RIGA TECHNICAL UNIVERSITY

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FUZZY-LOGIC BASED ADMISSION CONTROL FOR MPLS-TE/GMPLS NETWORKS

Summary of Promotion Thesis

Riga 2011

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Faculty of Electronics and Telecommunications

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PROMOTION THESIS

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The public defense of the promotion thesis, submitted for the degree of Doctor of Engineering Science, takes place at the Faculty of Electronics and Telecommunications of Riga Technical University, 12 Azenes St., Room 210, Riga, Latvia, on the 15th December of 2011 at 17:00.

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CONFIRMATION

I confirm that the promotion thesis, submitted to Riga Technical University in fulfillment of the requirement for the degree of Doctor of Engineering Sciences, is my own work. The promotion thesis has not been submitted for a scientific degree to any other university.

Jans Jelinskis…………………………….

Date: ……………………………………….

The promotion thesis is written in Latvian and contains introduction, four chapters, main conclusions and recommendations, list of bibliography, 2 appendices, 90 figures, 174 pages in total. The bibliography includes 148 sources.

GENERAL DESCRIPTION OF THE THESIS

Topicality of the Subject Matter

Nowadays, the traffic management deals with many unresolved issues including traffic engineering of high-speed optical telecommunications networks. Along with the rapid development of multimedia applications [15], the assurance of quality of service (QoS) to end users has become one of the most important problems in electronic communications.

The traffic management of access networks and small sub-networks does not produce significant problems, since most of these Internet subsections are not constantly overloaded. In turn, the effective and proactive traffic management at a back-bone level plays a decisive role to ensure an effective use and sustainability of the parameters of QoS within acceptable limits.

At present, the main role at back-bone network level is played by a multi-protocol level switching with traffic engineering (MPLS-TE), which will evolve into a generalised MPLS (GMPLS) to ensure data transmission in super-fast optical transmission networks based on FTTx un PON transmission technologies. [6, 3, 4, 13, 17, 5, 7].

The setup of LSP in MPLS-TE networks can be accomplished by means of the RSVP-TE protocol. The RSVP-TE is described in detail in IETF RFC3209 and expanded in RFC5151. Making a CAC decision, it allows setting up a LSP channel of MPLS-TE networks, taking into account such restrictive parameters as the available bandwidth and the exact number of hops.

In February of 2003, the MPLS Group of IETF decided to abandon the development of the alternative signalling protocol CR-LDP (RFC3212) and focus solely on the development of the RSVP-TE protocol. The reason of that was the review of the first GMPLS realizations, published in June 2002, which showed that 21 out of 22 analyzed solutions implemented the RSVP-TE protocol and only one – the CR-LDP protocol [56]. Thus, the development and modifications of the RSVP-TE protocol are also applicable to the management layer of GMPLS networks, which is considered to be the main management technology of NGN networks.

Taking into account all the above, we can say that the problem of the traffic management for MPSL-TE networks is gaining topicality. The modern MPLS networks set up LSP mostly manually, reserving resources by means of the RSVP-TE protocol. Traffic routing is accomplished via pre-set LSP, based on pre-defined classes of QoS.

While reserving resources by means of the RSVP-TE protocol, a problem occurs if the CAC control is accomplished by means of the classic CAC algorithm, according to which a connection is allowed if available resources exceed required resources of a link.

A connection is rejected if the required resources are below the available resources of a connection link. Such an LSP management method does not take into consideration the QoS requirements of an application and the characteristic values of QoS of a network. The new LSP flows are connected despite the class of QoS, which the session data belong to, and despite the fact that such QoS parameters as packet delay, packet delay jitter and packet loss have to be ensured to data carrier.

The promotion thesis introduces some modifications of the RSVP-TE protocol in order to ensure the selective set-up of an LSP tunnel in MPLS-TE networks. The introduced modifications allow implementing dynamic, application-controlled LSP management and ensure the control of QoS parameters at the moment of connection set-up.

In order to ensure the selective management of traffic, two main methods can be applied:

- massive decision-making systems, based on the successive evaluation of multiple parameters and large-scale bases of *IF-THEN* rules;
- fuzzy-logic decision-making systems.

The latter implements a compact IF-THEN data base, provides a fast response based simultaneously on many criteria and does not require a high preciseness of input variables.

Nowadays, the studies of the CAC management are raising a great interest. It affects a wide range of telecommunications services and networks [19, 20, 18, 21, 55, 27, 2, 54]. Some recent research studies have been also dedicated to the CAC management of MPLS networks [14, 1]. However, as the author of the thesis knows, the application of fuzzy logic to the CAC management of MPLS networks was analyzed in only one research study [25], which, however, did not consider the QoS controlling mechanism at the stage of an LSP set-up.

All the above problems motivated the author to address this issue and resulted in this promotion thesis. The thesis is dedicated to the application of fuzzy-logic methods to solving a CAC task in NGN networks with MPLS-TE/GMPLS management layer, using the RSVP-TE protocol.

Aims and Tasks

Taking into account the forecasts predicting a rapid growth of multimedia traffic in modern telecommunications networks, the new requirements for the traffic management of the MPLS-TE management layer are advanced, such as the ability to provide the dynamic setup of an application-controlled LSP and proactive traffic management, sustaining the parameters of QoS within the accepted limits.

These requirements demand new solutions to be applied to the LSP flow management, ensuring the QoS requirements within a point-to-point connection.

Therefore, the main aim of the promotion thesis was to introduce a new method for designing the fuzzy-CAC algorithm, which would eliminate these shortcomings, as well as to estimate the fuzzy-CAC abilities within the MPLS-TE (GMPLS) traffic transmission / management system using the RSVP-TE protocol and the dynamic LSP setup.

In order to achieve the advanced goals, the following problems were solved:

- To analyze scientific literature, find effective solutions for systems with proactive management and uncertainty, and apply them to solve a certain problem;
- To determine the limits of the modern traffic management paradigms;
- To develop the MPLS-TE and fuzzy-CAC models for practical research studies, which would serve as a basis for simulating an experimental network realization, as well as to identify the factors limiting QoS and their limits for the MPLS-TE, taking into account the existing service level agreements (SLA) and the properties of a selected model;
- Taking into account the limits of a model and implementing a heuristic approach, to develop the fuzzy inference system, which would provide the selective LSP setup and sustain the QoS parameters within the pre-defined limits;
- To develop the experimental MPLS-TE communication system and simulation environment as well as to accomplish the practical realization of the classic threshold-CAC and fuzzy-CAC algorithms under identical conditions to make a further comparison of produced results;
- To analyze the adaptation methods of the fuzzy-CAC algorithm, such as modifying the membership functions of input linguistic variables and post-processing the fuzzy-CAC responses.

Research Methods

The fuzzy-CAC inference systems (FIS) and MPLS-TE network models were developed. In the practical part of the thesis the MPLS-TE communication system was studied by applying the RVSP-TE protocol and the CAC-management with both a classic threshold and a fuzzy-CAC realization, with further comparison of produced results.

In order to achieve the advanced targets, the heuristic sampling, test-and-trial procedures as well as experimental measurements were applied in the thesis.

Research Results and Scientific Novelty

The scientific novelty of the thesis refers to introducing the CAC management of the RSVP-TE protocol implemented in the MPLS-TE communication method by means of fuzzy logic.

The fuzzy-CAC solution introduced by the author provides the appropriate QoS parameters of the LSP flows such as the packet delay, packet delay jitter and packet losses.

As the author knows, this is the first time when the CAC algorithm based on fuzzy logic was introduced to set up the LSP in MPLS-TE networks, taking into account the fuzzy samples of input and output parameters as well as the IF-THEN-rule knowledge base.

The author claims that this is the first time, when the efficient fuzzy-CAC, complying with the pre-defined requirements, was implemented in the experimental MPLS-TE communication system.

This promotion thesis is the first research study dedicated to the effectiveness of the fuzzy-CAC integrated into the MPLS-TE communication systems, and it involves not only theoretical and simulation studies but also verifies the effectiveness of the proposed fuzzy-CAC algorithm at the packet level. The experimental MPLS-TE communication network was developed to satisfy these purposes.

Original Results

- There was developed the new fuzzy-CAC management method, which is capable of managing the RSVP-TE protocol of the MPLS-TE (GMPLS) networks by means of fuzzy logic.

- There was identified the optimal (from the point of view of the utilization criterion and limits) fuzzy-CAC FIS structure, which involves:
  - linguistic variables of the fuzzy-CAC input and output parameters;
  - types and parameters of the membership functions of linguistic variables;
  - base of IF-THEN rules;
  - typed and parameters of the fuzzification curves for input parameters;
  - de-fuzzification methods for output parameters.

- Based on the results of this research study, the recommendations regarding the use of all the FIS elements were provided

- There was proposed the original classification method for the states of the fuzzy-CAC, which involves three different responses:
  - admit the LSP setup;
  - reject the LSP setup;
  - admit the LSP setup with reservation of additional resources.

This solution allows providing the so called “safety cushion” for high-priority LSP flows of a link, which is directly proportional to high-priority LSP flows of the link.

- There were found some relations between the RSVP-TE reserved resources, fuzzy-CAC rejected flows and the threshold coefficient for post-processing the FIS response of the fuzzy-CAC solution. It allows us making the instantaneous adjustments of the fuzzy-CAC policy depending on the changes of external environment.

- The developed design method makes it possible to implement adaptive algorithms, which take into account the changes of external environment.

- By applying the fuzzy-CAC algorithm and setting up the LSP channels in a selective way, the link utilization decreases as compared to the threshold-CAC method, sustaining, at the same time, the QoS parameters within accepted limits.

Practical Significance

- The fuzzy-CAC FIS model was developed, verified and validated.
- There was developed the practical fuzzy-CAC realization applied for the management of the RSVP-TE protocol within the MPLS-TE network, as well as the experimental product.
- The experimental MPLS-TE communication network with the management of the RSVP-TE protocol, based on fuzzy logic, provides a technological basis for a wide range of research studies aimed at the application of fuzzy-CAC preserving the appropriate QoS parameters.
- Based on the experimental MPLS-TE communication network and implementing the fuzzy-CAC management of multiple routers by means of appropriate software (e.g., JADE), it is possible to implement the cooperation of multiple fuzzy-CAC agents via a multi-agent connection.
- The developed experimental network and corresponding software were used in developing bachelor's and master's theses;
- There was developed the method of correcting the performance of the MPLS-TE router, which is capable of managing the RVSP-TE protocol by means of the fuzzy-CAC inference system (FIS).

Main Scientific Results

- It was proved that the CAC decision-making policy of the RSVP-TE protocol, applied in the MPLS-TE networks, was based solely on the available bandwidth of a link. This approach ensures effective traffic management in the MPLS-TE networks. The CAC management, developed in the thesis, is based on the fuzzy-logic decision-making mechanism, and enables the simultaneous analysis of multiple QoS parameters at the decision-making moment. This performs the selective setup of LSP channels taking into account the QoS requirements on the application side and the QoS parameters of a network. At the same time, this enables sustaining the QoS parameters within accepted limits.
- The CAC solution, based on fuzzy logic, decreases the number of rejected LSP flows as well as increases the number of connections of high QoS level, sustaining the QoS parameters within the accepted limits.
- The fuzzy-CAC solution with three CAC decisions, which include admitting the LSP connection with additional resource reservation, ensures proactive traffic management developing the so called "safety cushion" for LSP channels, the "size" of which is directly proportional to the admitted high-priority LSP flows and ensures sustaining the QoS parameters within accepted limits.
- The estimation of performance of the fuzzy-CAC algorithm, implemented within the MPLS-TE experimental network reserving the resources of the RSVP-TE

protocol at the moment of setting LSP channels, shows that even in the case of an overloaded network characterized by “bursty” traffic, the fuzzy-CAC enables the selective control of LSP flows and lighter degradation of QoS parameters.

- It was proved that it is possible to perform fast post-processing of the responses of the fuzzy decision-making mechanism by setting a proper threshold for the fuzzy-CAC responses, which instantly modifies the policy of the fuzzy-CAC algorithm without changing the membership functions of linguistic input variables and / or the base of IF-THEN rules.
- It was proved that applying such methods of output de-fuzzification of membership functions as SOM, MOM and LOM, the volume of the base of IF-THEN rules decreases. In turn, this disables the effective post-processing of fuzzy-CAC responses.

