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UNIVERSITATEA TEHNICĂ
DIN CLUJ-NAPOCA

FACULTY OF AUTOMATION AND COMPUTER SCIENCE

Eng. Adrian Lucian Peculea

PHD THESIS

(abstract)

CONTRIBUTIONS TO THE DEVELOPMENT OF QOS (QUALITY OF SERVICES) IN COMPUTER NETWORKS

Advisor,
Prof. Dr. Eng. Iosif IGNAT

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str. Constantin Daicoviciu nr.15, 400020 Cluj-Napoca, România
tel. +40-264-401200, fax +40-264-592055, secretariat tel. +40+264-401209, fax +40-264-401280
e-mail: info@utcluj.ro, http://www.utcluj.ro/

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1. Introduction

Classical computer networks use best-effort model, a model which assumes that the main task of the network is to provide data to the destination. Transported traffic types have been diversified with the development of computer networks, and several types present some constraints on the transport parameters such as minimum bandwidth, delay, delay variation or data loss. Transport procedures affect traffic flows, which require traffic characterization and setting requirements for quality of service. To allow applications using these types of traffic to communicate in the network, while respecting the imposed constraints, the services are defined with the specific traffic parameters that must be followed and quality of service is implemented (Quality of Service - QoS) to enable compliance with these parameters.

The thesis is organized into nine chapters. The first chapter provides an introduction to the comprehensive field of computer networks quality of service and summarizes the chapters of this work. The second chapter describes the quality of service in computer networks. The third chapter covers the field of computer networks performance optimization. The fourth chapter deals with the field of computer networks quality of service frameworks, a field that defines the implementation methods of quality of services across multiple network equipment. In the last part, the conclusions of this chapter are detached, by comparing and highlighting the advantages and disadvantages of the described frameworks. It is noted that each presented framework has its shortcomings, which is why developing new QoS frameworks is a necessity. The fifth chapter presents an original approach for implementing quality of service in computer networks. Starting from a new organization of the bandwidth, a new framework is designed and developed with the intended role of ensuring end-to-end quality of service through admission control and self-adaptive bandwidth reconfiguration (SAR). This framework overcomes the disadvantages of the frameworks presented in the previous chapter. The sixth chapter presents a software system for developing and testing QoS sensitive frameworks and technologies. The system is designed for testing and validating the performance of different QoS technologies and frameworks and is composed of two modules, a benchmarking software module and a software system for developing and testing QoS sensitive frameworks and technologies. The benchmarking software module evaluates the performances of computer networks and QoS frameworks by generating traffic test and then measuring the main QoS parameters. The software system for the development of QoS sensitive frameworks and technologies allows the evaluation of the functionalities and performance of different QoS technologies, using an experimental methodology. The seventh chapter presents the experimental results that validate the performance of the proposed framework, namely the framework to ensure end-to-end quality of service through admission control and self-adaptive bandwidth reconfiguration, SAR. The proposed framework is compared with the On-Demand QoS Path framework. To test the proposed framework, the software system for developing and testing QoS sensitive frameworks and technologies, described in chapter six, is used. The eighth chapter highlights the final conclusions of this work, the original elements, and some possible further developments. The ninth chapter presents a list of references used by the author in preparing the thesis. Finally, as an annex, the research and teaching activity of the author, in the recent years, is presented.

2. Quality of service in computer networks

Types of traffic in computer networks, their requirements and the network transport procedures, require the definition of the necessary traffic types services and, the implementation of various technology to ensure the parameters required for these services [KUMAR04] [DĂDÂRLAT02].

The service represents the performance with which the customer receives the traffic and is usually defined by a contract between a client and a provider. Quality of Service (Quality of Service - QoS) is the network capability to provide better services for the selected traffic over various technologies.

Measuring instruments (benchmarking) [HASSAN04] generate network test traffic and measure network parameters such as transfer rate (throughput), delay or delay variation. Various techniques have been developed to measure the delay [HOLLECZEK06] [SHALUNOV06] or to estimate bandwidth [PRASAD03].

