

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Why Distributed Multimedia? . . . . .	3
1.2	Limitations of Client/Server Streaming . . . . .	4
1.3	Towards Network-Integrated Multimedia Middleware . . . . .	4
1.4	Goals of this Thesis . . . . .	5
1.5	Main Contributions of this Thesis . . . . .	8
1.6	Outline of this Thesis . . . . .	10
<b>I</b>	<b>Foundations of Multimedia Middleware</b>	<b>15</b>
<b>2</b>	<b>Foundations of Locally Operating Multimedia Systems</b>	<b>17</b>
2.1	Terminology . . . . .	17
2.1.1	Multimedia . . . . .	17
2.1.2	Multimedia Architecture . . . . .	19
2.1.3	Examples for Multimedia Applications . . . . .	19
2.2	Characterization of Multimedia Systems . . . . .	20
2.2.1	Data Streams . . . . .	21
2.2.2	Devices . . . . .	23
2.2.3	Processing . . . . .	25
2.2.4	Networking . . . . .	27
2.2.5	Synchronization . . . . .	30
2.2.6	Quality of Service . . . . .	32
2.3	From Best-Effort to Predictable QoS . . . . .	35
2.3.1	Hiding Best-Effort . . . . .	36
2.3.2	Adaptation . . . . .	38
2.4	Common Abstractions . . . . .	39
2.4.1	Processing Elements . . . . .	40
2.4.2	Flow Graphs . . . . .	41
2.4.3	Data Encapsulation . . . . .	42
2.5	Examples for Multimedia Architectures . . . . .	42
2.5.1	Industry Approaches . . . . .	42
2.5.2	Open Source Approaches . . . . .	45
2.6	Summary . . . . .	46

<b>3</b>	<b>Foundations of Distributed Systems</b>	<b>49</b>
3.1	Terminology . . . . .	49
3.1.1	Distributed System . . . . .	49
3.1.2	Middleware . . . . .	50
3.2	Challenges for Distributed Systems . . . . .	51
3.2.1	Goals . . . . .	51
3.2.2	General Requirements . . . . .	51
3.2.3	Transparency . . . . .	51
3.2.4	Masking out Heterogeneity . . . . .	52
3.2.5	Openness . . . . .	53
3.2.6	Reflection . . . . .	53
3.3	Common Abstractions . . . . .	54
3.3.1	Programming Models for Middleware . . . . .	54
3.3.2	Proxy Design Pattern . . . . .	56
3.3.3	Distributed Objects . . . . .	57
3.3.4	Implicit and Explicit Binding . . . . .	59
3.4	Standards for Distributed Object Computing . . . . .	59
3.4.1	Common Object Request Broker Architecture . . . . .	60
3.4.2	Reference Model for Open Distributed Processing . . . . .	62
3.4.3	Discussion . . . . .	64
3.5	Summary . . . . .	65
<b>4</b>	<b>Challenges for Distributed Multimedia Systems</b>	<b>67</b>
4.1	Overview . . . . .	67
4.2	Requirements for Multimedia Middleware . . . . .	69
4.2.1	Distributed Flow Graphs . . . . .	69
4.2.2	Network Transparent Control . . . . .	69
4.2.3	Network Transparent Cooperation . . . . .	70
4.2.4	Distributed Synchronization . . . . .	74
4.2.5	Device Discovery and Management . . . . .	74
4.2.6	Predictable Quality of Service . . . . .	75
4.3	Additional Dimensions of Heterogeneity . . . . .	76
4.3.1	Multimedia Devices, Processing, and Architectures . . . . .	76
4.3.2	Device Discovery and Management . . . . .	76
4.3.3	Networking and Middleware Technologies . . . . .	77
4.3.4	System Characteristics . . . . .	78
4.3.5	Existing Applications . . . . .	79
4.3.6	QoS Management . . . . .	79
4.4	Coping with Dynamics and Complexity . . . . .	79
4.4.1	Adaptation and Reconfiguration . . . . .	80
4.4.2	User and Device Mobility . . . . .	81
4.4.3	Seamless Service Provision . . . . .	83
4.4.4	Collaborative Multimedia Applications . . . . .	83
4.4.5	Automatic Application Setup . . . . .	85
4.5	Summary . . . . .	86

