TABLE OF CONTENTS

Abstract iii

Resumen v

Resum vii

List of Acronyms xviii

List of Figures xxiv

List of Tables xxix

List of Symbols xxx

Acknowledgments ix

Chapter 1 Introduction 1

1.1 Context of the PhD thesis 1

1.2 Research Goals 3

1.3 Methodology 4

1.4 Structure of the Thesis 7

Chapter 2 Multimedia Synchronization 11

2.1 Introduction 11

2.2 Definitions 11

2.3 Classification of Temporal Multimedia Synchronization Types 14

2.4 IDMS Use Cases 19

2.5 Challenges: Delay and Delay Variability Factors 26
2.6 Impact of Delay Variability and Playout Rate Deviations on IDMS ... 30
2.7 Magnitude of Delays and Delay Differences in Real Scenarios..... 33
2.8 Human Perception on Delay Differences 34
2.9 Summary 38
Chapter 3 IDMS Components and Classification 39
3.1 Introduction 39
3.2 Components of an IDMS Solution 39
3.3 Involved Entities in the IDMS Process..... 41
3.4 Architectural Approaches for IDMS 41
3.5 Control Schemes for IDMS 42
3.6 Overview of Control or Adjustment Techniques for IDMS 44
3.6.1 Basic adjustment techniques 45
3.6.2 Preventive adjustment techniques 47
3.6.3 Reactive adjustment techniques 48
3.6.4 Common adjustment techniques 50
3.6.5 Discussion 51
3.7 Quality Metrics to Assess the IDMS Performance..... 51
3.8 Summary 55
Chapter 4 Related Work..... 57
4.1 Introduction 57
4.2 Multimedia Synchronization Surveys and Classification..... 58

4.3 Brief Description of Existing IDMS Solutions 65

4.4 Taxonomy of Existing IDMS Solutions 73

4.5 Summary 80

Chapter 5 Qualitative Comparison Among Architectural Approaches for IDMS . 83

5.1 Introduction 83

5.2 Network-based vs Terminal-based Approaches 83

5.3 Comparison among IDMS Schemes 85

5.4 Summary 93

Chapter 6 Key Requirements for IDMS 95

6.1 Introduction 95

6.2 Key requirements for IDMS 96

6.3 Summary 98

Chapter 7 RTP/RTCP Protocols 99

7.1 Introduction 99

7.2 Multimedia Delivery Protocols: Relevance of RTP/RTCP 99

7.3 RTP/RTCP Delivery and Multiplexing Features 101

7.4 RTP/RTCP for Intra-Media and Inter-Media Synchronization (RFC 3550) 102

7.4.1 RTP (Real-Time Transport Protocol) 102

7.4.2 RTCP (RTP Control Protocol) 106

7.5 RTCP Reporting Rules 111

7.5.1 Regular RTCP Feedback (RFC 3550) 111

7.5.2 Early RTCP Feedback (RFC 4585) 113

7.5.3 Rapid Inter-Stream Synchronization (RFC 6051) 114

7.5.4 SDP Modifiers for RTCP Bandwidth (RFC 3556) 116

7.6 Summary 117

Chapter 8 RTP/RTCP-based IDMS Solution 119

8.1 Introduction 119

8.2 Suitability of RTP/RTCP for IDMS 119

8.3 Background: Preliminary Version of our RTP/RTCP-based IDMS Solution 122

8.4 New Standard RTCP Extensions for IDMS (RFC 7272) 126

8.5 Clock Synchronization Mechanisms for IDMS 131

8.6 Architectures and Functional Entities for IDMS 134

8.7 Exchange of IDMS Messages in each Control Scheme 137

8.8 Master Reference Selection Policies 141

8.9 IDMS Target Playout Point and Asynchrony Calculation 145

8.10 Fault Tolerance 146

8.11 Playout Adjustment Techniques 148

8.11.1 Aggressive Adjustments: Playout Skips & Pauses 148

8.11.2 Smooth Adjustments: Adaptive Media Playout (AMP) 149

8.12 Coherence 153

8.13 Summary 154

Chapter 9 Early-Event Driven (EED) RTCP Feedback for IDMS 155

9.1 Introduction 155

9.2 Immediate Initial RTCP IDMS Settings Packet 156

9.3 Dynamic EED Reporting of IDMS Settings 157
9.4 Rapid (Re-)Synchronization Request 160
9.5 Rapid Accommodation of Latecomers 161
9.6 Reduction of Channel Change Delays 163
9.7 Summary 166
Chapter 10 Evaluation Methodology and Prototype Implementation 167
10.1 Introduction 167
10.2 Evaluation Methodology 167
10.3 Prototype Implementation in NS-2 170
10.3.1 Introduction to NS-2 170
10.3.2 Native RTP/RTCP Implementation in NS-2 171
10.3.3 Other Existing RTP/RTCP Implementations in NS-2 172
10.3.4 New Developed RTP/RTCP Module for NS-2 173
10.3.4.1 RTP Management 173
10.3.4.2 RTCP Management 174
10.3.5 Integration of the IDMS functionality 174
10.3.6 Playout Buffering Policy in NS-2 (Intra-Media Synchronization) 175
10.3.7 Video Quality Evaluation Toolset 178
10.4 Prototype in a Real Media Framework (GStreamer) 182
10.4.1 Introduction to GStreamer 182
10.4.2 RTP/RTCP Support in GStreamer 184
10.4.3 Transmission and Reception Pipelines 185

10.4.4 Clock Synchronization 188
10.4.5 Integration with RTSP and SDP Modules 188
10.4.6 End-to-end delay measurements 188
10.5 Summary 191
Chapter 11 Evaluation in NS-2 193
11.1 Introduction 193
11.2 Simulation Setup and Scenario 193
11.3 Intra-Media Synchronization 195
11.4 Evaluation of SMS 198
11.4.1 Synchronization Policy to the Fastest Sync Client 198
11.4.2 Synchronization Policy to the Slowest Sync Client 202
11.4.3 Synchronization Policy to the Mean Playout Point 204
11.4.4 Synchronization Policy to the Media Server Nominal Rate 206
11.4.5 Buffer Fullness Variation 208
11.5 Evaluation of DCS 210
11.6 Comparison between SMS and DCS 212
11.6.1 Interactivity 212
11.6.2 Coherence 214
11.6.3 Playout Asynchrony Distribution 216
11.7 Evaluation of EED RTCP Feedback for IDMS 217
11.7.1 Interactivity Comparison between Regular and EED RTCP Feedback 217
11.7.2 Fine Synchronization for Media-Related Events 221

11.7.3 Rapid Accommodation of Latecomers 222
11.8 Evaluation of M/S Scheme for IDMS 224
11.9 Traffic Overhead 228
11.10 Computational Load 229
11.11 Summary 230
Chapter 12 Conclusions and Future Work 231
12.1 Conclusions 231
12.2 Future Work 234
12.2.1 Advanced IDMS use cases in RTP streaming 234
12.2.1.1 IDMS for Different Streams 234
12.2.1.2 Scalable IDMS Solution 235
12.2.2 IDMS in Web-Based Technologies 236
12.2.3 Context-aware IDMS 237
12.2.4 QoE Perception Tests 237
12.2.5 Optimized AMP Techniques 238
12.2.6 Standardization 238
References 239
APPENDIX A Publications 259
Summary 259
List of Publications 259
Publications Under Review 263