Resource Adaptation Methods for Improving Multimedia Streaming Throughput to Mobile Nodes in Heterogeneous Wireless Environments

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DOCTORAL DISSERTATION
for the degree of
PHILOSOPHIAE DOCTOR (PhD)

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February 2014

Abstract

The thesis formulates effective strategies for delivery of streaming content for mobile users in resource-limited networks. We consider the entire end-to-end delivery path from the source to the destination. In the work, we take into account *1)* the presence of a large number of mobile devices operating inside an area with overlapping coverage of several mobile networks; and *2)* the ability of the mobile devices to exploit several network technologies and to be connected to different access points simultaneously. We aim to improve the performance of the whole system by jointly considering users' requirements and network limitations and by identifying and implementing adaptation mechanisms for different parts of the delivery path. Taking into account the complexity of the whole system, the thesis aims to design mechanisms operating in a decentralized manner with partial knowledge of the system.

For this purpose, we study the ADIMUS architecture which addresses the problem of distributing streaming content for mobile users. The ADIMUS architecture clearly separates the system into two distinct parts: the backbone part of the network and the wireless part. We study resource adaptation mechanisms for both of these parts that include *1)* overlay routing for the backbone and *2)* multi-access approaches for heterogeneous wireless network. For overlay routing in the backbone, we consider multipath streaming techniques. For the wireless part, we improve the utilization of resources by intelligently redistributing mobile devices among the available wireless connections. To evaluate the adaptation mechanisms for both of these parts, we build mathematical models for the overlay network and for the heterogeneous wireless network. These mathematical models are used as upper bounds for operation of the adaptation solutions. We also define the lower bounds to these solutions based on earlier proposed solutions from the literature.

For the overlay network, we develop and evaluate a distributed rate-allocation algorithm for delivery of video in a Video-on-Demand (VoD) system built upon multipath delivery. The algorithm's operation is based on information collected by overlay nodes. The algorithm is evaluated in the OMNet++ simulation environment and analyzed against the aforementioned lower and upper bounds. We show that the algorithm performs close to the optimal solution in terms of proportionally fair bandwidth allocation between receivers of the overlay part of the architecture.

For the heterogeneous wireless network, we consider the network selection to use for multi-user environments with possible multicast configurations that allows the network to perform load balancing, improve the users' overall QoS, and increase the throughput of the networks. The novelty of the proposed solutions is that the network selection is done in a decentralized manner with only limited information available to decision makers. The solutions are evaluated through multiple simulations. We show that the solutions provide a substantial improvement in

performance compared to their lower bounds.

We also investigate a multiple connection approach for multicast groups with mobile terminals connecting to several networks simultaneously and receiving data through multiple paths. We show that the total usage of resources is reduced compared to a single path approach.

Preface

This dissertation is submitted to the Department of Informatics, Faculty of Mathematics and Natural Sciences, University of Oslo, in partial fulfillment for the degree Philosophiae Doctor (PhD). My main supervisor has been Wolfgang Leister, Assistant Research Director at Norwegian Computing Center (NR), Lars Holden, Managing Director at Norwegian Computing Center (NR), and Stein Gjessing, Professor at Department of Informatics, University of Oslo.

The research has been carried out in the period 2006 to 2014, at the Norwegian Computing Center (NR).

Acknowledgments

Thesis structure

This thesis is divided into three parts. **Part I** introduces the scope and goals of the research, and discusses the methodology and main findings of the thesis. It provides an overview of the main contributions published in international journals and conference proceedings. **Part II** contains the research contributions, and in **Part III**, we provide relevant appendices.

Part I – Chapter 1 describes the background and motivation of the work, and defines the scope of the research. It outlines the *scientific method* applied in the thesis. Further in this chapter, we define the research goals and the research questions that we need to address in our work. In Chapter 2, we provide a state-of-the-art literature review and a knowledge base that can be used to enhance the understanding of the presented research results. The discussion of the main contributions and a summary of each included *research paper* is presented in Chapter 3. The Chapter 4 summarizes the main contributions and outcomes of the research, and provides suggestions for future work.

Part II – This part contains the following eight journals and conference publications:

- **Paper A**   An Architecture for Adaptive Multimedia Streaming to Mobile Nodes.

- **Paper B**   A Benchmarking System for Multipath Overlay Multimedia Streaming.

- **Paper C**   Maximizing video quality for several unicast streams in a multipath overlay network.

- **Paper D**   Multipath Rate Allocation Algorithm for Overlay Networks with Feedback From Overlay Nodes.

- **Paper E**   Team Decision Approach for Decentralized Network Selection of Mobile Clients.

- **Paper F**   Network Selection for Multicast Groups in Heterogeneous Wireless Environments.

- **Paper G**   Heterogeneous Wireless Network Selection: Load Balancing and Multicast Scenario.

- **Paper H**   Exploring Network Selection Techniques for Multicast Groups in Heterogeneous Wireless Environments.

A brief summary and a detailed list of the publications and related work is provided in the **List of publications**.

Part III contains one appendix with a list of related acronyms and their descriptions.

List of publications

Part II of this thesis provides an overview of papers A-H. The author of this thesis is the principal contributor and first author of papers B-H. She is the third author of paper A.

    An overview and analysis of the ADIMUS architecture is provided in Paper A. In Papers B and C, we defined a mathematical model of an overlay network for the backbone part of the ADIMUS architecture. Further, we introduced an algorithm for allocating the available bandwidth for streaming video in a multipath multisource overlay system. The algorithm operated by exploiting local knowledge of the network topology and networking parameters such as available bandwidth. The mathematical model defined in Papers B and C was used for evaluating the algorithm performance. In Paper E, a network selection for a multi-access network with a focus on load balancing was considered. We presented both the mathematical model of the system and decentralized algorithms that were evaluated using this model. In Paper F, we continued to study the network selection with a focus on a multicast scenario. Paper G is an invited journal paper and it extends the findings of Papers E and F. Paper H is an invited journal paper and it extends the results of Paper F with a multiple path streaming case.

Main contributions

Paper A   Wolfgang Leister, Tiia Sutinen, Svetlana Boudko, Ian Marsh, Carsten Griwodz, and Pål Halvorsen. "An Architecture for Adaptive Multimedia Streaming to Mobile Nodes", *Proc. MoMM 2008, November 24-26, 2008, Linz, Austria*, pages 313-316, ISBN 978-1-60558-269-6, DOI 10.1145/1497185.1497250, 2008.

Abstract: *We describe the ADIMUS architecture which addresses the problem of maintaining the subjective quality of multimedia streaming for a mobile user. In contrast to other works, the entire end-to-end path of the video stream is considered. Adaptation mechanisms for maintaining quality include time-critical handovers, overlay routing and network estimation techniques. Our architecture is built on overlays that provides the necessary functionality for a video streaming service. The paper highlights the key components that ADIMUS advocates to support quality streaming from server to mobile client.*

Paper B   Svetlana Boudko, Wolfgang Leister, Carsten Griwodz, and Pål Halvorsen. "A Benchmarking System for Multipath Overlay Multimedia Streaming", *Proc. ICME 2008, June 23-26, 2008, Hannover, Germany*, pages 853-856, ISBN 978-1-4244-2570-9, DOI 10.1109/ICME.2008.4607569, 2008.

Abstract: *The rapid growth of the Internet multimedia services brings new challenges to how multimedia streams can be delivered to the users over bandwidth-constraint networks. Different strategies that exploit multipath streaming in order to provide better utilization of the Internet resources have been proposed by the research community. However, there exists no metric that allows us to evaluate how close these strategies are to the optimal resource utilization. This paper proposes a static benchmarking system that models the best possible distribution of streams along multiple paths in an overlay network that is shared by several senders and receivers. We have tested it with several different network topologies, and present the test results in this paper.*

Paper C   Svetlana Boudko, Wolfgang Leister, Carsten Griwodz, and Pål Halvorsen. "Maximizing video quality for several unicast streams in a multipath overlay network.", *Proc. IMSAA 2010, December 15-17, 2010, Bangalore, India*, pages 1-5, ISBN 978-1-4244-7931-3, DOI 10.1109/IMSAA.2010.5729398, 2010.

Abstract: *A streaming system that uses an overlay network for multipath streaming needs to make decisions concerning the distribution of the available bandwidth among all of its clients. This decision making should aim at delivering the best possible quality to all clients while providing an optimal utilization of the network resources. We consider a scenario where videos are hierarchically layered-encoded and most requests are negligibly overlapped in time. It implies that using multicast is not efficient, and instead, the streams are striped and allocated to multiple paths from the server to the client. To evaluate how well the rate-allocation algorithms approach optimality, we have earlier built a benchmarking system that provides the optimal solution for assigning available bandwidth to delivery paths. However, as video quality is not linearly related to bitrate, the trivial maximization of the total consumed bandwidth does not necessarily maximize the video quality. To address this problem, we define a metric that assesses video quality for a group of clients that we use as a utility function in the revised benchmarking system. Due to its concavity, this utility function distributes the bandwidth resources proportionally fair between the clients of the system.*

Paper D   Svetlana Boudko, Wolfgang Leister, Carsten Griwodz, and Pål Halvorsen. "Multipath Rate Allocation Algorithm for Overlay Networks with Feedback From Overlay Nodes.", *Proc. ITST 2011, August 23-25, 2011, St. Petersburg, Russia*, pages 468-473, ISBN 978-1-61284-668-2, DOI 10.1109/ITST.2011.6060103, 2011.

Abstract: *We develop and evaluate a rate-allocation multipath algorithm for delivery of video in a Video-on-Demand (VoD) system built upon an overlay network. To evaluate how well the rate-allocation algorithms approach the optimum, we have earlier built a benchmarking system that provides the optimal solution for assigning available bandwidth to delivery paths. This solution is also proportionally-fair. We implement a distributed algorithm for multipath rate allocation that operates based on information collected by overlay nodes. The algorithm is evaluated in the OMNet++ simulation environment and analyzed against the aforementioned benchmarking.*

Paper E   Svetlana Boudko, Wolfgang Leister, Stein Gjessing. "Team Decision Approach for Decentralized Network Selection of Mobile Clients.", *Proc. WMNC 2012, September 19-*

Abstract: *We consider a network selection problem for a group of mobile clients that operate in a heterogeneous wireless access network environment and that are equipped with multiple access network interfaces. The involved networks cooperate in order to improve their own, and the mobile clients' performance. We formulate the problem as a team decision problem. In this formulation, several decision variables are involved and these decisions are made by several decision makers with access to different information but contributing to a common goal. The novelty of the proposed approach is that the network selection is done in a decentralized manner with only limited information available to decision makers. We present two decentralized algorithms to this problem, which we compare and evaluate in the OMNet++ simulation environment.*

Paper F   Svetlana Boudko, Wolfgang Leister. "Network Selection for Multicast Groups in Heterogeneous Wireless Environments.", *International Conference on Advances in Mobile Computing and Multimedia*, pages 167-176, ACM ISBN: 978-1-4503-2106-8ISSN, 2013.

Abstract: *Coexistence of various wireless access networks and the ability of mobile terminals to switch between them make an optimal selection of serving networks for multicast groups a challenging problem. Since optimal network selection requires large dimensions of data to be collected from several network locations and sent between several network components, the scalability can easily become a bottleneck in large-scale systems. Therefore, reducing data exchange within heterogeneous wireless networks is important. We study the decision-making process and the data that needs to be sent between different network components. We present two decentralized solutions to this problem that operate with reduced sets of information. We define the upper and lower bounds to these solutions and evaluate them in the OMNet++ simulation environment. Both solutions provide a substantial improvement in performance compared to the lower bound.*

Paper G   Svetlana Boudko, Wolfgang Leister, Stein Gjessing. "Heterogeneous Wireless Network Selection: Load Balancing and Multicast Scenario", *Journal On Advances in Networks and Services*, pages 118 - 135, ISSN 1942-2644.

Abstract: *The increasing demand for real-time multimedia streaming from mobile users makes important deployment of multicast services in wireless networks. Coexistence of various wireless access networks and ability of mobile terminals to switch between them make an optimal selection of serving mobile networks for multicast groups a challenging problem. Since scalability can easily become a bottleneck in large-scale networks, we study the decision-making process and selection of the data that needs to be exchanged between different network components. In this paper, we present two decentralized solutions to this problem that we compare and evaluate in the OMNet++ simulation environment.*

Paper H   Svetlana Boudko, Wolfgang Leister, Stein Gjessing. "Exploring Network Selection Techniques for Multicast Groups in Heterogeneous Wireless Environments", *Accepted*

Abstract: *Coexistence of various wireless access networks and the ability of mobile terminals to switch between them make an optimal selection of serving networks for multicast groups a challenging problem. Since optimal network selection requires large dimensions of data to be collected from several network locations and sent between several network components, the scalability can easily become a bottleneck in large- scale systems. Therefore, reducing data exchange within heterogeneous wireless networks is important. We study the decision-making process and the data that needs to be sent between different network components. To analyze the operation of the wireless heterogeneous network, we built a mathematical model of the network. The objective is defined as a minimization of multicast streams in the system. To evaluate the heuristic solutions, we define the upper and lower bounds to their operation. The proposed heuristic solutions substantially reduce usage of bandwidth in mobile networks and exchange of information between the network components. We proposed the approach that allows network selection in a decentralized manner with only limited information shared among the decision makers. We studied how different sets of information available to decision makers influenced the performance of the system. The work also investigates the usage of multiple paths for multicast in heterogeneous mobile environments. We showed that the total usage of resources is reduced compared to a single path approach.*

Related work

The related work consists of conference and journal papers, it also includes conference and seminar presentations, and the final project report. This work contributed to fulfilment of the thesis and its main publications but these presentations and publications are less significant than the main contributions.

