RIGA TECHNICAL UNIVERSITY
Faculty of Electronics and Telecommunications
Institute of Telecommunications

Andris SKRASTIŅŠ
Doctoral Student of the Study Programme "Telecommunications"

RESOURCE AND ADMISSION MANAGEMENT IN NEXT GENERATION NETWORKS

Summary of the Doctoral Thesis

Scientific supervisor
Professor, *Dr. sc. ing.*
GUNARS LAUKS

RTU Press
Riga 2017

Skrastins A. Resource and Admission Management in Next Generation Networks. Summary of the Doctoral Thesis. – R.: RTU Press, 2016. – 49 p.

Printed according to the decision of RTU Promotion Council "RTU P-08" of 8 December 2016, Minutes No. 37

EIROPAS SOCIĀLAIS FONDS

EIROPAS SAVIENĪBA

ISBN 978-9934-10-922-5

DOCTORAL THESIS

PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFFIC DEGREE OF DOCTOR OF ENGINEERING SCIENCES (TELECOMMUNICATIONS)

To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council "RTU P-08" on 16 March 2017 at the Faculty of Electronics and Telecommunications of Riga Technical University, 12 Azenes Street, Room 201.

OFFICIAL REVIEWERS

Professor *Dr. habil. sc. ing.* Ernests Petersons
Riga Technical University, Faculty of Electronics and Telecommunications

Professor *Dr. sc. comp.* Guntis Barzdins
University of Latvia, Institute of Mathematics and Computer Science

Researcher *Dr. sc. comp.* Kaspars Sudars
Institute of Electronics and Computer Science

DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences (Telecommunications) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Andris Skrastiņš……………………………. (Signature)

Date: ………………………

The Doctoral Thesis has been written in the Latvian language; it consists of the Introduction, 4 Chapters, Conclusion, and Bibliography with 116 reference sources. It has been illustrated by 78 figures. The volume of the present Doctoral Thesis is 162 pages.

LIST OF ABBREVIATIONS

AggSessAC	*Aggregated Session Admission Control*
ARP	*Address Resolution Protocol*
CAC	*Connection Admission Control*
CAIDA	*Center for Applied Internet Data Analysis*
DiffServ	*Differentiated Services*
DNS	*Domain Name System*
DPI	*Deep Packet Inspection*
FAN	*Flow-Aware Networks*
FPGA	*Field-Programmable Gate Array*
GPU	*Graphics Processing Unit*
HTTP	*Hypertext Transfer Protocol*
IETF	*Internet Engineering Task Force*
ETSI	*European Telecommunications Standards Institute*
ICMP	*Internet Control Message Protocol*
IntServ	*Integrated Services*
ISP	*Internet Service Provider*
ITU-T	*International Telecommunication Union, Telecommunication Standardization Sector*
M2M	*Machine-to-Machine*
MBAC	*Measurement-based Admission Control*
MPLS	*Multiprotocol Label Switching*
MPPS	*Million Packets Per Second*
NGN	*Next Generation Network*
PBAC	*Parameter-based Admission Control*
PHB	*Per-Hop Behaviors*
P2P	*Point-to-Point*
QoS	*Quality of Service*
RACF	*Resource and Admission Control Functions*
RSVP TE	*Resource Reservation Protocol Traffic Engineering*
SLA	*Service Level Agreement*
SNMP	*Simple Network Management Protocol*
ThresholdAC	*Threshold Admission Control*
ToS	*Type of Service*
TCP	*Transmission Control Protocol*
UDP	*User Datagram Protocol*
VLAN	*Virtual Local Area Network*
VNI	*Cisco Visual Networking Index*

GENERAL DESCRIPTION OF THE THESIS

Topicality of the Research

Development Trends. Rapid development of the telecommunications industry has contributed to online services and network convergence, where the Internet Protocol based data transmission has become a basis for modern communication systems and is known as *Everything over IP*. The desire to increase the living comfort and automation of various functions contribute to new Internet online services and each of these services attracts new users, increases the total amount of data and increases the number of data streams to be served. At present, information technology is used in every area of our lives, by increasing a number of new services and devices connected to the Internet. As a result, development trend known as the Internet of Things (IoT) has evolved where machine-to-machine (M2M) communication is one of fast-growing sectors [2] (see Fig. 1). It should be noted that every new thing connected to the Internet is a new potential data generating source.

According to forecasts presented by Cisco, in 2019 there will be around 11 billion Internet connected wireless devices, in contrast to 7.3 billion in 2014, which represents an increase of 50 % (see Fig. 2). According to the latest forecast by Cisco, about 33 % of all global Internet traffic will be generated by different types of mobile wireless devices and only 66 % will be fixed Internet traffic from wired devices in 2019 [2], but over the next 5 years traffic generated by mobile wireless devices will increase 3 times between 2015 and 2020 [7]. These growth rates and new services raise challenges for traffic management by increasing a number of connections to be processed in the access control module.

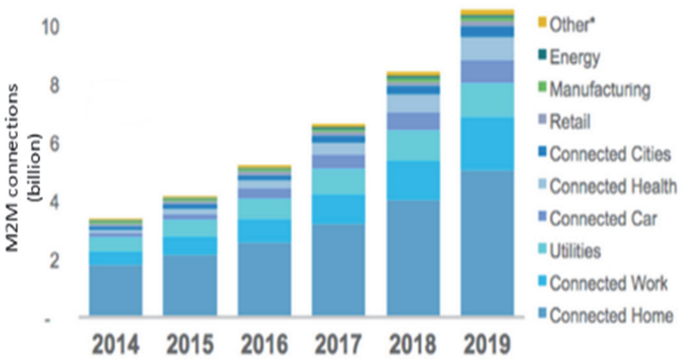

Fig. 1. Cisco VNI forecast for IP M2M connections growth rate [2].

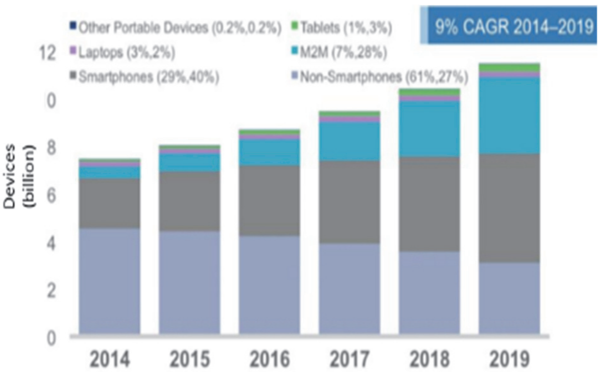

Fig. 2. Cisco VNI forecast for global mobile data traffic growth rate [6].

Time Scale. In a modern backbone network, a number of new connections processed by edge nodes are measured in tens to hundreds of thousands per second [65], [66]. High intensity of new connection requests requires access management solutions to operate in the time scale of tens microseconds to few milliseconds (see Fig. 3). It is also highlighted by the research that the lifetime of 80 % of flows is no longer than few seconds and the flows contain only up to few tens of packets [19], [34], [47], [56], [65].

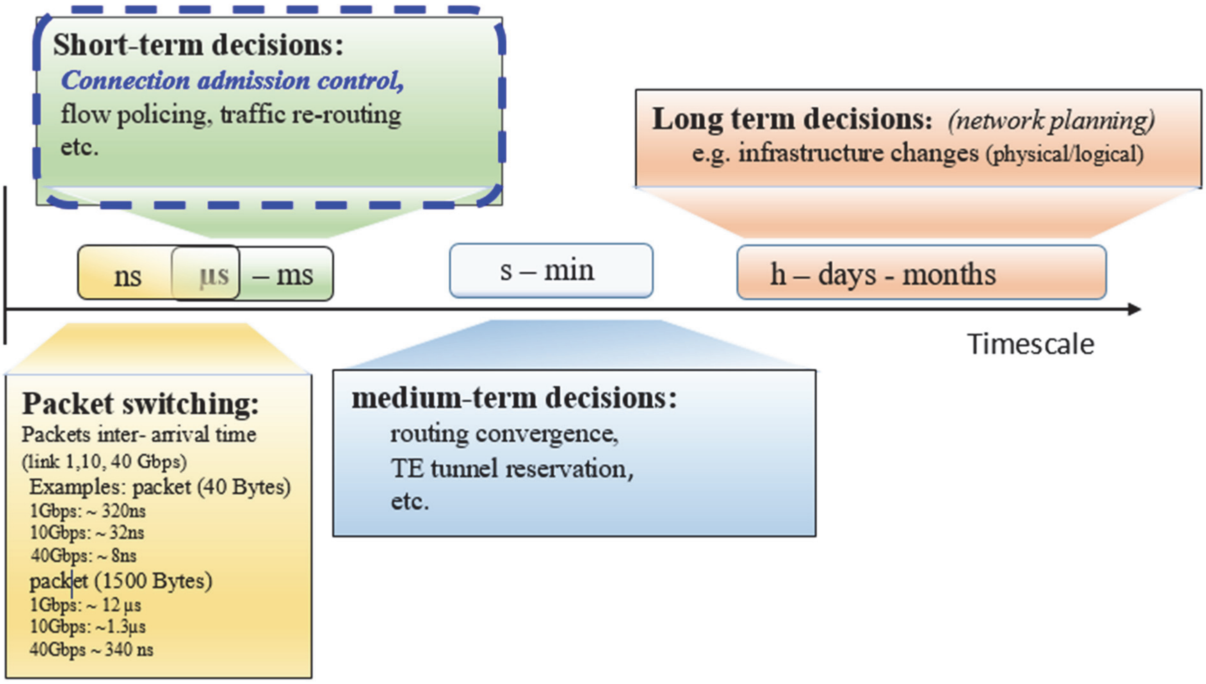

Fig. 3. Timescale for traffic control and management plane.

Service Differentiation. By its nature, the main task of the resource and admission control functions (RACF) is the efficient distribution of available resources and maximizing the benefits from allocated resources, while ensuring the appropriate SLA requirements for the recipients. Various online services and applications have resulted in service differentiation at the access level and priority-based admission management policy, especially in situations characterized by a lack of bandwidth resources. Often, higher quality requirements are related to a higher price of service. Priority-based access control policy requires making selective connection approval that needs mutual evaluation and comparison of new connection requests at the moment of decision making. However, to implement comparative and priority-based admission management it is necessary to change one common characteristic in existing approaches – all of them process new connection requests in order of their arrival and the CAC decisions are taken immediately without the ability of mutual choice among closely following requests, which prevent the implementation of a priority-based strategy. Therefore, a critical question arises: *What kind of data flows will be accepted in moments, when there is a lack of bandwidth resources*?

ITU-T. The International Telecomunication Union – Telecomunication Standardization Sector (ITU-T) has also analysed and developed recommendations [21], [22], which specify a general architecture, interfaces (reference points), requirements and main tasks for the resource and admission control functions (RACF) in next generation networks (NGN). **ITU-T Rec. Y.2171 defines admission management as** *a set of actions/policies taken by the network at session set-up phase in order to accept or reject a service based on requested performance and priority criteria and the availability of necessary resources.* The number of priorities and management policy configuration are predefined by network operators. However, these recommendations are provided as guidelines only, but certain RACF functional realizations are left for network providers, equipment and software developers to decide.

Topicality of the Problem. Everything described above allows to formulate the problem. The existing access control solutions immediately react to a new connection request. It forms a sequential and independent admission request processing strategy in order of their arrival and this processing manner does not allow implementing the mutually comparative, priority-based and pro-active admission management policy by analysing several admission requests simultaneously during the decision-making process. There are several properties that do not support the existing admission management solutions:

- a lack of ability to perform selective and priority-based management;
- a lack of ability to accumulate requests for further analysis;
- a lack of comparative evaluation among closely following requests;
- a lack of capacity to avoid independent and instantaneous decision-making process;
- a lack of pro-active decision-making approach.

In addition, sequential, instantaneous and mutual non-comparative flow processing manner promotes that each priority class tends to get the same rejection probability without contributing to priority-based access decision-making. The question then arises: *"How to expand choice opportunities and reduce uncertain information conditions to make selective and prioritized decision-making and increase the benefits from decisions made and data flows accepted?"*.

All the above-mentioned problems motivated the author to address this issue and resulted in this Doctoral Thesis. The Thesis is devoted to the development of new access control method and evaluation. The task implied creating an effective solution from the perspective of computing resources suitable for the use in modern high-speed data networks and implementing pro-active, selective and priority-based admission management.

The Aim and Tasks of the Research

Taking into account the new requirements for the modern telecommunications networks and problems mentioned above, **the aim of the Doctoral Thesis** is to develop a new connection admission management agent and solution, which is able to provide cross-evaluation of several admission requests, thus expanding the decision-making capabilities by enabling selective, priority-based and pro-active admission management, ensuring an increase in network revenue from the accepted connections.

To achieve the aim of the Doctoral Thesis the following tasks have been defined:

1. to estimate the suitability of existing resources and admission management methods and solutions to admission management task by highlighting their shortcomings;
2. to determine the characteristics and current trends in today's data flows and their created challenges in the network management plane;
3. to define a new admission management method, which would be the basis for the development of an experimental AggSessAC model;
4. to develop programmatic agents for the defined admission management method that can be implemented in routers by extending their functionality;
5. to supplement router functionality available in the INET framework with the AggSessAC programmatic agent designed by the author, creating an experimental prototype for evaluation in the OMNeT++ simulation environment;

6. to develop an experimental network simulation environment, to analyse the proposed method and to evaluate its effectiveness in comparison with admission management method that uses the classical approach for processing a new connection request;
7. to determine the impact of AggSessAC method parameters on the achieved results, to make recommendations for parameter selection bounds and adaptation capabilities.

Research Methodology

In the Doctoral Thesis, the extensive analysis of Internet data flows has been performed based on the experimental measurement results obtained by the author, and the obtained conclusions have been compared with results of other existing studies. A comprehensive analysis of Internet data flows from different perspectives – packets, flow and protocol – has allowed justifying the topicality of research and served as the basis for the development of new approach for admission management.

Mathematical modelling in MATLAB has been performed to evaluate an initial concept of designed admission management.

An experimental prototype of the proposed admission management method has been tested on router available in the INET framework by creating an experimental prototype for evaluation in the OMNeT++ simulation environment. Simulation experiments have been performed to analyse the developed admission management operation, the parameters have been assessed and the effectiveness of AggSessAC metdod has been compared with a classical request processing approach.

Statistical methods for analysis of traffic measurement and simulation results have been used in the research.

The Results and Scientific Novelty of the Research

The author of the Thesis has developed a new connection admission management method and solution for high-speed NGN networks. In the Thesis, a new management functional agent has been developed and named AggSessAC (*Aggregated Session Admission Control*) by creating an experimental product and performing its evaluation.

Taking into account the increasing volume of traffic, growing number of data flows and router performance development, the author proposes performing temporary accumulation of new connection requests prior to decision-making by directing new session initialization packets to a separate queue. Such an action allows making decisions a pro-active, priority as well as making mutual comparison among the collected requests, thus raising the obtained revenues from decisions taken. As far as it is known for the author of the Thesis, such an approach to resource and admission management was not previously studied.

The concept of the proposed method includes (see Fig. 4) flow classification, keeping flow-state table, aggregation of new connection requests and placing them on a separate queue. New connection request aggregation allows bringing the virtualization of parallel processing into connection admission management and reducing uncertain conditions at the moment of decision-making process. In the Thesis, an ***admission request*** *represents the packets that belong to* ***a new single data flow (session)*** received by an admission management entity. It should be clarified that the terms used in the Thesis such as ***"admission request"***, ***"new connection request"*** and ***"new flow request"*** are used as synonyms.

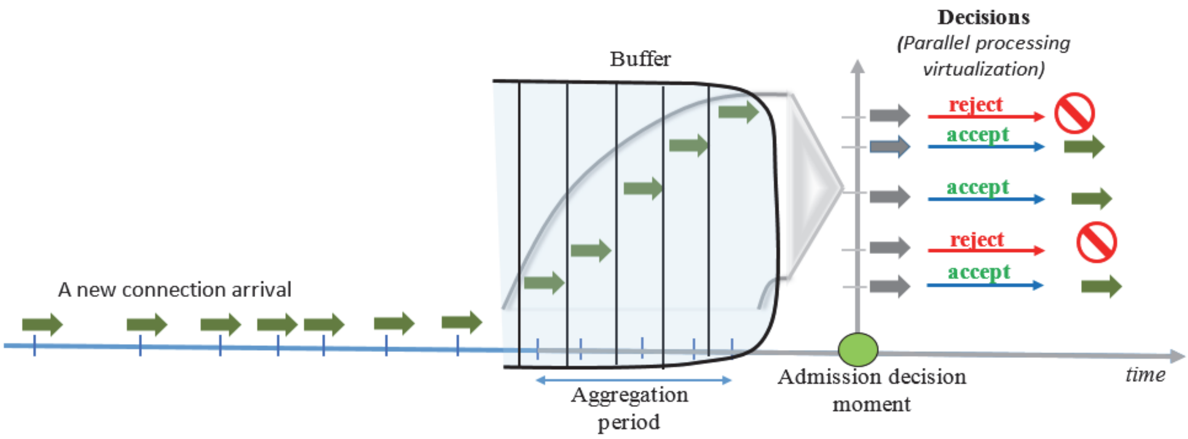

Fig. 4. New connection processing paradigm proposed in the Thesis
(request aggregation allows using the virtualization of parallel processing).

Practical Value of the Research

- A new resource and admission management has been developed and an experimental model for verification and validation of the proposed method has been implemented;
- The functional programmatic agent of the proposed method has been developed using C++ programming language by allowing one to extend router functionality;
- During the research the proposed admission management method has been implemented on router available in the INET framework by creating an experimental prototype used for the evaluation in the OMNeT++ simulation environment and in other studies carried out by students and researchers.

The Thesis to be Defended

1. With an increasing data flow intensity (new flow/s), which in the Next Generation Networks has already been measured with a magnitude of 10^3or higher, and to implement the access management policy requirements, decision-making on new connections can be made by inducing a delay for new session initializations, as a result, if compared with existing access management solutions, at the time of decision-making, the set of accumulated sessions is analysed, allowing for a more selective choice according to the accumulated number of requests, thus reducing uncertainty in the decision-making moment.
2. AggSessAC access management method increases the number of flow connections with the highest priorities, ensuring the fulfillment of the management policy requirements with regard to the service priority levels and increasing access management efficiency.
3. The developed AggSessAC access management method, which is based on artificial short-term decision-making process delay (used for new connection request accumulation), is suitable for use in the on-line high-speed (gigabit) transmission links, ensuring that the induced session initialization delay does not affect the quality of the already approved data flows and does not exceed a margin of a few (<5) ms.

Approbation of Research Results

The main results of the Thesis have been presented at 8 international scientific conferences.