Hypotheses to Defend

- In comparison to the classic threshold-CAC algorithm, the CAC algorithm based on fuzzy logic and applied to managing reservation of the RSVP-TE resources (as well as GMPLS resources, in future), ensures the maximum average utilization of a link sustaining the pre-defined degradation limits of QoS.
- In comparison to the classic threshold-CAC algorithm, the fuzzy-CAC solution enables the selective procedure of traffic flows to develop the LSP tunnels within MPLS-TE networks (as well as future GMPLS networks) and increases the number of connections of high-class QoS, ensuring the appropriate QoS parameters.
- By applying the fuzzy-CAC algorithm instead of the classic threshold-CAC algorithm within MPLS-TE networks (as well as GMPLS networks, in future), it is possible to decrease the number of flow connections non-complying with QoS requirements of a link at the moment of setting the LSP, and, in this way, to decrease the number of admitted data flows disconnected early due to the discrepancy of QoS parameters.
- In comparison to the classic threshold-CAC algorithm, the fuzzy-CAC solution can provide fast and effective real-time modification of traffic management policy within the MPLS (as well as GMPLS in future) routers, adopting it to an unsteady network environment.

Approbation of Research Results

The effectives of the fuzzy-CAC algorithm was tested in comparison with the classic threshold-CAC algorithm applied to the RSVP-TE, at both the flow level and the packet level, proving its ability to ensure the selective setup policy for the LSP and proactive traffic management paradigm.

The main results of the promotion thesis were declared at the following conferences:

1. Electronics and Electrical Engineering, Kaunas (Lithuania), May 21-23, 2007.

2. 48th International Scientific Conference of Riga Technical University, Riga (Latvia), Oct. 12, 2007.
3. Electronics and Electrical Engineering, Kaunas (Lithuania), May 20-22, 2008.
4. Electronics and Electrical Engineering, Kaunas (Lithuania), May 13-15, 2009.
5. 8th Regional International Conference of IEEE on Computational Technologies in Electrical and Electronics Engineering, Irkutsk, Listvjanka (Russia), July 11-15, 2010.
6. Electronics and Electrical Engineering, Kaunas (Lithuania), May 18-20, 2010.
7. 18th Telecommunications Forum TELFOR 2010, Belgrade (Serbia), Nov. 23-25, 2010.
8. Electronics and Electrical Engineering, Kaunas (Lithuania), May 17-19, 2011.
9. 11th International Conference on Telecommunications, ConTEL 2011, Graz, (Austria), June 15-17, 2011.
10. 12th IEEE International Conference on High Performance Switching and Routing, Cartagena (Spain), July 4-7, 2011.

Fourteen scientific papers were published in scientific journals:

1. Jeļinskis, J., and G. Lauks. "Optimal Policy for LSP Control in MPLS Networks." *Electronics and Electrical Engineering*. Lithuania, Kaunas, 2007. 65-68.
2. Jeļinskis, J. "Heuristic Algorithm for Optimal LSP Set Up Policy in MPLS Networks. Scientific Papers of Riga Technical University 7(2007): 23-26.
3. Jeļinskis, J., and G. Lauks. "Approximation of Internet Traffic Using Robust Wavelet Neural Networks." *Electronics and Electrical Engineering* 6.86(2008): 81-84.
4. Jeļinskis, J., and G. Lauks. "Data Mining for Managing Intrinsic Quality of Service in MPLS." *Electronics and Electrical Engineering* 5.85 (2008): 33-36.
5. Jeļinskis, J. "Heuristic Algorithm for Robust Approximate Hurst Parameter Estimation with Wavelet Analysis and Neural Networks." *Scientific Journal of Riga Technical University* (Series "Telecommunications and Electronics") 8(2008): 12-15.
6. Bobrovs, V., J. Jeļinskis, Ģ. Ivanovs, and G. Lauks. "Research of Traffic Management in FTTx Optical Communication Systems." *Latvian Journal of Physics and Technical Sciences* 2 (2009): 41-55.
7. Lauks, G., and J. Jeļinskis. "Metamodelling of Queuing Systems Using Fuzzy Graphs." *Electronics and Electrical Engineering* 4.92 (2009): 61-64.
8. Jeļinskis, J., and G. Lauks. "Detection of Trends of Internet Traffic Using Sequential Patterns." *Electronics and Electrical Engineering* 4.93(2009): 3-6.
9. Jeļinskis, J., and G. Lauks. "Fuzzy Approach for QoS Aware Application Driven Traffic Control in GMPLS Networks." Proceedings of the IEEE Region 8 International Conference on Computational Technologies in Electrical and Electronics Engineering. July 2010, Irkutsk, Russia. IEEE, 2010. 199-203.

10. Jeļinskis, J., G. Rutka, anf G. Lauks. “Fuzzy-CAC for LSP Setup in GMPLS Networks.” *Electronics and Electrical Engineering* 5.101 (2010): 31-34.
11. Jeļinskis, J., and G. Lauks. “Fuzzy CAC Adaptation for Effective Traffic Control in GMPLS Networks.” *Proceedings of the 18^{t} Telecommunications Forum TELFOR 2010*. Nov. 2010, Belgrade, Serbia. 10-13.
12. Jelinskis, J., A. Skrastins, and G. Lauks. “Practical Fuzzy-CAC Realization for Effective Traffic Engineering in MPLS-TE Network.” *Electronics and Electrical Engineering*. 4.110 (2011): 30-34.
13. Jelinskis, J., A. Skrastins, and G. Lauks. “Fuzzy-CAC based Traffic Management in MPLS-TE Networks.” *Proceedings of the 11th International Conference on Telecommunications ConTEL 2011*. June 20011, Graz, Austria, 2011. 389-395.
14. Jelinskis, J., A. Skrastins, and G. Lauks. “Fuzzy-CAC Driven MPLS-TE Realization.” Proceedings of the 12th IEEE International Conference on High Performance Switching and Routing. July 2011, Spain, Cartagena. 146-150.

The results of the promotion thesis were applied in many research projects:

1. *Research into the Traffic Integration in IP-over-WDM networks*, project No. ZP2008/16 (2008/2009).
2. *Research into Reliability and Security of Electronic Communication Systems* within the 5th state research programme *New Electronic Communication Technologies*, project of Riga Technical University No. V7408.1. (2007, 2008, 2009).
3. *Research into the Last-Mile Traffic Management in Optical Communication Systems*, project Nr.: ZP2007/13 (2007/2008)
4. *Algorithms for Optimal Routing in Embedded Networks*, project No. 05.1649, (2007 , 2008)

Volume and Structure of the Thesis

The promotion thesis contains 176 pages. It consists of an introduction, four chapters, bibliography and appendices.

The introduction contains a brief review of modern traffic engineering problems and highlights the topicality of research studies accomplished in the thesis, as well as the aim and tasks of the thesis.

Chapter 1 briefly examines the management paradigm of modern communication systems, pointing at its advantages and disadvantages as well as advantages and disadvantages of the fuzzy-logic approach. Further, the overview of the concept of fuzzy logic and its history is given along with the examples of fuzzy-management systems and the most important fields of use. This chapter also describes in detail the elements of fuzzy inference system such as the membership functions of linguistic variables, main fuzzy-logic operations, the methods of fuzzification of input parameters and the methods of de-fuzzification of output parameters. The author also gives some examples of using fuzzy logic in different fields of telecommunications, paying a special attention to the application of fuzzy-logic to solving the CAC tasks.

Chapter 2 describes the reference models of both the MPLS-TE communication system and the fuzzy-CAC inference system studied in the thesis. The chapter also sets the goals and gives a ground for estimating the performance of the fuzzy-CAC inference model as well as the degradation limits of QoS required for reaching these goals. The heuristic research method as well as the diagram of the simulation environment of the MPLS-TE communication system, required for a rapid prototyping of a fuzzy-CAC decision-making system, is examined. The author explains how to select the fuzzification curves of input parameters and the membership functions of input and output linguistic variables applied in the proposed fuzzy-CAC decision-making system. The base of IF-THEN rules, the methods of response post-processing for the fuzzy-CAC system, the background of selecting the type of a fuzzy system and the decision surfaces produced by the fuzzy-CAC algorithm are examined in this chapter as well.

Chapter 3 describes in detail the experimental implementation of the MPLS-TE communication system, which contains both an MPLS-TE network and the management block of the fuzzy-CAC algorithm as well as the traffic generating and receiving blocks. The scenarios of experiments and the analyzed QoS parameters are described as well. The chapter contains the detailed description of the experimental results and compares the effectiveness of the fuzzy-CAC algorithm introduced by the author with the classic threshold-CAC algorithm.

Chapter 4 examines the adapting mechanism of the introduced fuzzy-CAC algorithm, which would ensure the effective adaptation of the algorithm to a rapidly changing external environment. The ability to adjust the performance policy of fuzzy-CAC algorithm in real time by modifying the membership functions of linguistic variables is considered. The author also shows how the modification of a decision-making threshold influences the performance of the MPLS-TE communication system. If a threshold is modified in a direct way, it does not influence the performance of the fuzzy-CAC decision-making system. However, this can be applied in order to provide an effective and very fast correction of the "behaviour" of the fuzzy-CAC system in real time.

The conclusion summarizes the main results of the promotion thesis as well as determines the directions for further research studies.

Appendices contain the most important initial codes of software applied to the practical realization of the fuzzy-CAC algorithm ensuring communication between the Cisco 2800 Series routers, as well as the initial Matlab codes for fuzzy inference system and the MPLS-TE model applied for testing the fuzzy-CAC algorithm.

SUMMARY OF THE THESIS

Chapter 1

Fuzzy logic is an extension of standard logic, and provides an opportunity to deal with the notion of approximate reasoning. Nowadays, fuzzy logic is becoming one of the most successful technological solutions in designing some complex management systems. In fact, it is a modelling method, which can be applied to solving the real-life problems. The theory of fuzzy samples, which is a base of fuzzy logic, resembles human reasoning, or decision-making tactics, and uses approximate or partial information of the system state and input variables. It is mainly used in order to express uncertainty and approximate information of the observed parameters in mathematical terms, as well as to provide some tools, which are capable of dealing with inaccuracy arising in many traffic engineering tasks [12].

The main property of fuzzy logic is its ability to transfer the instantenous image of input variables to output variables, based on the IF-THEN rules. Fuzzy logic can deal with mathematical complexity of many problems. It works with fuzzy terms, fuzzy samples and fuzzy operations, and allows making decisions based on IF-THEN fuzzy rules [22].

The detailed mathematical description and the aspects of implementing the concept of fuzzy logic may be found in many scientific publications of its founder, professor *Lotfali Askar-Zadeh* [30 - 53].

Chapter 2

The author of this thesis sets himself apart from routing tasks. As a result, all the author's research studies may be accomplished by applying a simplified scheme, which sets up an LSP (Label Switched Path) between only two network devices.

Reference Model for the MPLS-TE Communication System

An LSP starts at an *ingress* LER (Label Edge Router), crosses one or more LSRs (label switching routers), and ends at an *egress* LER. Thus, the minimal number of the required switches is three – two LER switches and one LSR switch (Fig.1). They provide two full hops in a trunk network and two hopes in an access network.

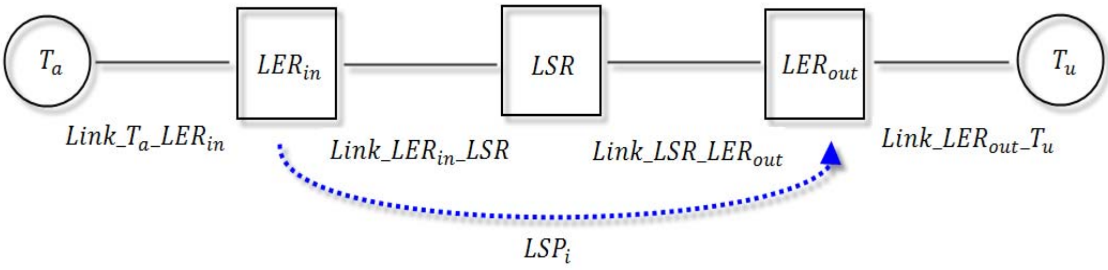

Figure 1 The layout of the MPLS-TE communication system applied to research studies

Fuzzy-CAC Reference Model

A fuzzy-CAC reference model is based on the standard fuzzy-inference method, which is cable to transfer an instantaneous pattern of input variables to output variables, based on conditional IF-THEN rules. Fuzzy-CAC reference model serves as a basis for designing a certain fuzzy interference system (FIS), which will be applied in comparative studies involving a classic threshold-CAC algorithm. The diagram of the fuzzy-CAC reference model, introduced in the paper, is shown in Fig.2.

