . . . .	111
5.5.3	Scheduling Multiple Tasks on the Same Processor . . . . .	114
5.6	Embedding the Analysis Functions into the Multiprocessor Analysis . . . . .	117
5.7	Summary . . . . .	118
<b>6</b>	<b>Interdependent Scheduling Analysis in the Presence Of Shared Resources</b>	<b>121</b>
6.1	Introduction . . . . .	121
6.1.1	Analysis Concept and Related Work . . . . .	121
6.2	Synchronous Shared Resource Requests . . . . .	125
6.2.1	Static Priority Preemptive Scheduler with Shared Resources . . . . .	126
6.2.2	Discussion on Alternative Handling of Synchronous Shared Resource Operations . . . . .	128
6.3	Asynchronous Shared Resource Requests . . . . .	130
6.3.1	Implementation and Scheduling Options . . . . .	130
6.3.2	Multithreaded Round-Robin . . . . .	133
6.3.3	Multithreaded Round-Robin with Shared Resources . . . . .	136
6.3.4	Task Synchronization Through Semaphores . . . . .	138
6.4	Embedding the Task's Busy Time Analysis into the Multiprocessor Analysis Procedure . . . . .	140
6.5	Summary . . . . .	141
<b>7</b>	<b>Latency of Shared Resource Operations</b>	<b>143</b>
7.1	Introduction . . . . .	143
7.1.1	Capturing the Aggregate Latency Of Shared Resource Operations . . . . .	143
7.1.2	Intractability of Exact Solutions . . . . .	144
7.2	Analysis of the Aggregate Request Latency . . . . .	145
7.2.1	Sum of Worst Cases . . . . .	145
7.3	Extended Scope Interference Analysis . . . . .	147
7.3.1	Bounding the Aggregate Busy Time For Work-Conserving Arbiters . . . . .	147
7.3.2	A Dedicated Analysis for Round-Robin Arbitration . . . . .	148
7.4	Resource Requests over multiple Hops . . . . .	149
7.4.1	Analysis Toolbox . . . . .	150

7.5	Monotonocity . . . . .	152
7.6	Experimental Illustration and Evaluation . . . . .	153
7.7	Summary . . . . .	154
<b>8</b>	<b>Applications</b>	<b>157</b>
8.1	The Timing of Multiprocessor Systems with Local Instruction Caches	157
8.1.1	Bounding Intrinsic Cache Misses . . . . .	157
8.1.2	Bounding Preemption-Related Cache Misses . . . . .	158
8.1.3	Experimental Evaluation . . . . .	162
8.1.4	Conclusion . . . . .	164
8.2	Performance Analysis of the StepNP Multiprocessor Platform . . . . .	165
8.2.1	Platform Architecture . . . . .	165
8.2.2	Image Processing Application . . . . .	166
8.2.3	Experiments . . . . .	166
8.2.4	Summary . . . . .	170
<b>9</b>	<b>Conclusion</b>	<b>171</b>
	<b>List of Publications</b>	<b>173</b>
	<b>References</b>	<b>178</b>