1. The 20th IEEE Symposium on Computers and Communications *(ISCC 2015)*, Larnaca, Cyprus, 6–9 July 2015.
2. The 29th IEEE International Conference on Advanced Information Networking and Applications *(AINA-2015),* Gwangju, Korea, 25–27 March 2015
3. The 22nd Telecommunications Forum TELFOR 2014, Belgrade, Serbia, 25–27 November 2014.
4. IET International Conference on Information and Communications Technologies *(IETICT 2013),* Beijing, China, 27–29 April 2013.
5. Electronics and Electrical Engineering, Lithuania, Palanga, 17–19 June 2013.
6. The 20th International Conference on Software, Telecommunications and Computer Networks *(SoftCOM 2012),* Split, Croatia, 11–13 September 2012.
7. Electronics and Electrical Engineering, Lithuania, Palanga, 18–20 June 2012.
8. Electronics and Electrical Engineering, Lithuania, Kauna, 17–19 May 2011.

A total of 11 scientific articles have been published in various scientific editions – 4 publications in scientific journals and 7 publications in full-text conference proceedings:

1. **Skrastiņš A**., Jeļinskis J., Lauks G., Comprehensive analysis of AggSessAC method for revenue maximization using OMNeT++// The Twentieth IEEE Symposium on Computers and Communications *(ISCC 2015)*, Larnaca, Cyprus, July, 2015, pp. 777–782. **(in *IEEE Xplore* and *Scopus* databases)**
2. **Skrastiņš A**., Lauks G. Evaluation of AggSessAC Admission Control Solution to Improve Network Revenue // *29th IEEE International Conference on Advanced Information Networking and Applications (AINA-2015)*, Gwangju, Korea, March, 2015, pp. 23–28. **(in *IEEE Xplore* and *Scopus* databases)**
3. **Skrastiņš A.** Admission Control Scheme for Effective Revenue Management in NGN Networks // 22nd Telecommunications Forum TELFOR 2014*,* Belgrade, Serbia, November, 2014, pp. 174–177. **(in *IEEE Xplore* and *Scopus* databases)**
4. **Skrastiņš A.**, Jeļinskis J., Lauks G. Evaluation of New Approach for Fair Downlink Bandwidth Distribution in TCP/IP Networks // IET International Conference on Information and Communications Technologies (IETICT 2013)*,* Beijing, China, April, 2013, pp. 117–123. **(in *IEEE Xplore* database)**
5. **Skrastiņš A**., Jeļinskis J., Lauks G. Fair Bandwidth Sharing Scheme based on Upload Traffic Control // Electronics and Electrical Engineering No. 20(1) ISSN 1392-1215, Electronics and Electrical Engineering, Lithuania, Palanga, June, 2013, pp. 96–99. **(in *Scopus* database)**
6. **Skrastiņš A**., Jeļinskis J., Lauks G. Evaluation of Selective Aggregated Session CAC for QoS Provisioning in All-Optical Networks // The 20th International Conference on Software, Telecommunications and Computer Networks (SoftCOM 2012)*,* Split, Croatia, September, 2012, pp. 1–5. **(in *IEEE Xplore* and *Scopus* databases)**
7. **Skrastiņš A**., Jeļinskis J., Lauks G. Selective Aggregated Session Control with QoS Provisioning for GMPLS Networks // Electronics and Electrical Engineering No. 122(6) ISSN 1392-1215, Electronics and Electrical Lithuania, Palanga, June, 2012, pp. 75–78. **(in *Scopus* database)**

8. Lauks G., **Skrastiņš A.**, Jeļinskis J. Testing the Null Hypothesis of Stationarity of Internet Traffic // Electronics and Electrical Engineering No. 112(6) ISSN 1392-1215, Electronics and Electrical Engineering, Lithuania, Kauna, May, 2011, pp. 29–32. **(in *Scopus* database)**
9. Jeļinskis J., **Skrastiņš A.,** Lauks G. Practical Fuzzy-CAC Realization for Effective Traffic Engineering in MPLS-TE Network // Electronics and Electrical Engineering No. 110(4), ISSN 1392-1215, Electronics and Electrical Engineering, Lithuania, Kauna, May, 2011, pp. 30–34. **(in *Scopus* database)**
10. Jeļinskis J., **Skrastiņš A.,** Lauks G. Fuzzy-CAC Driven MPLS-TE Realization // 12th IEEE International Conference on High Performance Switching and Routing, Spain, Cartagena, July, 2011, pp. 146–150. **(in *IEEE Xplore* and *Scopus* databases)**
11. Jeļinskis J., **Skrastiņš A.,** Lauks G. Fuzzy-CAC based Traffic Management in MPLS-TE Networks //11th International Conference on Telecommunications, ConTEL 2011, Graz, Austria, June, 2011, pp. 389–395. **(in *IEEE Xplore* and *Scopus* databases)**

The results of the Doctoral Thesis have been applied in three research projects:

1. "Design of High Speed Optical Access Networks and Elements" Project No.: 2010/0270/2DP/2.1.1.1.0/10/APIA/VIAA/002.
2. "Smart City Technologies for Human Lives Improvements", Project No.: 2013/0008/1DP/1.1.1.2.0/13/APIA/VIAA/016.
3. "Applications of Mathematical Structures Based on Fuzzy Logic Principles in the Development of Telecommunication Network Design and Resource Control Technologies", Project No.:2013/0024/1DP/1.1.1.2.0/13/APIA/VIAA/045.

The Scope and Structure of the Doctoral Thesis

The volume of the Thesis is 162 pages. The thesis consists of an introduction, list of abbreviations, 4 chapters, conclusions and bibliography.

The introduction contains a brief review of modern network problems and highlights the topicality of the performed research as well as states the aim and tasks of the Thesis.

The first chapter of the Thesis is dedicated to a brief analysis of the traffic management solutions as well as review of existing access management solutions is performed and their classifications are obtained. The chapter includes an overview of ITU-T recommendations and their proposed guidelines for resource and admission control in NGN networks. Possible solutions such as the developed AggSessAC method compatible with the QoS assurance approaches are analysed to create an admission control solution suitable for modern high-speed (gigabit) networks.

The second chapter considers the requirements of a modern high-speed data network for admission management solutions. This chapter includes a comprehensive Internet traffic analysis from the data flow perspective, assessing flow intensity, flow volume, flow duration, packet size and number of packets per flow as well as inter-arrival distribution in cross-section of different communication protocols. It also analyses the flow types that dominate in the current Internet data networks. Based on the Internet traffic analysis results and conclusions regarding the number of the processed flows, the analysis of flow classification performance is performed. Flow classifier ability to work in online regime on high-speed data links with throughput ≥1 Gbps is also estimated. Conclusions drawn in this chapter outline the current situation in the Internet and the requirements for access management as well as justify the necessity of the developed AggSessAC method in modern high-speed data networks.

The third chapter is devoted to AggSessAC agent and solution development. The AggSessAC functional block (agent) is implemented, as well as agent parameters and selection are defined. AggSessAC functional agent is implemented in OMNeT++ environment by extending the functionality of router available in the INET framework with the developed admission management approach.

The fourth chapter is devoted to simulation experiments for the evaluation of the developed AggSessAC admission management in the OMNeT++ simulation environment. Verification and validation of AggSessAC functional block is performed. Experimental network scheme contains a router, the functionality of which is supplemented by the developed AggSessAC functional block. The chapter provides the estimation of AggSessAC parameters and their impact on the overall efficiency under different input traffic and different number of priority levels.

In the conclusion, the main results of the research are presented.

DETAILED DESCRIPTION OF THE RESEARCH

Chapter 1

The first chapter is devoted to the analysis of the resource and admission management solutions, as well as contains discussion of the recommendations and describes criteria to be taken into account when planning new connection admission management implementation. The chapter presents the research results related to bandwidth management and QoS enforcement capabilities. The forecasting method opportunities for expansion of knowledge base at the moment of decision making are evaluated as well. Access management is one of the elements of resources and data flow management, which allows managing and organizing resource distribution in situations characterized by a lack of available resources. When planning the development of admission management solutions, it is necessary to take into account a number of different sub-tasks, including packet/flow classification, queuing, available resource monitoring, resource sharing and other tasks, where coordinated management of these sub-tasks can lead to the desired result. It should be mentioned that the ITU-T has developed ***recommendations for resource and admission management in the NGN networks***. Recommendation Y.2111 provides a general resource and admission management functions (RACF) and structure consisting of functional blocks, while Y.2171 defines the criteria and guidelines, which should be followed making a priority-based admission decision:

- three basic criteria to be considered in decision-making moment:
  - required performance criteria (throughput, delays, etc.);
  - priority;
  - actual availability of resources.
- traffic with higher priority level receives higher assurance for admission;
- priority levels are not directly dependent on the transport layer metrics, which is defined in QoS classes of ITU-T Rec. Y.1541, and each network operator may adopt additional priority levels;
- number of priorities is not limited and may be extended in the future.

When planning the development of access control method, it has been designed to ensure:

- selective, priority-based and pro-active decision-making process;
- high performance and compatibility with modern traffic engineering solutions to ensure proper QoS levels.

The Thesis briefly describes two ***standardized QoS assurance approaches:***

- integrated services (IntServ);
- differentiated services (DiffServ).

These two solutions exist as the basis for traffic management solutions for packet networks [3], [60].

Integrated services work on a flow-level and use the end-to-end resource reservation. Current IntServ solutions assume a stateful network, in which each router maintains per-flow state information to keep track of each flow, but it also creates resource tracking and reservation problems in the network with high data flow intensity [1], [14]. High data flow intensity requires resource reservation done quickly, but end-to-end resource reservation takes time to clarify the availability of necessary end-to-end resources, and it also limits the method implementation for use on individual data flows (sessions) in high-speed data networks.

Unlike IntServ solution, the DiffServ operates at the packet-level by making a decision independently based on Per-Hop Behavior (PHB) packet forwarding treatment at the edge of the network. PHB management uses the packet labeling that determines service priority of a particular packet. In a DiffServ case, the end-to-end QoS provision will depend on the congested point in the network, thus providing only relative QoS guarantees, where some traffic classes will have relatively better QoS than other classes without specifying any quantitative QoS guarantees. To address these problems, a number of studies have been performed to combine both packet-level and flow-aware networking in order to meet end-to-end data flow QoS guarantees (see [28] [43] [46], [49]).

According to ITU-T Rec.Y.2111, it is possible to distinguish two kinds of QoS provision types [22]:

1. *Absolute QoS* – management is based on QoS parameters (packet delay, jitter, packet loss, etc.), and/or resource reservation and provides quantitative guarantees.
2. *Relative QoS* – management is based on the priority packet processing applied when it is difficult to provide absolute QoS guarantees in complicated networks.

Absolute QoS guarantees can provide two basic solutions:

1. *Resource reservation* – IntServ principle, the main drawback of which is performance problems on high-speed networks.
2. *Bandwidth monitoring/management* – it is used to maintain link utilization within pre-defined limits preventing completely filling up the bandwidth of link. Efficiency of bandwidth management can be increased by using it in conjunction with the appropriate admission management that select data flows to fill the available bandwidth. In the Thesis, AggSessAC admission management method is designed for use together with the following solution.

The Thesis also contains a short ***analysis of existing admission management solutions***. According to operational approaches aimed to ensure QoS, the existing admission management solutions can be divided into 2 groups:

1. Measurement-based admission control (MBAC) solutions;
2. Parameter-based admission control (PBAC) solutions.

In MBAC case, channel QoS parameter measurement results are used while making admission decisions.

Two types of measurements can be identified [59]:

1. passive measurements – performed by the buffer size analysis to determine the network QoS parameters and the fact that there is correlation among buffer size, link utilization and packet loss;
2. active measurements – performed by injecting *probes* to determine the end-to-end performance at a given moment (delay, jitter, packet loss).

At the session level of MBAC implementation for each new connection request, it can cause significant performance problems and limit the use of such methods with high-speed gigabit networks. In this case, measurement acquisition speed becomes very important. Therefore, there is always the issue of the measurement frequency – too rare measurements may not reflect the true situation in a network at the decision-making moment, while frequent measurements illustrate the actual situation more accurately; however, they require more bandwidth and computational resources.

Two types of PBAC solutions can be designated with resource reservation and without. The benefit of PBAC solutions with the resource reservation is an ability to provide strong QoS guarantees. In turn, for PBAC solutions only based on the bandwidth control and management of outbound link, the key benefits are their relatively simple implementation and high performance; therefore, they are more suitable for the implementation of the online mode. However, with *bursty traffic*, the PBAC solution makes it difficult to maintain adequate bandwidth implementation of outbound link – a too high traffic load will make it difficult to ensure QoS requirements, while a too low load will lead to inefficient use of resources. Description of MBAC and PBAC principles can be found in scientific papers (see, e.g., [5], [15], [23], [24], [32], [33], [38], [41], [50], [64]).

In addition to QoS provision capabilities, which are organized through the admission management method, the author of the Thesis has conducted research on the fuzzy logic based admission control for MPLS-TE networks [25], [26], [27]. In these studies, on the basis of individual flow control in the online mode, necessary resources have been reserved by using RSVP-TE protocol, as result, the dynamic MPLS-TE channel traffic control has been obtained demonstrating the trade-off between channel utilization and provision of QoS guarantees. These studies have demonstrated that it is possible to fulfill QoS requirements by maintaining the channel bandwidth load below a certain limit (< 85 %) and leaving a place for traffic bursts. Thus, it can be concluded that the control and maintenance of permitted bandwidth utilization threshold simplifies admission management, avoiding time-consuming and frequent QoS parameter measurements such as packet end-to-end delay by enabling one to build a high-performance solution. It also reduces the necessary computing resources that are particularly important for developing session-level admission management at high intensity of a new admission request. In order to increase an efficient use of resources, such solutions can be supplemented with dynamic bandwidth utilization threshold maintenance, using previously mentioned fuzzy-logic; however, they will be more resource demanding. This type of approach, in principle, provides a possibility to maintain a “buffer zone” for traffic bursts in order to fulfill QoS requirements and in combination with traffic engineering solutions can increase the efficient use of resources, such as MPLS-TE.

The authors in studies [54], [55] underline the MPLS layer as one of the potentially suitable location for deployment of admission management scheme in the backbone networks, where MPLS-TE tunnel capabilities help ensure end-to-end QoS guarantees within a core network with multiple traffic classes.

A similar approach has been analysed in the research [4] where traffic allocation among MPLS-TE tunnels is organized on a packet-level using DiffServ, but the desire of the author of the Thesis is to transform this principle to the flow-level management. It requires an appropriate admission management scheme that performs the allocation of priority-based data flows among tunnels, replacing the DiffServ approach with the AggSessAC admission management method developed by the author (see Fig. 5).

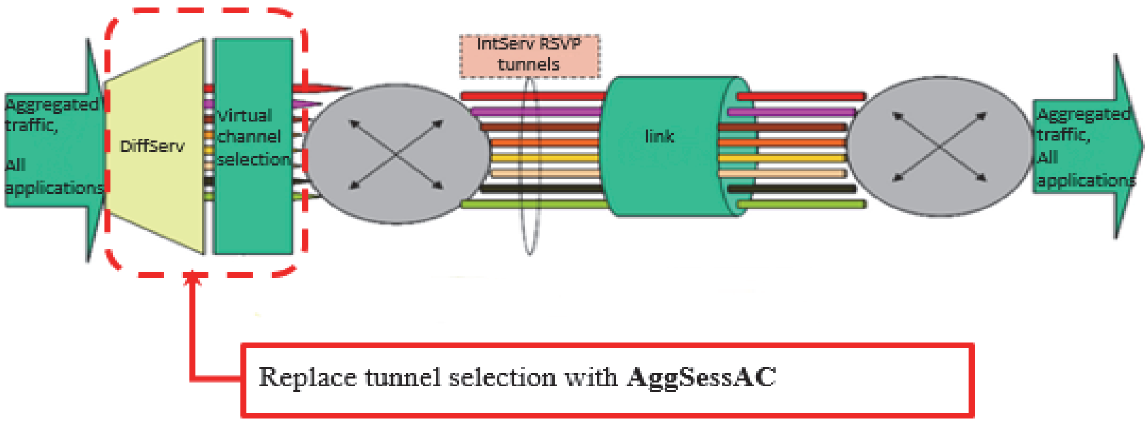

Fig. 5. AggSessAC scheme allows replacing packet-level management (DiffServ approach) with the priorized flow-level admission management.

Based on the previously conducted research, the author of the Thesis has developed a new resource and admission management solution – AggSessAC.

1. *AggSessAC admission management method is designed for use in high-speed gigabit networks, which allows implementing a session-level differentiated management policy and providing a wider admission choice among requests at the moment of decision-making.*
2. *In this solution, AggSessAC works as an operator that deploys the flows among virtual links while traffic engineering (TE) organizes resource availability and allows crossing the backbone network with just one hop and making one admission decision at the edge router of the network (see Fig. 6).*

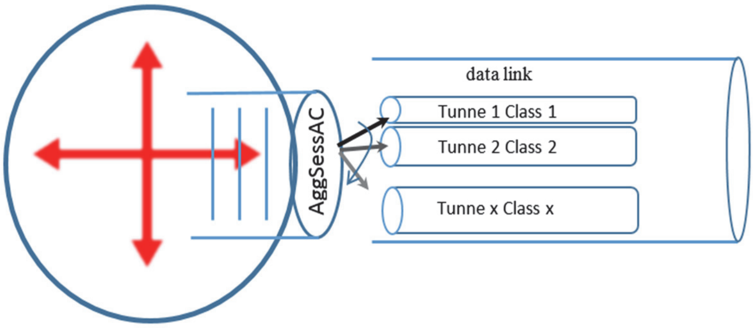

Fig. 6. AggSessAC method with TE solutions.

All of the admission management solutions known by the author of the Thesis have one feature – admission requests are processed independently in order of their arrival, thus failing to ensure evaluation capabilities among very close to the following requests; it causes problems to implement selective and priority-based admission control. Priority-based admission strategy could be implemented, if a set of admission requests at the admission management entity is received at the moment of decision-making, thus providing selectivity similar to packet scheduling in queue with DiffServ solution. The set of admission requests can be obtained:

1. by accumulating connection requests in queue – this approach get real values of requirements of requests; however, the accumulation of request set requires delay.
2. by predicting future admission requests – it does not require delay, but forecasting results are always probabilistic.

By using forecasts with training, we need historic information that would link prediction results to network processes. In this case, part of the input training data contains the past information, and therefore forecast results will always be correlated with historical information. This is more suitable for trend forecasting, rather than for accurate value forecasting of admission request. Based on the research results obtained in the field of prediction, the author of the Thesis has decided not to involve forecasting tools in an admission management scheme in order to reduce uncertain information conditions at the moment of decision-making.

The proposed AggSessAC method is considered to be a PBAC approach that keeps a flow-state table and separate buffer for accumulation admission requests by ensuring mutual evaluation of differentiated multiple requests at the moment of decision-making. The focus of the Thesis is the development of AggSessAC admission method that suitable for high-speed gigabit networks with abilities to perform priority-based admission and increase revenues from admitted traffic.