R1   Svetlana Boudko, Wolfgang Leister. "Adaptive Multimedia Streaming (Adimus)" Simula seminar, Geilo; 2008-02-01

R2   Wolfgang Leister, Ian Marsh, Svetlana Boudko, Tiia Sutinen. "Adaptive Internet Multimedia Streaming", NORDUnet Conference 2008, Helsinki, Finland; 2008-04-09

R3   Wolfgang Leister, Svetlana Boudko, Till Halbach Røssvoll. "Estimation of Subjective Video Quality as Feedback to Content Providers", The Fifth International Conference on Systems and Networks Communications (ICSNC), 2010, Nice.

Abstract: *Concerning video transmission on the Internet, we present a model for estimating the subjective quality from objective measurements at the transmission receivers and on the network. The model reflects the quality degradation subject to parameters like packet loss ratio and bit rate and is calibrated using the results from subjective quality assessments. Besides the model and the calibration, the main achievement of this paper is the model's validation by implementation in a monitoring tool. It can be used by*

content and network providers to help swiftly localise the causes of a possibly poor quality of experience (QoE). It also can help content providers make decisions regarding the adjustment of vital parameters, such as bit rate and other error correction mechanisms.

R4 Wolfgang Leister, Svetlana Boudko, Till Halbach Røssvoll. "Adaptive Video Streaming through Estimation of Subjective Video Quality", International Journal On Advances in Systems and Measurements, 2011.

Abstract: *Concerning video transmission on the Internet, we present a model for estimating the subjective quality from objective measurements at the transmission receivers and on the network. The model reflects the quality degradation subject to parameters like packet loss ratio and bit rate, and is calibrated using the prerecorded results from subjective quality assessments. Besides the model and the calibration, the main achievement of this paper is the model's validation by implementation in a monitoring tool. It can be used by content and network providers to swiftly localise the causes of a poor quality of experience (QoE). It also can help content providers make decisions regarding the adjustment of vital parameters, such as encoding bit rate and error correction mechanisms. We show how the estimated subjective service quality can be applied for decision making in content delivery networks that consist of overlay networks and multi-access networks.*

R5 Wolfgang Leister, Tiia Sutinen, Svetlana Boudko, Ian Marsh, Carsten Griwodz, and Pål Halvorsen. "ADIMUS – Adaptive Internet Multimedia Streaming", Final Project Report, 2010.

Abstract: *This document is the final scientific report of the ADIMUS project which was funded by the NORDUnet3 programme. ADIMUS addresses the problem of enhancing the quality of multimedia streams at run-time based on the perceived quality. We present an architecture that addresses the different requirements from end-to-end for a mobile terminal. The architecture comprises an overlay network in the long-distance part, while the multi-access network employs cross-layer technology. Both parts interact, and use adaptation techniques shown in this report. We also present quality estimation techniques for both audio and video streams. This report is based on the scientifc papers published during the project, and sets these papers into the context of the ADIMUS project.*

R6 Svetlana Boudko, Wolfgang Leister, Stein Gjessing. "Multicast Group Management for Users of Heterogeneous Wireless Networks.", *Proc. CONTENT 2012, July 22-27, 2012, Nice, France*, pages 24-27, ISBN 978-1-61208-220-2, 2012.

Abstract: *Today mobile devices are typically equipped with multiple access network interfaces. Another important issue is a coexistence of heterogeneous wireless access networks. The selection of optimal serving mobile networks for multicast streams is a challenging problem. We consider a network selection problem for multicast groups of mobile clients that operate in a heterogeneous wireless access network environment. We identify several decision makers solving this problem and present our view on what kind of information is needed to be exchanged between these decision markers.*

R7 Svetlana Boudko, Wolfgang Leister, Stein Gjessing. "Optimal Network Selection for Mobile Multicast Groups", *Proc. ICSNC 2012, November 18-23, 2012, Lisbon, Portugal,*

pages 224-227, ISBN 978-1-61208-231-8, 2012.

Abstract: *Mobile devices are typically equipped with multiple access network interfaces, supporting the coexistence of heterogeneous wireless access networks. The selection of an optimal set of serving mobile networks for multicast streams is a challenging problem. We consider a network selection problem for multicast groups of mobile clients that operate in a heterogeneous wireless access network environment. We present a solution to this problem with an optimal allocation of mobile users to multicast groups when multiple mobile networks are available for operation. This solution is suited for small scale networks and can be used as reference for complex networks.*

Other scientific activities

- Peer Reviewer, Wireless Telecommunications Symposium, 2009.

- Session Chair, The Fourth International Conference on Creative Content Technologies, 2012.

- Session Chair, The Seventh International Conference on Systems and Networks Communications, 2012.

- Session Chair, The International Conference on Advances in Mobile Computing and Multimedia, 2013.

- Programme Committee Member, The Eighth International Conference on Systems and Networks Communications, 2013.

Contents

PART I:

Introduction

Chapter 1

Introduction

1.1   Background and motivation

Internet video streaming is taking a significant portion of the Internet services and the amount of these services delivered over wireless access technologies is expected to increase exponentially during the next few years.

According to Cisco [25], global mobile data traffic grew 70 percent in 2012. Global mobile data traffic reached 885 petabytes per month at the end of 2012, up from 520 petabytes per month at the end of 2011. Overall mobile data traffic is expected to grow to 11.2 exabytes per month by 2017, a 13-fold increase over 2012. Mobile data traffic will grow at a CAGR of 66 percent from 2012 to 2017. By the end of 2013, the number of mobile-connected devices will exceed the number of people on earth, and by 2017 there will be nearly 1.4 mobile devices per capita. There will be over 10 billion mobile-connected devices in 2017, including machine-to-machine (M2M) modules, which will exceed the world's population at that time (7.6 billion). Mobile network connection speeds will increase 7-fold by 2017. The average mobile network connection speed (526 kbps in 2012) will exceed 3.9 megabits per second (Mbps) in 2017. In 2017, 4G will be 10 percent of connections, but 45 percent of total traffic. In 2017, a 4G connection will generate 8 times more traffic on average than a non-4G connection. Two-thirds of the world's mobile data traffic will be video by 2017. Mobile video, which quality of service is especially vulnerable to bandwidth fluctuations, will increase 16-fold between 2012 and 2017, accounting for over 66 percent of total mobile data traffic by the end of the forecast period. This growth poses extra challenges both for mobile network resources and for resources of the backhaul infrastructure that connects a mobile network to the backbone Internet. In fact, it can also cause bottlenecks in the backbone Internet.

This constantly increasing demand for mobile bandwidth implies that significant improvements in how the data are delivered to mobile users and in how resources are allocated in mobile networks are needed to avoid degradation in service quality and, possibly, congestion collapse. Another issue to take into account is that several thousands of mobile devices can operate simultaneously inside one limited area that has overlapping coverage of different mobile networks, such as UMTS, WLAN, WiMAX, and LTE. Some groups of these devices can listen to the same feeds from the same Internet locations while being connected to different access points. Therefore, joint consideration of allocating some users to different networks can considerably
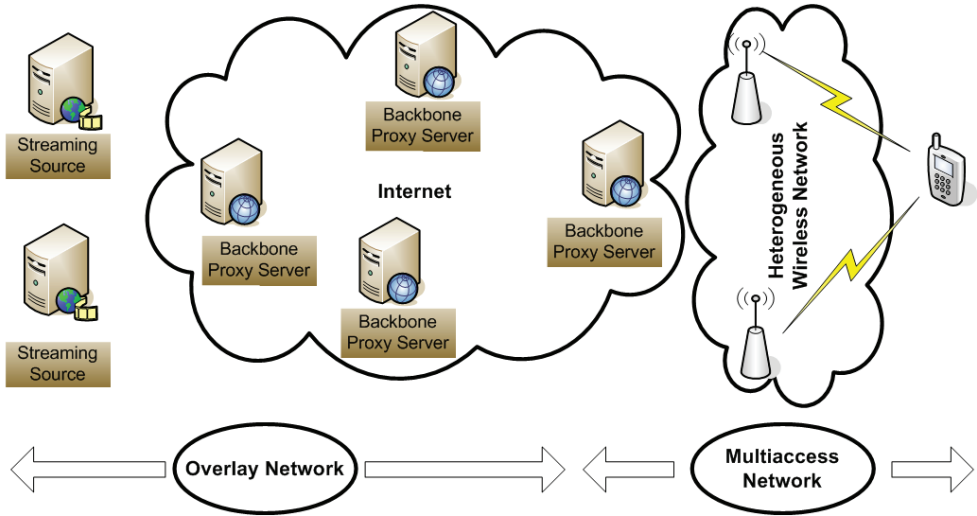
Figure 1.1: ADIMUS Architecture.

improve the performance of the whole system. To avoid negative effects of resource limitations we need to consider the resource allocation problem from a different angle, including collaboration between mobile user nodes and networks to reduce the overall utilization of resources. By intelligently redistributing mobile devices among the available wireless connections, the networks can accommodate more users, improve the users' QoS and increase the revenue of the networks.

Referring to wireless access networks, the ability to be connected to several network technologies simultaneously offers new possibilities to formulate effective strategies for network selection.

The research done in this thesis has been part of the ADIMUS (ADaptIve MUltimedia Streaming) project that has been funded by the NORDUnet3 Programme. The project period was from 2006 to 2010. The research was conducted in close collaboration with researchers at the VTT Technical Research Centre of Finland, the Computer and Network Architecture Group at SICS in Sweden, and the University of Oslo.

1.2 Scope

In this work, we develop methods that optimize the delivery of multimedia streams from the service providers to their mobile users accessing the Internet through multi-access terminals. We consider the whole delivery path from the source to the destination. Instead of focusing on one specific user or a group of users with homogeneous requirements, we focus our research on groups of mobile users with different sets of requirements and access networks. In other words, we consider a delivery system that consists of multiple service providers streaming video content via IP-based networks to multiple mobile terminals. These mobile terminals may use diverse network technologies and different types of terminals to access and view the content. As the content is transmitted from a service provider to a mobile terminal, its quality is

degraded by several factors that are specific to different parts of the network infrastructure. To minimize these degradations, we optimize the usage of resources both in the overlay network of the backbone and in the heterogeneous wireless network. For this purpose, we proposed a delivery architecture that is referred to as the *ADIMUS* architecture [53] in this work. The ADIMUS architecture divides the delivery system into two parts: the *overlay network* and the *heterogeneous wireless network*. Within these parts, we concentrated our research on developing the data delivery schemes that are able to adapt to the availability of the network resources and optimize the usage of the resources. Also, the terms: *heterogeneous wireless network* and *multi-access network* are used interchangeably in this thesis.

The ADIMUS architecture, shown in Figure 1.1, comprises a delivery infrastructure based on an overlay network, which includes streaming source nodes at the service provider, backbone proxy servers (BPS), and multi-access mobile terminals. Thus, the ADIMUS architecture includes the following elements:

- In the backbone network, the data are routed through an overlay network which implements application-layer routing servers. To adapt to varying resource availability in the Internet, the overlay network monitors connections and makes application-layer forwarding decisions to change routes in the backbone.

- Near the mobile terminal, a heterogeneous wireless system provides application adaptation and network selection mechanisms to minimize the usage of resources in the wireless networks and support multiple types of mobility.

Though in this thesis, we consider the whole delivery path from the service provider to the end user, the analysis and implementation of the adaptation algorithms was conducted separately for different parts of the ADIMUS architecture. The reason for applying this approach is the different technology and therefore the nature of adaptation to available resources in the backbone and inside the wireless multi-access network. The mechanisms developed for these parts of the architecture can operate independently from each other and we consider that there is little or no information that needs to be exchanges between these two subsystems. This limitation is also important for the system to be able to function in a decentralized manner.

1.3 Method of the thesis

Following the background discussion and the scope of the research, this section introduces the research method used in this thesis. We chose to use the engineering method specified in the research done by Glass [31]. This method includes the following four phases that are discussed in more details in this section: *1*) the informational phase including gathering or aggregating information via reflection, literature study and survey; *2*) the propositional phase including proposing and formulating a method, algorithm, model theory or solution; *3*) the analytical phase including analyzing and exploring a proposition leading to a formulation of a principle or theory; and *4*) the evaluative phase including evaluation of a proposition by means of experiments, field studies or other forms of analysis.

The project divides the delivery of multimedia streams into two parts: *1*) the wired infrastructure, and *2*) the wireless infrastructure. The four research phases were performed separately

for each part of the streaming architecture. When the outcomes of the evaluation phase indicated that the propositional and analytical phases needed to be revised, the proposed methods and solutions were reworked and reevaluated until the required result was achieved.

1.3.1   Informational Phase

The literature research included a broad study of various scientific papers in several areas related to the scope of the research. In this phase, the goals of the thesis were outlined. In the beginning, we studied the existing solutions that address multimedia streaming in general. The literature study is presented in Section 2. For the backbone part of the architecture, the literature research included multipath routing and streaming, peer-to-peer streaming and overlay networks 2.1. For the mobile domain, we looked at different wireless technologies, hand-off methods and management included prediction techniques for both vertical and horizontal handoffs, admission control and network selection in heterogeneous wireless networks 2.2.

Further in our work, we also studied various optimization methods that are applicable for network optimization. Clearly, we revisited the literature study continuously during the next three phases. As the research goals were refined and research questions were identified in the propositional phase, we needed to repeat the study of scientific papers with better focus on specific research areas. In addition, keeping us updated about *1*) new findings from the related scientific research; *2*) new wireless standards; and *3*) different evaluation studies published specifically for the wireless domain allowed us to adjust the research work to the recent findings.