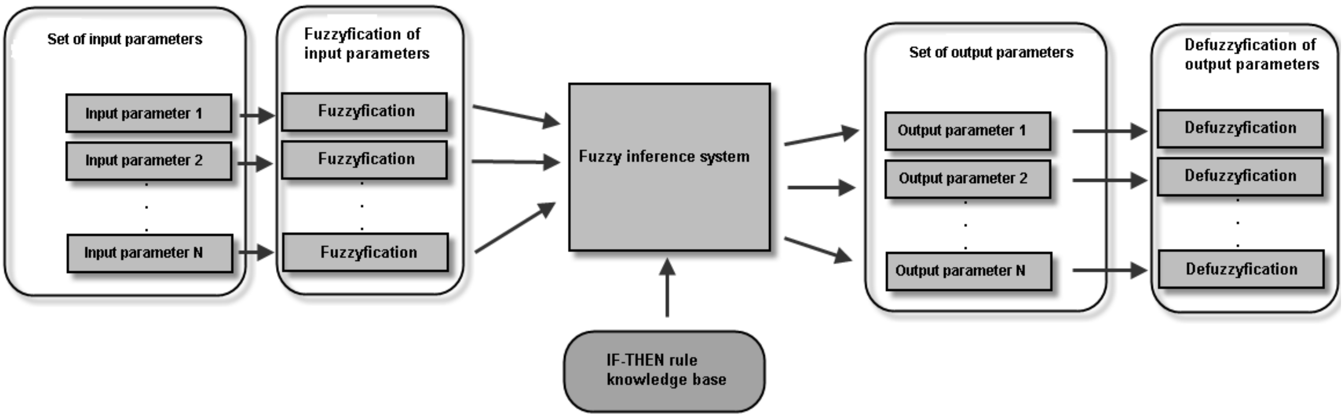

Figure 2 Fuzzy-CAC reference model

The fuzzy-CAC solution introduced in the promotion thesis requires three input parameters:

1. **$Bw\_r(t_i)$ – the ratio of a required bandwidth to an available bandwidth measured at t_i - the moment of making a CAC decision.**
2. **$QoS\_c(t_i)$ – the class or level of QoS, which the application requires at t_i**
3. **$Delay\_l(t_i)$ – packet delay between an ingress LER_{in} and an egress LER_{out} measured at t_i.**

The introduced fuzzy-CAC solution requires one output variable, which determines a fuzzy-logic decision.

$CAC\_f(t_i)$ – a fuzzy-CAC response, which is a de-fuzzified output value of the fuzzy-inference module.

Taking into account the above defined values of input parameters and the states of fuzzy-CAC samples, the introduced fuzzy-CAC activity can be described by the following pseudo-code:

```
START fuzzy-CAC
FOR $i$ = 0 TO n STEP 1
    READ $Bw\_rq(t_i)$
    READ $Bw\_aw(t_i)$
    READ $Delay\_l(t_i)$
```

```
        READ $QoS\_l(t_i)$
        CALCULATE $Bw\_r(t_i)$
          CALCULATE $CAC\_f(t_i)$
            IF $CAC\_f(t_i) < 5 - s_1$
            THEN $f\_CAC$ = „Admit” AND $LSP_i$ = 0;
            ELSE IF $CAC\_f(t_i) > 5 - s_1$ AND $CAC\_f(t_i) < 5 + s_2$
            THEN $f\_CAC$ = „Admit” AND $LSP_i$= $Bw\_rq(t_i)$
            ELSE IF $CAC\_f(t_i) > 5 + s_2$
            THEN $f\_CAC$ = „Admit with additional resource reservation”&&
            $LSP_i$= $Bw\_rq(t_i) \cdot k$
             END IF
NEXT $t_i$
AND FOR
END fuzzy-CAC
```

where

$Bw\_rq(t_i)$ - the resources required by an application at t_i - the moment of making a CAC decision [Mbps];

$Bw\_aw(t_i)$ – the resources available for a link at t_i [Mbps];

$Delay\_l(t_i)$ - the average packet delay observed between the time moments t_i and t_{i-1} [ms];

$QoS\_l(t_i)$ - the QoS class required by an application at t_i;

LSP_i -the LSP (Label Switched Path) resources reserved by RSVP-TE (Resource Reservation Protocol - Traffic Engineering) at t_i [Mbps];

s_1 and s_2 – thresholds for the fuzzy-CAC responses;

k – the reservation coefficient for additional resources.

We formulate below the goals, which have to be achieved in order to design the optimal, or close to optimal, fuzzy-CAC inference system.

1. **Ensure the maximum average link utilization taking into account the degradation limits of QoS parameters.**
2. **Set up an LSP channel by applying the selective procedure to traffic flows in such a way, which increases the number of connections of high-class QoS, taking into account the degradation limits of QoS parameters.**

3. **Decrease the number of flow connections, which do not comply with the QoS requirements of a link at the moment of setting an LSP.**

The limits of QoS degradation mentioned above are based on the SLA – *service level agreements,* carried out between large trunk-network operators. The SLA data for two European trunk-network operators, which represent *NNT Communication – NNT Europe* and *Sprint Network* may be found in [23, 26]. The last one offers some different SLA for MPLS networks. The data on SLA for the U.S. trunk network represented by *Internap*, *Qest* and *Verio* can be found in [16, 24, 29], respectively.

The topological properties of such networks as *Verizon*, *AT&T* and *Sprint Networks* determine the average number of connection hops within a trunk network, which comprises 2.7 [11]. Modifying the SLA data for two hops within our experimental MPLS-TE network, we arrive at the QoS limits in the case of the fuzzy-CAC algorithm, which determine a requested performance of the fuzzy-CAC algorithm (see Table 1).

Table 1

PMT packet delay	PMT packet loss in a network	PMT average jitter
33 ms	0.15 %	0.7 ms

Heuristic Selection of the Fuzzy Inference System

Taking into account a high complexity of the advanced tasks, the author decided to apply a heuristic research method, resulting in the solution close to optimal. The heuristic selection method, applied in the thesis, is based on multiple realizations of the initial raw fuzzy-CAC decision-making system, which was designed and tested taking into account the simplified simulation model of an MPLS-TE communication system proposed by the author and implemented in MATLAB environment (see Fig.3). The best realizations were modified and extended. There were achieved some results in this way, which were the closest to the performance targets set for the fuzzy-CAC system.

The following parameters of a fuzzy-CAC system has to be determined in order to achieve the advanced goals:

- for each input parameter – the number of linguistic variables and the membership functions of linguistic variables;

- for each output parameter – the number of linguistic variables and the membership functions of linguistic variables ;
- *fuzzification* curves of input parameters
- The method of de-fuzzification of output parameters
- Base of IF-THEN rules
- Type of decision-making system - *Mamdani, Tugaki-Sugeno.*
- The method of post-processing for an output parameter

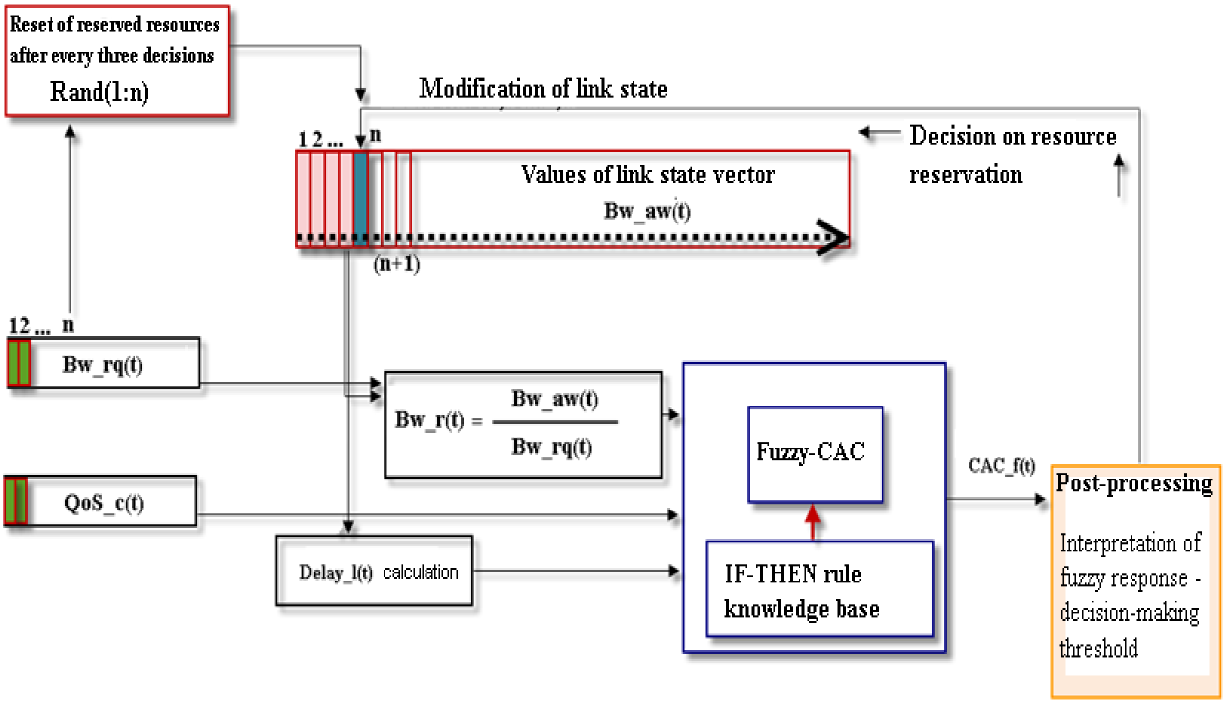

Figure 3 Algorithm for simulating the MPLS-TE communication system

In order to provide a proper operation of the simulated MPLS-TE network, the packet service time (see Fig.4) was adopted as the initial state of a simulated system before the stage of *fuzzification*.

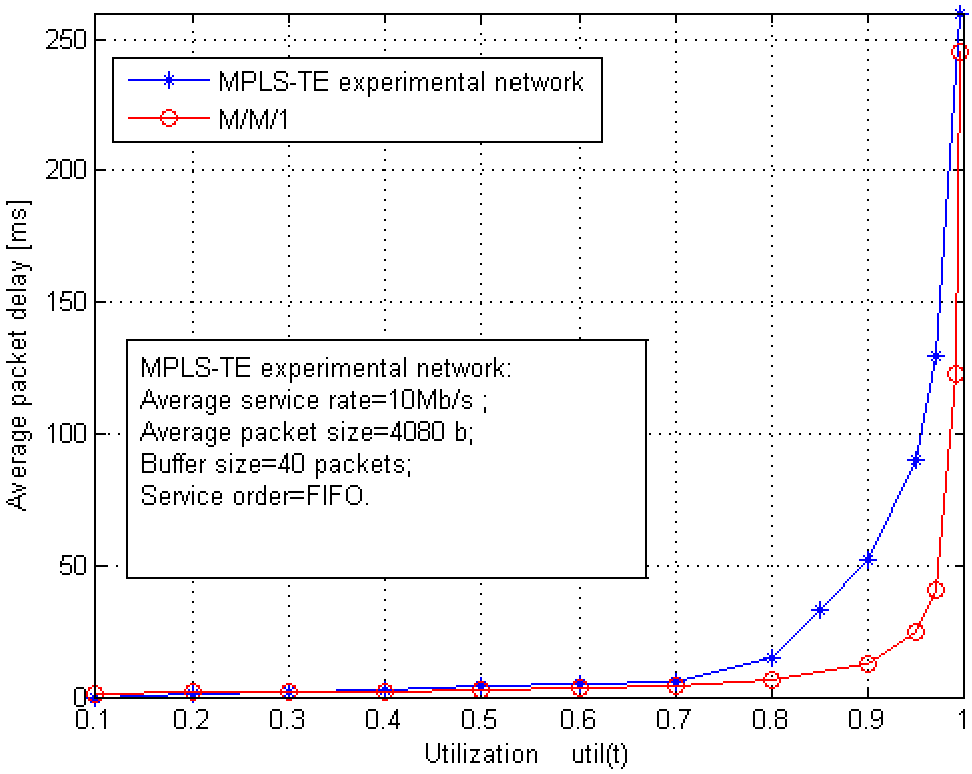

Figure 4 The packet delay against the link utilization in the experimental MPLS-TE network

The simulation environment of the MPLS-TE communication system was applied in order to pick up quickly the best fuzzy-CAC decision-making solutions, which, after some further modifications of linguistic variables as well as modifications of the base of IF-THEN rules, were tested in practice within an experimental MPLS-TE communication network.