Chapter 2

Before offering some new traffic management paradigm, it is important to accurately characterize the *Internet traffic* today. The first part of this chapter is devoted to the traffic analysis of various cross-sections by characterizing the traffic from the perspective of packets, flows and protocols. It makes possible to draw up a "map" for future actions, which gives a reasonable opportunity to adopt a new management techniques or to withdraw some existing techniques. Traffic is always changing – due to changes in protocol algorithms, application requirements and user behavior. Today's realities show that the arrival rate of new flows in core networks is significantly increased, and we can see the emergence of many flows with a short lifetime, which load network edge nodes as well. All of these things create new challenges for a traffic management plane. The author has performed an extensive Internet traffic analysis, which gives answers to the basic question – what abilities are needed for an advanced admission management solution? The conclusion is that a modern admission management method based on available resources should ensure selective, proactive, priority-based decision making with high performance and compatible with traffic engineering solutions. The second part of this chapter is devoted to data flow classification options and the evaluation of performance achievements by assessing the classifier abilities to work at the level of individual sessions in high-speed gigabit networks.

For the analysis, the author uses traffic log files obtained from one Latvian company, which uses, manages and controls a wide range of telecommunications network infrastructures across the whole territory of Latvia. In order to make extensive studies, the previously mentioned measurement data are compared with publicly available traffic statistical data from the *Center for Applied Internet Data Analysis* (CAIDA) – the research institution that monitors the core network in the United States [57].

Analysis of Internet Data Flows

The analysed data capture has been obtained with *tcpdump* utility, and flow classification has been performed using *wireshark* packet analyser [63]. Classification has been carried out using 3 and 5 flow identification features (see Table 1). In the case with 5 features, by analysing UDP and TCP protocols and their port numbers – uniquely distinguished flows increased up to 5 times. This shows that in case of IP flow *identification* it is important to make a transport layer information analysis, thereby dramatically increasing the resolution of IP flows, although it requires more computing resources.

In case of IPv6, classification is facilitated by a flow label field in the IP header. In this case, it would be sufficient to use 3 fields in the IPv6 header, respectively, a source and a destination IP address and a flow label. This can help avoid a transport layer analysis, which makes it easier to perform the encrypted traffic classification.

Flow directions are also important in admission management solutions. Captured trace-file analysis shows that the distribution of the flow duration contains a very similar picture in both the upload and download directions (see Figs. 7 and 8). With regard to the assessment of flow duration, 7 time ranges have been introduced: the flows up to 100ms long, from 100 ms to 1s, the 1s to 5s, from 5s to 10s, from 10s to 1min, from 1s to 2min, and flows that are longer than 2 minutes.

Table 1

Number of Identified Flows on the Experimental Trace

Flow direction	3 flow identification keys (IP protocol, Source IPv4 address, Destination IPv4 address)	5 flow identification keys (IP protocol, Source/destination IPv4 address, Source/destination UDP/TCP ports)
Upload	10602	–
Download	9862	–
Upload TCP	–	31153
Upload UDP	–	25438
Download TCP	–	31015
Download UDP	–	23909

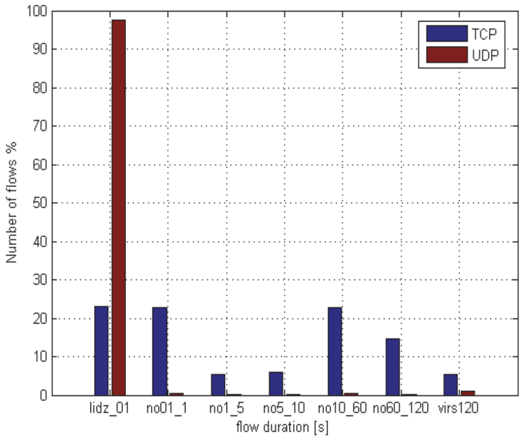

Fig. 7. Histogram with upload data flow duration (7 bins).

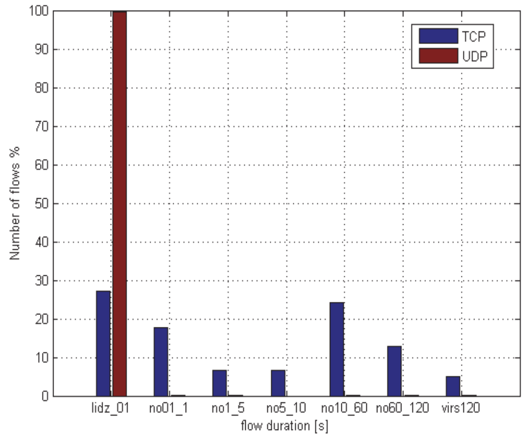

Fig. 8. Histogram with download data flow duration (7 bins).

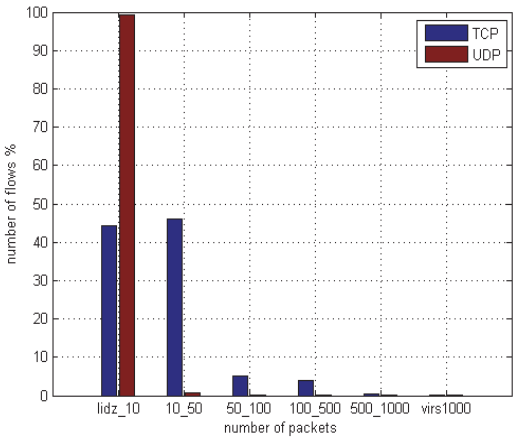

Fig. 9. Histogram with upload data flow size [packets] (6 bins).

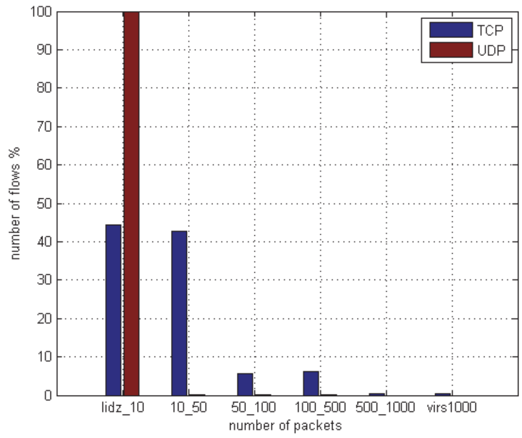

Fig. 10. Histogram with download data flow size [packets] (6 bins).

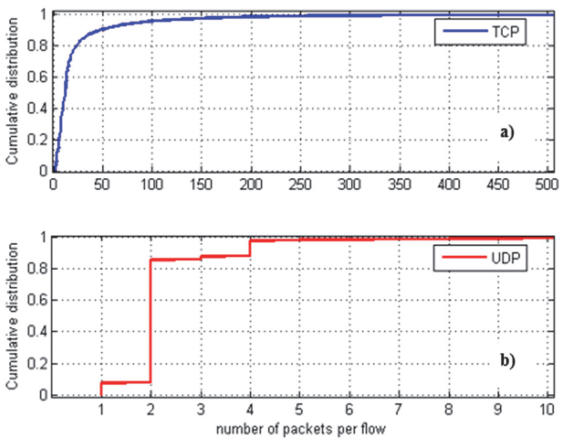

Fig. 11. Cumulative distribution of upload data flow size(a) zoom – up to 500 packets for TCP; b) zoom – up to 10 packets for UDP flows).

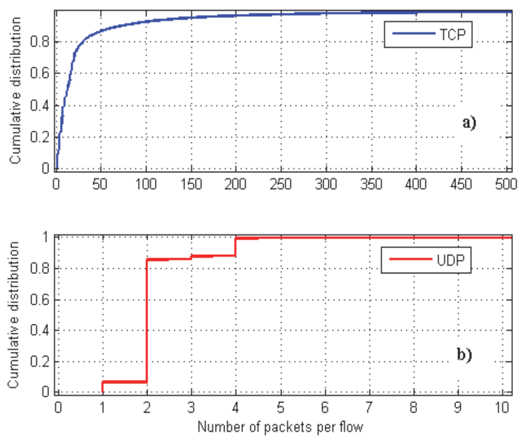

Fig. 12. Cumulative distribution of download data flow size(a) zoom – up to 500 packets for TCP b) zoom – up to 10 packets for UDP flows).

The main thing which the author would like to mention is ***the large number of short flows*** that contain only a few packets and have a very short lifetime. For example, TCP flows in a download direction provided in Fig. 8 showed that about 55 % of the flow lengths were smaller than 10 seconds, and only 6 % of the flows were longer than 2 min. Results showed that 44 % of TCP flows did not contain more than 10 packets and about 90 % of the flows did not contain more than 50 packets (see Fig. 10). A similar situation is also observed in an upload direction (see Figs. 7 and 9).

In case of UDP flows, the results in Figs. 11 and 12 show that the captured experimental traffic in about 99 % of the UDP flows in one direction does not contain more than 2 packets, and the situation is identical for upload and download directions. When considering the applications that used the UDP as a transport protocol, it was found that almost all UDP flows accounted for a domain name service (DNS) and network monitoring service based on SNMP protocol.

CAIDA Data Analysis

In order to obtain a more comprehensive picture of the range values of the traffic metrics, in which modern admission management solutions should work, the author of the Thesis has analysed publicly available internet traffic data published by the CAIDA research center. Data are collected on a core network between Chicago and San Jose cities in the U.S. at a channel speed of 10 Gbps. CAIDA data are updated every month and have been analysed by other researchers.

In the author's opinion, the most comprehensive studies in the field of Internet traffic are [47] and [65]. The authors *X. Zhang, W. Ding* [65] have carried out an extensive study, analysing the Internet flows at different cross-sections: the number of active flows, new flows per second, the flow rate (packets/s, bits/s), flow volume (in bytes), distribution of flow lifetime, flow distribution by transport protocols and other flow characteristic features. The article analyses the CAIDA data as well as data collected in China Education and Research Network. (CERNET) that also supports 10 Gbps transmission rate (see Figs. 13 and 14).

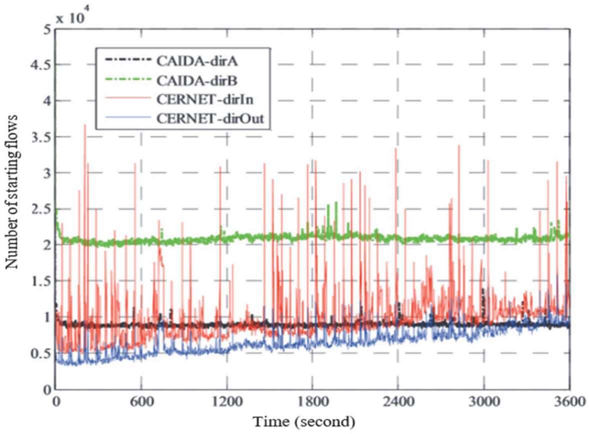

Fig. 13. Number of new flows per second on a 10 Gbps channel [65].

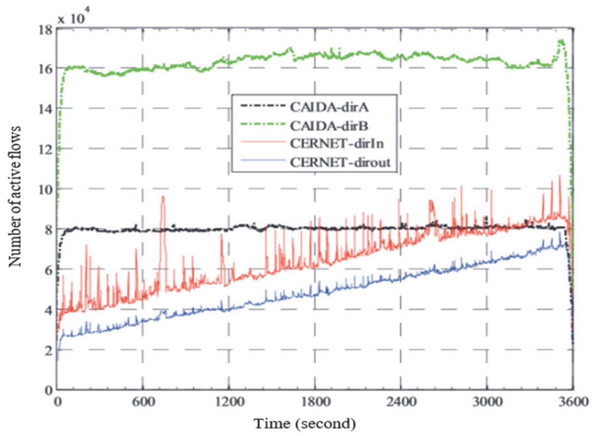

Fig. 14. Number of active flows per second on a 10 Gbps channel [65].

Table 2 depicts the average values of Internet flows in the period from March 2014 to March 2015. In direction dirA at the average link utilization 21 % (2.1 Gbps) results in an average of 10,000 new flow/s, while the direction of dirB, 44 % link utilization (4.4 Gbps) results in around 30000 new flow/s. The results show that the ***lifetime of around 80 % of flows is 3–6 seconds.*** All the above-mentioned results lead to a conclusion that there is high new flow intensity, which should be processed on high-speed gigabit networks and is already measured on 10 Gbps link in the range of 10,000 to 100,000 new flow/s.

Table 2

Statistics for the year 2014/2015 on 10 Gbps Backbone Link in Chicago
(Trace Statistics from CAIDA monitored OC192 link)

Channel	Average channel utilization (Gbps)	Average number of packets per second	Number of starting flows per second
Chicago dirA	2.11	332826	9796
Chicago dirB	4.42	597480	26097

A large number of short lifetime TCP and UDP flows indicate high intensity of new flows. It should be noted that TCP flow, if measured by traffic volume in bytes, is the dominant transport protocol on the Internet, but from the perspective of a number of new flows, the UDP starts overtaking the TCP. A new high flow rate is one of the preconditions that allowed the author of the Thesis to consider the opportunity of proposing a new approach to an admission management solution.

Packet-Level Flow Analysis

Traffic profile can be characterized by the above-mentioned parameters – bits/s, packets/s or flows/s. Taking into account the proposed AggSessAC admission management solution, a separate buffer has been used for accumulation of new flow initialization packets, a packet-level traffic analysis has been performed by assessing a packet size and distribution of packet inter-arrival time. The analysis has been performed using the trace files obtained by the author, and the gained results were compared with the previously mentioned CAIDA data.

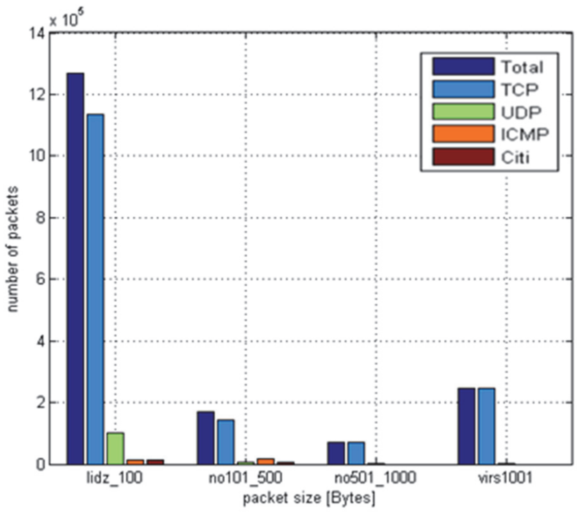

Fig. 15. Packet size in upload direction
(four ranges– up to 100 B, 101 B – 500 B, 501 B – 1000 B, above 1001 B).

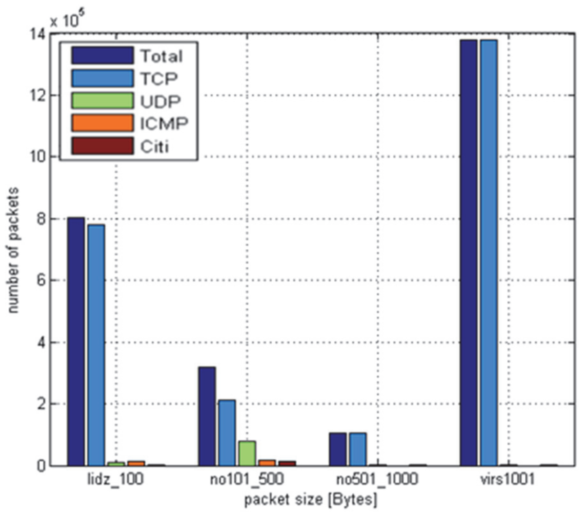

Fig. 16. Packet size in download direction
(four ranges – up to 100 B, 101 B – 500 B, 501 B – 1000 B, above 1001 B).

As shown in Figs. 15 and 16, the TCP is the leading transport protocol – in an upload direction it represents about 91.6 % of the total number of packets, while the remaining part consists of UDP (5.7 %), ICMP (1.7 %) and other protocols (1 %). Download direction shows quite similar results – traffic consists of TCP (95.3 %), UDP (3.1 %), ICMP (1 %) and other protocols (0.6 %). Results have shown that more than 90 % of UDP flows do not exceed 100 to 200 bytes. These results are depicted in Figs. 17 and 18.

In situations, where the traffic mainly consists of data generated by UDP-based P2P applications, the size of UDP packet in the downstream direction is over 1400 bytes.

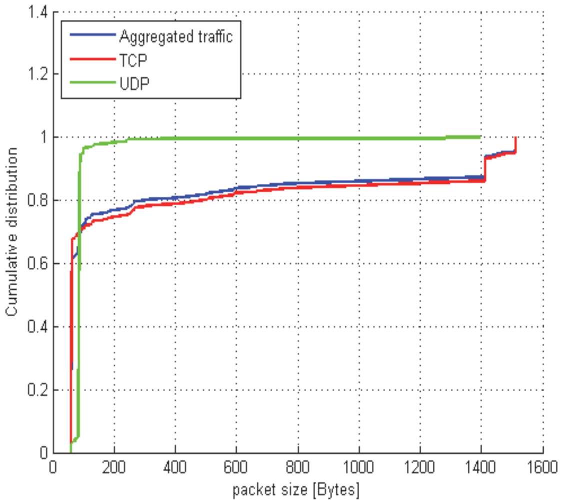

Fig. 17. Cumulative distribution of packet size in upload direction.

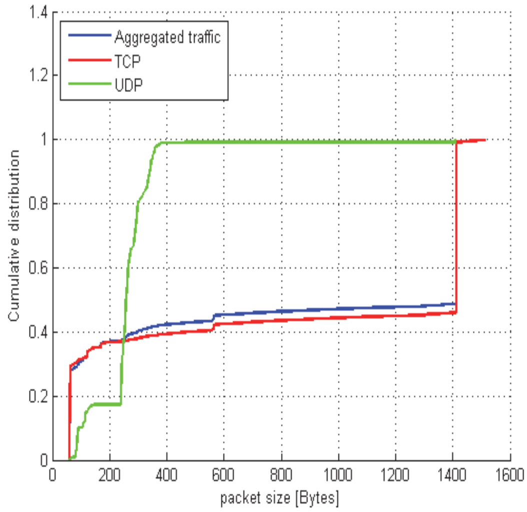

Fig. 18. Cumulative distribution of packet size in download direction.

Statistics of CAIDA research center does not include information about each transport layer protocol, but it confirms the conclusion that there are basically two types of dominant packets in traffic: small size (from 100 to 200 bytes) and large size packets (over 1400 bytes) (see Fig. 19). This means that the average calculated packet length, which should be around 500 to 600 bytes, does not describe the actual packet length in today's Internet backbone networks.