For providing QoS over IP networks, the network must perform two tasks [PARK05] [SZIGETI05]. The first task is to differentiate between types of traffic or service. This task is performed at user-network and network-network interfaces and includes marking techniques and packet classification. The second task is to differentiate between traffic classes. The task is performed by the network, including traffic selection (Traffic Policing), active management of queues (Active Queue Management - AQM) and packets planning (Packet Scheduling) and modeling (Packet Shaping).

3. Performance optimization in computer networks

Performance optimization in computer networks has as main objectives hot spots congestion reduction and improving resource use in computer networks.

Multiprotocol Label Switching [WANG01] [VISWANATH98] uses a switching architecture and presents several advantages such as QoS support, traffic engineering support, support for virtual private networks (Virtual Private Network - VPN) or multimedia support.

Traffic Engineering [WANG01] [AWDUCHE99] deals with performance optimization of operational networks. The main objective is to reduce hot spots congestion and to improve network resource utilization through traffic distribution within the network. Other optimization objectives of traffic engineering include: minimizing network congestion and packet loss, improving links use, minimizing the total delay of packets and increasing the number of customers using the same equipment.

4. Quality of service frameworks in computer networks

Quality of service frameworks in computer networks are sets of mechanisms that run over multiple network equipment with the aim of ensuring network services.

Integrated Services [WANG01] [STALLINGS02] have developed a novel architecture for resource allocation, which aims to meet the requirements of real-time applications. The basic idea is reserving resources for each flow. The purpose of the Integrated Services is based on maintaining IP datagram network model, while reserving resources for real time applications.

The Integrated Services architecture uses a set of mechanisms and protocols for explicit reservation of resources in the Internet. Before transmitting packets, applications reserve resources along the route.

Integrated services have standardized two service models: guaranteed service and controlled load service. In addition to these two services there is also a best-effort service which does not guarantee quality of service.

For the Integrated Services, the RSVP protocol (Resource Reservation Setup Protocol) [ZHANG93] was developed by the IETF as a resource reservation setup protocol for the Internet.

Differentiated Services architecture is a simple architecture that provides several levels of service. If in the Integrated Services architecture resources are allocated to the individual flows, Differentiated Services model [PETERSON07] divides traffic into a small number of classes and allocates resources based on these classes.

In the Differentiated Services approach [WANG01] [CARLSON98] traffic is divided into a few groups called forwarding classes. Forwarding class of the packet is coded in a field of the IP packet header. Each forwarding class represents a predefined forwarding treatment in terms of discarding priority and bandwidth allocation. Individual classes represent aggregated traffic.

In the Differentiated Services network, network border nodes (boundary nodes or edge nodes) and the nodes within the network (internal nodes or core nodes) have different responsibilities. Edge nodes have two functions: packet classification and traffic conditioning. Core nodes forward packets based on the forwarding classes from the packet header.

Forwarding treatment is described by the term per-hop behavior *(Per-Hop Behavior* - PHB). Each PHB is represented by a 6-bit value called *Differentiated Services Codepoint* (DSCP). All packages with the same DSCP are referred as *aggregate behavior*, and receive the same forwarding treatment.

On-Demand QoS Path (ODP) [YANG05] provide end-to-end QoS guarantees to individual flows with less overhead than Integrated Services and maintaining the scalability level comparable to that of the Differentiated Services. ODP exercises per-flow admission control and end-to-end bandwidth reservation at network borders. Inside the network ODP differentiates traffic classes as in the case of Differentiated Services.

ODP defines two types of routers: border router (edge router) and interior router (core router). Edge routers make the decision of admission or rejection for each input flow, map the traffic flows to their corresponding classes and forward packets belonging to the admitted flows in the network. Core routers recognize classes of traffic and provide service differentiation based on those classes.