---

<b>II</b>	<b>Network-Integrated Multimedia Middleware</b>	<b>89</b>
<b>5</b>	<b>An Open Middleware Architecture for Network-Integrated Multimedia</b>	<b>91</b>
5.1	Architectural Decisions . . . . .	91
5.1.1	Open and Integrating Micro-Core Architecture . . . . .	91
5.1.2	Mediating Proxy Objects . . . . .	93
5.1.3	Unified Messaging System . . . . .	93
5.1.4	Object-Oriented Interfaces . . . . .	94
5.1.5	Reflective Middleware . . . . .	94
5.1.6	Communication Channels . . . . .	95
5.1.7	Generic Multimedia Middleware Architecture . . . . .	96
5.1.8	Local Specialization . . . . .	96
5.2	Overview . . . . .	97
5.3	Summary . . . . .	98
<b>6</b>	<b>An Integrating Communication Framework</b>	<b>101</b>
6.1	Serialization Framework . . . . .	101
6.1.1	Requirements . . . . .	101
6.1.2	Architecture . . . . .	102
6.1.3	Implementation . . . . .	103
6.1.4	Realized Serialization Strategies . . . . .	107
6.1.5	Discussion . . . . .	110
6.2	Unified Messaging System . . . . .	111
6.2.1	Message Base Type . . . . .	111
6.2.2	Events and Composite Events . . . . .	112
6.2.3	Buffers . . . . .	113
6.2.4	Interfaces for Different Interaction Paradigms . . . . .	113
6.2.5	Dispatching . . . . .	114
6.2.6	Discussion . . . . .	116
6.3	Communication Architecture . . . . .	117
6.3.1	NMM Object . . . . .	117
6.3.2	Proxy Object . . . . .	118
6.3.3	Instream Connections with Jacks . . . . .	118
6.3.4	Out-of-band and Instream Communication . . . . .	119
6.3.5	Discussion . . . . .	120
6.4	Interfaces . . . . .	120
6.4.1	Base Class . . . . .	121
6.4.2	Interface Definition Language . . . . .	121
6.4.3	IDL Extensions . . . . .	122
6.4.4	Code Generation . . . . .	123
6.4.5	Discussion . . . . .	124
6.5	Binding Framework . . . . .	125
6.5.1	Requirements and Overview . . . . .	125
6.5.2	Transport Strategies . . . . .	128
6.5.3	Out-Of-Band Communication Channels . . . . .	132
6.5.4	Instream Communication Channels . . . . .	133
6.5.5	Parallel Bindings . . . . .	133