By applying the method of gravitation centre in the process of de-fuzzification, the decision surfaces of a fuzzy-CAC algorithm were obtained (see Figs. 5-7). They describe the reaction of a decision-making system to all the possible combinations of input variables, produced by applying the pre-defined IF-THEN rules.

In order o preserve the information the answers contain, the method of de-fuzzification has to take into account the results of a whole fuzzy sample. For example, this can be achieved by applying the centroid or COG (centre of gravity) de-fuzzification method. In the process of de-fuzzification, it returns the central point on a surface below a membership-function curve, and the X-coordinate is considered to be a de-fuzzified value. In this promotion thesis, the COG de-fuzzification method was applied in the realizations of the fuzzy-CAC algorithm (see Fig.8).

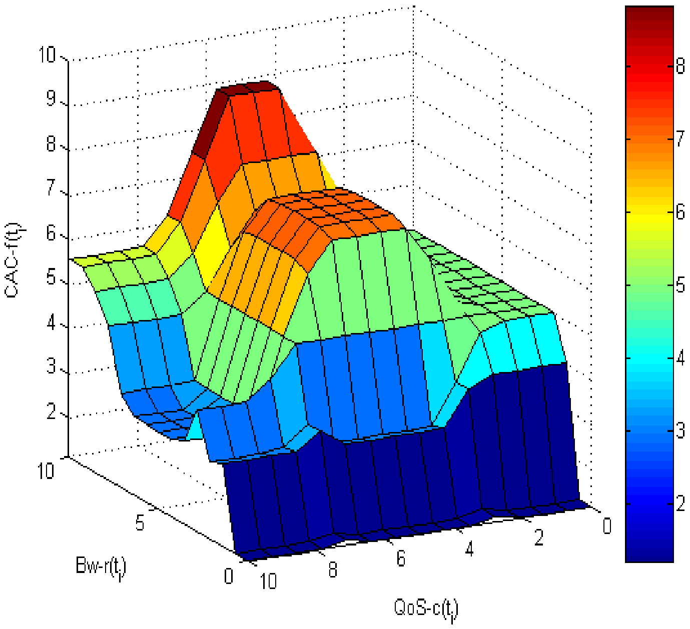

Figure 5 Decision surface of the fuzzy-CAC decision-making mechanism in the case of input variables QoS_c(t) and Delay_l(t)

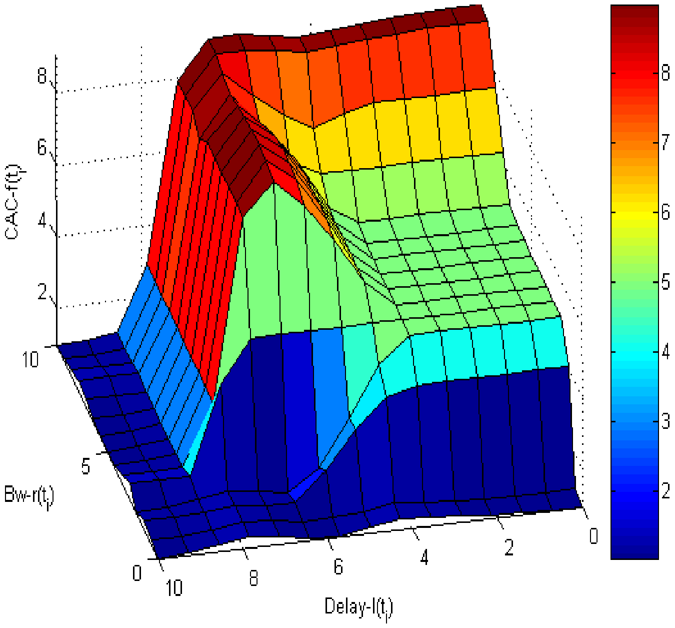

Figure 6 Decision surface of the fuzzy-CAC decision-making mechanism in the case of input variables Delay_l(t) and Bw_r(t)

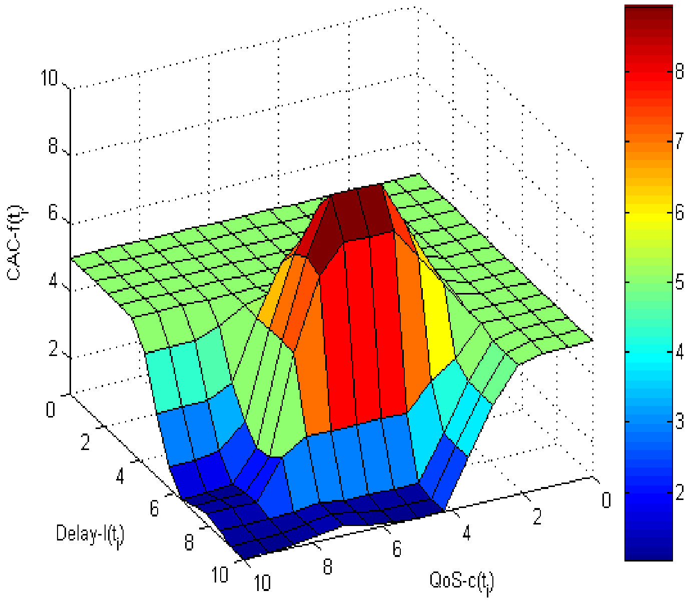

Figure 7 Decision surface of the fuzzy-CAC decision-making mechanism in the case of input variables QoS_c(t) and Bw_r(t)

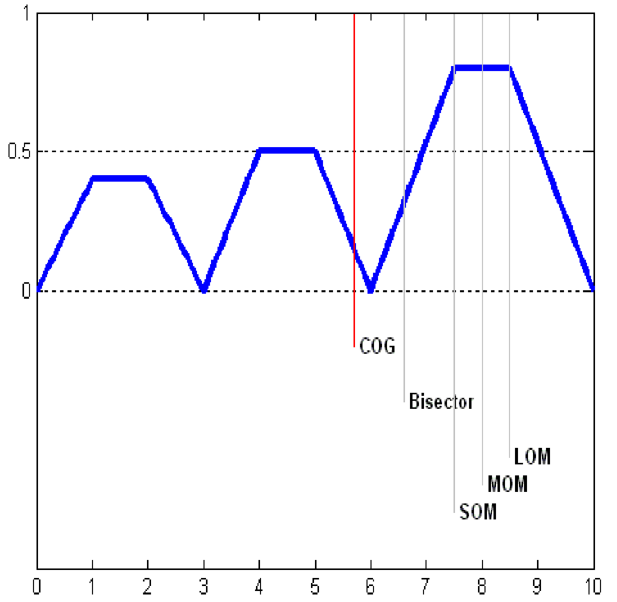

Figure 8 Results produced by the de-fuzzification methods COG, Bisector, SOM, MOM and LOM

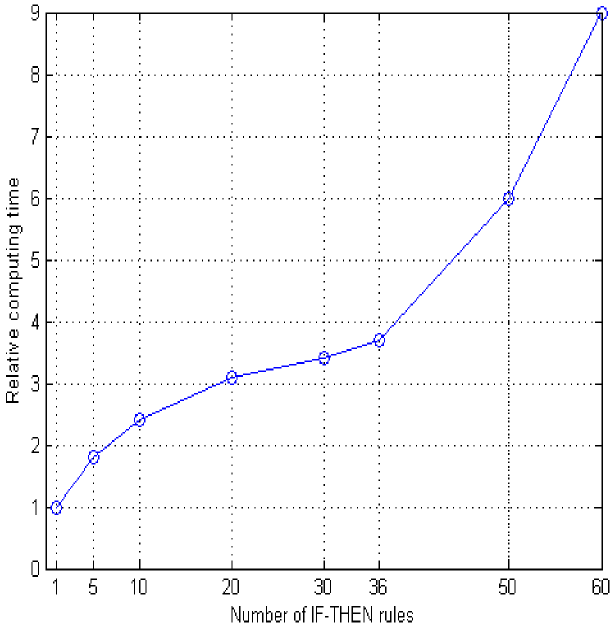

Figure 9 The number of rejected LSP connections against the number of applied IF-THEN rules for the 1,500 cases produced by the fuzzy-CAC decision-making system

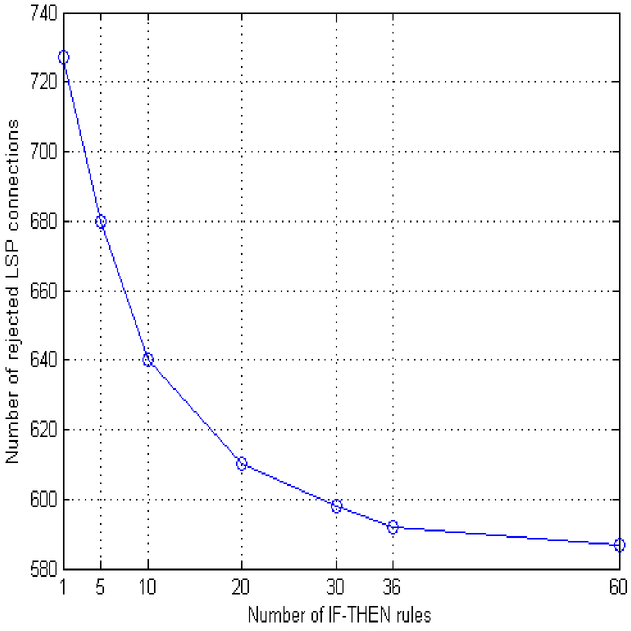

Figure 10 Increase of the relative time necessary for making a decision, against the number of IF-THEN rules, for 1,500 analyzed cases

In order to achieve the pre-defined performance goals of a fuzzy-CAC system, the IF-THEN rule base consisting of 36 rules, was selected taking into account the results of heuristic studies The size of the IF-THEN rule base was determined taking into account the time required for calculations and the number of simultaneously rejected LSP flows (see Figs. 9-10).

Post-Processing of a Fuzzy-CAC Decision

The procedure of post-processing incorporates the comparison of a fuzzy-CAC response with a threshold parameter, resulting in rejecting an LSP connection, admitting an LSP connection or admitting it with reserving some additional resources.

Since the output value after de-fuzzification may fall between 0 and 10, it is required to set a threshold, the comparisons to which allows making certain CAC decisions (see Fig.11).

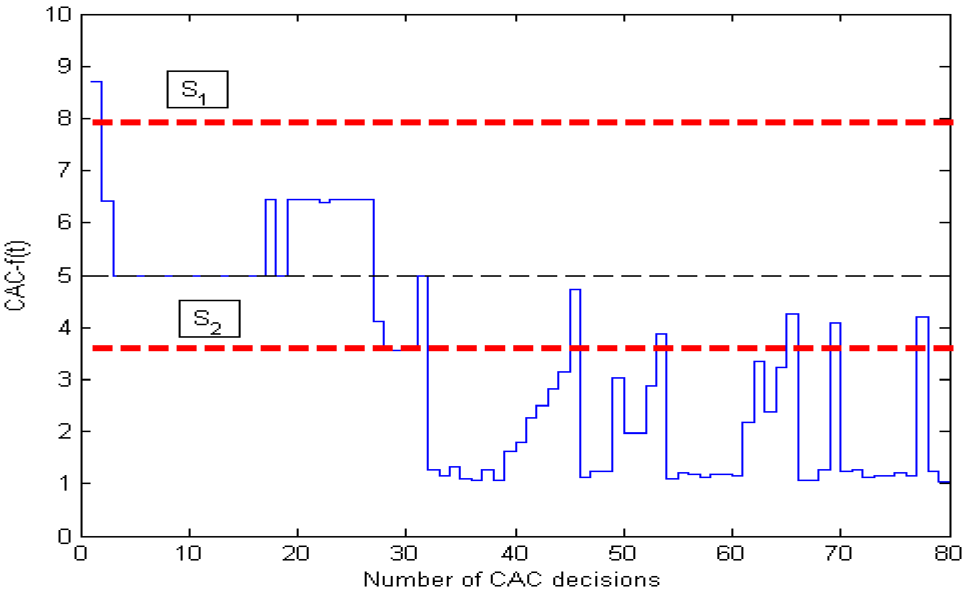

Figure 11 Threshold parameters for $CAC\_f(t_l)$ post-processing

The post-processing of a FIS response confines the information about a required CAC response. However, this is necessary for obtaining a CAC decision in numerical form.