Bandwidth is organized hierarchically. Each physical line is statically divided into several Provisioned Links (PLs). Each PL is reserved for a traffic class, having a one to one mapping between supported traffic classes by the physical link and PL’s. Each PL is divided into several trunks, each trunk being dedicated to an edge router. A trunk belonging to a PL supports traffic flows belonging to the corresponding PL's traffic class, coming from the assigned edge router, to any destination. An edge router monitors the available bandwidth for each trunk assigned to the router and performs local admission control without hop-by-hop network signaling. A Virtual IP Path (VIP) is a path from a source edge router to a destination edge router for a particular class of traffic, and represents a concatenation of trunks belonging to the source edge router, over a source-destination path. Bandwidth is assigned statically to PL’s based on long-term traffic prediction. The bandwidth assigned for the trunks belonging to the same PL is dynamically adjusted according to short-term changes in traffic.

The presented frameworks use different approaches to provide services in computer networks, each framework showing advantages, but also drawbacks. Differentiated Services have several advantages such as scalability and efficiency of bandwidth use, but presents a major disadvantage: it does not guarantee bandwidth and delay limits for individual flows. Integrated Services guarantee bandwidth and delay limits for individual flows and use bandwidth efficiently, but present scalability problems. On-Demand QoS Path guarantees bandwidth and delay limits for individual flows and have the advantage of scalability, but bandwidth is used inefficiently.

5. End-to-end quality of service framework through admission control and self-adaptive bandwidth reconfiguration

In order to eliminate the disadvantages mentioned above, it was developed, implemented and proposed a new framework for ensuring end-to-end quality of service through admission control and self-adaptive bandwidth reconfiguration (Admission Control Self-Adaptive Bandwidth Reconfiguration QoS framework - SAR), which allows for bandwidth redistribution between classes [PECULEA09].

In this approach, the physical line is divided into two main sections, one part being the Guaranteed Line (LG) that guarantees a minimum bandwidth (where applicable) for the traffic classes, and a common part called Common Line (LC), which can be used by any traffic class. Having two separate sections, the framework guarantees a minimum bandwidth for any trunk and provides a common bandwidth that can be used by all trunks, regardless of the traffic class to which they belong. This allows for a better use of bandwidth and reduces the number of rejected flows.

The proposed framework serves the user networks and defines two types of routers, edge and core, and common bandwidth control entities. Edge routers, connected to the networks served by the framework, determine the bandwidth requirement for each input flow, make the admission or rejection decision for each input flow, reconfigure dynamically the bandwidth assigned for the trunks, map flows to the appropriate traffic classes and transmit network packets belonging to the admitted flows. Core routers, connected to edge or core routers, recognize traffic classes and provide class based service differentiation. Common bandwidth control entities monitor and update the common bandwidth utilization and accept or reject trunks' request for additional bandwidth, received from the edge routers.

The bandwidth is hierarchically organized. Each Physical Line is divided in two sections. A first section guarantees the minimum bandwidth, which can be also 0, for each class and each trunk. The second section, LC, offers a common bandwidth which can be used by every trunk function of their bandwidth requirements, irrespective to their belonging traffic class or edge router. So, trunks can acquire additional bandwidth without being conditioned by the available bandwidth of the belonging class. First section is statically divided in several Guaranteed Class Links (LGCs). Each LGC is reserved to a traffic class, existing a one to one mapping between the traffic classes supported by the Physical Line and LGCs. Each LGC is divided several trunks, each trunk being dedicated to an edge router. A trunk belonging to a LGC supports the flows belonging to the traffic class that corresponds to the considered LGC, originating from the edge router to which the trunk is assigned, irrespective to their destination. An edge router keeps track of available bandwidth of its assigned trunks and performs admission control locally, without hop-by-hop signaling through network. The bandwidth assigned to trunks has a minimum guaranteed value and, by using LC, is dynamically adjusted function of the network traffic modifications.

Function of the entities for common bandwidth control, there are three possible approaches: Central Control, Router-Aided and Edge-to-Edge.