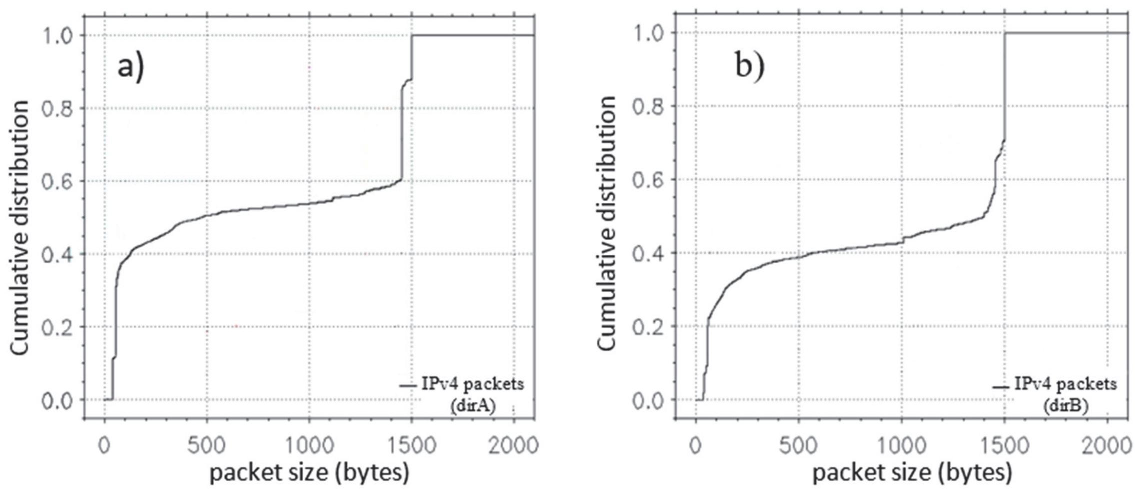

Fig. 19. Cumulative distribution of packet size: a) direction-A, b) direction-B, (CAIDA statistic) [57].

It can be concluded that all distributions with respect to incoming time are relatively close, and within the next one could be called Weibull and lognormal (Fig. 20). While analysing other studies, one recent article [18] on packet inter-arrival time distribution should be mentioned that also Weibull, Pareto, gamma, exponential and lognormal distributions as the closest ones. The study recognizes Pareto and Weibull distributions to be close for both TCP and UDP protocols.

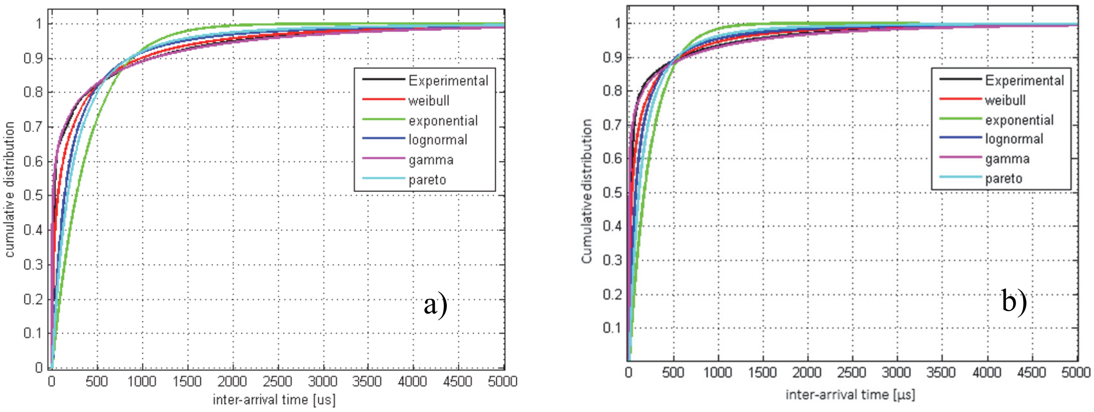

Fig. 20. Cumulative distribution functions of packet inter-arrival, zoom in up to 5 ms: a) upload, b) download.

Analysis of Various Studies in the Field of Data Flows

Knowing that the experimental data analysis is not a comprehensive Internet traffic describer, the author extends his research by performing the analysis of other studies, which would allow for a more accurate assessment of the current situation and identification of the main features in the field of data flow.

With regard to **flow volume** *[in bytes]* and *[in packets]*, most of today's Internet traffic flows are made of TCP protocol sessions; it is also confirmed by other studies [10], [13], [31], [66]. This is due to TCP flow control mechanism, which is more suitable for the Internet environment by allowing one to adjust the transmission speed by the receiving side and providing lost packet re-transmission.

The following results for the high number of UDP flows and their small sizes are also highlighted by the authors of Volfsburg University in their research [19]. The research [19] has showed that 91.6 % of the UDP flows in one direction contain no more than 1 packet; 98.7 % contain no more than 5 packets and 99.6 % contain no more than 10 packets.

The author of the Thesis would like to emphasize research [35], in which UDP/TCP flow ratio was estimated at two various service provider networks. Volume ratio of UDP/TCP varied in the range of 0.02–0.11 (with average of 0.06) showing that the TCP volume contributed to most traffic. Considering the number of flows, the flow ratio varied in the range of 0.04–2.00 (with average of 0.7) across the networks where there was higher variation than the volume. The average duration of Internet flows which contain more than 50 packets has shown that ***approximately 80 % – 90 % of the flows are not longer than 1 minute and 50% of flows are not longer than 10 seconds.*** It should be noted that > 40 % of the UDP amounted to DNS requests on port 53, which are short and small volume flows, while a similar percentage of TCP traffic goes to port 80 with the HTTP protocol.

The authors in [66] also performed a comparison of UDP and TCP traffic and concluded that the number of UDP flows tripled and reached TCP flow counts, although UDP traffic volume in bytes was almost unchanged, but packet ratio between UDP and TCP even slightly decreased. The average number of packets in UDP flows is less than 10 packets. UDP protocol is mostly used for signaling data transport in various P2P applications, DNS service, monitoring services and other applications that are not sensitive to packet loss.

Flow Classifiers

Traffic classification is an important task for all traffic management solutions, which need to classify the data flows into various categories based on many criteria and its performance becomes especially important in cases, when classification should be carried out in the online mode, which is also consistent with connection admission control solution proposed by the author of the Doctoral Thesis. For example, the authors [29] point out that in order to carry out packet classification at OC-768 40 Gbps link rate in the worst case scenario, with a packet length of 40 bytes, processing time cannot exceed 8 ns for each packet. Therefore, in this chapter the author also analyses a modern classifier ability to operate in high-throughput links at a speed over >1 Gbps in the online mode.

High performance achievements in the traffic classification field are based on the use of new methods, customization of specific programmable integrated circuits for classification tasks, as well as broader use of parallel processing in multi-core computing systems.

While dividing classification methods according to their modes of operation, we can define [11]:

- Offline – previously collected datasets are used for flow classification and applied for research, statistics collection, report creation.
- Online – traffic flow analysis and classification in the online mode. It is commonly used for network management tasks that require an online decision-making and policy implementation.
- Cyclic – flow classification at regular intervals. The collected traffic is analysed at specific time intervals. This approach is suitable for building inventory and for generation of reports. This approach is close to online network state depiction.

Types of classification methods can be divided into three categories [9], [37], [45]:

- Port-based classification;
- Deep packet inspection classification (DPI);
- Machine learning-based classification (ML).

Port-based traffic classification uses only a packet header field analysis and is one of the most widely used methods because it does not need huge computing resources. A packet header fields are standardized, so this method is often embedded in the kernel of router operating system or in the processor of interface cards. Payload analysis method provides high flow distinguishing capability, but it requires high computational resources and it cannot be used for encrypted traffic classification. Traffic classifiers based on machine learning are able to use predefined knowledge base to perform traffic classification with the opportunities to learn from experience, to gain new skills and improve the pre-defined knowledge base. Such methods are more suitable for offline mode classification.

The research [11] compares performance of port-based classification, PortLoad (simplified DPI, which inspects only the first 32 payload bytes) and DPI flow classification solutions. The average classification time using the DPI method increased by 85 % compared to the port-based method and by 2.8 % compared to PortLoad method. CPU usage in DPI case increased 5 times and the required memory – 6 times.

Active research in the packet classification field is conducted by Professor *Viktor K. Prasanna* with his colleagues from the University of Southern California [16], [17], [29], [30], [48], [49], [50], [58]. The current achievements in the field of the classification performance are described below.

In the study [39], the authors demonstrated performance that can be achieved on the software-based classifiers that are mounted on widely available multi-core platforms. The 8 CPU core platform demonstrated the capacity ranges from 10 to 15 Gbps, depending on the classification set of conditions, which accounted for performance of up to 48 million packets per second (MPPS).

In the research [49] on 16-core CPU, authors achieved 60 MPPS high-throughput packet classification at 1K (1000) condition rule sets and 30 MPPS performance at 32K (32000) conditional rule set. These results were obtained in the online mode by examining 15 flow-level features during the classification process, and then a set of conditions was analysed, which determined further actions. The same authors in study [58] with reduced sets of conditions reached 98 MPPS high performance.

GPU graphics processors are widely used to increase classifier performance. For example, research [36] using freely available NVIDIA Fermi GPU showed that the online packet classifier was able to achieve 24 Gbps throughput and handling up to 12 million flows/s.

Another performance enhancing direction is the usage of programmable digital integrated circuits – FPGA. It is worth noting the research by *Ganegedara T. and V. K. Prasanna* [39], who achieved 400+ Gbps high performance during the first implementation, and these researchers were the first known who used FPGA-based solution.

It should be noted that the results obtained by the extensive research analysis in the traffic classification field confirm classifier performance in the online mode on high-throughput links and are suitable to use it with the admission management solution developed by the author of the Thesis. It is worth noting multi-core CPU popularity to increase router performance and even specially adapted CPUs that accelerate packet inspection and improve online mode analysis, such as new generation *QuantumFlow Processor* by Cisco company [58], or a series of routers with multi-core processors produced by MikroTik company [8].

Traffic management model that operates at the session level is necessary not only to make the session classification, but also to maintain the table of per-flow state with active sessions. As a result, the time parameter that determines when the session is inactive and could be removed from a per-flow table is really important. One of the solutions how to maintain a table of active flow state in high-speed data networks is to implement multi-level flow tables. For example, the authors of the studies [61], [62] offer a solution how to perform pre-flow state tracking for high-speed routers. They use a combination of tables of per-flow state and store in them the hash values obtained from the flow identification features, thus speeding up the search process. These tables are known as the flow time containers with the *specified time range for each of them*, thus ensuring that several flow tables (containers) with different time ranges are used, and search always begins with the most latest (most actual).

In this chapter, it is clearly shown that the packet classification is already able to work on links with the capacity of 40 Gbps and higher, processing tens and even hundreds of millions of packets per second. Conclusions about high intensity of data flows that exist in today's Internet networks and performance achievements of modern data flow classifiers have served as the conditions enabling the author of the Thesis to put forward a new approach of admission management. The implementation of new method and results are presented in the following chapters.

A broad analysis of potential service classes and priority levels is included in this chapter. Prioritization contains a number of stages. Generalized block diagram of developing a set of priorities for traffic control and management tasks is given by the author of the Thesis in Fig. 21. Diversity of network services and applications defines different QoS requirements with a number of criteria (e.g., delay, loss, jitter, traffic volume, etc.), according to which services are distributed among the QoS classes (as described in ITU-T G.1010 and Y.1541). However, the QoS class is not always an appropriate parameter for management tasks to indicate a service priority of other services. Therefore, QoS classes are divided into types of services (ToS) and those are granted priorities by evaluation of various criteria, such as QoS requirements, service type, price and other that are considered important by ISP.

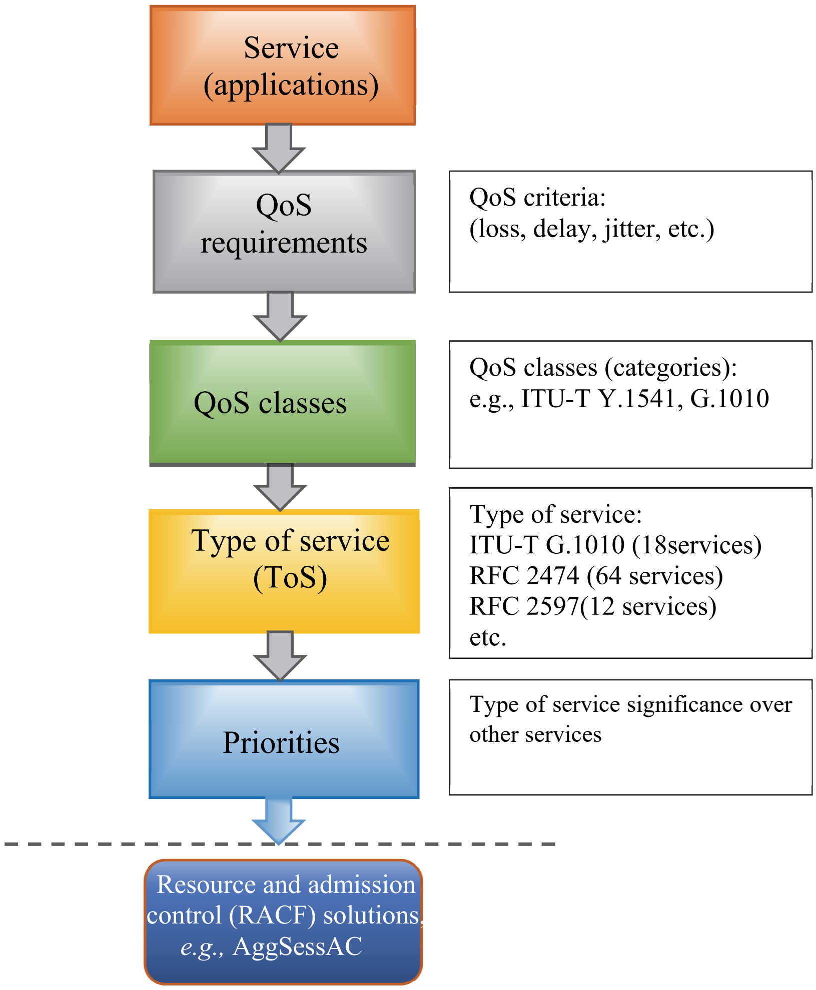

Fig. 21. Generalized block diagram of developing a set of priorities for traffic control and management tasks.

ITU-T, IETF, ETSI and the IEEE organizations have been involved in development of recommendations that define QoS classes and their classification by different types of services. For example, RFC971 describes the eight service types and the ability to define up to 8 priority levels, RFC 2474 defines 12 service types with 12 potential priority levels. For more information on analysis of recommendations with respect to potential QoS classes, types of service and their priorities one can read the full version of the Thesis, as well as explore some references (see, e.g., [12], [42], [53]).

Chapter 3

The development and experimental evaluation of AggSessAC programmatic agent have been performed in OMNeT++ simulation environment using the INET framework library. Functionality of AggSessAC programmatic agent has been implemented within router software of the INET framework.

The Concept of the Designed AggSessAC

The concept of the designed AggSessAC admission management is to replace traditional, instant, sequential and independent new request admission processing strategy with short-term aggregation of new connection requests (packets) on a separate queue. This is a form of processing, which is opposite to the traditional admission management and allows implementing the mutually comparative, priority-based and pro-active admission management policy by analysing several requests simultaneously during decision-making.

Conceptual request processing differences between a traditional approach (ThresholdAC) and AggSessAC admission management method are depicted in Fig. 22.

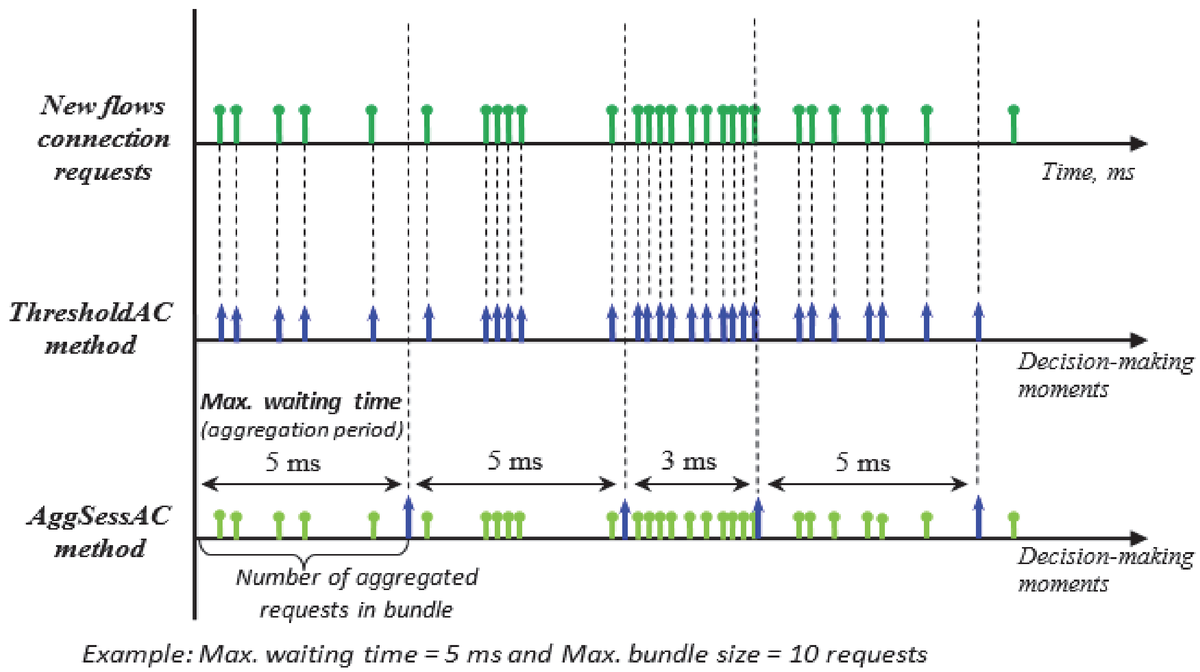

Fig. 22. Comparison of admission request processing strategy between a traditional ThresholdAC and the proposed AggSessAC method.

Within AggSessAC method, a new connection request accumulation is controlled by two parameters:

- ***maximum waiting time*** A_{max} (ms) – time of aggregation period for new connection request accumulation, where

$$A_{max} \in \mathbb{R}_{>0}; \qquad (1)$$

- ***maximum bundle size*** B_{max} [new connection requests] – queue size for connection requests, where

$$B_{max} \in \mathbb{Z}_{>0} = \{1,2,3,\ldots\}. \qquad (2)$$

AggSessAC decision-making trigger:

IF *(*$A == A_{max}$*) or (*$B == B_{max}$*)*

Make decision

THEN

Continue to accumulation (aggregation) of a new connection request

where

A – actual waiting time (duration of a new connection aggregation), ms

B – actual bundle size, number of connection requests.