6.5.6	Establishment of Bindings . . . . .	137
6.5.7	Realized Transport Strategies . . . . .	141
6.5.8	Discussion . . . . .	143
6.6	Summary . . . . .	144
<b>7</b>	<b>A Generic Multimedia Middleware Architecture</b>	<b>145</b>
7.1	Overview . . . . .	145
7.2	Nodes as Processing Elements . . . . .	148
7.2.1	Node Types . . . . .	150
7.2.2	State Machine . . . . .	151
7.3	Jacks as Connecting Elements . . . . .	155
7.3.1	Queueing Model . . . . .	155
7.3.2	Jack Groups . . . . .	156
7.4	Multimedia Data Formats . . . . .	158
7.4.1	Format Definition . . . . .	158
7.4.2	Modeling Dependencies . . . . .	159
7.4.3	Quality Model . . . . .	161
7.4.4	Interacting with Formats . . . . .	161
7.4.5	Discussion . . . . .	163
7.5	Distributed Flow Graphs . . . . .	163
7.5.1	Connection Setup . . . . .	163
7.5.2	Composite Nodes . . . . .	164
7.6	Memory Management . . . . .	166
7.6.1	Buffers . . . . .	166
7.6.2	Buffer Managers . . . . .	167
7.6.3	Events and Composite Events . . . . .	168
7.7	Generic Processing Model . . . . .	168
7.7.1	Concurrent Processing . . . . .	169
7.7.2	Generic Base Classes . . . . .	170
7.7.3	Instream Interaction . . . . .	171
7.7.4	Examples for Instream Interaction . . . . .	177
7.7.5	Format Analysis and Instream Format Change . . . . .	178
7.8	Distributed Synchronization . . . . .	179
7.8.1	Architectural Elements . . . . .	180
7.8.2	Sink Synchronization . . . . .	182
7.8.3	Source Synchronization . . . . .	187
7.8.4	Remarks on Global Clocks . . . . .	190
7.9	Developing Plug-ins . . . . .	191
7.10	Summary . . . . .	192
<b>8</b>	<b>Summary for Network-Integrated Multimedia Middleware</b>	<b>193</b>
8.1	Performance Evaluation . . . . .	193
8.1.1	Out-of-Band Interaction . . . . .	193
8.1.2	Instream Interaction . . . . .	196
8.1.3	Parallel Binding . . . . .	199
8.2	Conclusions and Future Work . . . . .	200

---

<b>III</b>	<b>Middleware Services</b>	<b>201</b>
<b>9</b>	<b>Registry Service</b>	<b>203</b>
9.1	Introduction . . . . .	203
9.2	Related Work . . . . .	205
9.3	Architectural Elements and Functionality . . . . .	206
9.3.1	Representing Plug-ins and Flow Graphs . . . . .	206
9.3.2	Discovery and Registration of Plug-ins . . . . .	208
9.3.3	Base Classes and Functionality . . . . .	210
9.3.4	Processing of Queries . . . . .	211
9.3.5	Reservation and Instantiation . . . . .	212
9.4	Results and Applications . . . . .	212
9.4.1	Programming Model . . . . .	213
9.4.2	Performance . . . . .	214
9.5	Quality of Service Management . . . . .	215
9.6	Conclusions and Future Work . . . . .	217
<b>10</b>	<b>Automatic Creation of Flow Graphs and Format Negotiation</b>	<b>219</b>
10.1	Introduction . . . . .	219
10.2	Challenges and Requirements . . . . .	220
10.2.1	Task specification . . . . .	220
10.2.2	Valid and Fully Configured Flow Graphs . . . . .	222
10.2.3	Quality Model for Flow Graphs . . . . .	222
10.2.4	Quality versus Costs . . . . .	223
10.2.5	Global Approach versus Distributed Dynamic State . . . . .	224
10.2.6	Setup Time versus User Satisfaction . . . . .	225
10.2.7	Discussion . . . . .	225
10.3	Related Work . . . . .	225
10.4	Building Flow Graphs . . . . .	228
10.4.1	Defining Sources and Sinks . . . . .	228
10.4.2	Building Flow Graphs for Media Playback . . . . .	229
10.4.3	Backtracking versus Parallel Branched Search . . . . .	232
10.4.4	Adding Local Quality Decisions to Graph Building . . . . .	233
10.4.5	Support for Distributed Flow Graphs . . . . .	233
10.4.6	Extending Graph Building for Arbitrary Tasks . . . . .	235
10.5	Quality-Driven Format Negotiation . . . . .	237
10.5.1	Overview and Motivating Example . . . . .	238
10.5.2	Construction of the Negotiation Graph . . . . .	239
10.5.3	Quality-Driven Search . . . . .	241
10.5.4	Discussion . . . . .	243
10.6	Results and Applications . . . . .	243
10.7	Conclusions and Future Work . . . . .	245
<b>11</b>	<b>Session Sharing</b>	<b>247</b>
11.1	Introduction . . . . .	247
11.2	Related Work . . . . .	251
11.3	Administration of Shared Flow Graphs . . . . .	252