The architecture of the framework is composed of two entities: *edge router* and *entity for common bandwidth control*. The edge router determines the necessary bandwidth for each input flow, takes the admission or rejection decision for each input flow, reserves the necessary bandwidth for each admitted flow, dynamically reconfigures the bandwidth assigned to trunks and classifies the packets belonging to the admitted flows. The entity for common bandwidth control monitors and updates common bandwidths utilization and accepts or rejects the additional bandwidth requests for trunks, received from edge routers. The communication between the two entities is realized through a predefined message set. The edge router is composed of two planes: *local resources monitoring plane* and *flow management and local resources control plane*. The entity for common bandwidth control is composed of two planes: *common resources monitoring plane* and *common resources control plane*.

6. Software system for developing and testing of QoS sensitive frameworks and technologies

In order to test and validate the functionalities and performances of the proposed QoS sensitive technologies and frameworks, a software system for developing and testing of QoS sensitive frameworks and technologies was designed and implemented. The system consists of two modules, a benchmarking software module and a software system for the development of QoS sensitive frameworks and technologies.

The benchmarking system is a software module used to generate traffic test and to measure key QoS parameters: delay, delay variation of IP packets (IP Packet Delay Variations - IPDV) and bandwidth [PECULEA07b] [IANCU07]. The developed system is a distributed application based on a client/server architecture, consisting of the following entities: QoS Benchmarking Manager (QBM), QoS Benchmarking Agents (QBAs) and QoS Benchmarking Protocol (QBP).

In order to develop and test different QoS technologies and frameworks, it was proposed, designed and implemented a software system for the development of QoS sensitive frameworks and technologies [PECULEA07a], which allows for the assessment of the performance and functionalities of different QoS technologies using an experimental methodology. The use of a physical test network, includes the adopted approach under experimental methodologies, methodologies that have proven accuracy close to that of real cases [HUGHES03]. The system developed allows the conversion of a computer into a software router, thus to achieving rapid, modular and extensive test configuration, while giving its users a reconfigurable set of traffic statistics.

The developed application implements two types of routers, edge and core. Edge routers identify traffic flows, mark the packets with their corresponding type of service and place them in the forwarding queues, accordingly to the QoS technology tested. Core routers have the responsibility to recognize traffic classes and to provide class-based service differentiation.

The development tool for QoS sensitive frameworks and technologies consists of the following modules: a network interface module, a routing application, a user interface module and an inter-routers communication protocol.

In order to implement the ODP and SAR frameworks, two software components have been developed in the routing module. An important feature of the two components is the ability to save information regarding the flows in the network and the control messages exchanged between edge routers. This feature allows the generation of several statistics based on stored information, statistics useful in auditing the behavior of the frameworks.

Also, an application for interpreting and displaying the saved statistics was developed. This allows viewing, in digital format, the types of messages received or sent, the number of messages of each type received or sent and the total number of messages for each edge router. The generated statistics permit to determine both the performance of the admission control method and the degree of network load due to specific control messages of the framework.

7. Experimental results

For comparative testing of ODP framework and SAR framework, the software system for developing and testing of QoS sensitive frameworks and technologies was used. The test network consisted of three edge routers and three served networks.

Traffic classes and traffic patterns were defined similarly in both frameworks tested. Four classes of traffic were considered. Two test traffic patterns were defined. In the first traffic pattern flows are injected from classes 2 and 3 and in the case of the second traffic pattern flows are injected from class 2. For both traffic patterns a balanced distribution of traffic from and to the served networks is ensured.

The tests were intended as a performance comparison between ODP and SAR frameworks. For this purpose the number of admitted flows in the network was taken into consideration, in order to determine the usage efficiency of network resources. Also, the number of control messages exchanged was monitored, for determining the degree of overhead added to the network, which influences the scalability of the frameworks. There have been two different tests. The first test injected into the network the traffic defined by the first traffic pattern and the second test injected into the network the traffic defined by the second traffic pattern.

Analyzing the results of tests it is shown that the number of flows admitted by the SAR framework is greater than the number of flows admitted by the ODP framework, which demonstrates a more efficient usage of network resources by the SAR framework. Also, by analyzing test results, it is shown that the number of control messages transmitted by the two frameworks is equal, which demonstrates that the more efficient usage of network resources for SAR framework does not imply a higher load with control messages and emphasizes the scalability of the proposed SAR framework. Reading the tests results it was found that there was no data packet lose, which confirms that the admission control technique eliminates the network congestion.