The aim of the proposed AggSessAC access management is to increase the effectiveness of a given management policy. Nowadays, networks require efficient resource allocation and they should ensure the prioritization of different services at the same time. The admission management policy used in simulation experiments has determined that sets of collected requests (bundle) are processed in such a way that higher priority flows are accepted first if bandwidth is available.

Admission management determines:

1. **Maintaining a maximum average link load in accordance with permitted throughput data rate, which is defined by a management policy.**

$$\forall t_i : \max \frac{\sum_1^n u(t_i)}{n}, \qquad (3)$$

where

- t_i – decision making moments, $i = 1,2,3\ldots;$
- n – a total number of decision-making moments during the experiment;
- $u(t_i) \in [0;1]$ – link utilization at decision making moment t_i.

2. **Promoting differentiated admission management implementation and higher priority request (*a new single data flow – session*) approval in each decision-making moment.**

$$\forall t_i : \max_{j^{(p)}_{accepted} \in B(t_i)} \sum\nolimits_0^a r(j^{(p)}_{accepted}(t_i)), \tag{4}$$

where

- $j_{accepted}(t_i)$ – accepted requests at each decision-making moment t_i;
- a – a number of accepted requests (accepted sessions);
- $B(t_i) \in [j(t_i)]$ – a bundle size (set of aggregated requests), where $j(t_i)$ – a new connection request at each decision-making moment t_i;
- $r(j^{(p)}_{accepted}(t_i))$ – the obtained revenue (benefits) from accepted requests $j_{accepted}$ with priorities p at decision-making moment t_i;
- $p \in \mathbb{Z}_{>0} = \{1,2,3,\ldots\}$ – priority of new connection request, in this experimental research traffic with 3, 5 and 8 priority levels was used.

Estimation of the ability of the developed AggSessAC method to provide selective and priority-based management has been made by linking the revenue calculation with priorities of accepted requests.

In the Thesis, the author uses the term "obtained revenue" adapted from the utility theory, which gained more attention after research paper [44] proposed by *J. von Neumann* and *O. Morgenstern*. These principles are also transferred to engineering tasks (e.g., [40]). Utility theory states that although it is not possible to measure the utility or "obtained revenue" derived from the product or service, it is usually possible to rank those in preference order with respect to the consumer. The rational action would be to spend money on additional goods or services, unless the obtained revenue from the utility is equal to or greater than that of any other goods or services.

By shifting principles of utility theory from the economy to the communication networks, wherein the context of access management the word "consumer" can be referred to "the management policies" and in this case a rational action will be to ensure that the highest priority traffic gets service preference to the lowest priority flows. The "price" of such benefits is a short delay in the decision-making process at the time of new session initialization.

Selective and priority decisions require implementing management policies, which can provide higher approval probability for higher priority flows; therefore, the obtained revenue is calculated as a benefit from priorities of the accepted requests.

Total revenue (Q) is calculated as follows:

$$Q = \sum\nolimits_0^m r^{(p)}_{j_{accepted}}, \tag{5}$$

where, *m – the total number of accepted requests* and $r^{(p)}_{j_{accepted}}$ *– the obtained revenue from the accepted request $j_{accepted}$ with priority p.*

Estimation of required buffer capacity (B_{max}) has been made in order to obtain knowledge about the range of necessary buffer size. Taking into account the TCP connection establishment process, which uses three messages (procedure is called a three-way handshake), if we delay the SYN message inside the buffer, the other packets from a particular new connection will not be received. In contrast to the TCP protocol, the UDP protocol works in connectionless mode and packets are transmitted without acknowledgment, so the aggregation period for UDP flows may require a larger buffer capacity than TCP. The situation where one data flow takes the full bandwidth of Ethernet link has been used for assessing the required buffer capacity. Idle period between transmission of Ethernet packets known as the inter-frame gap (IFG) has been taken into account when calculating the maximum amount of data received in the aggregation period. Tables 3 and 4 contain the maximum theoretical size of aggregation buffer for different data rates and packet sizes.

Table 3

The Theoretical Maximum Aggregation Buffer (Bundle) Size at Different Data Rate (packet size ***1500 B***)

Data rate	**Inter-frame gap [ns]**	**Maximum buffer size [Bytes]**			
		waiting time (aggregated period)			
		10 ms	1 ms	0.1 ms	0.01 ms
100 Mbps	960	124 KB (82 packets)	12.4KB (8 packets)	–	–
1 Gbps	96	1240 KB (826 packets)	124 KB (82 packets)	12.4 KB (8 packets)	–
10 Gbps	9.6	12.4 MB (8266 packets)	1240 KB (826 packets)	124 KB (82 packets)	12.4 KB (8 packets)
40 Gbps	2.4	49.60 MB (33066 packets)	4960 KB (3306 packets)	496 KB (330 packets)	49.6 KB (33 packets)
100 Gbps	0.96	124 MB (82666 packets)	12.4 MB (8266 packets)	1240 KB (826 packets)	124 KB (82 packets)

Table 4

The Theoretical Maximum Aggregation Buffer (Bundle) Size at Different Data Rate (packet size ***100 B***)

Data rate	**Inter-frame gap [ns]**	**Maximum buffer size [Bytes]**			
		waiting time (aggregated period)			
		10 ms	1 ms	0.1 ms	0.01 ms
100 Mbps	960	110 KB (1100 packets)	11 KB (110 packets)	1.1 KB (11 packets)	110 B (1 packets)
1 Gbps	96	1100 KB (11000 packets)	110 KB (1100 packets)	11 KB (110 packets)	1.1 KB (11 packets)
10 Gbps	9.6	11 MB (110000 packets)	1100 KB (11000 packets)	110 KB (1100 packets)	11 KB (110 packets)
40 Gbps	2.4	44 MB (440000 packets)	4400 KB (44000 packets)	440 KB (4400 packets)	44 KB (440 packets)
100 Gbps	0.96	110 MB (1100000 packets)	11 MB (110000 packets)	1100 KB (11000 packets)	110 KB (1100 packets)

It is obvious that at the speed of 1 Gbps and aggregation period of 1 ms the theoretically required buffer memory capacity does not exceed 124 KB, comprising 82 packets that are 1500 bytes long or 1200 packets that are 100 bytes long.

Having performed the analysis of internet traffic, it can be stated that there are thousands of new connections per second on 1 Gbps links, but on 10 Gbps links new connection flows already exceed many tens of thousands per second. Here one can see an example of 5000 new requests/s, which represents an average of 0.2 ms inter-arrival time. This means that 50 requests for simultaneous analysis will need an average of 10 ms long aggregation period. Theoretically required maximum cache size at different speeds for this time period can be found in Tables 3 and 4.

In turn, at 20,000 new flows/s, the average inter-arrival time will be 0.05 ms and accumulation of 50 new requests will require an average of 2.5 ms. Reducing the accumulated requests to the number of 10, the average accumulation will take only 0.5 ms.

The following items can serve as a basis for the initial bundle size selection by network engineers and designers, while taking into account logical considerations and prerequisites:

- monitoring information of network average number of new flows per second;
- maximal limitations of aggregation period (threshold of induced delay);
- revenue/loss considerations:
  - the smaller the bundle size, the lower the required aggregation period and the induced delay;
  - too small bundle size or too short aggregation time reduces the number of requests to be evaluated at the same time and, as a result, the methods selectivity decreases.

Simulation Tool

Essentially, a router is a computer with the custom operating system. As the author was not able to access and modify the router manufacturer operating system source codes, the developed resource and access management solution prototype implementation was made in OMNeT++ discrete event simulation environment based on INET library [20]. The OMNeT++ gives the possibility to emulate a network infrastructure starting from the physical layer simulations, packet processing in buffers, data and transport level protocols, routing protocols, up to the OSI application layer. The relative time scale that is available in OMNeT++ has allowed to evaluate such parameters as the average aggregation time and aggregation average queue length dependence on predetermined average inter-arrival time distribution as well as those dynamical changes with time.

INET library has been updated using the developed AggSessAC agent (source code), which has been integrated into the INET available router software as the additional functional block, thus creating a fully functional AggSessAC admission control experimental prototype.

AggSessAC functional block (agent) has been developed in OMNeT++ available INET framework within the output buffer of router Ethernet interface as the additional functional block (Fig. 23). The developed project and source files are available in public repository athttps://github.com/askrastins/aggsessac.

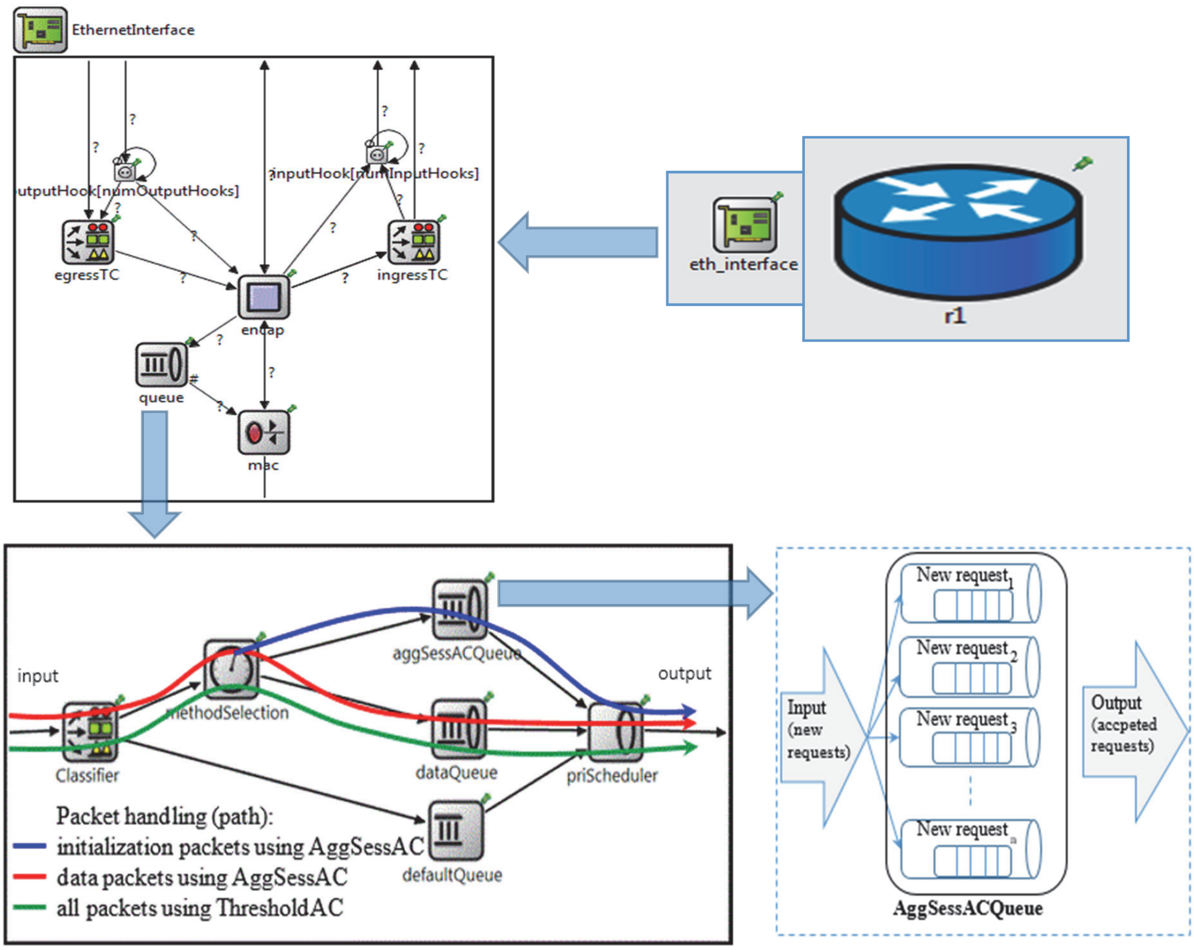

Fig. 23. Structure of AggSessAC module implemented within the output queue of router interface in the OMNeT++ simulation environment and the packet forwarding path according to applied method.

According to Fig. 23, the developed AggSessAC agent comprises a number of functional modules. Each module corresponds to the separate C++ source file. For more information on the main methods of the developed classes see Chapter 3 of the Doctoral Thesis.

As shown in AggSessAC agent functional block diagram (see Fig. 24), the classifier main task is to find out whether a received frame includes the IP packet and to direct it towards methodSelection module, but if it is something else (such as ARP message) the task is to direct it to defaultQueue queue. MethodSelection module allows setting the selected admission management method – ThresholdAC or AggSessAC – as well as implementing the current and available bandwidth monitoring and accounting.

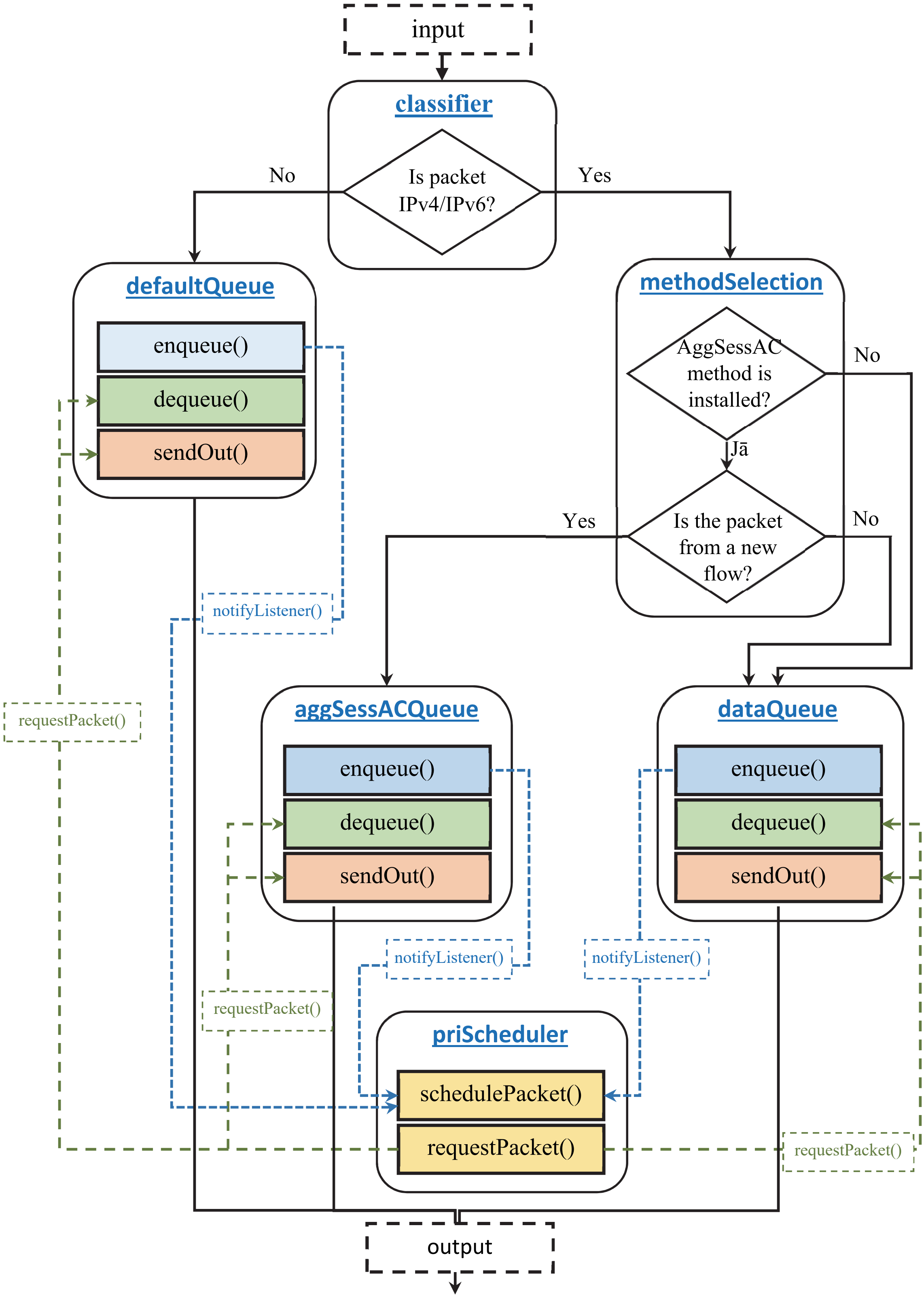

Fig. 24. General software architecture of AggSessAC functional agent.

Three queues are used in modules: defaultQueue, dataQueue and aggSessACQueue, respectively (see Figs. 23 and 24). DataQueue module performs ThresholdAC admission management, while aggSessACQueue performs the developed AggSessAC admission management, ensuring new connection request packet accumulation, as well as the analysis of requirements of requests and decision-making on control actions. Main functions of queue modules are inherited from the base class – *PassiveQueueBase.cc* that provides packet queuing – *enqueue(),* packet removal from queues – *dequeue()*, forwarding – *sendout()*, as well as notification of the arrival of a new packet into the queue – *notityListener()*. Queue ensures that each time the new packet arrives into the queue, it is notified by queues inherited *notifyListener()* method to the priScheduler module, which is capable of calling queues methods enqueue() and then sendout(). This ensures the packet is withdrawn from the queue and sent to the communication link. PriScheduler module monitors if there are packets in queues as well as monitors actual queue sizes. Response to the notifyListener() messages is subject to and managed through the modules that simulate the communication link. In the case of AggSessAC, the priScheduler module and *notityListener()* method are also dependent of aggregation period. *NotityListener()* method calls aggSessACQueue queue according to this period, or if an aggregation group of connection request has reached a pre-defined maximum value. Queues are being serviced in order of priority, where the highest priority is given to the defaultQueue queue, the second highest – the aggSessACQueue queue and the lowest priority is assigned to the dataQueue queue. This ensures that at the decision-making moment, the most recent admission requests are being processed first and are being forwarded as soon as possible, and only then packets from previously accepted flows that are in dataQueue.

To sum up, it should be emphasized that the proposed AggSessAC solution is based on a simple yet effective approach, where multiple new connections are processed simultaneously at the decision-making moment, thus providing mutual flow request evaluation and selective flow acceptance. To implement AggSessAC solution, all flow connection requests are aggregated and while performing flow classification, the new request packets are separated from the already approved data flows. The solution needs to maintain flow state information and to bring into the system architecture new buffer of flow initialization packets, where all the new flow initialization packets are moved.

In order to control aggregation duration, the solution needs to follow such parameters as the maximal bundle size and the maximum aggregation period. As a result, the differentiated packet management solution has been obtained, and in this case the selection occurs at the flow level and is handled by the admission management method. This makes possible to operate with a fully reliable resource request data set.

Chapter 4

This chapter is devoted to the evaluation of AggSessAC functional agent developed by the author of the Thesis. The results obtained by simulation are also analysed to make sure that the AggSessAC solution works efficiently and to get all the data that characterizes AggSessAC performance.