By changing the values of s_1 and s_2, it is possible to adjust the fuzzy-CAC traffic management policy and provide a required degree of LSP selectivity. If an excessively wide range of values for the CAC decision “Reject a Connection” is reserved, then the resources of a link are not fully utilized. In contrast, if an excessively large range of values is left for accepting the CAC decision “Admit a connection”, the resources of a link are utilized better, along with non-accepted degree of QoS degradation. In turn, reserving a wide range of values for the CAC decision “Admit a connection with reserving additional resources”, a high weight of a “safety cushion” will result in unreasonably low utilization of a link.

By applying test-and-trial routine to develop a fuzzy-CAC algorithm, the author arrived at the conclusion that a symmetric threshold provides a required performance of the fuzzy-CAC inference system.

Coefficient for Reserving Additional Resources

If the decision „Admit a connection with reserving additional resources” is made and the request for an LSP is accepted, the RSVP-TE can reserve more resources than it is required by the application. In this case, the combination of high QoS requirements, low packet delays and large values of $Bw\_r(t_l)$ results in developing the so called “safety cushion”. It allows sustaining the required level of QoS not only for the new connected LSP flows but also for all the existing flows. Moreover, the “safety cushion” is directly proportional to the active high-priority LSP flows of a link.

It is important to select a reservation coefficient in such a way, which is capable of providing the required effectiveness of the fuzzy-CAC algorithm. As a result of test-and-trial procedures, the reservation coefficient was set to $k = 2$. It means that in the case of the decision „Allow a connection with reserving additional resources”, the RSVP-TE will reserve two times more resources in a link then it is required by the application.

Chapter 3

The effectiveness of performance of the fuzzy-CAC algorithm, in comparison with the classic threshold-CAC algorithm, was tested by using real routing equipment. In order to accomplish this task, the MPLS-ME experimental communication network as well as required software were designed, which allowed verifying in practice the effectiveness of the fuzzy-CAC solution introduced by the author and obtain QoS parameters characterizing a network.

Experimental MPLS-TE Network

The practical implementation of the MPLS-TE communication system was based on three CISCO-2800-Series routers, which were a part of the laboratory routing equipment belonging to the Faculty of Electronics and Telecommunications of Riga Technical University. They allow designing and analyzing the performance of small MPLS-TE networks. The data of this research study concerning the admitted and rejected LSP connections, the resources reserved by the RSVP and QoS parameters of traffic passing via network segments allowed the author to make some important conclusions about the effectiveness of the fuzzy-CAC algorithm in comparison with the classic threshold-CAC algorithm.

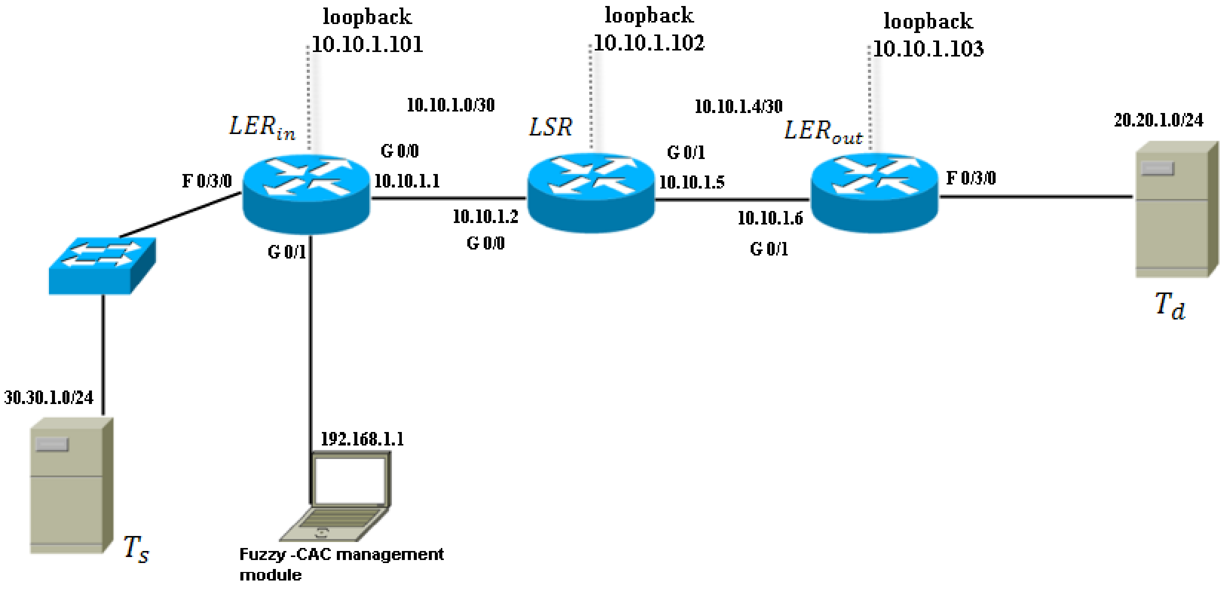

Figure 12 Physical circuit of the experimental network designed for testing the fuzzy-CAC algorithm

The LSP tunnels were established between the LER_{in} and LER_{out} by applying the fuzzy-CAC algorithm and the classic threshold-CAC algorithm. The generated data flow was transported from a generating end T_a to a receiving end T_d as well.

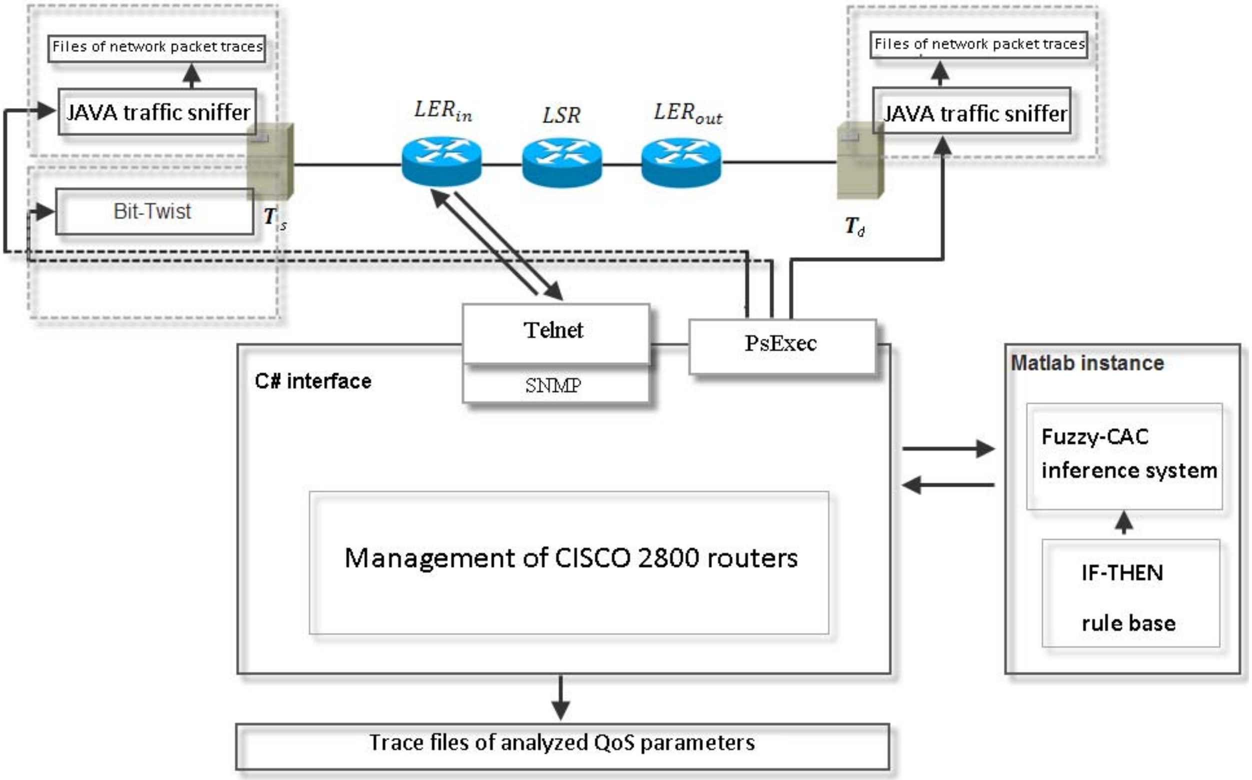

Figure 13 Software architecture implemented within the experimental network designed for testing the fuzzy-CAC algorithm

The architecture of management software, implemented within the experimental fuzzy-CAC network, is shown in Fig.13. The main C#-based management block of the experimental network enabled the communication with CISCO 2800-Series router, which was established via Telnet protocol. The CISCO 2800-Series router operated in the MPLS-TE mode. The router could receive some management instructions such as the instruction to establish the LSG channel and to return the information required for operating the CAC algorithm and testing its performance, for example, the list of active and inactive LSP channels, the state of a buffer, delays over a link, the number of lost packets, packet delay jitter, etc.

Measurements

The majority of the QoS parameters, required for evaluating the effectiveness of the MPLS-TE experimental communication system, were obtained by using the Cisco IOS IP Service Level Agreements [9] (see Fig.14). The techniques and preciseness of measurements performed within the Cisco IOS IP SLA are described in [10, 8, 28].

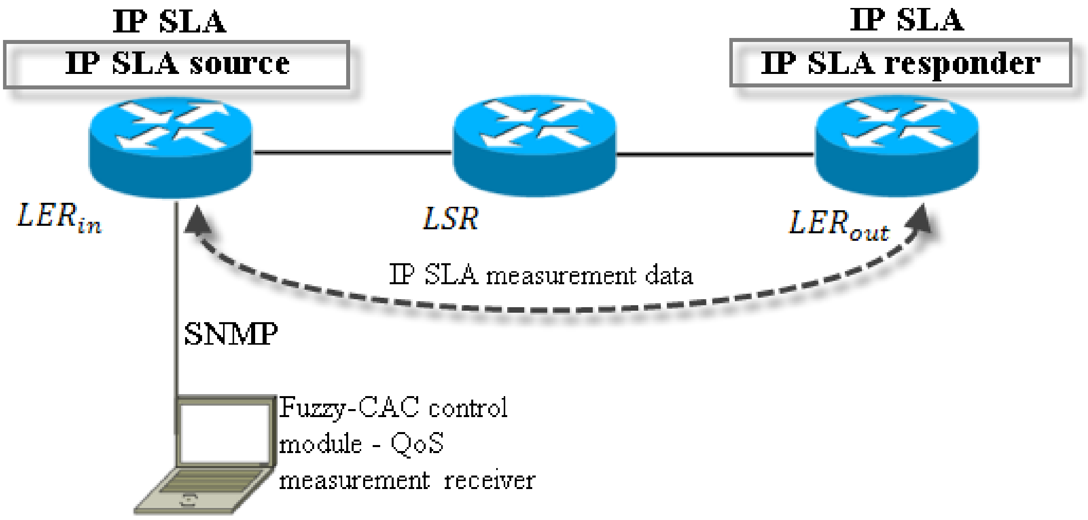

Figure 14 Cisco IP SLA measurement scheme for QoS parameters within the MPLS-TE experimental communication system

The practical realizations of the fuzzy-CAC algorithm were tested by applying two main scenarios. The first, optimistic scenario excluded the presence of "bursty" traffic and only considered the connection of a requested flow to the initially free 10Mbps-channel, which was filled taking solely into account the information about flow connections or rejections provided by both the fuzzy-CAC algorithm and the classic threshold-CAC algorithm (see Fig.15).