8. Final conclusions and possible further developments

The frameworks for implementing quality of service in computer networks are sets of mechanisms that run over multiple network equipments to ensure services. The paper presents in detail three existing frameworks: Integrated Services, Differentiated Services and On-Demand QoS Path. Each framework uses a different approach and has certain drawbacks. Thus, the main disadvantage of the Differentiated Services framework is that it does not guarantee bandwidth and delay limits for individual flows, Integrated Services framework presents serious problems of scalability and On-Demand QoS Path framework has as main drawback the inefficient bandwidth utilization. In addition, the On-Demand QoS Path framework does not specify a mechanism for determining the bandwidth required for each input flow or for the management of rejected flows.

To eliminate the above mentioned drawbacks, **a new organization of the bandwidth was elaborated and proposed.** The physical line is divided into two main sections, Guaranteed Line (LG), which guarantees a minimum bandwidth for traffic classes, and Common Line (LC), which can be used by any traffic class. In this way, a minimum bandwidth for any trunk is guaranteed and a common bandwidth is provided that can be used by all trunks, regardless of the traffic class to which they belong. The proposed bandwidth organization **allows for a more efficient utilization of the network resources and a greater number of admitted flows.**

To take advantage of the proposed bandwidth organization, a new **framework for ensuring end-to-end quality of service through admission control and self-adaptive bandwidth reconfiguration was proposed, developed and implemented (Admission Control Self-Adaptive Bandwidth Reconfiguration QoS framework - SAR).** This framework allows for redistribution of the bandwidth between classes. The ODP framework was used as the starting point for the development of the SAR framework. **The new framework, SAR,** uses the proposed bandwidth organization, **allowing the increase of the traffic volume it handles, guaranteeing end-to-end quality of service** through network resources monitoring, admission control and resource reservation for new flows. The architecture of the framework is composed of two entities, the edge router and the entity for common bandwidth control, which allows for three practical configuration approaches: Central Control, Router-Aided and Edge-to-Edge. The three approaches, similar to ODP framework's approaches, allow for choosing the optimal configuration according to the characteristics of each network. In addition to the ODP framework, **SAR has the advantage of a more efficient utilization of network resources and includes a mechanism for determining the bandwidth required for each type of input flow, based on the network policy in which SAR is implemented.** Also, in order eliminate the additional processing at the framework's entities and the additional loading of the network with control messages, SAR integrates a mechanism that identifies the packets belonging to rejected flows and removes them without additional admission control. This mechanism is implemented without forcing the applications that use network services to include a communication protocol with the framework. This will keep the heterogeneous characteristic of computer networks and allows any application to take advantage of the network services and the proposed framework.

Another contribution is the **development, design and implementation of a software system for developing and testing of QoS sensitive frameworks and technologies.** This system consists of two modules, a benchmarking software module and a software system for the development of QoS sensitive frameworks and technologies. The main advantage of this system is that it **allows testing and validation of the functionalities and performances of QoS technologies and frameworks, in a complex environment, with accuracy close to that of real cases,** using a physical test network.

The developed benchmarking system brings many benefits. A first advantage is the possibility to define and store complex traffic patterns that can be reloaded for making further measurements, to test various QoS techniques based on the same traffic characteristics. Another advantage is the accuracy of measurements and the possibility to control the tests, after the deployment of the QBA agents, from one station without having to restart on each test station the benchmarking application.

The software system for the development of QoS sensitive frameworks and technologies, through its modular software solution, allows for adapting the developed system to run various end-to-end QoS frameworks, just by changing or modification of some components. Also, the systems allows to save traffic statistics, such as number of flows admitted/rejected, or the number and type of control messages used by the evaluated frameworks, and viewing of these statistics in digital format. Thus, the system allows in-depth analysis of the frameworks' behavior.