In order to evaluate the developed AggSessAC functional agent, the required network topology has been created in OMNeT++ environment for simulation experiments (see Fig. 25).

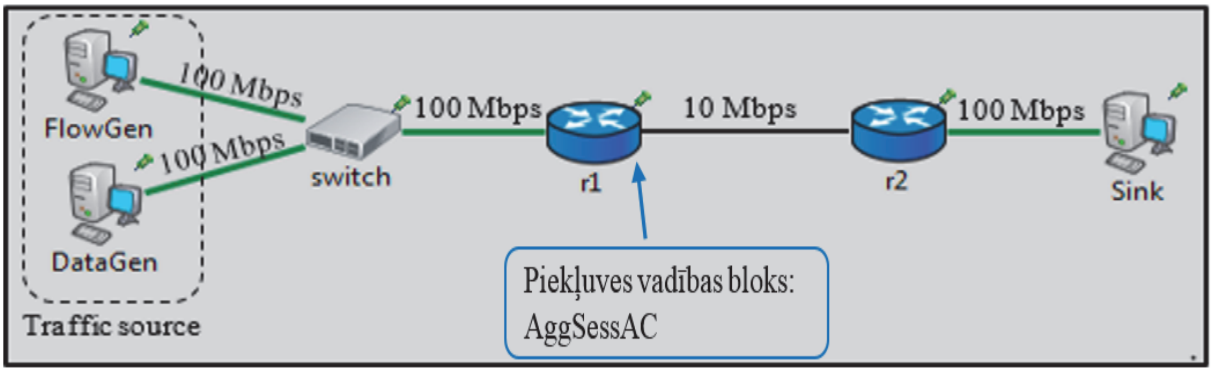

Fig. 25. Experimental network scheme in the *OMNeT++* simulation environment.

Experiment Scenarios and Obtained Results

Simulation experiment scenarios include the analysis of the following parameters:

- evaluation of the obtained revenue using various selected AggSessAC parameters;
- average aggSessACQueue queue length at the decision decision-making moment;
- average time spent by the request in AggSessACQueue queue at the decision-making moment;
- impact on the link load;
- evaluation of the obtained revenue using different input traffic patterns;
- cumulative distribution of the priorities of the approved connections.

Estimation of AggSessAC Method Setup Parameters

The section analyses the AggSessAC method setup parameters – the maximum bundle size and the maximum aggregation period – choice of their values, their mutual dependence and impact on the total revenue.

Traffic that is generated on the input side:

- New admission request inter-arrival distribution – exponential with an average value of 5ms (~ 200 new flow/s).
- Flows sizes – gamma distribution with a mean value of 450 Kbps (flows from 50 to 2000 Kbps) – have been used in all subsequent simulation experiments.
- New flows requests with 8 priority levels, where 1 is the lowest priority, and 8 – the highest priority (see Fig. 26).

New flow connection requests are 5 times more frequent than deactivations of previous connected flows, which determines that links all the time are overloaded and all requests cannot be accepted.

In Figs. 27, 28 and 29, one can see AggSessAC parameter evaluation measurement results obtained during 30s simulation period, within which 5917 connection requests have been received.

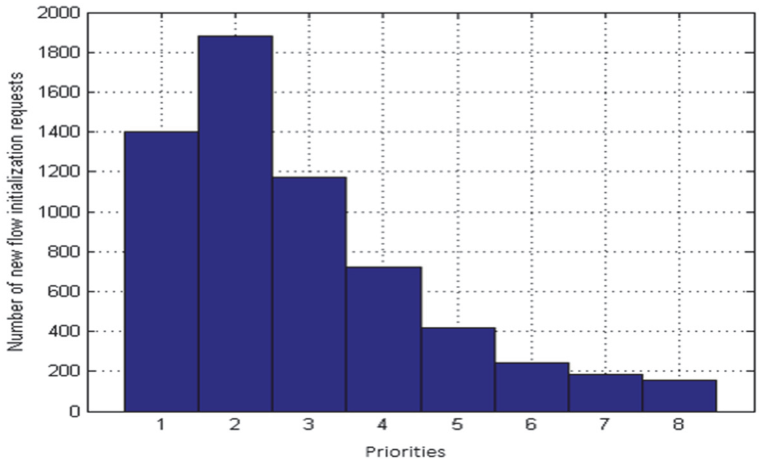

Fig. 26. Pattern with input traffic priorities
(more low-priority requests).

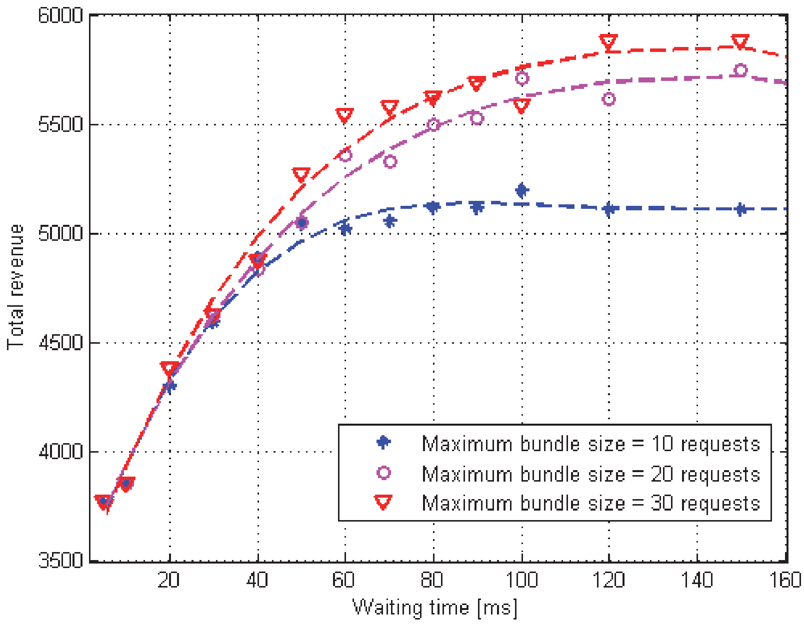

Fig. 27. Total revenue using AggSessAC method depending on the waiting time
for three different bundle sizes.

One can see rapidly increasing revenue obtained with different bundle sizes when the aggregation period is increased (see Fig. 27). This can be explained by an increase in selectiveness at the decision-making moment. The results show how the limit of the aggregation set works, as when it is reached, the revenue is not growing further. **This means that by knowing the average intensity of new connection requests, one can determine the aggregation period,** which is suitable for setting up an aggregation bundle size, so at decision-making moment the set of aggregated requests (bundle) is full at almost all times (see Fig. 28). The results shown in Fig. 28 demonstrate the average AggSessACQueue queue length with respect to different bundle sizes and aggregation periods (the AggSessACQueue module is shown in Fig. 23).

In this scenario, the average flow inter-arrival time is 5 ms, which means that average 50 ms are needed to accumulate 10 requests. They will apply to 20: ~ 100 ms, 30: ~ 150 ms, which are also suitable limits for aggregation period setup. It allows claiming that by using the selected bundle size and following the average new connection arrival rate, it is possible to make adaptive solutions which are able to tune the aggregation period in the online mode. When using the AggSessAC in the network, it is important to know the average intensity of new connections, which makes it possible to set the AggSessAC initial parameter values more accurately. Those parameters are the bundle size and the aggregation period.

Numeric values in three cases with three different bundle sizes and suitably chosen aggregation periods that are provided in Tables 5 and 6.

Table 5

Numerical Simulation Results Using AggSessAC Method for Three Different Bundle Sizes

Simulation time 30 s					
Max. bundle size [new flow requests]	Max. waiting time (aggregation period) [ms]	Total number of flows	Number of rejected flows	Number of accepted flows	Number of decision-making moments
10	50	**5917**	**4676**	**1241**	**680**
20	100	**5917**	**4747**	**1170**	**335**
30	150	**5917**	**4785**	**1131**	**222**

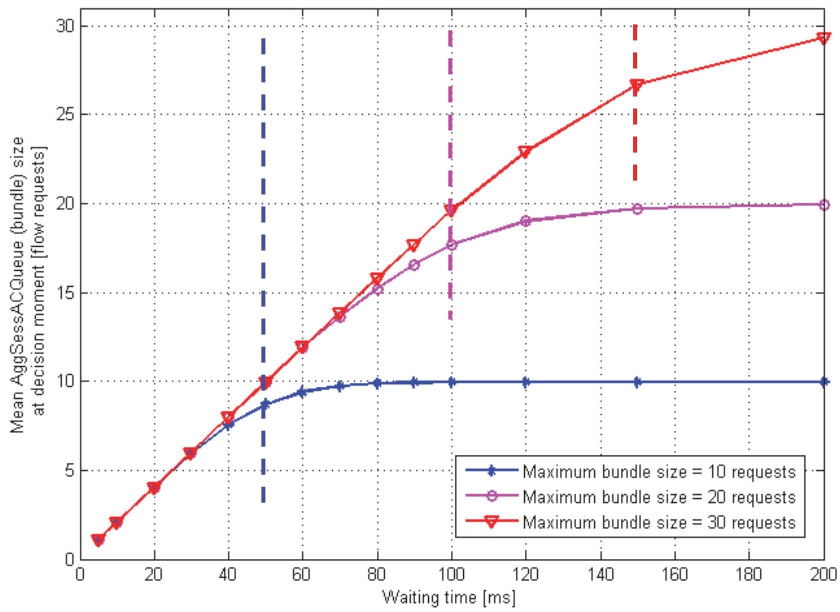

Fig. 28. Mean AggSessACQueue queue (bundle) size at decision-making moment depending on the waiting time (aggregated period) for three different bundle sizes.

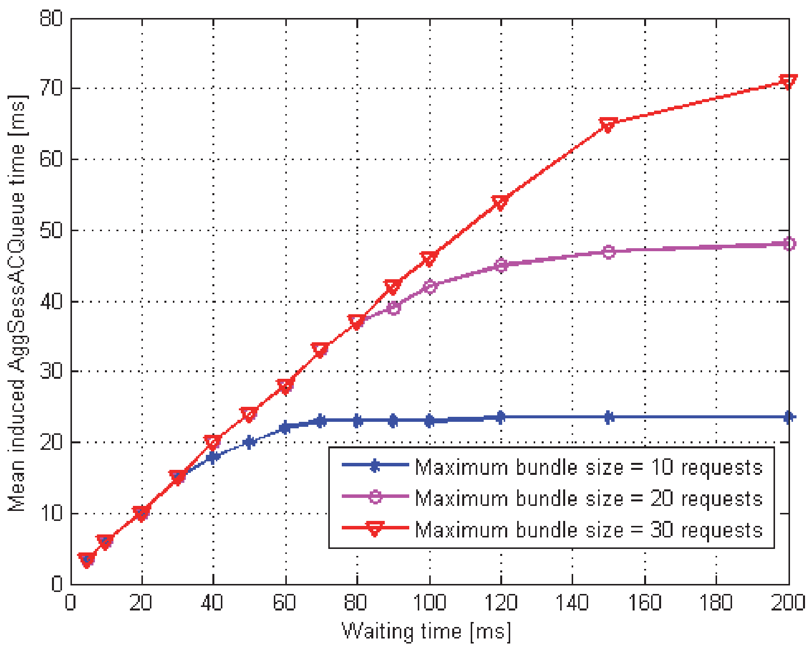

Fig. 29. Mean induced AggSessACQueue queuing time for new requests depending on the waiting time at three different bundle sizes.

Table 6

Numerical Results – Mean AggSessACQueue Size and Mean Induced AggSessACQueue Queuing Time of a New Flow Admission Requests at Decision-Making Moment

Simulation time 30 s			
Max. bundle size [new flow requests]	Max. waiting time (aggregation period) [ms]	Mean AggSessACQueue size [requests]	MeanAggSessACQueue queueing time [ms]
10	50	**8.7**	**21**
20	100	**17.7**	**42**
30	150	**26.9**	**65**

Figure 29 shows the mean induced AggSessACQueue time, which is mean time spent by the new connection initialization packet in AggSessACQueue.

The time spent by a new connection request in the queue makes the *"price"* that AggSessAC solution *"has to pay"* for the possibility to analyse the set of requests at the decision making, thus allowing one to realize selectiveness and implement a pro-active and priority-based admission management policy. Based on the results summarized in Table 6, one can conclude that the average time spent by new connections in the queue is not greater than one half of the selected aggregation period, if the aggregation period is calculated based on information about average intensity of new requests. Substantiation of this conclusion can also be seen in Fig. 30, which depicts the results of simulation experiments with the bundle size of 10 and aggregation period of 50 ms. New requests that arrive later during one aggregation period spend shorter time in AggSessACQueue queue.

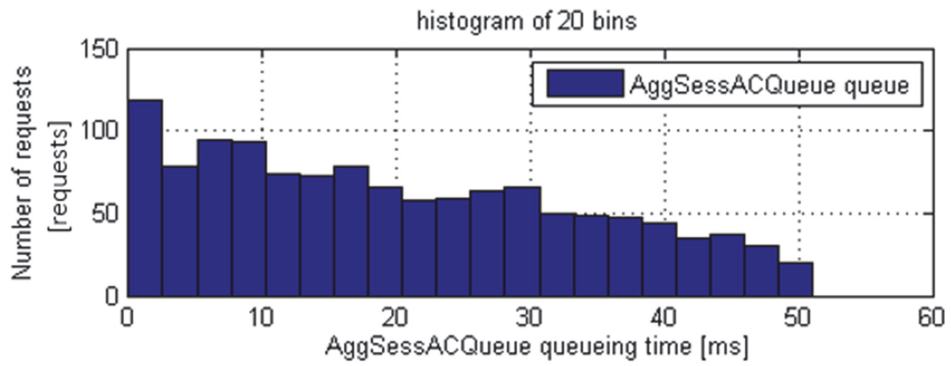

Fig. 30. Queueing time for accepted requests.

Impact on the Bandwidth Utilization

Figure 31 shows the results of impact on bandwidth utilization using the AggSessAC and the approach ThresholdAC method. Numerical values are given in Table 7.

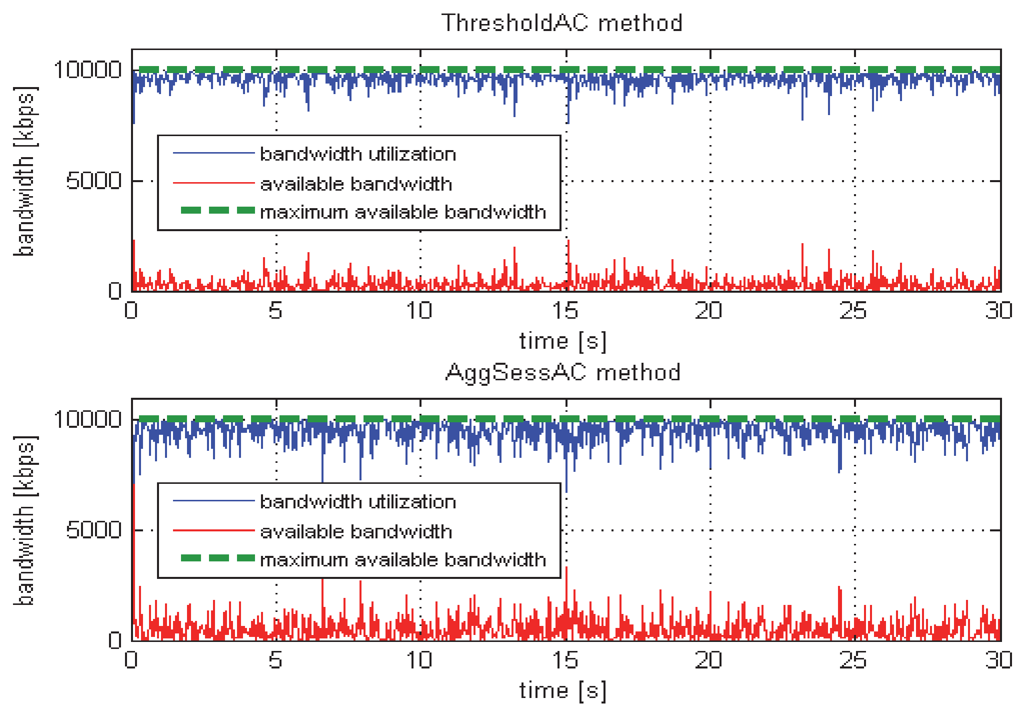

Fig. 31. Bandwidth utilization on 10 Mbps channel with ThresholdAC and AggSessAC method (max. bundle size – 10 and max. waiting time – 50 ms and exponential request inter-arrival time).

In case the AggSessAC method is used, the mean bandwidth utilization is slightly lower if compared to the case when the ThresholdAC method is in use. The main reason is that flows, which are becoming inactive and disabled during an aggregation period, are not so quickly replaced by new ones, as all of the newly accepted flows are connected at the end of the aggregation period. However, it is important to emphasize that a significant impact is created only when AggSessAC is installed in a network where quantitative indicators are unsuitable for this method:

1. The ratio between values of disabled flows (bps) and the total bandwidth;
2. The ratio between the chosen aggregation period and the request intensity.

First of all, in this simulation scenario 10 Mbps throughput channel has been used, with an average flow request size of 450Kbps, which means that on average one disabled flow effect constitutes 4.5 % of the total bandwidth. If we attribute this to a 1 Gbps channel, now it forms only 0.045 %, and in the case of 10 Gbps channel – just tiny 0.0045 %. Secondly, when the channel bandwidth is increasing, we can expect a higher intensity of new flows at the network congestion times, and this in turn leads to shorter aggregation periods. These results confirm the statement of the author of the Thesis that the method is designed for use in high-speed (> 1 Gbps) data networks, thus responding to high intensity of new connections within modern networks.

Table 7

Bandwidth load with ThresholdACand AggSessAC method on 10 Mbps channel

Numerical values with AggSessAC			
Max. bundle size [new flow requests]	Max. waiting time (aggregation period) [ms]	Mean channel load [Mbps]	Difference from ThresholdAC [%]
5	25	9.61	−0.6
10	50	9.42	−2.6
20	100	9.05	−6.4
30	150	8.54	−11.7
Numerical values with AggSessAC			
–	–	9.67	–

Evaluation of the Obtained Revenue

In this case, the calculation of the obtained revenue is based on the desire to achieve the priority-based admission management, the policy of which states that higher priority flows should receive higher advantage of approval.