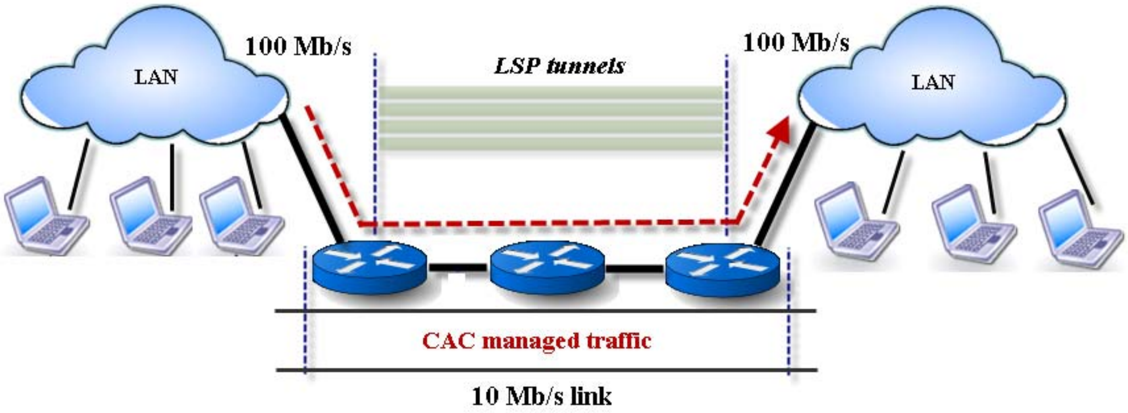

Figure 15 Optimistic scenario of the link communication policy

The second, pessimistic scenario implemented the analysis of the effectiveness of both the fuzzy-CAC algorithm and the threshold-CAC algorithm by using the 10Mbps-link, which was filled with the 6Mbps "bursty" data flow. In this case, the utilization of the left 4 Mbps bandwidth was managed by applying the CAC algorithm. This allowed estimating the performance of the fuzzy-CAC and threshold-CAC algorithms under critical conditions, when packet losses of a router are significant and a routing buffer is fully or partially filled during all the time of research studies (see Fig. 16).

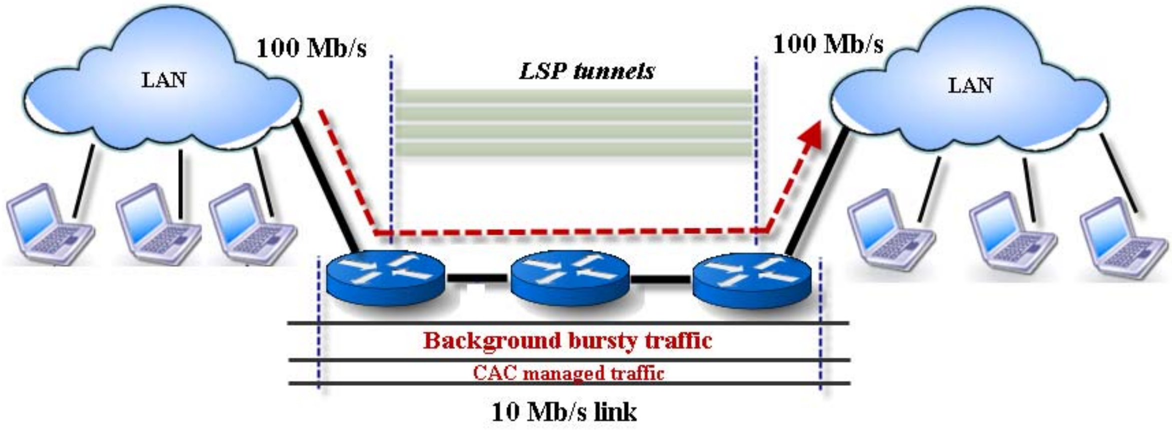

Figure 16 Pessimistic scenario of the link communication policy

Results of Practical Studies

The results of the comparative study, estimating the performance of both the fuzzy-CAC algorithm and the threshold-CAC algorithm for the number of decisions equal to 3000, are given below. Carrying out the analysis of the average values, we can see that already at the average level of utilization stabilized at 0.84, the 33-ms delay limit, set by the QoS degradation requirements, is achieved in the case of the fuzzy-CAC algorithm. The estimates of packet delays and packet delay jitter are still below the QoS degradation limits. In the case of designing the fuzzy-CAC decision-making system, which allows to make these parameters closer to the QoS degradation limits, packet delays are always longer than the degradation limit set to 33 ms.

The experimental realization of the fuzzy-CAC algorithm showed that:

- in comparison to the classic threshold-CAC algorithm, the link utilization (the resourced reserved by the RSVP-TE):
    - decreases ≈ 10 per cent in the case of optimistic scenario (Fig. 17);
    - decreases ≈ 15 per cent in the case of pessimistic scenario (Fig. 18).

- packet delays between LERin and LERout:
    - decrease by ≈ 2.3 times in the case of optimistic scenario (Fig. 19)
    - decrease by ≈ 2.6 times in the case of pessimistic scenario (Fig. 20)

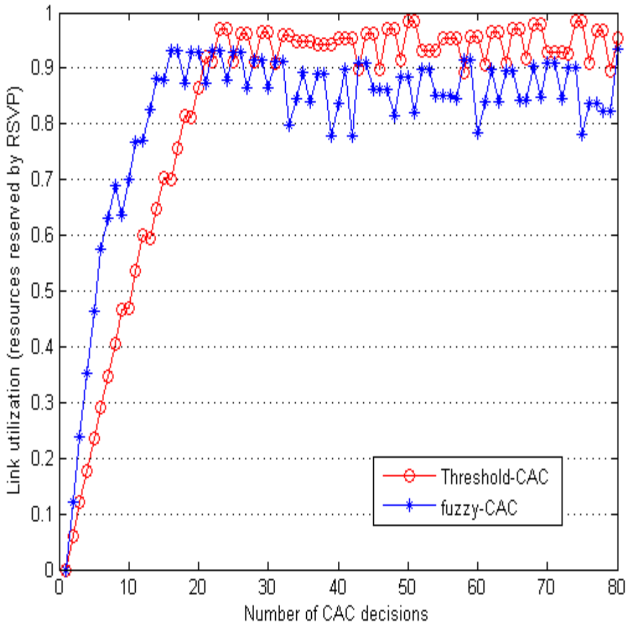

Figure 17 Link utilization (LSP tunnel resources reserved by the RSVP-TE, optimistic scenario)

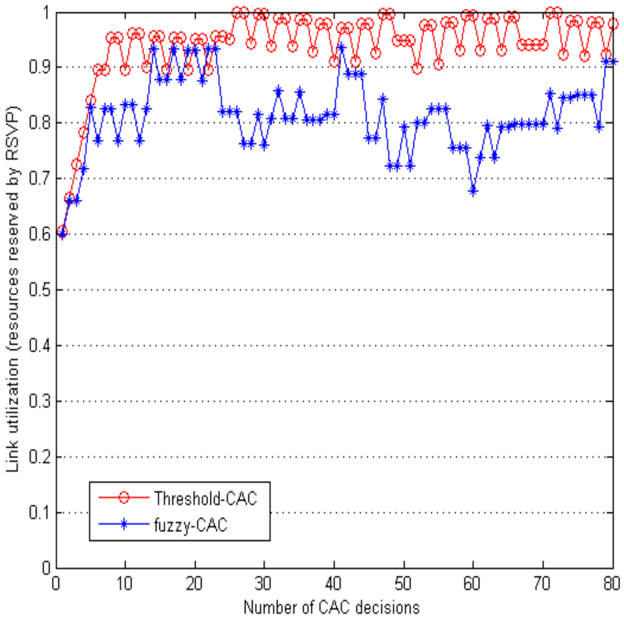

Figure 18 Link utilization (LSP tunnel resources reserved by the RSVP-TE, pessimistic scenario)

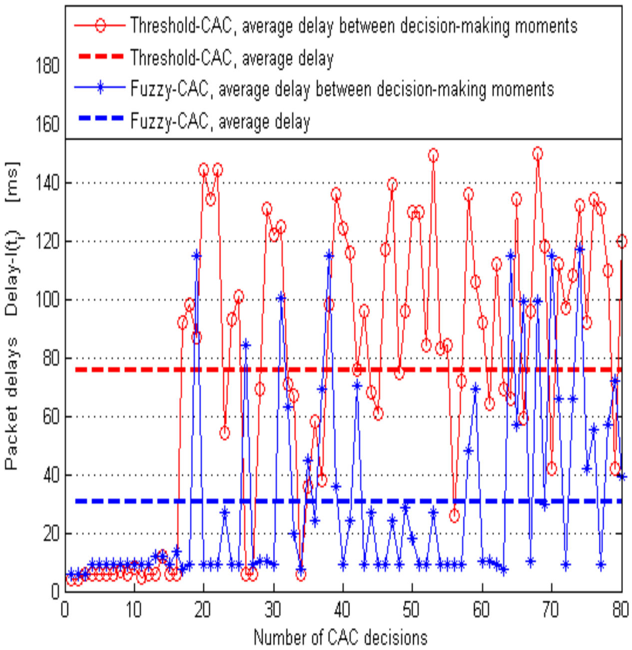

Figure 19 Average packet delays between decision-making moments and the average delay estimated for 3,000 cases (optimistic scenario)

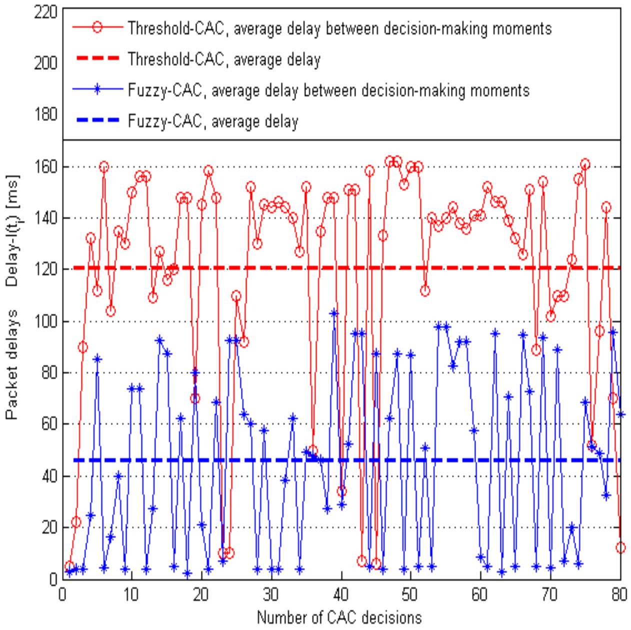

Figure 20 Average packet delays between decision-making moments and the average delay estimated for 3,000 cases (pessimistic scenario)

- By applying the fuzzy-CAC algorithm, packet cumulative losses between LERin and LERout:
  - decrease by ≈ 30 times in the case of optimistic scenario (Fig. 21);
  - decrease by ≈ 3 times in the case of pessimistic scenario (Fig. 22);
- By applying the fuzzy-CAC algorithm, the utilization of the LERin buffer:
  - decreases by ≈ 8 times in the case of optimistic scenario (Fig. 23);
  - decreases by ≈ 2 times in the case of pessimistic scenario (Fig. 24);
- By applying the fuzzy-CAC algorithm, the packet loss jitter between LERin and LERout:
  - decreases by ≈ 5 times in the case of optimistic scenario (Fig. 25);
  - decreases by ≈ 3 times in the case of pessimistic scenario (Fig. 26).