1.3.2   Propositional Phase

Through discussions with the members of the ADIMUS project, the delivery infrastructure for media streaming was designed. In this thesis, we refer to the ADIMUS architecture as it is presented in Paper A [53]. For the ADIMUS architecture, we decided to perform the research separately for two architectural parts. This decision addresses the different nature in how QoS degradation and packet losses occur in these two parts of the network, thus, requiring different adaptation and estimation techniques for these two parts. In the backbone, the content is transmitted from streaming servers through the Internet without resource guarantees. Typical reasons for changes in resource availability are congestion and route failures. In the wireless network, QoS may suffer from high bandwidth variation, jitter, instability of wireless channel and connection outages caused by handovers. Both parts have different timing requirements when performing adaptation decisions: while the wireless network must react fast to movements and consequently changes in resource availability for mobile nodes, the decisions in the overlay network can be done at a slower pace.

For adaptation in the backbone part of the infrastructure, we proposed to use an overlay network built upon a set of proxy servers located in the Internet. The adaptation mechanisms were implemented in the proxy servers and were aimed to work around congestion and route failures. For adaptation in the wireless part of the infrastructure, we considered to take advantage of multi-accessibility of a wireless heterogeneous network and perform the network selection for multi-user environments in a way that allows the wireless network to accommodate more users, improve the users' overall QoS, and increase the throughput of the networks.

1.3.3 Analytical Phase

For this phase, the research questions were defined and analyzed. There were several issues to consider in the analyses that included the scalability of the system and the availability of the information required for the system operation. To analyze the operation of a system, we formulated the mathematical models for both architectural parts.

To analyze the operation of the backbone overlay network, we built a mathematical model of the network. For this model, we defined a problem that optimized the assignment of the available bandwidths of the overlay paths to multiple streams. We applied a logarithmic utility function, which expressed the video quality of multiple users and mapped well to the idea of providing the proportionally fair allocation of the available bandwidths among the streams. It means that solving the optimization problem not only provides us with the maximum of the total bandwidth but also different streams get their fair share of the bandwidth. Due to the concavity of the utility function, and the convexity and compactness of the feasible region, defined by the constraints of the problem, the solution of the optimization problem was a unique vector. To solve the problem, we took advantage of the MATLAB Optimization Toolbox. We used the function *fmincon* that solves this type of problems.

To analyze the operation of the wireless heterogeneous network, we focused our research on the network selection problem for multi-stream multi-user environments. Studying this problem, we considered two representative scenarios. In the first scenario, we consider load balancing in the wireless heterogeneous network. To provide better load balancing between the networks, and to avoid disturbing ping-pong effects, joint coordination, and information exchange between the users and the base stations is essential; both the clients and the networks can benefit from cooperative handoffs. However, due to strict bandwidth and power limitations of mobile networks, and also due to scalability issues, a complete information exchange between mobile users and networks is not feasible. To facilitate an incomplete information exchange, the network selection was formulated as a team decision problem [38, 67]. Team decision theory is concerned with determining the optimal decisions, given a set of information for each of several decision makers, that work together to achieve a payoff. These optimal decisions can be either person-by-person optimal or team optimal. In person-by-person optimal cases, each person makes the decisions that optimize the individual's payoff, but not necessarily the team payoff. These cases are optimal for a particular team member, given that the decision functions for other members are fixed. In team optimal cases, the group payoff is optimized. Team optimality is a stronger condition, and is thus harder to achieve. Taking into account that person-by-person optimal strategies may result in unfair distribution of the resources, we used team optimal strategies for our analysis.

In the second scenario, we considered the network selection problem with possible multicast configurations. The problem was formulated as a location allocation problem that belongs to a class of integer programming problems. The objective was defined as a minimization of multicast streams in the system. To solve this problem, we have taken advantage of the GNU Linear Programming Kit (GLPK) version 4.49 [54]. This is an ANSI C package that is intended for solving large-scale linear programming and mixed integer programming problems.

1.3.4   Evaluative Phase

We realize that full-scale field experiments for a system that is built upon *1*) an overlay backbone network consisting of several nodes; *2*) several wireless networks; and *3*) several hundred users are problematic and expensive to carry out. Therefore, we chose to evaluate the solutions that were proposed and analyzed in previous phases using multiple simulations. We realize that usage of real world traces evaluates performance only for these particular scenarios. Therefore, we chose to use random generated synthetic data since these data allow more comprehensive performance evaluation by using a large number of variations. Taking into account the mobility of the end users, modeling of movements was important for our evaluation. For the simulation of movements of mobile nodes, we looked at different studies concerning mobility models for the wireless communications [8, 19]. In the random waypoint model, the location of mobile nodes, their velocity and direction of the movement are chosen randomly and independently of other nodes. We captured the randomness of these parameters by random time during which any mobile network in consideration is available to a mobile user.

Evaluations and simulations were performed in the overlay network and the wireless heterogeneous network separately. For simulations, we used the OMNet++ environment [66]. OMNet++ is a simulation library and framework, primarily developed for the simulation of communication networks and other distributed systems [78], which covered well the scope of the research. In each research paper, we evaluated and discussed the results of the research. The results were quantified by using the corresponding metrics selected for the proposed solutions. For the operation of the solutions, we defined the upper and low bounds and applied them in our evaluations. By the *upper bound*, we mean the theoretical best possible operation of the system that can be achieved with fully known the state of the system. For the *lower bound*, we used existing solutions, when these were applicable to the scope of the research. For evaluating the outcomes of the solutions implemented in the overlay network, we compared the results with the references from the literature. These included a round robin strategy as proposed by Castro et al. [20], which we also extended to a weighted round robin algorithm. For evaluating the solutions implemented in the wireless network, we modified the algorithms from the literature [72, 74, 84] and applied them as an *upper bound* estimation, while a modification of the algorithm by Ormond and Murphy [62] was applied as a *lower bound* estimation.

1.4   Research Goals and Research Questions

Analyzing the scope of the research and the method of the thesis defined in Sections 1.2 and 1.3, respectively, we define the research goals that we need address in our work. For each research goal, we also define the research questions that we need to investigate and answer to reach the corresponding goal.

1.4.1   Research Goals

Following the method of the thesis, we studied existing research areas and findings that related to multimedia streaming and data transmissions for different scenarios and architectural concepts (Goal 1). These findings were analyzed (Goal 2) and evaluation models were defined for
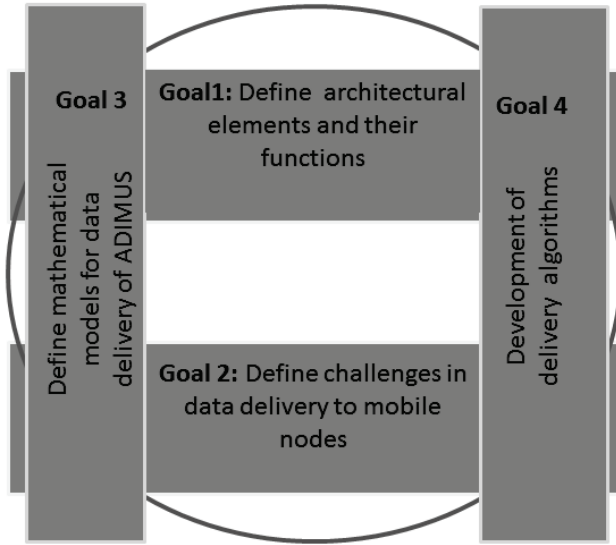
Figure 1.2: Research goals of thesis. The figure shows the structure of the research goals and their interrelations.

multisource multipath streaming scenarios in heterogeneous networks (Goal 3). Basing on the results from the analytical phase, we proposed new solutions that we evaluated using the finding of the evaluation stage (Goal 4). The research goals and their subgoals are defined as follows.

Goal 1: Identify architectural elements and their functions of the delivery infrastructures for multimedia streams from the backbone Internet to mobile devices connected to wireless heterogeneous networks.

Goal 2: Detect challenges for efficient data delivery of multimedia streams from backbone servers to mobile devices connected to wireless networks.

> **Subgoal 2-1:** Define challenges for efficient data delivery of multimedia streams in the backbone Internet.

> **Subgoal 2-2:** Define challenges for efficient data delivery of multimedia streams in the heterogeneous wireless network.

Goal 3: Define mathematical models for data delivery from backbone servers to mobile devices connected to wireless networks.

> **Subgoal 3-1:** Formulate the optimal solution in terms of resource utilization for delivery of multimedia streams in the backbone Internet.

> **Subgoal 3-2:** Formulate the optimal solution in terms of resource utilization for delivery of multimedia streams in the heterogeneous wireless network.

Goal 4: Define and develop algorithms operating in dynamically changing networking environments with partial knowledge of the system.

Research Goals	Research Questions
Goal 1	Research Questions Q1, Q3, Q4, Q5
Goal 2, Subgoal 2-1	Research Questions Q1, Q2
Goal 2, Subgoal 2-2	Research Questions Q1, Q2
Goal 3, Subgoal 3-1	Research Question Q6
Goal 3, Subgoal 3-2	Research Question Q7
Goal 4, Subgoal 4-1	Research Questions Q8, Q9
Goal 4, Subgoal 4-2	Research Questions Q10, Q11

Figure 1.3: Mapping of research goals and research questions.

Subgoal 4-1: Develop decentralized approaches for data delivery of multimedia streams in the backbone Internet.

Subgoal 4-2: Develop decentralized approaches for data delivery of multimedia streams in the heterogeneous wireless network.

1.4.2   Research Questions

To achieve these goals, the following research questions were identified and analyzed in the work.

Research Question Q1: What are main causes for reduction of QoS of multimedia streams along the delivery paths?

Identifying these causes allows us to specify mechanisms that can adapt data delivery to resource availability for maintaining quality for data transmissions in the wireless infrastructure and overlay routing in the wired Internet. We study several networking scenarios to understand how the QoS is be affected in resource limited networks.

Research Question Q2: What is the state of the art of delivery infrastructure for multimedia streaming in the wired and wireless Internet?

We studied the existing solutions and identified the aspects that we needed to improve or develop for efficient content distribution. When possible, we aimed to specify the solutions that could be used as lower bounds for evaluating the outcomes of the implemented algorithms.

Research Question Q3: What are the main components of the system and what are their functions?

Identifying these components allows outlining of the operational requirements for resource adaptation algorithms and the routines these algorithms rely on.

Research Question Q4: How much information available to any given component needs to be exchanged?

This question is important to answer for designing of decentralized algorithms. Here, we define what kind of information is available to a component, what information is used

by the component to perform its functions and what information is transmitted over the network to be process by other components.

Research Question Q5: From the architectural design, how to disseminate this information in an efficient manner?

We need to define mechanisms for information dissemination and how this information is to be exchanged in a way that reduces signaling overhead across the whole network.

Research Question Q6: What optimization methods are applicable in the wired Internet?

To evaluate the mechanisms for data delivery in the backbone Internet, we need to define a mathematical model for the overlay network and formulate a corresponding optimization problem.

Research Question Q7: What optimization methods are applicable in wireless networks?

For the heterogeneous wireless network, we build a mathematical model for the multi-access network.

Research Question Q8: How can we reduce the data exchange in the backbone network?

Providing high definition content for large scale distribution is expensive and a standard client-server model does not provide users with acceptable service. Adding more components to the content transmission schemes requires certain coordination and data exchange between them. Defining algorithms for these components that can efficiently operate by exploiting incomplete knowledge of the network topology and networking parameters can certainly reduce signaling overhead.

Research Question Q9: How can we decentralize the problem for the backbone network if the centralized approach is not applicable?

The question is a consequent follow-up of the Question 8. We need to study the problem of whether the components with different, though correlated information, can compute efficient solutions for content delivery without or with limited communication between each other.

Research Question Q10: How can we reduce the data exchange within heterogeneous wireless networks?

Optimization routines in large-scale systems, e.g., optimal network selection, require large dimensions of data to be exchanged inside the system, implying that the scalability can easily become a bottleneck. The problem becomes even more challenging due to inaccurate and insufficient information, the dynamic nature and inability to collect the information continuously in wireless networks. Optimally allocating users to different wireless networks requires certain information about the networks' conditions, users' channel state information and their preferences to be transmitted in real time between the decision makers. Reducing the amount of information for decision making is therefore important for improving performance of wireless networks and reducing signaling overheads.

Research Question Q11: How can we decentralize the problem if the centralized approach is not applicable?

Optimization routines in large-scale systems often require an implementation of a centralized unit to perform coordination, information exchange and optimization routines. However, for several reasons, it can be infeasible. An efficient decentralization of network selection solution is therefore important for wireless networks, since it improves utilization of the network resources and QoS of users.

The mapping of the research goals to the research questions is shown in Figure 1.3.

Chapter 2

State of the Art

This work focuses on rational delivery of multimedia streams from their sources on the Internet to their users connected to wireless networks. Through this work, we constantly elaborated a multi-concept approach by considering multiple users, multiple streams in the system, multi-access capabilities of mobile users, and multipath delivery of streaming content. This approach implies that the decisions are made collaboratively in a multi-interface, multi-technology environment and multiple network points of attachment. In this chapter, we investigate the related work concerning efficient data delivery in both the wired internet and wireless heterogeneous environments. For the wired Internet, we focus on multipath routing and for wireless heterogeneous environments we investigate the network selection problem.