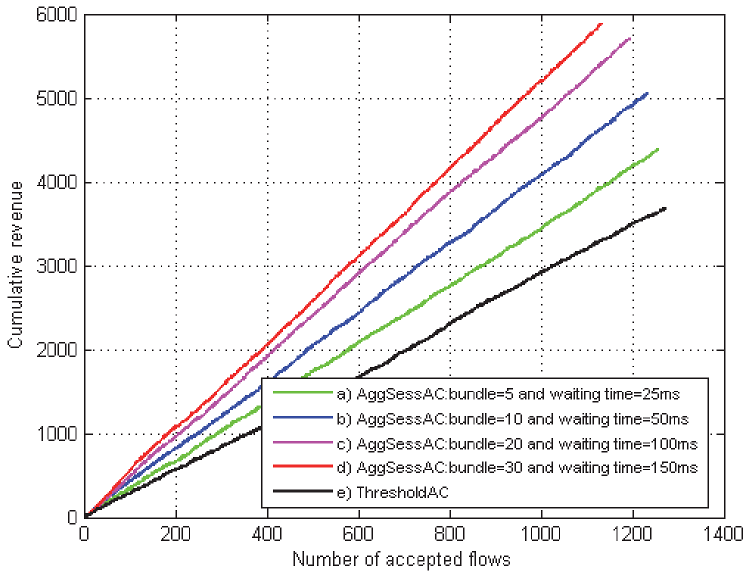

Fig. 32. Cumulative revenue growth with ThresholdAC and AggSessAC method
(at exponential admission request inter-arrival time).

The obtained results in this particular scenario show that the cumulative revenue is 15 % – 37 % higher while using the AggSessAC solution if compared to the cases when ThresholdAC solution is used. The cumulative revenue depends on the number of requests to be evaluated at the same time at the decision-making moment. Results in Fig. 32 demonstrate that increasing the selectiveness of decision-making increases the decision quality. As a result, a bigger number of high quality flows approved increase the cumulative revenue and promote the fulfilment of the management policy.

It should be emphasized that it is possible to achieve such efficiency and implement the priority-based and pro-active management policy using the AggSessAC method because it provides mutual evaluation of multiple requests (bundle) at the moment of decision-making rather than one individual request at a time, as it is in the case of traditional admission management methods.

Evaluation of the Obtained Revenue with Respect to Different Input Priority Distributions

This simulation scenario is configured to generate traffic with exponentially distributed inter-arrival time – 3 different traffic models are used:

a) traffic with the trend to contain more low priority flows than the high priority flows (Fig. 33 (a));
b) traffic that includes the same number of lower and higher priority flows with a relatively smaller number of average priority flows (Fig. 33 (b));
c) traffic with the trend to contain more high priority flows than low priority flows (Fig. 33 (c)).

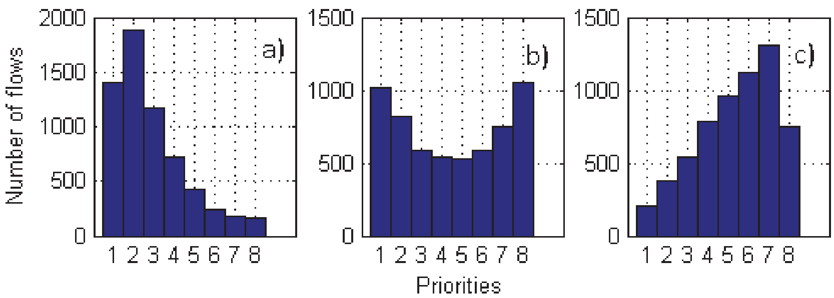

Fig. 33. Input traffic priority patterns.

Results in Fig. 34 show the cumulative revenue at three different input priority patterns (according to Fig. 33) and exponential inter-arrival time distribution using AggSessAC and ThresholdAC methods. It should be noted that while calculating the difference in percent between cumulative revenues provided by ThresholdAC and AggSessAC methods (see Fig. 35), it can be concluded that it mostly differs in the cases where the input traffic contains a lot of low priority flows according to Fig. 33 (a). It shows the AggSessAC solution efficiency in implementation of the priority based management policy and the ability to highlight a small number of high priority flows in the case of low-priority background traffic.

Results from Fig. 36 show that the traditional ThresholdAC method gives in the output a very similar picture to the data in the input, which is due to a lack of choice possibility among requests at the decision-making moment, while in the case of AggSessAC approved flows, the picture varies considerably demonstrating the ability of the AggSessAC to implement the defined management policy.

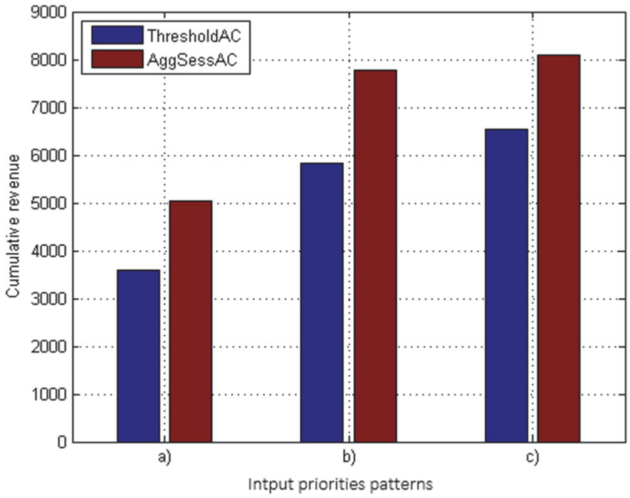

Fig. 34. Cumulative revenue at three different input priority pattern according to Fig. 33 (max. bundle size – 10 and max. waiting time – 50 ms).

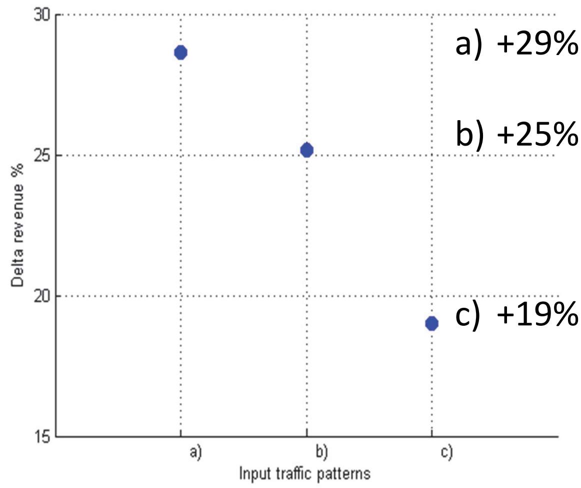

Fig. 35. Delta revenue (obtained difference between ThresholdAC and AggSessAC according to Fig. 34).

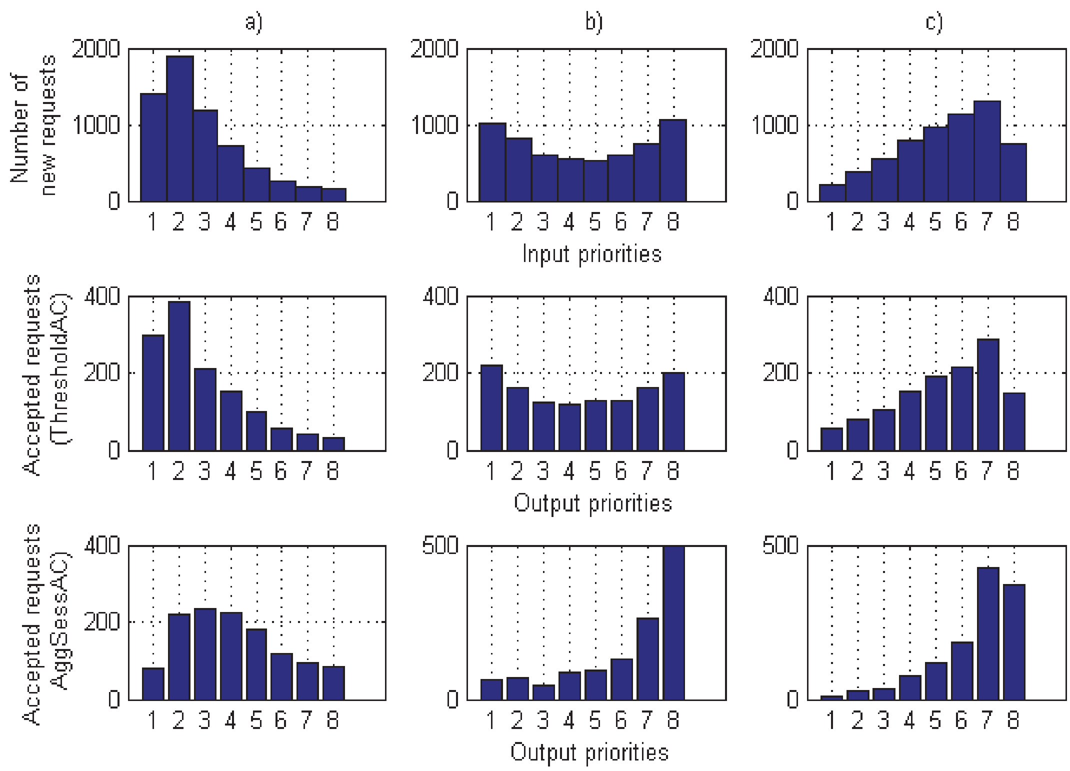

Fig. 36. Histograms of priorities from accepted flows at three different input priority patterns using ThresholdAC and AggSessAC methods.

Impact of Input Flow Inter-Arrival Time Distribution on AggSessAC Performance

The author has also evaluated the performance of the developed **AggSessAC** admission management method with different flow inter-arrival time distributions. Lognormal, exponential and gamma distribution have been chosen with the mean value of 5 ms. Different dispersions have been chosen: 3 ms, 5 ms and 7 ms.

Smaller dispersion of new flow inter-arrival time leads to longer AggSessACQueue queue at the time of the decision-making, and, as a result, we have a bigger number of flow requests for simultaneous evaluation (see Fig. 37). Figure 38 demonstrates that the dispersion of new flow inter-arrival time affects the dissipation of the decision-making moments. Bigger dispersion of new flow inter-arrival times prevents from setting suitable AggSessAC parameter values. By evaluating results reported in Table 8, one can conclude that smaller changes in dispersion along with different distributions do not have significant impact on increase of cumulative revenue and results are very similar for all distributions.

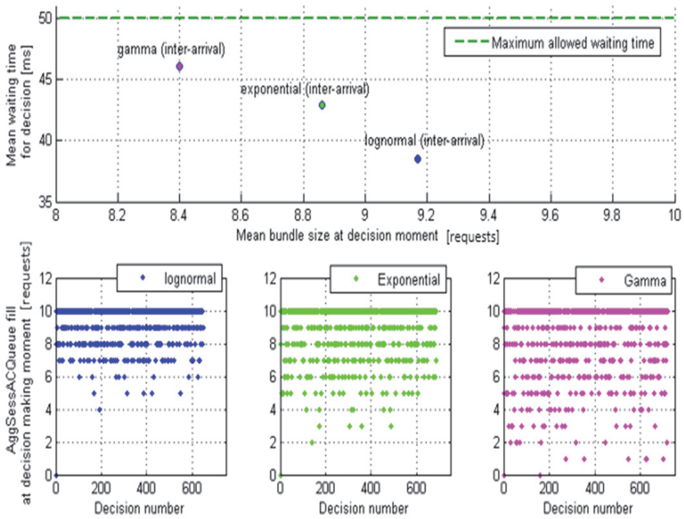

Fig. 37. Mean waiting time and mean AggSessACQueue size at decision moment (max. bundle size – 10 and max. Waiting time – 50 ms).

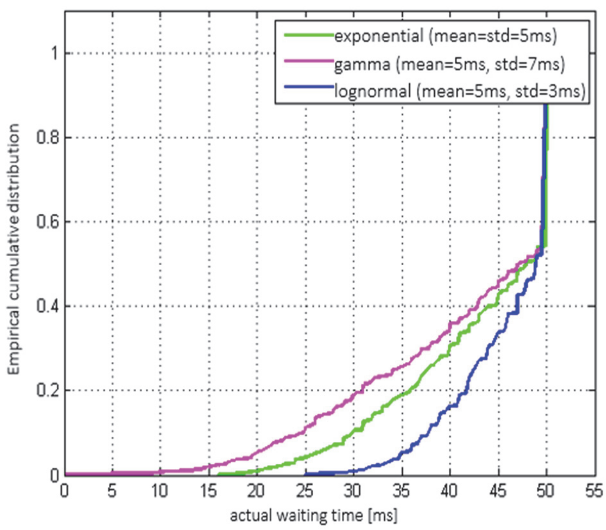

Fig. 38. Empirical cumulative distribution of actual waiting time (max. bundle size – 10 and max. waiting time – 50 ms).

Table 8

Numerical Results Using AggSessAC and ThresholdAC Method

Simulation time – 30 sec							
Distribution of new flow inter-arrival time	***ThresholdAC solution***		***AggSessAC Solution***				
	Revenue	Number of decision	Revenue	Number of decision	Mean waiting time [ms]	Mean AggSessACQueue fill at decision moment [requests]	**Revenue growth**
lognormal	3616	5960	5050	649	46	9.17	**+28.4 %**
exponential	3592	6014	5032	688	44	8.86	**+28.6 %**
gamma	3519	6035	4965	718	42	8.40	**+29.1 %**

Selectivity

The section evaluates the AggSessAC solution performance capabilities with different numbers of traffic priority levels and different priority distributions. Incoming traffic flows are with exponential inter-arrival time and gamma distribution for flow sizes. Bundle size – 10 requests and aggregation period –50 ms.

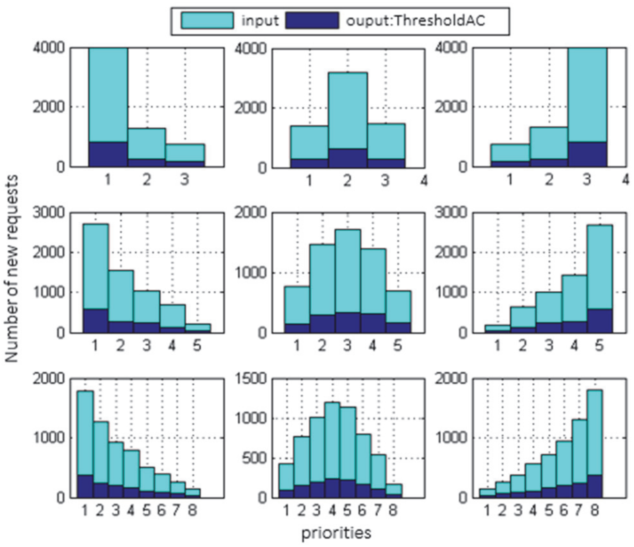

Fig. 39. Input generated and output obtained histograms of accepted flows using ThresholdAC method.

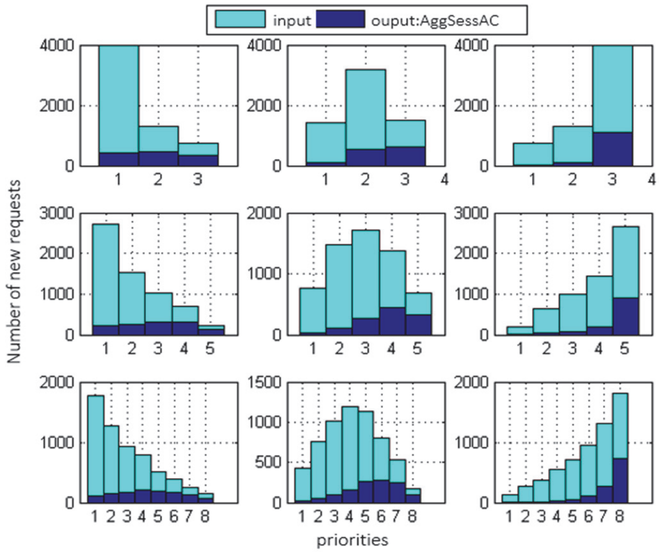

Fig. 40. Input generated and output obtained histograms of accepted flows using AggSessAC method.

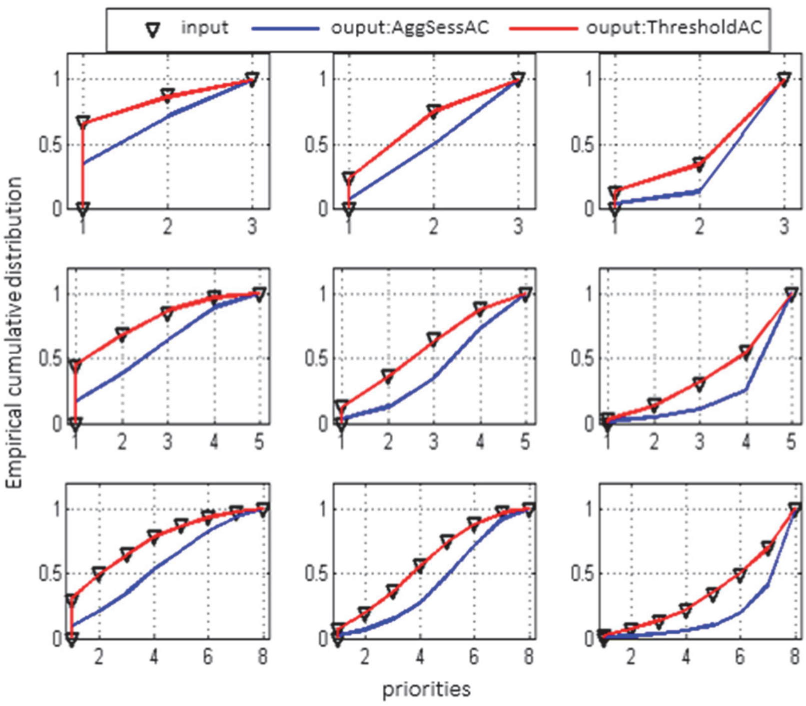

Fig. 41. Input generated and output obtained empirical cumulative distribution of priorities of accepted flows using ThresholdAC and AggSessAC method.

Numeric values for connections of the flows with different priorities, as well as trends can be seen by comparing Figs. 39 and 40. Results in Fig. 39 show that ThresholdAC method, which examines only one request per decision-making moment, makes the output structure of the types of accepted flows the same as at the input. Traditional ThresholdAC access management cannot provide a priority based policy and all the priority classes tend to get the same rejection possibility.

In Fig. 40 one can see the ability of the AggSessAC solution to change the priority structure of the admitted flows. This is also clearly depicted in Fig. 41, where in case of the AggSessAC empirical cumulative distribution curve at the output significantly differs from the input distribution. The direction of changes of empirical cumulative distribution curve at the output depends on the management policy in use. Changes in case of the AggSessAC are achieved due to the method ability to provide mutual evaluation of multiple requests and, as a result, different connections are accepted.