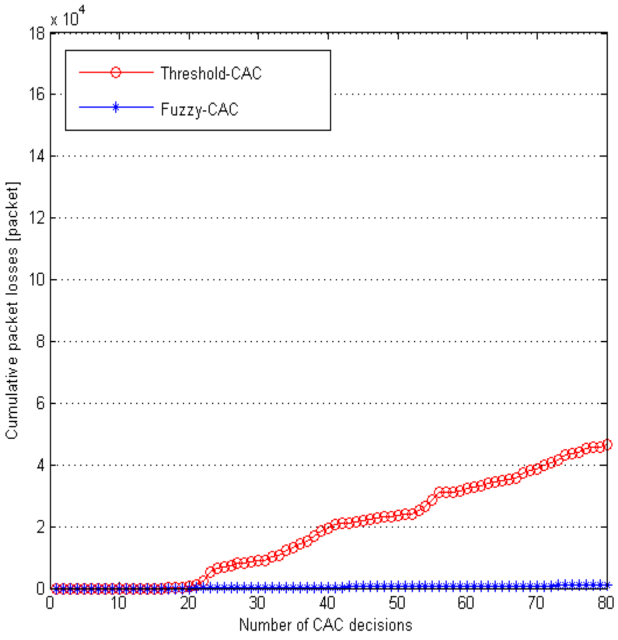

Figure 21 Cumulative packet losses (optimistic scenario)

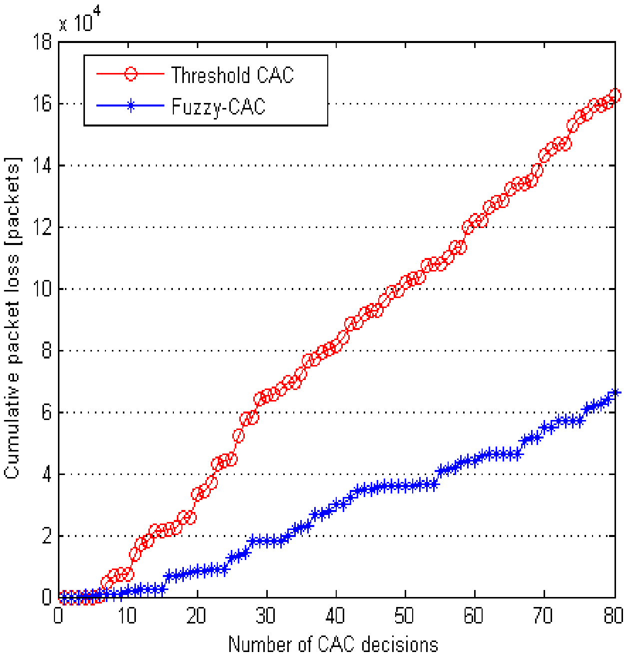

Figure 22 Cumulative packet losses (pessimistic scenario)

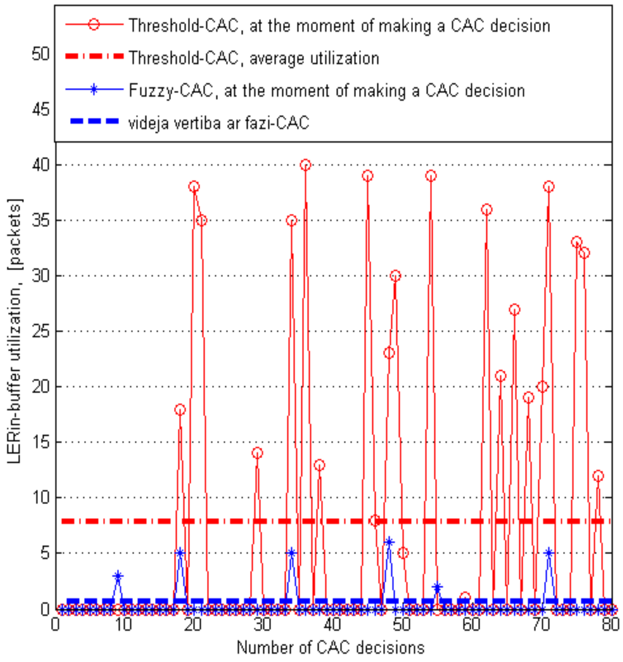

Figure 23 The instantaneous and average buffer utilization for the LERin-router (optimistic scenario for the buffer size of 40 packets)

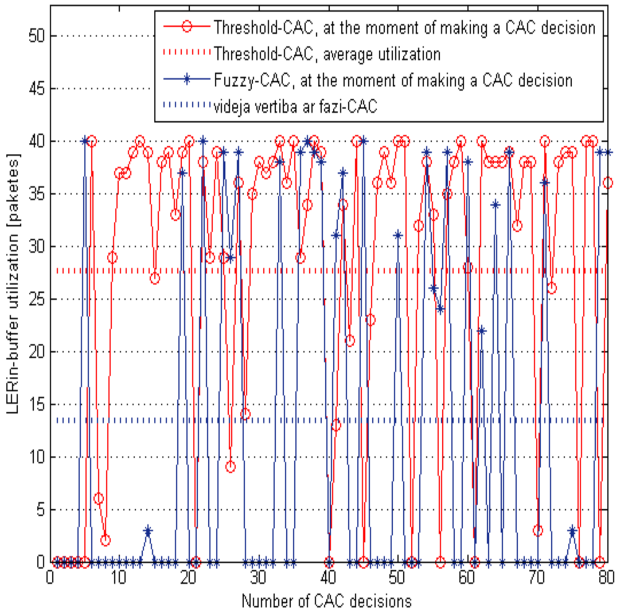

Figure 23 The instantaneous and average buffer utilization for the LERin-router (pessimistic scenario for the buffer size of 40 packets)

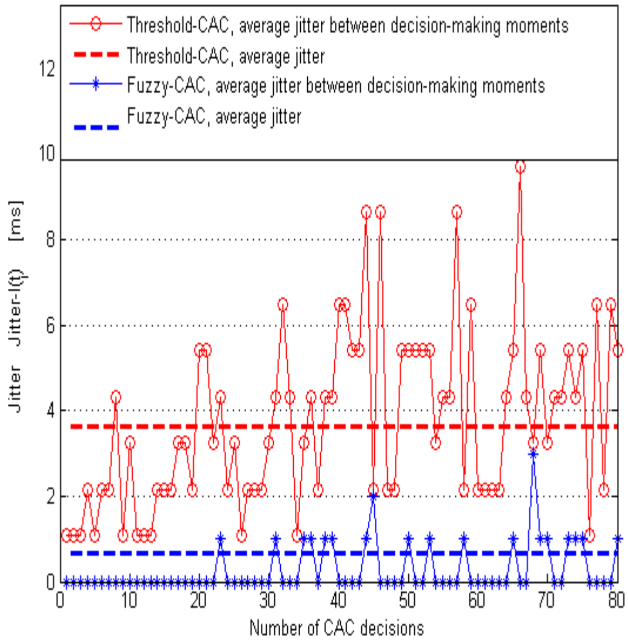

Figure 25 Jitter at the moment of making a CAC decision (optimistic scenario)

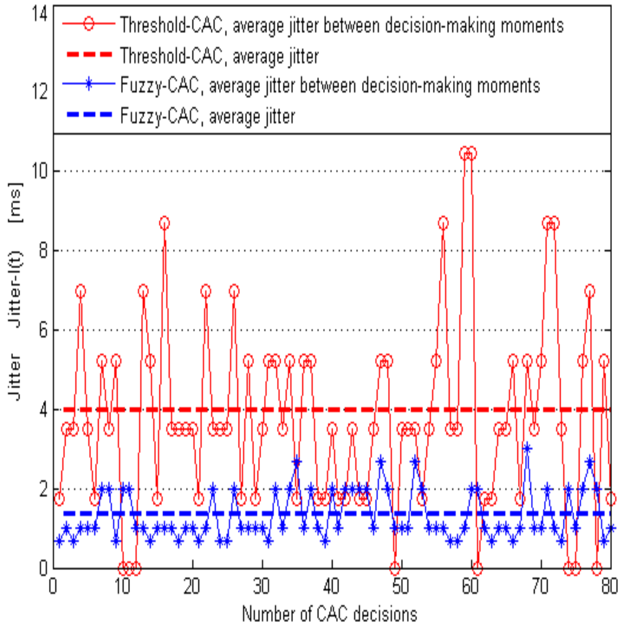

Figure 26 Jitter at the moment of making a CAC decision (pessimistic scenario)

The QoS parameters obtained for both the fuzzy-CAC algorithm and the classic threshold-CAC algorithm in the case of optimistic and pessimistic scenarios, 3,000 cases considered in each of them, are shown in Tables 2-3.

Table 2

Parameter Means – Optimistic Scenario –3,000 Cases Considered		
Parameter	Threshold-CAC	Fuzzy-CAC
Average link utilization	**0.94**	**0.84**
Packet loss, %	**3.10**	**0.10**
Jitter, ms	**3.3**	**0.6**
Buffer utilization, packets	**8**	**1**
Packet delay, ms	**77**	**33**

Table 3

Parameter Means – Pessimistic Scenario –3,000 Cases Considered		
Parameter	Threshold-CAC	Fuzzy-CAC
Average link utilization	**0.97**	**0.82**
Packet loss, %	**11.80**	**3.90**
Jitter, ms	**4.0**	**1.3**
Buffer utilization, packets	**28**	**14**
Packet delay, ms	**121**	**46**

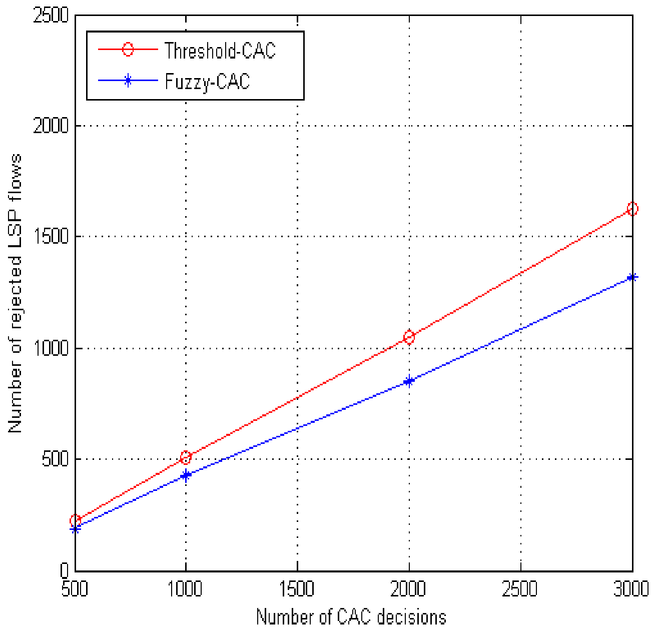

Figure 27 The number of rejected LSP flows in the case of the threshold-CAC and fuzzy-CAC algorithms (optimistic scenario)

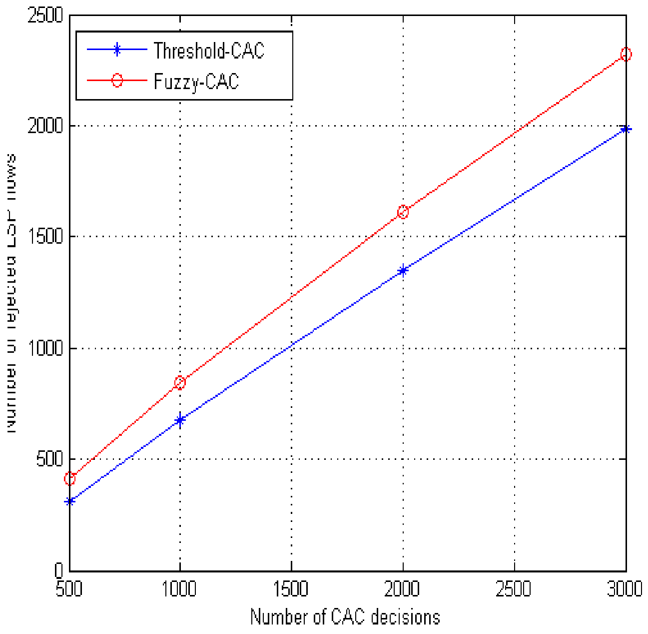

Figure 28 The number of rejected LSP flows in the case of the threshold-CAC and fuzzy-CAC algorithms (pessimistic scenario)

- By applying the fuzzy-CAC algorithm, the number of rejected LSP flows:
  - decreases ≈ 15 per cent in the case of optimistic scenario (Fig. 27);
  - decreases ≈ 18 per cent in the case of pessimistic scenario (Fig. 28);
- In the case of the threshold-SAS algorithm:
  - In 60 per cent of all the cases considered – the LSP flows, which are rejected by the fuzzy-CAC scenario, are connected (optimistic scenario, Fig. 29);
  - In 80 per cent of all the cases considered – the LSP flows, which are rejected by the fuzzy-CAC scenario, are connected (pessimistic scenario, Fig. 30);