2.1   Multipath Routing in the Wired Internet

Several studies have proposed multipath streaming to increase the total available end-to-end bandwidth [24, 34, 56], provide tolerance to packet loss and reduce the impact of congestion. There are mainly two ways of implementing multipath routing. This can be done either in the network layer exploiting, for example, traffic engineering techniques [73], or in the application layer using overlay networks [33]. When implemented in the network layer several routing protocols and algorithms can be used including the OSPF Optimized Multipath protocol (OSPF-OMP) [76], Multipath Distance Vector Algorithm(MDVA) [59], and Quality of Service (QoS) routing mechanisms [35]. However, these algorithms have serious drawbacks since they require routers to maintain detailed information about all paths between the router and every possible destination. As a consequence, they scale poorly. Implementing multipathing at the network layer also requires a certain cooperation between Internet Service Providers (ISPs), implying that the ISPs need to use the same routing protocol. In addition, ISPs are unlikely to allow others to control the traffic going through their networks.

Implementing multipath streaming in the application layer by using overlay networks helps to overcome the problems in deployment related to ISPs. However, it is certainly less efficient in terms of latency. For application layer, multiple paths can be constructed using peer-to-peer networks or overlay networks that are built upon proxy nodes deployed in the Internet, also known as Content Distribution Networks (CDNs). The peer-to-peer (p2p) streaming paradigm [69] was introduced in the 2000s as a possible remedy to reduce the load in content providers' net-

works. Several application level multipath solutions [18, 20, 37, 70, 77, 85] have been proposed, mainly meant for peer-to-peer (p2p) streaming. Though these solutions focus mostly on peer management in the overlay network and on peer selection for constructing the best possible topologies, some of these works also consider how the streaming rates should be allocated to multiple paths.

Hefeeda et al. [37] introduce a robust, topology-aware p2p streaming system that is built upon a p2p look-up, topology inference and monitoring system. This system selects a set of the best peers for a streaming session. The candidate peers are selected based on the goodness metric of a peer. This goodness metric is a function of the peer's availability for streaming and a product of the goodness of all segments comprising the path between the peer and the receiver. The goodness of a segment is calculated as a function of packet loss and available bandwidth between the peer and the receiver, and the level of sharing of the segment. It is assumed that the receiver is able to obtain a full knowledge about the underlay topology and network parameters between itself and the candidate peers.

SplitStream [20] is built upon an overlay network called cooperative environments, and is used for multicast and content distribution. In SplitStream, multiple trees are built and used for streaming in order to balance the forwarding load. The peers are organized in trees in a way that each peer serves as an internal node in one tree and as a leaf node in other trees. This principle guarantees that the failure of one node will affect only one tree. The content is split into several stripes, which are then multicast using separate trees.

Outreach [70] is another topology construction algorithm intended to optimize the p2p over-lay construction. It maximizes the utilization of the peers' available upload bandwidth in order to minimize the bandwidth requirements on the streaming server.

While partly reducing costs for the content providers, instead, the p2p systems create significantly more traffic in ISPs networks [80]. Even when peers belong to one ISP there is no guarantee that the feed from one peer to another peer is delivered via the shortest path routing. Karagiannis et al. [45] show that p2p traffic can cross ISP network boundaries several times, rendering p2p solutions ISP-unfriendly. As a result, ISPs need to take the costs for increased p2p traffic or stop this kind of traffic completely. In addition, p2p systems suffer from peers' instability where peers can unpredictably appear in and disappear from the streaming process. While these drawbacks can be tolerated for downloading operations, these are destructive for life or video-on-demand streaming. As peers are often asymmetric in terms of upload and download bandwidths, several peers are usually needed to serve one newly arriving peer.

Alternatively to p2p solutions, Content Distribution Networks (CDN) [27] aim to improve network performance by delivering content from multiple proxies located in geographically different sites (points of presence) of the Internet. Content providers can buy services from these networks for hosting and delivery of the content providers' data.

The bottlenecks in the Internet can be characterized as the bottlenecks of the first, the middle and the last mile [63]. This study shows that the middle mile is gaining more importance as the ISPs have invested many resources in their networks. Even for the mobile Internet, 4G networks allow for 1 Gbps for low mobility connections, and 100 Mbps for high mobility connections [41]. While p2p systems reduce the traffic only of the first mile, CDNs can, when wisely planned and deployed, address the challenges of the first, middle and last miles [63]. Other certain advantages of the CDNs over p2p solutions are: stability, relatively easiness to

obtain knowledge about network resources and network topology, can be combined with some other multimedia functionality like transcoding, caching and forward error correction.

Akamai [5] is the largest CDN network, and has today approximately 85000 servers in 72 countries. It handles 15-20% of the daily Web traffic. The AkamaiEdgePlatform [28] uses different techniques to secure quality streaming for their clients, also using multiple paths to deliver the video content. However, for multipath delivery, the AkamaiEdgePlatform simply sends multiple copies of the same stream over different routes. Sending multiple copies is not efficient use of the Internet resources.

In addition to p2p systems and CDNs, some works studied multipath streaming without specifying any infrastructure for the implementation. A simple TCP-based multipath streaming algorithm has been proposed by Wang et al. [77]. Here, a server opens several TCP connections, one for each path, and stripes video content over these connections. However, the authors do not consider how the multipath infrastructure is built, and they do not study possible trade-offs between multiple streams.

Bui et al. [18] study how to use the Markov Decision Process framework for multipath data transfers. The proposed solution considers only one sender-receiver pair, which is not a realistic scenario for video streaming. Also another study [44] limits its research to a single sender-receiver pair, and assumes knowledge of all network parameters.

2.2 Wireless Heterogeneous Networks

Availability of various wireless network technologies and continuous development of mobile devices and services lead to complex and highly dynamic networking and challenge resource limitations of wireless access networks.

To tackle this challenge, the IEEE 802.21 Media Independent Handover (MIH) standard [40] advises mobile nodes and networks to perform handover decisions collaboratively, in an environment with multi-interface, multi-technology user equipment and multiple network points of attachment. However, the network selection problem is challenging with multiple decision criteria, such as user preferences, user movements, operations performed, battery limitations, mobile device types, network load and service provider cost. This problem becomes even more challenging due to inaccurate and insufficient information for decision making, the dynamic nature and inability to collect all necessary information due to computational limitations of the devices and large dimensions of the data involved.

Being originally introduced for use in the wired Internet, multicast is an efficient method for point-to-multipoint communications, which reduces drastically the traffic load when the same content is sent to a large group of users. The 3rd Generation Partnership Project (3GPP) and its successor 3GPP2 defined the *Multimedia Broadcast and Multicast Service* (MBMS) and the *Broadcast and Multicast Service* (BCMCS) [1], respectively. The Long-Term Evolution (LTE) project introduced *LTE Broadcast*, also denoted as *evolved Multimedia Broadcast Multicast Service* (eMBMS) [2]. Different types of applications like video conferencing, file distribution, live multimedia streaming, IPTV can benefit from deploying multicast networking. It is also advantageous in cases of the flash crowd phenomenon when the popularity of a certain item increases rapidly over a short period of time. The *LTE whitepaper* [29] shows that already

from three to five subscribers in one cell site achieve break-even of cost between unicast and multicast.

To the best of our knowledge, the research field regarding selection of a network in heterogeneous wireless networks from a perspective of multicast delivery is not well explored. In what concerns network selection for mobile multicast groups, several research areas can be considered as related work *1*) handoff management in wireless networks; *2*) admission control and network selection; *3*) multicast in wireless networks; *4*) LTE-Advanced Heterogeneous Networks.

2.2.1   Handoff Management in Mobile Networks

Prediction-based techniques have been suggested in several studies [6, 23, 64, 75] aiming to reduce handoff delays.

To represent the movement behavior of a mobile user, Paramvir et al. [64] propose a two-level user mobility model consisting of a local level and a global level. A hierarchical location prediction algorithm is proposed based on an approximate pattern-matching algorithm implemented in the global level and Kalman filtering techniques implemented in the local level.

Akyildiz and Wang [6] propose a mobility model that uses historical records and stochastic behavior of mobile users to predict their future position. The model is built upon a framework of user mobility profiles (UMP). In the proposed prediction algorithms, many factors are taken into consideration including velocity and direction of mobile users, historical records, stochastic model of cell residence time and path characteristics. The authors claim that these algorithms predict more accurately than previous schemes. However, the complexity of the algorithms make them impractical for mobile applications.

In two studies, Tseng et al. [75] and Choi et al. [23] propose using cross-layer information to perform layer-3 handoff in parallel with or prior to the layer-2 handoff. However, these schemes can lead to false alarms and cause unnecessary MIP registrations. Ray et al. [68] conclude that deciding upon the ideal choice and timing of cross-layer triggers in order to reduce layer-3 latency is still an open problem.

Vertical handoff is the handoff between the networks of different wireless technologies and has been addressed in several studies [21, 36, 46, 61, 71, 79, 86]. While horizontal handoffs are typically triggered when the received signal strength (RSS) of the serving access router drops below a certain threshold the vertical handoff can be initiated due to other reasons such as user preferences or network conditions including coverage, bandwidth, cost and power consumption. The decision process is therefore more complex for vertical handoffs than for horizontal ones.

While some authors only use RSS as an input parameter for the handoff decision process [6, 83], others combine the use of RSS with bandwidth information [22, 52, 82]. Using cost functions has been proposed earlier [36, 71, 86]. Nasser et al. [60] propose a cost function that depends of the cost of service, security, power consumption, network conditions and network performance. However, in their evaluation, all weights except the bandwidth weight are set to zero. This renders their cost function to a function of one parameter: bandwidth.

Algorithms based on fuzzy logic or artificial neural networks in combination with multiple criteria [21, 61, 79] suffer from high handover delay because of their complexity and the training process. Unfortunately, the authors of these algorithms did not provide throughput results.

Recently, some studies [72, 84], proposed solutions for group vertical handoffs in heterogeneous environments. These studies consider scenarios when many mobile users send handover requests almost at the same time. In these scenarios, the influence of multiple users is important to consider for optimal network selection. The solutions presented in both studies require a centralized approach to be adopted to implement the proposed schemes. The obvious drawback of this approach is a poor scalability of these solutions.

2.2.2 Admission control and Network Selection in Wireless Networks

Ormond and Murphy [62] propose a network selection approach that uses a number of possible utility functions. Their solution is user-centric and does not present any multicast scenario. An interplay between different users and networks is not considered either. Ormond and Murphy conclude that the impact of multiple users operating in the same region needs to be further examined.

Gluhak et al. [32] consider the problem of selecting the optimal bearer paths for multicast services with groups of heterogeneous receivers. The proposed algorithm selects the bearer path based on different optimization goals. However, Gluhak et al. address the problem only for the ideal static multicast case without taking into account users crossing different cells. In addition, it requires that the knowledge of the conditions in wireless networks and preferences of receivers is fully shared. In their work, multicast membership does not change during the duration of a service, and multicast groups are not built with consideration of users' movements. In our opinion, this is not a realistic case for wireless networks. Also, the proposed selection algorithm is built upon a rule according to which the receivers are partitioned into two sets: the receivers for which only one network is available versus the receivers for which several networks are available. The impact of the users inside the second group, as a result of this partitioning, is neglected.

Tragos et al. [74] propose a generic admission control algorithm that allows network selection for 4G heterogeneous wireless networks. The algorithm aims to provide maximum utilization of the network, prevent overloading situations and ensure best QoS. However, implementation of the algorithm requires the presence of a centralized entity.

Khan et al. [49] present a game theoretic solution for resource allocation and call admission in wireless networks using cooperative games. The main goal is to increase the utilization of the available bandwidth and to reduce the call blocking. The solution is applicable to wireless network scenarios where networks are willing to cooperate. Kalai-Smorodinsky Bargaining Solution is used to solve the cooperative game. The authors also propose the request distribution algorithm that allows to allocate the request to several different networks and split the requested bandwidth between these networks. Similar to Tragos et al. [74], the implementation requires also a centralized entity that is responsible to handle bargains between the participating networks.

2.2.3 Multicast in Wireless Networks

The Multicast Mobility (multimob) working group [58] focuses its activity on supporting multicast in a mobile environment. The main goals of the group are to work out mechanisms for

supporting multicast source mobility and mechanisms that optimize multicast traffic during a handover. The group also documents the configuration of IGMPv3/MLDv2 in mobile environments. In this sense, they extend the IGMPv3/MLDv2 protocols for implementation in the mobile domain and improve *Proxy Mobile IPv6* to handle multicast efficiently. However, they do not consider any modifications across different access networks.

The Long-Term Evolution (LTE) project introduces evolved Multimedia Broadcast Multicast Service (eMBMS) [2]. This standard covers technically the terminal, radio, core network, and user service aspects that provide a point-to-multipoint service for transmitting data from a single source to multiple recipients. The performance is improved due to higher and more flexible LTE bit rates, single frequency network (SFN) operations, and carrier configuration flexibility. The eMBMS Service Layer offers a Streaming- and a Download Delivery Method and is enhanced with video codec for higher resolutions and frame rates and forward error correction (FEC), and the radio network with procedures to ensure MBMS reception in a multifrequency LTE network. eMBMS also allows LTE network and backhaul offloads.

Yang and Chen [81] propose a bandwidth-efficient multicast algorithm for heterogeneous wireless networks that is formulated as an Integer Linear Programming problem that is solved using Lagrangian relaxation [30]. The algorithm deals only with constructing optimal shortest path trees for multicast groups. In this approach, important parameters such as cost of service, user's velocity, etc. are not considered.

Jang et al. [43] present a mechanism for efficient network resource usage in a mobile multicast scenario. This mechanism is developed for heterogeneous networks and implements network selection based on network and terminal characteristics and Quality of Service (QoS). However, in the proposed mechanism, the network selection is performed purely based on terminal's preferences, the network perspective is not considered, and the solution does not optimize the utilization of network resources.

Hou et al. [39] propose a cooperative multicast scheduling scheme for multimedia services in IEEE 802.16 based wireless metropolitan area networks (WMAN). The scheduling is considered for one base station that further re-sends the data to multiple subscriber stations. These are grouped into different multicast groups and the users are assigned to the groups. The authors consider two approaches to select multicast groups for services: the random selection and the channel state aware selection. The process is controlled by the base station and limited to one network technology. No network heterogeneity is considered.