11.3.1	Shared Nodes and Edges . . . . .	252
11.3.2	Storage and Retrieval . . . . .	253
11.4	Definition of Overlapped Flow Graphs . . . . .	253
11.4.1	Complete Overlap . . . . .	254
11.4.2	Partial Copy Overlap . . . . .	255
11.4.3	Partial Output Overlap . . . . .	256
11.5	Session Sharing Procedure . . . . .	257
11.5.1	Overview . . . . .	257
11.5.2	Finding Overlapping Graphs . . . . .	257
11.5.3	Valuation of Solutions . . . . .	261
11.5.4	Setup of Shared Flow Graphs . . . . .	263
11.5.5	Discussion . . . . .	263
11.6	Results and Applications . . . . .	264
11.6.1	Shared DVD Playback . . . . .	266
11.6.2	Shared TV Access . . . . .	268
11.7	Conclusions and Future Work . . . . .	273
<b>12</b>	<b>Seamless Reconfiguration</b>	<b>275</b>
12.1	Introduction . . . . .	275
12.2	Related Work . . . . .	277
12.3	Seamless Handover Procedure . . . . .	278
12.3.1	Master-Slave Approach . . . . .	278
12.3.2	Specification and Setup of the Slave Graph . . . . .	281
12.3.3	Establishing a Global Time Base . . . . .	281
12.3.4	Synchronized Handover . . . . .	283
12.3.5	Destruction of the Master Graph . . . . .	286
12.3.6	Extensions and Optimizations . . . . .	287
12.3.7	Discussion . . . . .	288
12.4	Results and Applications . . . . .	289
12.4.1	Programming Model . . . . .	289
12.4.2	Performance . . . . .	292
12.5	Conclusions and Future Work . . . . .	294
<b>IV</b>	<b>Applications</b>	<b>297</b>
<b>13</b>	<b>Clic – Command Line Interaction and Configuration</b>	<b>299</b>
13.1	Overview . . . . .	299
13.2	Case Study – Video Wall . . . . .	300
13.2.1	Two-Screen Video Wall . . . . .	301
13.2.2	Two-Screen Video Wall with Overview on Third Screen . . . . .	302
13.2.3	Dynamically Adding Systems . . . . .	303
13.2.4	Discussion . . . . .	304
13.3	Conclusions and Future Work . . . . .	304

---

<b>14 Recording and Playback of Presentations</b>	<b>307</b>
14.1 Hardware Setup . . . . .	307
14.2 Recording Application . . . . .	308
14.3 Playback Application . . . . .	310
14.4 Conclusions and Future Work . . . . .	312
<b>15 Networked and Mobile Multimedia Home Entertainment</b>	<b>313</b>
15.1 Introduction . . . . .	313
15.2 Related Work . . . . .	315
15.3 Hardware Setup . . . . .	316
15.3.1 Stationary Systems . . . . .	316
15.3.2 Mobile Systems . . . . .	318
15.4 Application Framework . . . . .	319
15.4.1 User Interface . . . . .	319
15.4.2 Architectural Elements and Functionality . . . . .	320
15.4.3 Application-Level Multi-Tasking . . . . .	322
15.4.4 Integrating Entertainment Options . . . . .	324
15.5 Realized Functionalities . . . . .	324
15.6 Sharing of Resources . . . . .	327
15.6.1 Simultaneous Live TV and Recording . . . . .	327
15.6.2 Sharing of Entertainment Options . . . . .	327
15.7 Seamless Integration of Mobile Systems . . . . .	329
15.7.1 Rich and Shared Multimedia Entertainment . . . . .	329
15.7.2 Mobility Support . . . . .	330
15.8 Conclusions and Future Work . . . . .	331
<b>V Final Summary, Conclusions, and Future Work</b>	<b>333</b>
<b>16 Final Summary, Conclusions, and Future Work</b>	<b>335</b>
16.1 Summary . . . . .	335
16.2 Conclusions . . . . .	341
16.3 Future Work . . . . .	342
<b>A Systems used for Benchmarks</b>	<b>345</b>