For the comparative testing of ODP and SAR frameworks the software system for developing and testing of QoS sensitive frameworks and technologies was used. For this purpose, the appropriate components for SAR and ODP frameworks were designed and implemented and a

test network composed of three edge routers and three served networks was configured. Traffic classes and traffic patterns were defined similarly in both frameworks tested. After testing and analyzing the results it was found that the **number of flows admitted for SAR framework is higher than in the case of ODP framework, which demonstrates a more efficient utilization of network resources.** Also, the **equal number of control messages transmitted by the two frameworks shows that SAR is a scalable framework.** Finally, tests confirmed that **admission control has eliminated network congestion.**

Original contributions made by the author in the development of quality of services in computer networks are:

1. Elaboration and proposal of a new method of organization and dynamical allocation of bandwidth, which enables, according to changes in network traffic, dynamic adjustment of bandwidth assigned to trunks.
2. The development, implementation and proposal of a new framework for ensuring end-to-end quality of service through admission control and self-adaptive bandwidth reconfiguration (Admission Control Self-Adaptive Bandwidth Reconfiguration QoS framework - SAR), which, using the proposed bandwidth organization, allows for redistribution of the bandwidth between classes and presents the following advantages: service guarantee, efficient utilization of network resources, scalability and determination of the necessary bandwidth for each type of input flow based on the network policy were the framework is deployed.
3. The development, design and implementation of a software system for developing and testing of QoS sensitive frameworks and technologies, system that has the following advantages: allows for testing and validation of the functionalities and performances of QoS technologies and frameworks with accuracy close to that of real cases by using physical test networks, offers the possibility to define and store complex traffic patterns that can be reloaded for further measurements with the purpose of testing different QoS techniques based on the same traffic characteristics, allows adapting the developed system to run various end-to-end QoS frameworks just by changing or modification of some components, enables complex analysis by processing specific data of traffic flows or control messages used by the evaluated frameworks.

These original contributions have been validated and highlighted by:

- An application for obtaining a national patent for invention
- An article submitted for publication in an ISI-indexed journal
- Four papers published in journals indexed in international databases

- Seven articles published in international conferences indexed in international databases
- Two papers published in un-indexed international conferences
- An award in an international conference indexed in international databases

Research in this area could be pursued through the following possible lines of development:

1. The development and implementation of mechanisms for bandwidth reconfiguration based on traffic characteristics prediction in order to reduce the network load by control messages;
2. The development and implementation of a communication protocol between the edge routers for distribution of information on traffic policies configured on the network;
3. The development of the implementations to be compatible with other routed protocols (IPv6);
4. Defining and implementing a communication interface between the framework and the dynamic routing protocols.

9. References

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10. Annex 1

National patent for invention submission:

1. **A. Peculea,** B. Iancu, V. Dădârlat - *Metodă de alocare dinamică a lățimii de bandă şi cadru de lucru pentru transmiterea în timp real a informațiilor în rețele de calculatoare;* Repository No.: A200900659/27.08.2009.

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2. B. Iancu, V. Dădârlat, **A. Peculea**, *Theoretical Perspectives on End-to-End QoS Frameworks for Heterogeneous Networks*, Fourth International PhD Symposium in Engineering, ISBN 978-963-7298-

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Awards

1. Best paper in "Software Applications" Section for the paper "Embedded System for Network Flow Identification", *2006 IEEE-TTTC International Conference on Automation, Quality and Testing, Robotics* (AQTR 2006), Cluj-Napoca, 25-28 May 2006.

Member of the research contracts:

1. *QAF - Quality of Service Aware Frameworks for Networks and Middleware*, Contract no. 328, CNCSIS Code no.1227, 2007-2010, project director: Prof. dr. ing. Vasile-Teodor Dădârlat.
2. *Router Reconfigurabil Securizat cu Suport QoS Bazat pe Tehnologia FPGA*, Contract no. 84, CNCSIS Code no. 1007, 2005-2007, project director: Prof. dr. ing. Zoltan Francisc Baruch.
3. *Cercetări privind rețelele active în proiectarea unor aplicații de înaltă performanță*, type C research contract with MEC, 7067 GR/2001, theme B1, 2001-2002, project director: Prof. dr. ing. Kalman Pusztai.