Several studies consider beamforming [55] and multiple antenna selection problem [57, 65] for wireless multicasting. The goal is to adapt the multicasting transmission using channel state information and to form beamforming vectors. To achieve a higher capacity, the authors maximize the minimum point-to-point capacity of a specified subgroup of the mobile nodes that participate in the multicast session [65]. In [57], the problem is considered as a joint problem for multiple co-channel multicast groups.

2.2.4   LTE-Advanced: Heterogeneous Networks

Though several improvements were introduced in the LTE-Advanced standard [3], the homogeneous networks with only macrocells deployments will not be able to cope with future mobile traffic. A step towards optimization of performance in wireless networks is done by LTE-
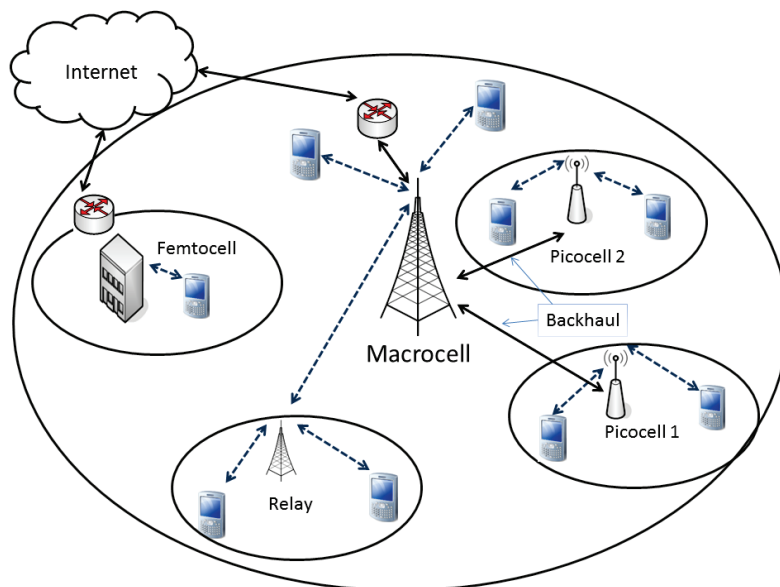
Figure 2.1: LTE Advanced Heterogeneous Network Architecture.

Advanced [4] through enhancements in network topology. The LTE-Advanced proposed implementation of heterogeneous networks (HetNets) topologies that combine utilization of both macrocells and small cells, the latter including micro, pico, femtocells and relays, each having different transmit power and access rules for user devices.

Macrocells

Macrocell is an outdoor base station and the main base station in the cell. The transmitted power is about 45 dBm. Macro cells are connected with each other through backhaul that are usually built upon a wired infrastructure. In some cases, e.g. for rural areas, wireless links can also be used.

Micro and Picocells

These cells are, usually, an outdoor low cost base stations with open access and a small coverage.They are connected with the macro cell using a backhaul link. The transmitted power is about 35 dBm. The range is about two kilometers wide for microcell and about 200 meters for picocell.

Femtocells

Femtocells are indoor base stations either with open or limited access and low transmitted power that is less than 23 dBm. Though these cells are positioned as an alternative to micro and picocells, their coordination with the macrocell still is not fully achieved in current deployments.

Relays

Relay stations receive, demodulate and retransmit the signals between base stations and mobile users. They can, also, decode the data and provide error correction. Relays are used to increase throughput and to extend coverage of cellular networks. Relays do not need wired connection to the base station therefore the backhaul costs can be saved.

In the HetNet network model, macrocells provide full coverage for a wide area and small cells cover some areas with extra traffic demand. It is a useful network architectural feature since the bandwidth demand is not uniform across the area and users and traffic are often concentrated in particular areas. Another important benefit of using small cells inside of a macrocell is to improve coverage in places where coverage of the macrocell is not sufficient, e.g. in cell edges. Since deploying extra macro cells in these areas results in additional interference, deployment of lower power picos is a better solution. It also gives a cost reduction. A typical LTE-Advanced HetNet scenario with a macro base station and several small cells is illustrated in Figure 2.1.

In this thesis, we evaluate network selection solutions considering both the LTE-Advanced HetNet network model and a general heterogeneous mobile network system with overlapping of several wireless technologies, e.g., WLANs and cellular networks. In our analysis, we recognize that the presented related work has not addressed several important aspects concerning the network selection for mobile multicast groups. We need to study how the users' movements influence the optimal selection of members for multicast groups and how the information needed for network selection is exchanged between the decision makers.

Chapter 3

Contributions and summary of papers

The second part of the dissertation consists of research contributions through eight published papers in peer-reviewed international conferences or journals. The author of this thesis is the principal contributor and first author of papers B-H. She is the third author of paper A.

Paper A   Wolfgang Leister, Tiia Sutinen, Svetlana Boudko, Ian Marsh, Carsten Griwodz, and Pål Halvorsen. "An Architecture for Adaptive Multimedia Streaming to Mobile Nodes", *Proc. MoMM 2008, November 24-26, 2008, Linz, Austria*, pages 313-316, ISBN 978-1-60558-269-6, DOI 10.1145/1497185.1497250, 2008.

Paper B   Svetlana Boudko, Wolfgang Leister, Carsten Griwodz, and Pål Halvorsen. "A Benchmarking System for Multipath Overlay Multimedia Streaming", *Proc. ICME 2008, June 23-26, 2008, Hannover, Germany*, pages 853-856, ISBN 978-1-4244-2570-9, DOI 10.1109/ICME.2008.4607569, 2008.

Paper C   Svetlana Boudko, Wolfgang Leister, Carsten Griwodz, and Pål Halvorsen. " Maximizing video quality for several unicast streams in a multipath overlay network.", *Proc. IMSAA 2010, December 15-17, 2010, Bangalore, India*, pages 1-5, ISBN 978-1-4244-7931-3, DOI 10.1109/IMSAA.2010.5729398, 2010.

Paper D   Svetlana Boudko, Wolfgang Leister, Carsten Griwodz, and Pål Halvorsen. " Multipath Rate Allocation Algorithm for Overlay Networks with Feedback From Overlay Nodes.", *Proc. ITST 2011, August 23-25, 2011, St. Petersburg, Russia*, pages 468-473, ISBN 978-1-61284-668-2, DOI 10.1109/ITST.2011.6060103, 2011.

Paper E   Svetlana Boudko, Wolfgang Leister, Stein Gjessing. " Team Decision Approach for Decentralized Network Selection of Mobile Clients.", *Proc. WMNC 2012, September 19-21, 2012, Bratislava, Slovakia*, pages 88-94, ISBN 978-1-4673-2994-1, DOI 10.1109/WMNC.2012.6416141, 2012.

Paper F   Svetlana Boudko, Wolfgang Leister. " Network Selection for Multicast Groups in Heterogeneous Wireless Environments.", *International Conference on Advances in Mobile Computing and Multimedia*, pages 167-176, ACM ISBN: 978-1-4503-2106-8ISSN, 2013.

Paper G   Svetlana Boudko, Wolfgang Leister, Stein Gjessing. "Heterogeneous Wireless Network Selection: Load Balancing and Multicast Scenario.", *Journal On Advances in Networks and Services*, pages 118-135, ISSN 1942-2644.

Paper H   Svetlana Boudko, Wolfgang Leister, Stein Gjessing. "Exploring Network Selection Techniques for Multicast Groups in Heterogeneous Wireless Environments", *Accepted for publication in International Journal of Pervasive Computing and Communications*, ISSN 1742-7371.

In addition, the research benefited from the results of the following related work.

Presentation R1   Svetlana Boudko, Wolfgang Leister. "Adaptive Multimedia Streaming (Adimus)" Simula seminar, Geilo; 2008-02-01.

Presentation R2   Wolfgang Leister, Ian Marsh, Svetlana Boudko, Tiia Sutinen. "Adaptive Internet Multimedia Streaming", NORDUnet Conference 2008, Helsinki, Finland; 2008-04-09.

Paper R3   Wolfgang Leister, Svetlana Boudko, Till Halbach Røssvoll. "Estimation of Subjective Video Quality as Feedback to Content Providers", The Fifth International Conference on Systems and Networks Communications (ICSNC), 2010, Nice.

Paper R4   Wolfgang Leister, Svetlana Boudko, Till Halbach Røssvoll. "Adaptive Video Streaming through Estimation of Subjective Video Quality", International Journal On Advances in Systems and Measurements, 2011.

Report R5   Wolfgang Leister, Tiia Sutinen, Svetlana Boudko, Ian Marsh, Carsten Griwodz, and Pål Halvorsen. "ADIMUS – Adaptive Internet Multimedia Streaming", Final Project Report, 2010.

Paper R6   Svetlana Boudko, Wolfgang Leister, Stein Gjessing. "Multicast Group Management for Users of Heterogeneous Wireless Networks.", *Proc. CONTENT 2012, July 22-27, 2012, Nice, France*, pages 24-27, ISBN 978-1-61208-220-2, 2012.

Paper R7   Svetlana Boudko, Wolfgang Leister, Stein Gjessing. "Optimal Network Selection for Mobile Multicast Groups", *Proc. ICSNC 2012, November 18-23, 2012, Lisbon, Portugal*, pages 224-227, ISBN 978-1-61208-231-8, 2012.

In Section 1.4, we defined the research goals of the thesis. Further, we identified the research questions that we needed to investigate and address in order to achieve these goals. This chapter revisits the research questions and explains how these questions are addressed by the included papers. In these papers, we investigate one or several research questions. The papers are not independent but are closely interrelated thematically. The findings from prior papers are often used in the subsequent papers.

The thematic progression, and how the different papers are interconnected, is shown in Figure 3.1. The research questions documented in Section 1.4 are:
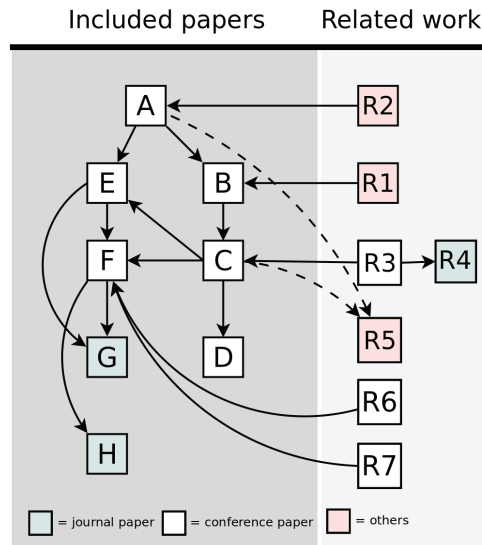
Figure 3.1: The thematic progression between the research contribution (included papers) and related work.

- **Research Question Q1:** What are main causes for reduction of QoS of multimedia streams along the delivery paths?

- **Research Question Q2:** What is the state of the art of delivery infrastructure for multimedia streaming in the wired and wireless Internet?

- **Research Question Q3:** What are the main components of the system and what are their functions?

- **Research Question Q4:** How much information available to any given component needs to be exchanged?

- **Research Question Q5:** From the architectural design, how to disseminate this information mostly efficiently?

- **Research Question Q6:** What optimization methods are applicable in the wired Internet?

- **Research Question Q7:** What optimization methods are applicable in wireless networks?

- **Research Question Q8:** How can we decentralize the problem for the backbone network if the centralized approach is not applicable?

- **Research Question Q9:** How can we reduce the data exchange within heterogeneous wireless networks?

- **Research Question Q10:** How can we reduce the data exchange within heterogeneous wireless networks?

- **Research Question Q11:** How can we decentralize the problem if the centralized approach is not applicable?

The scientific contributions are mapped to the research questions in Table 3.1. *Part I* of the thesis gives an introduction to the problem area, describe the current "state-of-the-art" research and mitigation strategies within the problem area, and, to some extend, evaluated the proposed theoretical approach. *Part II* of the thesis contains the full papers.

Scientific contributions	Research Questions
Part I of the thesis	Questions Q1, Q2, Q3
Paper A	Research Question Q1
Paper B	Research Question Q6
Paper C	Research Question Q6
Paper D	Research Questions Q8, Q9
Paper E	Research Questions Q3, Q4, Q5, Q7, Q10, Q11
Paper F	Research Questions Q3, Q4, Q5, Q7, Q10, Q11
Paper G	Research Questions Q3, Q4, Q5, Q7, Q10, Q11
Paper H	Research Questions Q3, Q4, Q5, Q7, Q10, Q11

Table 3.1: Mapping of scientific contributions and research questions.

3.1   Paper A: Contributions and summary

An Architecture for Adaptive Multimedia Streaming to Mobile Nodes

Paper A [53] provides an overview and analysis of the ADIMUS architecture. It outlines the requirements and the resource adaptation mechanisms that support QoS sensitive multimedia streaming over a best effort Internet path from the ADIMUS backbone proxies to mobile clients. The paper clearly separates the system into the backbone subsystem and the heterogeneous wireless subsystem and discusses the interface between them. It addresses the different nature of adaptation to available resources in the backbone and inside the heterogeneous wireless network. While routing in the backbone suffers from router failures and congestion, in the wireless networks, the mobility of users and instability of wireless connections degrades the quality of connection.

The two subsystems have also different timing requirements. While the multi-access network must react very fast to handover decisions, decisions computed in the backbone part of the network can be slower. Also, the notion of a link interface for a wireless channel differs from that for a wired network. For the backbone subsystem, we considered the ways to overcome packet loss and bandwidth limitations in the Internet during the delivery of multimedia streams. As the routing in the wired Internet is determined by policies of the routers and cannot be controlled by the end hosts, there is no guarantee that the path selected to deliver multimedia streams is provided with sufficient available bandwidth. At the same time, an alternative path or

several alternative paths can be found in the network, which utilization gives higher throughput and can significantly improve the quality of the delivered stream.