Regardless of the number of priorities of the input traffic and of the distribution of the flows by the priority levels, the **AggSessAC solution increases the quality of the decisions made and, as a result, the cumulative revenue increases depending on the targets of the management policy in use. This is achieved because the AggSessAC solution can implement a selected priority-based management policy and provide the selective flow acceptance at the decision-making moment.**

MAIN RESULTS OF THE DOCTORAL THESIS

During the development of the Doctoral Thesis, the following main results and conclusions have been obtained:

- Growing range of IT services determines that the NGN networks – in relation to any previous generation networks – will be more resource demanding for online services and implementation of the defined management policies. The NGN networks provide shared management and transport layers. Any next generation network will require higher requirements for the management layer that also includes the resource and admission management tasks – they should become faster, more efficient and selective.
- Number of data flows is constantly growing in networks, i.e., the existing resources and access management makes working in μs – ms range at this moment. According to the latest Cisco Compound Annual Growth Rate research, mobile connections through IEEE802.11 access points are constantly growing, bypassing the mobile operator networks and directly loaded fixed network access nodes. The access nodes are loaded with high new flow intensity. Moreover, today, 80 % of TCP flows are characterized by length of 3–10 seconds. Although the amount of UDP traffic (bps) on the Internet is about 10 %, the number of UDP flows is approximately equivalent to the number of TCP flows and more than 80 % of the length of the UDP flows (packets) has dropped to a minimum – contains only a few data packets.
- The existing admission management solutions react instantaneously, sequentially and independently to each new incoming connection request, reducing the opportunity to make selective and priority-based decisions. In this case, the opportunity to selectively choose the priority units can be based only on algorithms with high resource consumption – forecasting, fuzzy logic and other complex solutions to implement a differentiated

management strategy. Forecasting tasks can be effective to identify possible future trends; however, the instantaneous (µs – ms) value prediction is weak and questionable to get reliable results, for example, requirements for the next connection requests.

- None of the studies known to the author of the Thesis consider a possibility of avoiding instantaneous and independent connection request processing, which analyses the set of new connection requests at the moment of decision-making in order to obtain selective and prioritized resources and admission management.
- The developed AggSessAC solution that is based on a short-term collection of requests allows bringing the virtualization of parallel processing into connection admission management and processing requests as a set of events, by enabling one to make comparisons and evaluation among closely following requests.
- The AggSessAC method developed in the Thesis is implemented as a software-based agent in OMNeT++ environment, by extending the functionality of a router available in the INET framework and creating an experimental prototype, which is available for students and researchers in other traffic management studies.
- The redirection of a new connection request to separate queue within the proposed AggSessAC admission management solution ensures that short-term (µs – ms) delay of decision-making does not affect the quality of previously accepted flows. Taking into account that the flow rate [new flows/s] on high speed (gigabit) internet data transmission links has already been measured with a magnitude of 10^3 or higher (analysis of internet traffic has shown that on 10 Gbps links even with magnitude of 10^4), it allows selecting a maximum bundle size, so as delay for new session initializations does not exceed a margin of a few (< 5) milliseconds.
- At the pre-defined bundle length and knowing the mean inter-arrival time of new flows, it is possible to determine the maximum waiting time so that the mean AggSessACQueue queue size (actual bundle size) is close to the pre-defined limit at the moment of decision-making.
- A too short aggregation period (maximum waiting time) reduces the expected efficiency of the AggSessAC method, if the collected number of requests is not close to the pre-defined bundle size at the moment of decision-making.
- Taking into account that AggSessAC method is designed for networks with throughput ≥ 1 Gbps and new flow rate [new flows/s] (measured with a magnitude of 10^3 or higher), the impact on link utilization does not exceed one hundredth of a percent of the total capacity.
- The results show that the selectivity and choice in decision-making contribute to a different flow type approval and provide a strong ability to implement the priority-based management policy by accepting a larger number of high-priority flows, even if the input traffic pattern contains many low-priority data flows compared to the sequential and independent request processing strategy.
- The developed AggSessAC solution provides selective choice and flow-level control, thus in any priority-based policy it is possible to increase the benefits according to the defined management strategy. High quality decision increases the overall efficiency of admission management. Quantitative results will always be dependent on the composition of flow-level of traffic, selected management policy, flow distribution in priority classes, and other parameters that characterize traffic flows.

The aim of the Doctoral Thesis has been achieved and the tasks completed. To summarize, it should be emphasized that the obtained results are very promising. The developed AggSessAC solution provides selective, priority-based and pro-active resource and admission management using a temporary collection of new connection requests in modern high-speed data networks with high intensity of new data flows. AggSessAC operates without affecting the quality of accepted data flows and does not require high computing resources or forecasting solutions to obtain additional information for effective decision-making.

BIBLIOGRAPHY

1. J. Baraković, H. Bajrić, S. Baraković, "Priority Level Configuration for Signaling Service Class," *2010 Third International Conference on Communication Theory, Reliability, and Quality of Service (CTRQ), 2010,* pp. 122–127.
2. T. Barnett, Cisco VNI Complete Forecast Update: Key Trends Include Mobility, M2M and Multimedia Content, May 27, 2015. Source – Cisco VNI*: Global IP Traffic Forecast, 2014–2019.* Internets. – *http://blogs.cisco.com/sp/2015-cisco-vni-complete-forecast-update-key-trends-include-mobility-m2m-and-multimedia-content.*
3. S. Blake *et. al.,* "An Architecture for Differenciated Services," IETF RFC 2475, Dec. 1998.
4. P. Carvalho, P. Solis, B. Queiroz, B. Carneiro, M. Deus. "A Traffic Analysis per Application in real IP/MPLS Service Provider Network," In: *Broadband Convergence Networks, BcN '07. 2nd IEEE/IFIP International Workshop*, 2007, pp. 1–5.
5. B. K. Choi, D. Xuan, C. Li, R. Bettati, and Wei Zhao, "Utilization-Based Admission Control for Scalable Real-Time Communications," In *Journal of Real-Time Systems*, Vol. 24, No. 2, 2003, pp. 171–202.
6. Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update 2014–2019, White Paper. Internets. – *http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white_paper_c11-520862.html.*
7. Cisco Visual Networking Index: Forecast and Methodology, 2015–2020, White paper. *Internets. – http://www.cisco.com/c/dam/en/us/solutions/collateral/service-provider/visual-networking-index-vni/complete-white-paper-c11-481360.pdf.*
8. Cloud Series Devices. Internets. – *http://cloudcorerouter.com/.*
9. A. Dainotti, A. Pescapè, and K. Claffy, "Issues and future directions in traffic classification,"*IEEE Network*, vol. 26, no. 1, pp. 35–40, Jan 2012.
10. I. Din, N. Saqib, A. Baig "Passive analysis of web traffic characteristics for estimating quality of experience," *GLOBECOM Workshops*, *2008 IEEE*. IEEE, 2008, pp. 1–5.
11. W. de Donato, A. Pescapè, and A. Dainotti, "Traffic Identification Engine: An Open Platform for Traffic Classification", IEEE Network, vol. 28, no. 2, Mar., 2014, pp. 56–64.
12. H. Ekström, "QoS Control in the 3GPP Evolved Packet System," *IEEE Commun. Mag*., Vol. 47, No. 2, Feb. 2009, pp. 76–83.
13. M. Feknous, T. Houdoin, B. Le Guyader, J. De Biasio, A. Gravey, J. A. Torrijos Gijon, "Internet traffic analysis: A case study from two major European operators," in *Proceedings of the 2014 IEEE Symposium on Computers and Communication (ISCC)*, Funchal, 23–26 jun., 2014, pp. 1–7.
14. P. Flavius, P. Ferdi, "Internet Service Delivery Models: Evolution and Current Issues," *2011 International Conference on Cyber-Enabled Distributed Computing and Knowledge Discovery (CyberC),* 2011, pp. 146–153.
15. S. Floyd, "Comments on Measurement-based Admissions Control for Controlled-Load Service," *Submitted to Computer Communication Review*, 1996.

16. V. R. Gandhi, Y. R. Qu, V. K. Prasanna, "High-throughput hash-based online traffic classification engines on FPGA," in Proc. *2014 International Conference on ReConFigurable Computing and FPGAs (ReConFig14),* Cancun, Dec. 2014, pp. 1–6.
17. T. Ganegedara and V. K. Prasanna, "StrideBV: Single Chip 400G+ Packet Classification," in *13th IEEE International Conference on High Performance Switching and Routing (HPSR)*, 2012, pp. 1–6.
18. E. Garsva, N. Paulauskas, G. Grazlevicius, L. Gulbinovic, "Packet Inter-arrival Time Distribution in Academic Computer Network, "*Electronics and Electrical Engineering*, No. 20(3) ISSN 1392-1215, Lithuania, Kauna, 2014, pp. 87.–90.
19. S. Gebert, R. Pries, D. Schlosser, and K. Heck, "Internet Access Traffic Measurement and Analysis," In *Proceedings of the 4th international conference on Traffic Monitoring and Analysis*, Viennna, Austria, 2012, pp. 29–42.
20. INET Framework. Internets. – *http://inet.omnetpp.org/.*
21. Recommendation ITU-T Y.2001 "General overview of NGN", 2004.
22. Recommendation ITU-T Y.2111, "Resource and Admission Control Functions in NGN", 2011.
23. S. Jamin, P. B. Danzig, S. Shenker and L. Zhang. "A Measurement-based Admission Control Algorithm for Integrated Services Packet Network," *IEEE/ACM Transactions on Networking*, Vol. 5, Iss. 1, 1997, pp. 56–70.
24. S. Jamin, S. Shenker, and P. Danzig. "Comparison of Measurement-based Admission Control Algorithms for Controlled-Load Service," in *Proc. of INFOCOM '97*, Vol. 3, April 1997, pp. 973–980.
25. J. Jelinskis, A. Skrastins, G. Lauks, "Fuzzy-CAC Driven MPLS-TE Realization," *12th IEEE International Conference on High Performance Switching and Routing*, Spain, Cartagena, Jul. 4.–7., 2011, pp. 146–150.
26. J. Jelinskis, A. Skrastins, G. Lauks, "Practical Fuzzy-CAC Realization for Effective Traffic Engineering in MPLS-TE Network," *Electronics and Electrical Engineering. – Kaunas: Technologija*, 2011. – No. 4(110), pp. 30.–34.
27. J. Jelinskis, A. Skrastins, G. Lauks. "Fuzzy-CAC based Traffic Management in MPLS-TE Networks," *11th International Conference on Telecommunications, ConTEL 2011*, Graz, Austria, Jun. 15.–17., 2011, pp. 389.–395.
28. Y. Jia, M. Chen, "A new architecture of providing end-to-end quality-of-service for differentiated services network," in *Proc. of IEEE Military Communications Conference 2001(MILCOM 2001)*, No. 1, Oct. 2001 pp. 1451–1456.
29. W. Jiang and V. K. Prasanna, "Large-scale wire-speed packet classification on FPGAs," in *Proc. FPGA '09. ACM*, 2009, pp. 219–228.
30. W. Jiang and V. K. Prasanna, "Scalable Packet Classification on FPGA," *IEEE Trans. VLSI Syst.*, Vol. 20, No. 9, 2012, pp. 1668–1680.
31. W. John and S. Tafvelin, "Analysis of internet backbone traffic and header anomalies observed," in *Proceedings of the 7th ACM SIGCOMM conference on Internet measurement. ACM*, 2007, pp. 111–116.
32. M. Kuļikovs and E. Pētersons "Real-Time Traffic Analyzer for Measurement-Based Admission Control," in *Proceeding of The Fifth Advanced International Conference on Telecommunications AICT2009,* Venice/Mestre, Italy, 2009, pp. 72–75.
33. M. Kuļikovs, E. Pētersons and S. Šarkovskis "Integral measurement process of incoming traffic for Measurement-Based Admission Control" in *Proceedings, 2010 IEEE Region 8 International Conference on Computational Technologies in Electrical and Electronics Engineering,* Russia, Irkutsk, Listvyanka, Vol. 1, 2010, pp. 183–186.
34. K. C. Lan and J. Heidemann, "A measurement study of correlations of Internet flow characteristics," *Computer Networks*, Vol. 50, No. 1, Jan. 2006, pp. 46–62.

35. D. Lee, B. E. Carpenter, N. Brownlee “Media Streaming Observations: Trends in UDP to TCP Ratio”, International Journal on Advances in Systems and Measurements, Vol. 3, No. 3 and 4, April, 2011, pp. 147–162.
36. R. Leira, P. Gomez, I. Gonzalez and J. E. Lopez de Vergara, “Multimedia flow classification at 10 Gbps using acceleration techniques on commodity hardware,” in *Proc. of SaCoNeT*, Vol. 3, Paris, 2013, pp. 1–5.
37. B. Li, J. Springer, G. Bebis, M. H. Gunes “A survey of network flow applications,” *Journal of Network and Computer Applications*, Vol. 36, No. 2, 2013, pp. 567–581.
38. X. Li, S. Paul. “Class-based Bandwidth Allocation and Admission Control for QoS VPN with DiffServ,” *Comsware 2006*, New Delhi, 2006, pp. 1–10.
39. Y. Ma, S. Banerjee, S. Lu, and C. Estan, “Leveraging Parallelism for Multi-dimensional Packet Classification on Software Routers,” *SIGMETRICS Perform. Eval. Rev.*, Vol. 38, No. 1, 2010, pp. 227–238.
40. M. Marstonand F. Mistree, “An implementation of expected utility theory indecision based design,” in *Proc. 10th International Conference on Design Theory and Methodology (DETC)*, Atlanta, GA, USA, 1998, pp. 1–11.
41. K. Mase and Y. Toyama, “End-to-End Measurement Based Admission Control for VoIP Networks,” *IEEE ICC*, 2002, pp. 1194–1198.
42. A. Meddeb, “Internet QoS: Pieces of the puzzle,” *IEEE Communications Magazine*, Vol. 48, No. 1, January 2010, pp. 86–94.
43. N. Moghim, S. M. Safavi and M. R. Hashemi, “Evaluation of a new end-to-end quality of service algorithm in differentiated services networks,” *IET Communications Magazine*, Vol. 4, No. 14, Sep. 2010, pp. 1687–1695.
44. J. von Neumann and O. Morgenstern, The Theory of Games and Economic Behavior, New York, USA: Princeton University Press, 1944.
45. T. Nguyen and G. Armitage, “A Survey of Techniques for Internet Traffic Classification Using Machine Learning, ”*IEEE Comm. Surveys Tutorials*, Vol. 10, No. 4, 2008, pp. 56–76.
46. S. Oueslati and J. Roberts, “A new direction for quality of service: Flow aware networking,” NGI 2005, Rome, April 18–20, 2005, pp. 226–232.
47. T. Pan, X. Guo, C. Zhang, J. Jiang, H. Wu, and B. Liuy, "Tracking millions of flows in high speed networks for application identification," in INFOCOM, 2012 Proceedings IEEE, March 2012, pp. 1647–1655.
48. Y. R. Qu, V. K. Prasanna “Compact Hash Tables for High-performance Traffic Classification on Multi-core Processors,” *2014 IEEE 26th International Symposium on Computer Architecture and High Performance Computing (SBAC-PAD 20014)*, France, 2014, pp. 17–24.
49. Y. Qu, S. Zhou, and V. K. Prasanna, “Scalable Many-Field Packet Classification on Multi-core Processors,” in *Proc. of SBAC-PAD*, Porto de Galinhas, Oct. 2013, pp. 33–40.
50. Y. Saito, M. Hasegawa, Y. Murata. “A Fast and Efficient End-to-End QoS Measurement Scheme for Real Seamless Handover,” *IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications. PIMRC 2007.* Athens, Sept. 2007, pp. 1–5.
51. R. Sharma, N. Kumar, S. Talabattula, “Performance of New Dynamic Benefit-Weighted Scheduling Scheme in DiffServ Networks,” in *Proc. Advances in Computing, Communications and Informatics (ICACCI 2014)*, Sept. 2014, pp. 2578–2583.
52. Z. Shijie, P. R. Nittoor, V. K. Prasanna, “High-Performance Traffic Classification on GPU” in *Proc. IEEE 26th International Symposium on Computer Architecture and High Performance Computing (SBAC-PAD 2014)*, Jussieu, Oct., 2014, pp. 97–104.
53. R. Stankiewicz, P. Cholda, and A. Jajszczyk. “QoX: what is it really?” *Communications Magazine*, Vol. 49, Iss. 4, Apr., 2011, pp. 148–158.
54. B. Statovci-Halimi, “Adaptive admission control for supporting class-based QoS,” *2010 6th EURO-NF Conference on Next Generation Internet (NGI 2010),* Paris, 2–4 June, 2010, pp. 1–8.

55. B. Statovci-Halimi, V. C. Emeakaroha. “Framework for multi-class and dynamic flow-aware admission control,” in *Proc. The 34th Annual IEEE Conference on Local Computer Networks (LCN 2009)*, Zurich, Oct. 2009, pp. 344–347.
56. Y. Sun, Z. Zhang, L. Guo, S. Bai, and J. Tan, “A Effective Algorithm for Counting Active Flows Based on Loop Bloom Filter,” in *Proc. IEEE International Conference on Networking, Architecture, and Storage (NAS)*, Chongqing, China, June 2008, pp. 104–109.
57. The CAIDA UCSD Statistical information for the CAIDA Anonymized Internet Traces, Internets – *http://www.caida.org/data/passive/trace_stats/.*
58. D. Tong, Y. R. Qu, V. K. Prasanna, “High-throughput traffic classification on multi-core processors,” *2014 IEEE 15th International Conference on High Performance Switching and Routing (HPSR),* Canada, 2014, pp. 138–145.
59. A. A. Wahid, J. Schormans, “Bounding the maximum sampling rate when measuring PLP in a packet buffer,” *Computer Science and Electronic Engineering Conference (CEEC),* Colchester, Sept., 2013, pp. 115–118.
60. P. White, “RSVP and Integrated Services in the Internet: A tutorial,” *IEEE Communications Magazine*, Vol. 35, No. 5, 1997, pp. 100–106.
61. B. Whitehead, C.-H. Lung, and P. Rabinovitch, “Tracking Per-Flow State – Binned Duration Flow Tracking,” in *Proc. of SPECTS*, Ottawa, July, 2010, pp. 73–80.
62. B. Whitehead, Chung-Horng Lung, P. Rabinovitch “An Efficient Approach to Per-Flow State Tracking for High-Speed Networks” in *Proc. of IEEE GLOBECOM 2010*, 6.–10. Dec, 2010, pp. 1–6.
63. Wireshark network protocol analyzer. Internets – https://www.wireshark.org/.
64. Z. Yongqing, M. Maode, and C. Tee-Hiang, “A Novel Multiple Access Scheme for Ethernet Passive Optical Networks,” *IEEE GlobeComm’03,* Vol. 5, 2003, Dec. 2003, pp. 2649–2653.
65. X. Zhang, W. Ding, “Comparative Research on Internet Flows Characteristics,” in *Proc. Networking and Distributed Computing (ICNDC 2012)*, Hangzhou, Oct., 2012, pp. 114–118.
66. M. Zhang, M. Dusi, W. John, and C. Chen, “Analysis of udp traffic usage on internet backbone links,” in *Ninth Annual International Symposium on Applications and the Internet, 2009. SAINT '09,* IEEE, Bellevue, WA, 2009, pp. 280–281.