In this paper, we considered several alternatives for implementing multipath routing. It can be done either in the network layer exploiting for example traffic engineering techniques [73] or in the application layer using overlay networks. The implementations in the network layer have serious drawbacks. They require routers to maintain detailed information about all paths between the router and every possible destination and therefore scale poorly. Implementing multipathing at the network layer also implies certain cooperation between ISPs including that all ISPs choose to use the same routing protocol. In addition, ISPs are unlikely to allow others to control the traffic going through their networks.

Implementing multipath streaming in the application layer by using overlay networks helps to overcome the problems in deployment related to ISPs. However, it is certainly less efficient in terms of latency. For application layer, we considered two alternatives: peer-to-peer networks and overlay networks built upon proxy nodes deployed in the Internet, or Content Distribution Networks (CDNs).

The peer-to-peer (p2p) streaming paradigm [69] was introduced in the 2000s as a possible remedy to this problem in order to reduce the load in content providers' networks. While partly reducing costs for the content providers, instead, the p2p systems create significantly more traffic in ISPs networks [80]. In addition, p2p systems suffer from peers' instability where peers can unpredictably appear in and disappear from the streaming process. These limitations of p2p streaming are especially unfavourable for wireless scenarios.

Contrary to the aforementioned alternatives, the advantage of using a CDN for multisource multipath streaming under these conditions is that streams can be split up and re-routed to improve the total amount of bandwidth that is available for streaming from the servers to every single client, even when individual overlay links have insufficient bandwidth. Clients that do not suffer from bottlenecks in the access network are likely to compete for the bandwidth on at least some overlay links. This is reflected in the architecture through resource efficient rerouting decisions at the application layer in the overlay network.

For the heterogeneous wireless subsystem, the user can switch between different access networks. However, the network selection problem is challenging with multiple decision criteria, such as channel state information, user preferences, user movements, battery limitations, mobile device types, network load and service provider cost. This problem becomes even more challenging due to inaccurate and insufficient information for decision making, the dynamic nature and inability to collect all necessary information due to computational limitations of the devices and large dimensions of the data involved. This is reflected in the architecture through adaptive network selection mechanisms in the multi-access network. The ADIMUS architecture is depicted in Figure 1.1.

The paper contributed to the Informational and Propositional Phases of the thesis addressing the Research Questions Q1-Q3. We outlined the main causes for QoS degradation for the two parts of the ADIMUS architecture, we defined the main components of the system, and we partly studied the existing solutions for content distribution.

3.2 Paper B: Contributions and summary

A Benchmarking System for Multipath Overlay Multimedia Streaming

Paper B [10] presents a benchmarking system for multipath media streaming of scalable media. We defined a mathematical model of an overlay network that delivered multimedia streams. For a given network topology, a set of overlay nodes, capacities of the links, and streaming demand from clients, the benchmarking system determines the optimal allocation of link bandwidth with the goal of allocating the maximum bandwidth to each of the streams. It defines an upper bound reference for operation of bandwidth allocating algorithms in multistream multipath environments. The benchmarking system solves the Linear Programming Problem that is defined in the paper.

To test the benchmarking system, we applied it to different network topologies. Cleary, the benchmark assigns the bandwidth shares of the individual overlay paths in a non-trivial way to achieve the optimum throughput. As a result, considerable resources are gained from alternative paths.

Since the calculation of the benchmark is rather computing-intensive, and since the knowledge of the entire system state is necessary for the calculation, this method is not suited for an implementation on a network node due to scalability reasons. However, the benchmarking system is intended to compare other algorithms with the optimal case provided by this work. We use it to quantify the difference between the optimal solution and solutions provided by algorithms that operate in dynamically changing networking environments with partial knowledge of the network.

Though, this system is developed for the overlay network, further in our work, we apply a similar approach to benchmarking algorithms of the multi-access subsystem of the ADIMUS architecture.

In the paper, we partially addressed the Research Question Q6. The paper contributed to the Informational and Analytical Phases of the thesis.

3.3 Paper C: Contributions and summary

Maximizing video quality for several unicast streams in a multipath overlay network

In Paper C [11], we continued to develop a tool that helped us to analyze the solutions for the backbone subsystem. We revised the mathematical model of multipath streaming for an overlay backbone network presented in Paper B [10] and considered the usage of a different utility function that better captured video quality. The choice of using a logarithmic utility function instead of a linear one, as by Boudko et al. [10], was motivated by the research results, presented by Koumaras et al. [50]. We used the video quality function defined in Koumaras et al. [50]. More important, applying logarithmic utility function in an optimization problem provided us with proportionally fair distribution of the network resources. To justify it, we evaluated different fairness strategies. We looked at several studies dedicated to quantitative

(a) Optimization with linear utility function

(b) Optimization with logarithmic utility function
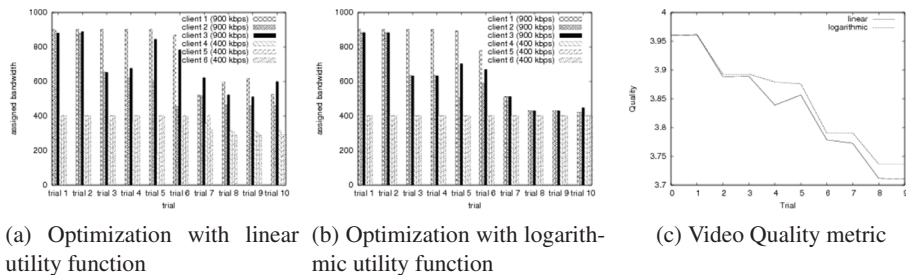
(c) Video Quality metric

Figure 3.2: Random network with decreasing total bandwidth

measures of fairness [7, 42, 47, 48] several strategies that included the max-min fairness and the proportional fairness. We found out that the proportional fairness better suited large scale systems [47, 48, 51] than the other measures. Therefore, this measure was chosen as a criterion for the system.

In our experiments, we compared the logarithmic benchmark with the linear one. An example of results for a random network topology is depicted in Figure 3.2. Our experiments showed that the logarithmic benchmark provides better bandwidth allocation in terms of achieved video quality over the whole set of users while providing the same optimal solution in terms of utilization of available bandwidth as depicted in Figure 3.2c. The logarithmic benchmark is also proportionally fair in allocating available bandwidth to different clients as shown in Figure 3.2a and Figure 3.2b.

The work presented in the paper addressed the Research Question Q6. We defined a mathematical model that allows evaluating of resource adaptation algorithms for the backbone overlay network.

3.4 Paper D: Contributions and summary

Multipath Rate Allocation Algorithm for Overlay Networks with Feedback From Overlay Nodes

In Paper D [12], we focused on solutions for the backbone subsystem. We developed a distributed algorithm for allocating the available bandwidth for streaming video in a multipath multisource overlay system. The overlay system is built upon proxy nodes deployed in the Internet. The algorithm operates by exploiting local knowledge of the network topology and networking parameters such as available bandwidth. It uses the feed-back from overlay nodes for decisions performed by the senders. To our knowledge, the previous work done in this direction focused on the rate allocation by the streaming server, while rate allocation by intermediate overlay nodes was not considered.

In the evaluated algorithm, the decision of rate allocation is done both in the senders and in the overlay nodes. For each receiver, the algorithm initializes the set of multiple paths and starts streaming using the direct path between the receiver and the source. If the path experiences congestion and is not provided with sufficient bandwidth to support requests the new path built upon the overlay nodes is added. If an overlay node experiences a bandwidth reduction over
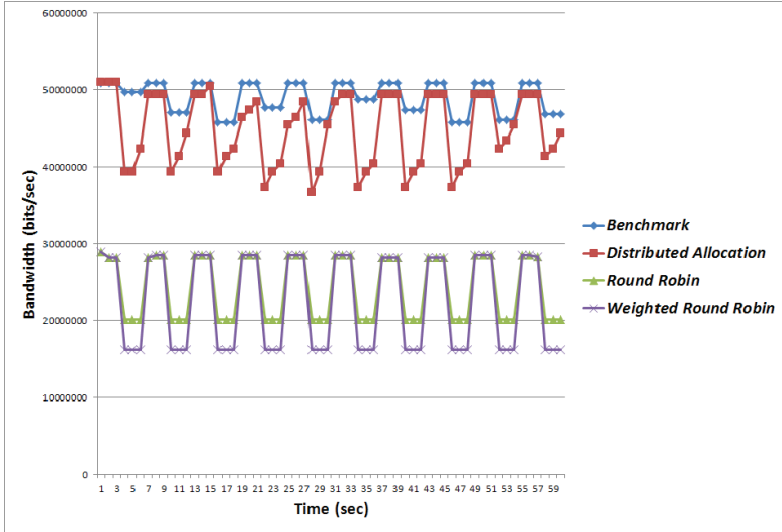
Figure 3.3: Aggregated bandwidth allocation

its outgoing overlay links it informs the senders that use this overlay link to perform the rate adjustment. The rates are sent to the senders. Several pairs sender-receiver can use the same overlay node. For the rate adjustment done in the overlay nodes, we used the min-max fairness strategy. For more information about the algorithm, please, refer to Paper D.

We evaluated the algorithm through multiple simulation runs using the OMNet++ environment, and compared the simulation results with the benchmark presented in Paper C. We also compared the simulation results with two round robin algorithms from the literature. The simulation results are depicted in Figure 3.3.

We addressed the Research Questions Q4, Q5, Q8 and Q9. To answer the Research Questions Q4 and Q5, we defined the scope of information required for overlay nodes and senders to perform the algorithm. To answer the Research Questions Q8 and Q9, the functionality and signaling was defined for overlay nodes and senders.

3.5   Paper E: Contributions and summary

Team Decision Approach for Decentralized Network Selection of Mobile Clients

In Paper E [15], we considered a network selection scenario for a group of users in a hotspot area like a crowded city center, a public transportation node or an exhibition site where a coverage of several base stations or access points from different networks is possible. We assumed a substantial overlap in coverage of these stations. The user terminals are capable of connecting to several access networks, and vertical handoffs between different networks are technically possible. Users located in the same cell of a mobile network can experience degradation in quality due to shortage of available bandwidth. We consider a situation when a base station
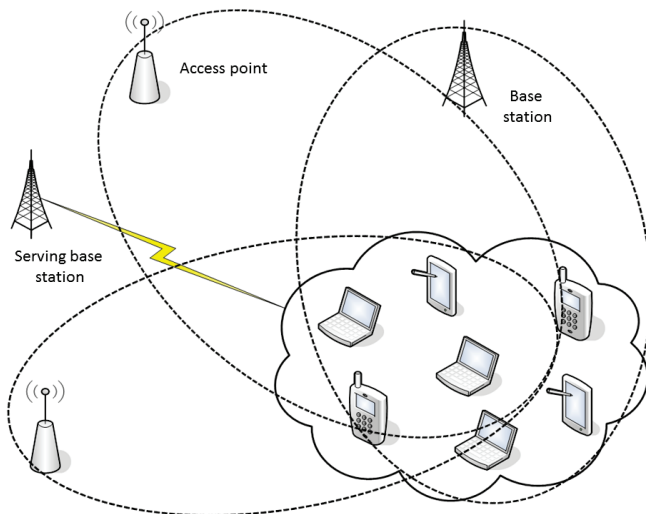
Figure 3.4: Network topology built upon multiple mobile networks with heterogeneous technologies to serve a group of clients.

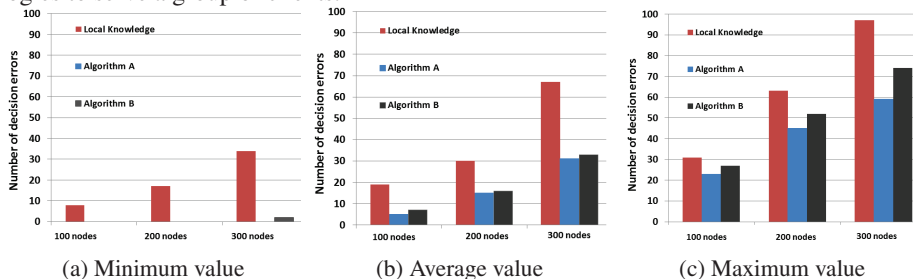(a) Minimum value   (b) Average value   (c) Maximum value

Figure 3.5: Decision errors from the simulation using one iteration of the algorithm run after network selection is triggered. The results for 100, 200, 300 mobile nodes are based on 1000 simulation runs for each group of nodes.

may act in a proactive way and monitor the available resources in adjacent cells. The users that are going to move to a cell that, at the moment, is not able to admit new users can be notified to perform a vertical handoff to another available network. Since users may have different preferences and request different types of service their utility functions are built upon different criteria. A representative scenario of such networking is shown in Figure 3.4.

For the information phase, we focused our studies on handoff management, admission control and network selection studies to address the challenges of resource allocation in the wireless networks and the "always best connected" concept. The proposed solution relied on predicting the movements of mobile nodes. Though movement prediction in wireless networks is outside the scope of this work, we needed this research to justify that the prediction can be performed with acceptable precision.

To provide better load balancing between the networks, and to avoid disturbing ping-pong effects, joint coordination, and information exchange between the users and the base stations is essential; both the clients and the networks can benefit from cooperative handoffs. However,

due to strict bandwidth and power limitations of mobile networks, and also due to scalability issues, a complete information exchange between mobile users and networks is not feasible. Decentralized network selection is therefore essential.

For the propositional and analytical phases, we presented a mathematical model of the system and formulated it as a team decision problem [38, 67] where several decision variables are involved. Team decision problems are concerned with determining the optimal decisions, given a set of information for each of several decision makers, that work together to achieve a payoff. In team decision problems, these sets of information are different though often correlated for different decision makers.

For evaluation phase, we defined upper and lower bounds to the system operation. The upper bound is achieved by applying a centralized solution with fully shared knowledge of the conditions in all evaluated networks. This reference can also be viewed as a modification of the algorithms [72, 74, 84] discussed in Chapter 2. The algorithm presented by Tragos et al. [74] is now extended to a multi-user scenario. The lower bound corresponds to a situation when all networks base their decisions only on local knowledge. The local knowledge reference can also be viewed as a modification of the algorithm by Ormond and Murphy [62] discussed in Chapter 2 and applied to a multi-user scenario.

Depending on how the knowledge of the system is shared among the networks, we differ between two versions of the distributed solution: the algorithm A and the algorithm B. The information about how these algorithms operate can be found in Paper E. We evaluated these in the OMNet++ environment. An example of simulation results for performing network selection is depicted in Figure 3.5. For more results, we refer to Paper E in *Part II*.

The work proposed in this paper includes the following two contributions. *1*) We propose a distributed solution that allows network selection in a decentralized manner with only limited information shared among the decision makers. *2*) By focusing our research on a group of mobile users, we study the impact of multiple users on decisions of the system. The paper contributed to all four phases of the thesis. In this paper, we addressed a number of Research Questions: Q3, Q4, Q5, Q7, Q10, and Q11. We revisited the main components and their functions of the wireless subsystem of the ADIMUS architecture, thus contributing to the Research Question Q3. To answer the Research Questions Q4 and Q5, we defined the information that the different components had to process, the information that had to be shared between the components and the mechanisms to share this information. We developed a mathematical model for the considered network scenario contributing to the Research Question Q7. We designed and analyzed the decentralized solution as a team decision problem contributing to the Research Questions Q10 and Q11.

3.6   Paper F: Contributions and summary

Heterogeneous Wireless Network Selection for Mobile Multicast Groups

In Paper F [9] studied the problem of forming mobile multicast groups for a multi-stream scenario in heterogeneous network environments. The paper combined all four phases of the
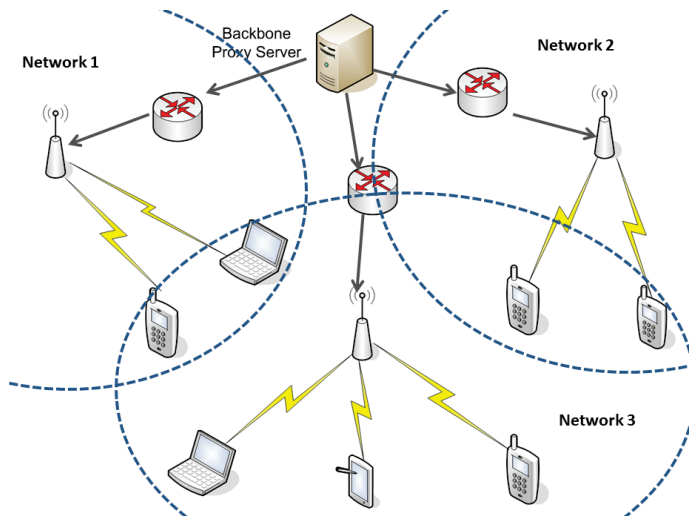
Figure 3.6: Multicast streaming scenario for a group of mobile clients served by several mobile networks before regrouping.
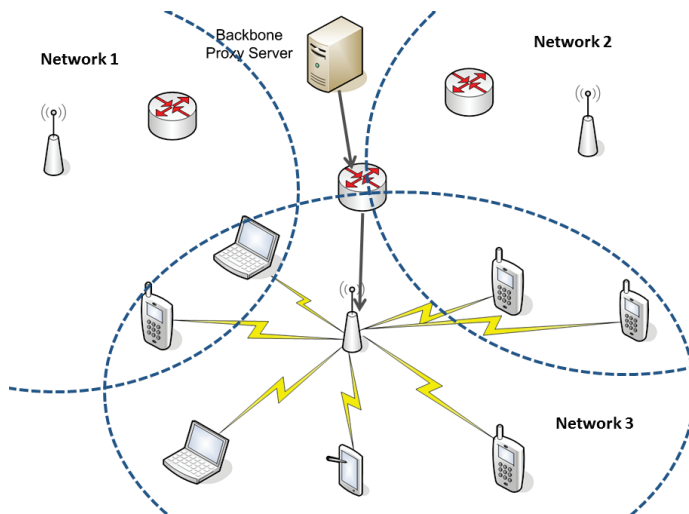

Figure 3.7: Multicast streaming scenario for a group of mobile clients switched to one mobile network after regrouping.

research method discussed in Section 1.3.

A detailed literature study was made for multicast solutions and network selection in heterogeneous wireless networks. We looked at different wireless technologies, standards, studies and white papers published by the main technology providers of the mobile market segment. We concluded that the state of the art had not addressed several important aspects related to the network selection for mobile multicast groups.

To address the network selection problem for several multicast groups, we proposed a repre-
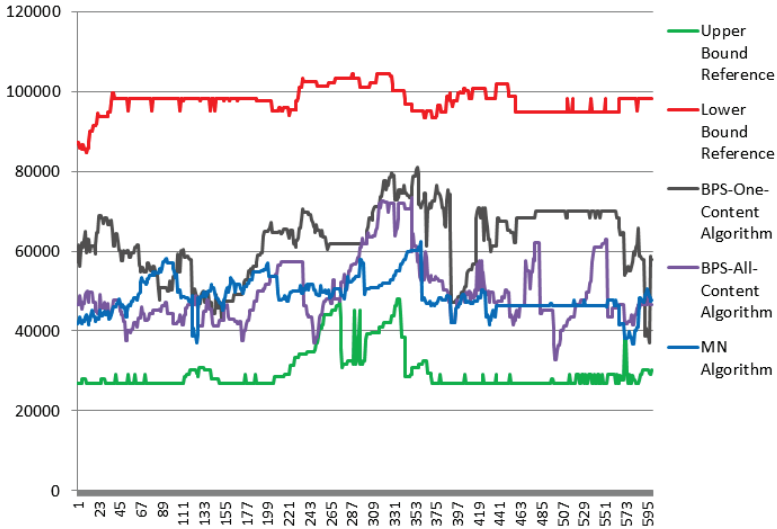
Figure 3.8: Total Bandwidth Consumption for simulations with background traffic changes applied. The x-axis shows time units. The y-axis shows consumed bandwidth in kbits. The results are an average of 500 simulation runs. The duration of one simulation run is 600 time units.

sentative scenario. In our scenario, the mobile terminals are capable to connect to several access networks, and vertical handoffs between these networks are technically possible. Such regrouping is beneficial as it saves network resources. Hence, the users that get the same content can exploit the same wireless link because the content can be broadcasted to them. The resources in the backhaul network are also better utilized because the content is now delivered to less number of mobile networks. An example of such reconfiguration is depicted in Figure 3.6 before reconfiguration and in Figure 3.7 after reconfiguration. For this scenario, we defined the main decision making components of the system, their functions and the information flow that facilitates regrouping of clients in multicast groups and network selection for the groups.

The mathematical model of the system was presented and formulated as an Integer Linear Programming Problem (ILP). We solved the problem of selecting the optimal network for multicast groups of mobile clients in multi-stream scenario based on mobile clients' preferences and location information. Since the knowledge of the entire system state is necessary for the calculation, we concluded that this method is not suited for large scale networks due to scalability reasons.

We evaluated the performance of the ILP package and found out that for solving the aforementioned problem that consisted of 5 mobile networks and 10 different streaming contents on a 2.83GHz Intel processor, the average CPU time estimates were 230 ms and 710 ms for 500 nodes and 1000 nodes respectively. These results showed that, for relatively large number of nodes, the problem could be solved within a reasonable time. Meaning, if the information can be effectively exchanged between the decision making components then the method can be used for small and average scale networks. Mostly important, we used the method as an upper bound

reference to evaluate the algorithms that allow network selection in a decentralized manner with only limited information shared among the decision makers.

Considering the problem as a decentralized incomplete information problem, we proposed two solutions that establish multicast groups and assign them to networks based on some partial information of the whole system. The operation is also performed by different components of the system with limited cooperation between the components. One solution operated on the information available on the BPS. The operation was triggered and perform by the BPS. For the second solution, the mobile networks (MN) coordinated and performed the network selection. We studied how the solution results depended on the information sets available for the decision making. We evaluated these solutions through multiple simulation runs. An example of simulation results is depicted in Figure 3.8. While the MN solution performed better than the BPS solution, the operation of the MN solution required more complex signaling across several mobile networks and BPSs than the BPS solution. More information concerning the evaluation of the solutions and their interpretation is provided in Paper F.

Our main achievement is decentralization of the network selection for mobile multicast groups, consideration of the impact of several multicast streams and incompleteness of information. In the paper, we addressed the Research Questions Q3, Q4, Q5, Q7, Q10, and Q11. For considered networking scenario, we revisited the main components and their functions of the wireless subsystem of the ADIMUS architecture (Q3). We studied the problem of what information had to be shared between different components and the mechanisms to share this information (Research Questions Q4, Q5). We developed a mathematical model for the considered network scenario thus contributing to the Research Question Q7. Designing and analyzing the distributed solution contributed to the answers of the Research Questions Q10 and Q11.

3.7 Paper G: Contributions and summary

Heterogeneous Wireless Network Selection: Load Balancing and Multicast Scenario

Paper G [16] is an invited paper based on two conference papers [13, 14], which are related work papers R6 and R7 as shown in Figure 3.1. The paper also extends the work presented in Paper E and Paper F. We consider the network selection for multi-user environments with possible multicast configurations that allows the network to perform load balancing. We extend the work presented in Paper E by evaluating a joint algorithm of the algorithms A and B. The joint algorithm was referred to as the algorithm AB. The results of this evaluation showed that the performance of the algorithm AB was slightly better the performance of the algorithm A. However, the gain in the performance was not so significant taking into account that the joint algorithm inherits the disadvantages of the algorithm B. It requires significantly more information to exchange between the networks than the algorithm A. It also requires more sophisticated mechanisms and protocols to be implemented in the networks, including security considerations and synchronization of the information flow. The information flow initiated by the algorithm AB is significantly less than the one initiated by the upper bound reference which requires the full network knowledge. However, it still demands the exchange of network

(a) Two hundred mobile nodes (b) Four hundred mobile nodes (c) Six hundred mobile nodes
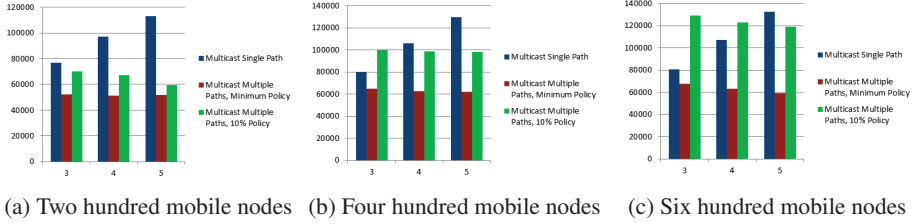
Figure 3.9: Average Results for Total Bandwidth Consumption. The results for 200, 400, and 600 mobile nodes are based on 2000 simulation runs. The x-axis shows the number of mobile networks in the test scenario. The y-axis shows consumed bandwidth in kbits.

information across the mobile networks on a fast time scale and low-latency basis, making it quite challenging to implement the algorithms in practice for large scale networks, as the upper bound reference.

The paper contributed to all four phases of the thesis. In this paper, we addressed the Research Questions Q3, Q4, Q5, Q7, Q10, and Q11.

3.8   Paper H: Contributions and summary

Exploring Network Selection Techniques for Multicast Groups in Heterogeneous Wireless Environments

Paper H [17] is an invited paper based on Paper F. Considering the same scenario as in Paper F, we extend the work by investigating the usage of multiple paths for multicast scenarios in heterogeneous mobile environments. Taking into account that channel conditions in a specific wireless network can vary drastically for users of the same multicast transmission, we used a node's *network profile* in paper F. This formulation implies that the network can satisfy the user's requirements only if the channel condition for this user is sufficient for receiving the requested stream. At the same time, using several connections for transmission gives better possibilities for establishing multicast groups. A mobile node can exploit the multipath streaming scheme and receive data from several networks concurrently. In this journal paper, we extend the work by formalizing a multiple connection approach for network selection in a multicast scenario. The study of the multiple path solution is limited to a full knowledge centralized approach. We formulate a mathematical model to the multiple path solution that is an NP-hard optimization problem and cannot be solved by common optimization solvers. We investigate a heuristic algorithm to solve the problem and discuss the future work regarding expanding the multiple paths solution to a decentralized approach. We show that the total usage of resources is reduced compared to the single path approach.

An example of simulation results for multipath multicast configuration is depicted in Figure 3.9. We addressed the Research Questions Q3, Q4, Q5, Q7, Q10, and Q11.

Chapter 4

Conclusion

This chapter concludes *Part I* of the thesis. It summarized the research and outlines the main contributions of the thesis. The chapter also discusses considerations and suggestions for future work.

4.1 Summary of the research

This research is a step towards providing adaptive multimedia-streaming on the Internet using multi-access technologies for the users of wireless heterogeneous networks. In this work, we considered the whole streaming chain from the content provider to the end user. We study adaptation as a mechanism that adjusts data transmission to the available bandwidth of the network. The adaptation mechanisms in this context, play the role of a traffic shaper, define transmission paths and allocate transmission rates to them. We also considered data transmissions with a focus on the whole network rather than one point-to-point delivery.

Challenges from diversity of the requirements of the different parts in the streaming chain are addressed by the ADIMUS architecture by dividing the network into two distinct parts. The overlay network addresses the adaptation goals in the Internet backbone, and the heterogeneous network addresses mobility adaptation goals. Together, the parts of ADIMUS architecture provide a framework on which streaming applications can be built.

In this thesis, we have chosen to put more focus on investigations in the multi-access part of the architecture than in the backbone overlay. We justify the choice by more challenging conditions for data transmissions in mobile networks than in the backbone Internet. This includes mobility and high heterogeneity of users, and necessity for handovers that complicates networking in wireless systems.

The research goals with the corresponding research questions, which were presented and discussed in Section 1.4, have been achieved. The addressing of the research goals and research questions in the papers is shown in Figure 4.2. The research results have been published in international conference proceedings and journals. This work also contributed with conference and seminar presentations.

4.1.1   Backbone Overlay Network

For data transmissions in the backbone Internet, we worked on algorithms for the overlay infrastructure that implemented multipath streaming. We looked at a solution that permitted us to overcome the limitations of a single path data transmissions in terms of available bandwidth. To be able to evaluate the functionality of the proposed solution, we defined a mathematical model of the overlay network as an upper bound for its operation. For the lower bound, we used some examples from the literature.

Our main achievement is an implementation of a distributed algorithm for allocating the available bandwidth for streaming video in a multipath multisource overlay system. The algorithm operates by exploiting local knowledge of the network topology and networking parameters such as available bandwidth. It uses the feed-back from overlay nodes for calculating decisions performed by the senders.

We showed that the presented algorithm provides a solution that is close to the optimal solution in terms of proportionally fair bandwidth allocation between receivers of the overlay part of the architecture. We, therefore, conclude that including overlay nodes in the process of bandwidth allocation gives sufficient performance gains and can be used to address the goals of the backbone part of the ADIMUS architecture.

4.1.2   Multi-Access Network

For data transmissions in the wireless heterogeneous network, we studied the network selection problem with a focus on *1*) load balancing; and *2*) forming mobile multicast groups in wireless networks. An important goal of this part of the research was defined as decentralization of the network selection solution and the ability to operate using limited information of the system.

The decentralization is important for future mobile networks, since it reduces signaling overheads and improves utilization of the network resources and QoS of users. We studied how the solution results depend on the information available for the decision making. We considered the problem for a multi-stream multi-server scenario. The candidate networks were selected for mobile clients based on their preferences and available resources of the networks. Similar to the backbone part, we defined the upper and lower bounds for the operation of this subsystem.

For load balancing scenario, the solution provides a substantial improvement in reduction of decision errors and signaling overhead in comparison with the lower bound that was defined based on the work specified in Chapter 2. The simulation results of our algorithms show that blocked calls can be reduced with approximately 60-50 % compared to the lower bound.

We evaluated three algorithms: Algorithms A, B and AB that differ in information using as an input for the algorithms. The experiments showed that all three algorithms deliver similar results, with some performance gains of Algorithms A and AB over Algorithm B. However, the analysis shows that the implementation of Algorithms AB and B requires development of mechanisms for synchronizing information about the network conditions and careful security considerations when information from one network is available to other networks. Operation of Algorithms AB and B requires significantly higher signaling between the networks and the users. We therefore conclude that Algorithm A is to be preferred over Algorithms AB and B.

For the multicast scenario, we proposed two solutions: the MN and BPS algorithms that establish multicast groups and assign them to networks based on incomplete information of the

whole system. The operation is also performed by different components of the system with limited cooperation between the components.

Compared to the work specified in Chapter 2, our main achievement is decentralization of the network selection for multicast groups, consideration of the impact of several multicast groups and incompleteness of information. We studied how the solution results depend on the information sets available for the decision making. Evaluating the test results shows that both algorithms provide a substantial improvement in performance compared to the lower bound reference. However, the operation of the MN solution requires complex signaling across several mobile networks and BPSs. In addition, it requires implementation and deployment of mechanisms and communication protocols that provide cooperation between the involved components.

For the multicast scenario, we also evaluated a multipath solution with streams which are split and sent over multiple connections. The problem formulation is NP hard and we proposed a heuristic algorithm to solve the problem. We showed that applying this algorithm reduced usage of the network bandwidth by 40% in comparison with the single stream solution. This solution was applied as a centralized solution and we foresee a decentralized approach as a possible future work.

Finally, we mention that the developed mathematical models for the both parts of the architecture that we used for evaluating upper bound limits of the evaluated solutions are applicable for some scenarios and network configurations. These can be applied in small cell networks deployed by the same provider where coordination between different network components can be implemented. The networks that are able to tolerate additional signaling caused by applying of centralized approaches can benefit from more complete information needed to compute decisions and, consequently, improve their performance.

4.2   Considerations and suggestions for further research

The scope of the work done in this thesis had certain limitations. While the ADIMUS architecture is not implemented as an integrated demonstrator yet, its design principles are shown for the parts it consists of. This research analyzed and designed the resource adaptation algorithms for these parts. Therefore, we consider an implementation of an integrated demonstrator and analysis of interactions between its main components as a possible step forward.

The developed algorithms were tested using multiple simulations. Though testing the algorithms in a simulation environment allows of comprehensive performance evaluation by using a large number of variations, we see that field experiments are also important to establish validity of the proposed solutions. While we realize that full-scale field experiments for several wireless networks and several hundred users are problematic and expensive to carry out, we expect that this type of experiments can be carried out on a limited scale.

Based on our evaluations of the multipath solution for the multicast scenario, we clearly see the potential benefits for transmission performance from further investigations in this field. Recently released report Cisco [26] confirms that existing mobile video optimization solutions are not sufficient to support the continuously increasing demand for high definition content. It implies that usage of multiple connections in multi-access networks and optimization of the

multipath routing is an important step to meet this demand. It is also worth to mention that using multiple paths for data transmission in wireless networks solves or, at least, simplifies the problem of handover. This problem can be handled by redistributing the transmission rate among the available connections without disrupting the user's session.

Implementing the multipath solution for the multicast scenario in a multi-access network is challenging because the formulation of this solution is NP-hard. The proposed multipath multicast approach has certain limitations and needs further investigation. In this thesis, we considered one heuristic algorithm as a possible solution. Investigating more applicable heuristics remains, therefore, an open issue. The implementation of the multipath multicast solution in the thesis was also limited to a centralized approach. Decentralization of the problem can be considered as future work. Distributing the optimization to different network components is crucial for heterogeneous wireless networks with the requirement that the exchange of network information must be done on a fast time scale and low-latency basis. Since the report shows that video traffic will continue to dominate, we need intelligent mechanisms that are capable of:

- take into account that the largest portion of multicast data in heterogeneous wireless networks is going to be multimedia data.

- operate for different quality layers of video already in lower levels of the network protocols; we foresee that already beamforming mechanisms can exploit knowledge about quality layers of transmitting data.

In a long time scale, the standardization of such mechanisms can be seen as an important part of the future work.

The research goals			Fulfilled
Goal 1	Identify architectural elements and their functions in delivery infrastructures for multimedia streams from the backbone Internet to mobile devices connected to wireless heterogeneous networks.		✔
	Research Question Q1	What are main causes for reduction of QoS of multimedia streams along the delivery paths?	Part I, Paper A
	Research Question Q3	What are the main components of the system and what are their functions?	Papers A,E,F,G,H
	Research Question Q4	How much information available to any given component needs to be exchanged?	Papers A,E,F,G,H
	Research Question Q5	From the architectural design, how to disseminate this information mostly efficiently?	Part 1, Papers A,E,F,G,H
Goal 2	Subgoal 2-1: Define challenges for efficient data delivery of multimedia streams in the backbone Internet.		✔
	Research Question Q1	What are main causes for reduction of QoS of multimedia streams along the delivery paths?	Part I, Paper A
	Research Question Q2	What is the state of the art of delivery infrastructure for multimedia streaming in the wired and wireless Internet?	Part 1
Goal 2	Subgoal 2-2: Define challenges for efficient data delivery of multimedia streams in the heterogeneous wireless network.		✔
	Research Question Q1	What are main causes for reduction of QoS of multimedia streams along the delivery paths?	Part I, Paper A
	Research Question Q2	What is the state of the art of delivery infrastructure for multimedia streaming in the wired and wireless Internet?	Part 1
Goal 3	Subgoal 3-1: Formulate the optimal solution in terms of resource utilization for delivery of multimedia streams in the backbone Internet.		✔
	Research Question Q6	What optimization methods are applicable in the wired Internet?	Part I, Papers B, C
Goal 3	Subgoal 3-2: Formulate the optimal solution in terms of resource utilization for delivery of multimedia streams in the heterogeneous wireless network.		✔
	Research Question Q7	Which optimization methods are applicable in wireless networks?	Papers E, F, G, H

Table 4.1: The fulfillment of the research goals and research questions.

The research goals			Fulfilled
Goal 4	Subgoal 4-1: Develop decentralized approaches for data delivery of multimedia streams in the backbone Internet.		✔
	Research Question Q8	How can we reduce the data exchange in the backbone network?	Paper D
	Research Question Q9	How can we decentralize the problem for the backbone network if the centralized approach is not applicable?	Paper D
Goal 4	Subgoal 4-2: Develop decentralized approaches for data delivery of multimedia streams in the heterogeneous wireless network.		✔
	Research Question Q10	How can we reduce the data exchange within heterogeneous wireless networks?	Papers E, F, G, H
	Research Question Q11	How can we decentralize the problem if the centralized approach is not applicable in heterogeneous wireless networks?	Papers E, F, G, H

Table 4.2: The fulfillment of the research goals and research questions (contd).

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PART II:

Scientific contributions

Paper A:
An Architecture for Adaptive Multimedia Streaming to Mobile Nodes

Wolfgang Leister, Tiia Sutinen, Svetlana Boudko, Ian Marsh, Carsten Griwodz, and Pål Halvorsen

Paper B:
A Benchmarking System for Multipath Overlay Multimedia Streaming

Svetlana Boudko, Wolfgang Leister, Carsten Griwodz, and Pål Halvorsen

Paper C:
Maximizing video quality for several unicast streams in a multipath overlay network

Svetlana Boudko, Wolfgang Leister, Carsten Griwodz, and Pål Halvorsen

Paper D:
Multipath Rate Allocation Algorithm for Overlay Networks with Feedback From Overlay Nodes

Svetlana Boudko, Wolfgang Leister, Carsten Griwodz, and Pål Halvorsen

Paper E:
Team Decision Approach for Decentralized Network Selection of Mobile Clients

Svetlana Boudko, Wolfgang Leister, Stein Gjessing

Paper F:
Network Selection for Multicast Groups in Heterogeneous Wireless Environments

Svetlana Boudko, Wolfgang Leister

Paper G:
Heterogeneous Wireless Network Selection: Load Balancing and Multicast Scenario

Svetlana Boudko, Wolfgang Leister, Stein Gjessing

Paper H:
Exploring Network Selection Techniques for Multicast Groups in Heterogeneous Wireless Environments

Svetlana Boudko, Wolfgang Leister, Stein Gjessing

PART III:

Appendices

Appendix i

List of terms and acronyms

Acronym	Description
3GPP	The 3rd Generation Partnership Project
3GPP2	The 3rd Generation Partnership Project 2
ADIMUS	Adaptive Multimedia Streaming Project funded by the NORDUnet3 programme
BPS	Backbone Proxy Server
CDN	Content Distribution Network
eMBMS	evolved Multimedia Broadcast Multicast Service
FEC	forward error correction
HetNet	Heterogeneous Network
IEEE 802.21	IEEE 802.21 is developing standards to enable handover and interoperability between heterogeneous network types including both 802 and non 802 networks.
IGMPv3	Version 3 of the Internet Group Management Protocol. The Internet Group Management Protocol is a communications protocol for IP networks that is used to establish multicast group memberships. Version 3 of IGMP adds support for "source filtering". This filtering may be used by multicast routing protocols to avoid delivering multicast packets to networks where there are no interested receivers.
ISP	Internet Service Provider
LTE	The Long-Term Evolution project
MBMS	Multimedia Broadcast and Multicast Service
MDVA	Multipath Distance Vector Algorithm uses a set of loop-free invariants to prevent the count-to-infinity problem and computes multipaths that are loop-free at every instant.
MIH	Media Independent Handover standard

MLDv2	Version 2 of Multicast Listener Discovery.MLD is a component of the Internet Protocol Version 6. It is used by an IPv6 router to discover the presence of multicast listeners on directly attached links, and to discover which multicast addresses are of interest to those neighboring nodes. MLDv2 adds the ability for a node to report interest in listening to packets with a particular multicast address only from specific source addresses or from all sources except for specific source addresses.
multimob	The Multicast Mobility working group
OSPF	Open Shortest Path First is a link-state routing protocol for Internet Protocol networks.
OSPF-OMP	OSPF Optimized Multipath protocol is a compatible extension to OSPF, providing a means for multipath routing.
P2P	Peer to peer system is a type of a decentralized system in which individual nodes, or peers, act as both suppliers and consumers of resources.
RTCP	The RTP Control Protocol is defined in RFC 3550. The protocol is used together with RTP to send control packets to participants in a call, provide feedback on the quality of service being provided by RTP, and aids synchronization of multiple streams.
RTP	The Real-time Transport Protocol is defined in RFC 3550 and is used as a format for delivering audio and video over IP networks.
SFN	single frequency network
WLAN	Wireless Local Area Network
WMAN	IEEE 802.16 based wireless metropolitan area network

Colophon

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