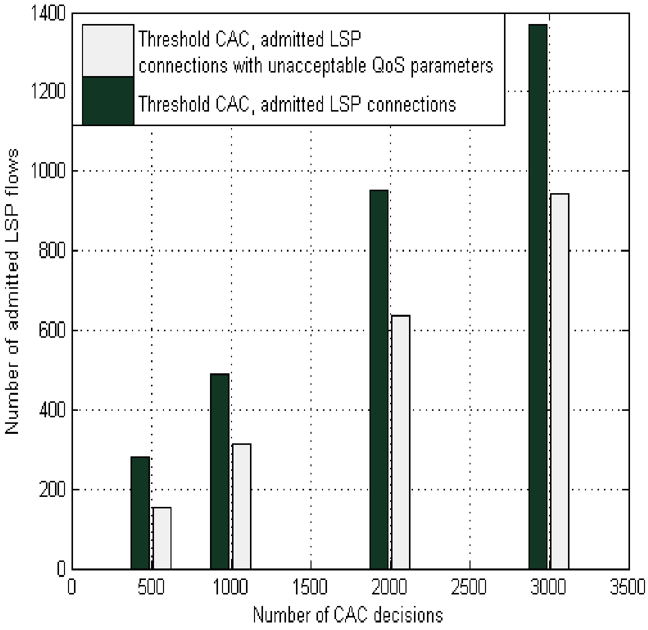

Figure 29 All the LSP connections in comparison with the connections of non-acceptable QoS, admitted by the threshold-CAC algorithm (optimistic scenario)

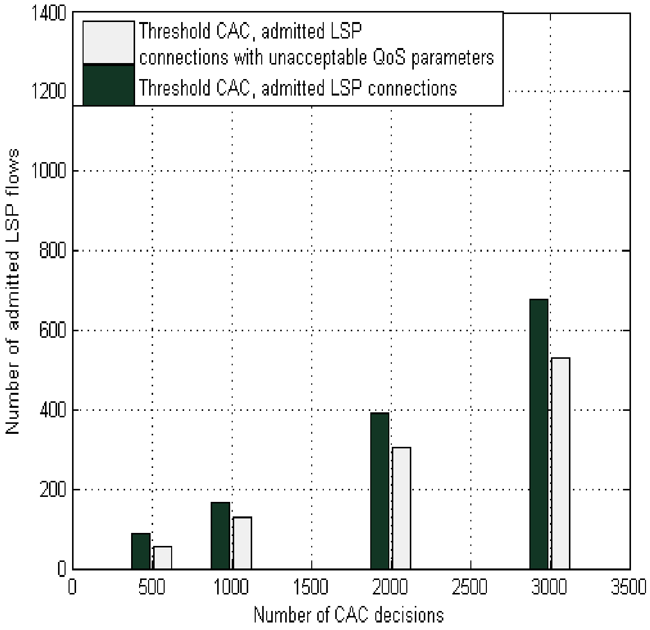

Figure 30 All the LSP connections in comparison with the connections of non-acceptable QoS, admitted by the threshold-CAC algorithm (pessimistic scenario)

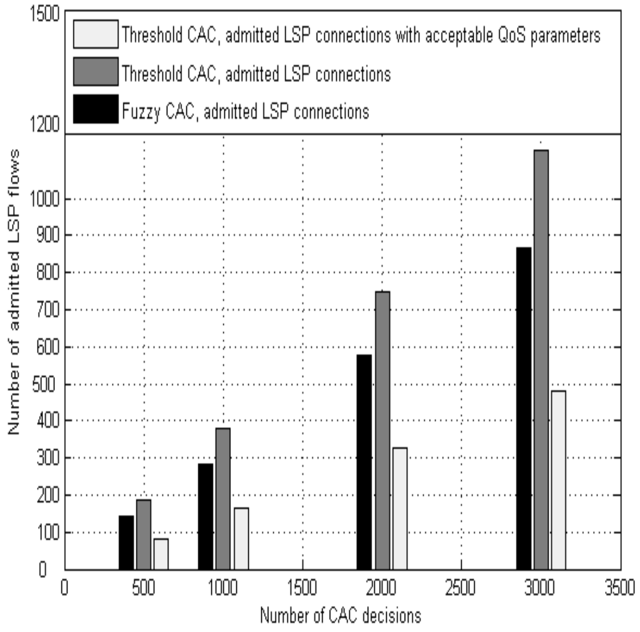

Figure 31 The LSP flow connections for both the fuzzy-CAC algorithm and the threshold-CAC algorithm (optimistic scenario)

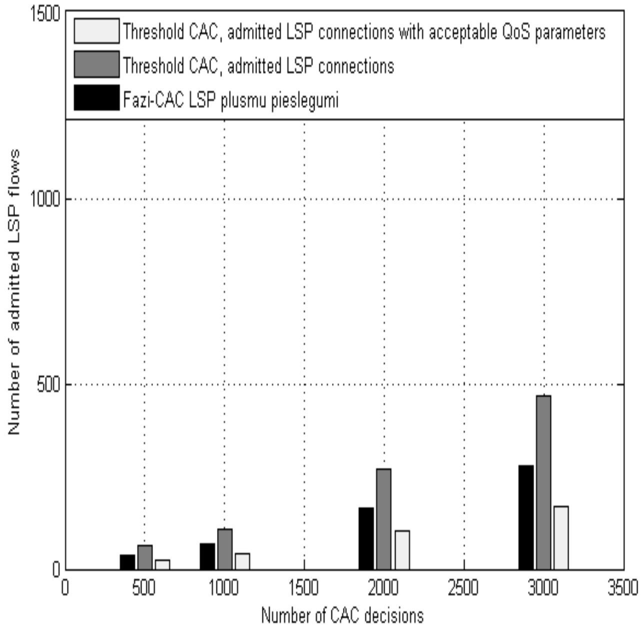

Figure 32 LSP flow connections for both the fuzzy-CAC algorithm and the threshold-CAC algorithm (pessimistic scenario)

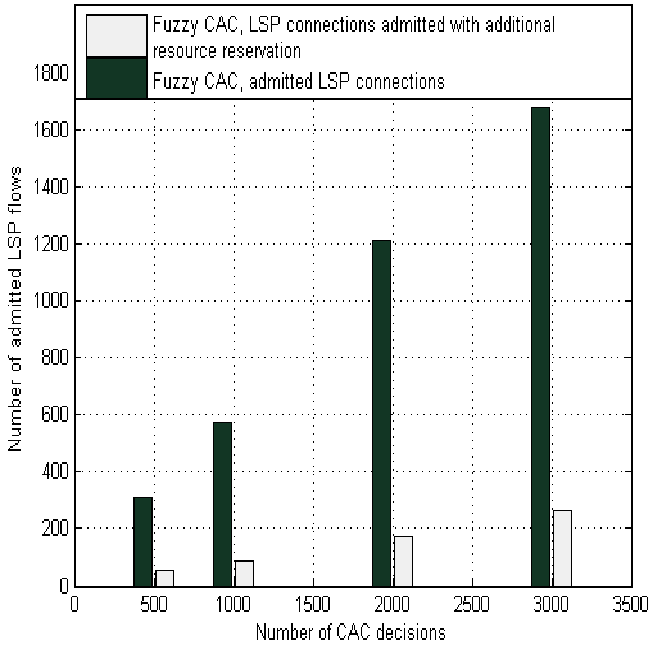

Figure 33 All the LSP flows in comparison with the flows with additional resource reservation admitted by the fuzzy-CAC algorithm (optimistic scenario)

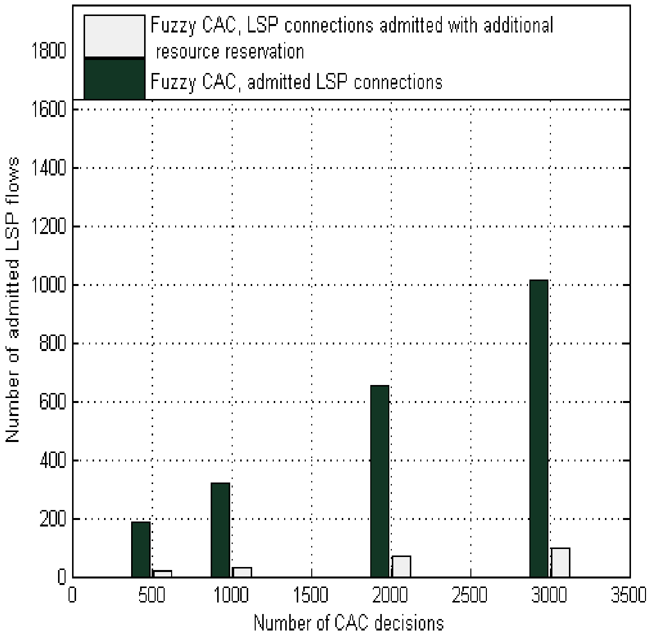

Figure 34 All the LSP flows in comparison with the flows with additional resource reservation admitted by the fuzzy-CAC algorithm (pessimistic scenario)

- By applying the threshold-CAC algorithm:
  - The high-priority LSP flows are connected ≈ 76 per cent more frequently in the case of optimistic scenario (Fig. 31);
  - The high-priority LSP flows are connected ≈ 60 per cent more frequently in the case of pessimistic scenario (Fig. 32);

- By applying the fuzzy-CAC algorithm:
  - If the additional bandwidth resources are reserved, ≈ 15 per cent of all the admitted flows are connected in the case of optimistic scenario (Fig. 33);
  - If the additional bandwidth resources are reserved, ≈ 10 per cent of all the admitted flows are connected in the case of pessimistic scenario (Fig. 34);

Chapter 4

Since the fuzzy-CAC decision-making system is making decisions under the circumstances, when the general behaviour of traffic and the values of parameters are not forecastable, it is necessary to carry out the analysis of the adaptive system of the fuzzy-CAC algorithm, which has the ability to accommodate to a rapidly changing environment.

Modification of Membership Functions

The goal of this research study was to change the membership functions of the linguistic input variables observed in the experimental fuzzy-CAC system in order to modify the general behaviour of the fuzzy CAC decision-making system. This provides the opportunity to increase the selectivity of the fuzzy-CAC algorithm towards new LSP channels established for transmitting data flows via data links without modifying IF-THEN rule base.

Therefore, in order to make the fuzzy-CAC management system more selective, we modified some membership functions of the input linguistic variables of the fuzzy interference system. In this particular case, in order to make the performance of the fuzzy-CAC system more selective and decrease the degradation of QoS parameters, the influence of variable $Delay\_l(t_i)$ upon decision-making logic was considered, changing its membership functions in the way shown in Figs. 35-36.

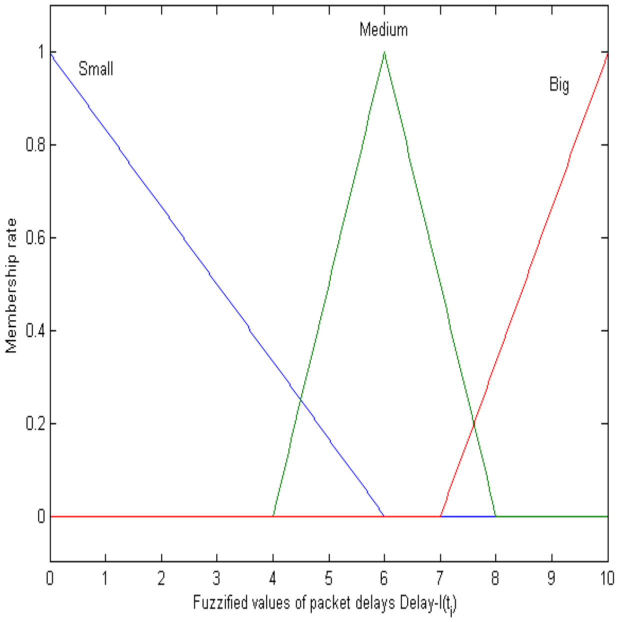

Figure 35 Membership functions of the linguistic input variable $Delay\_l(t_l)$ prior to modification

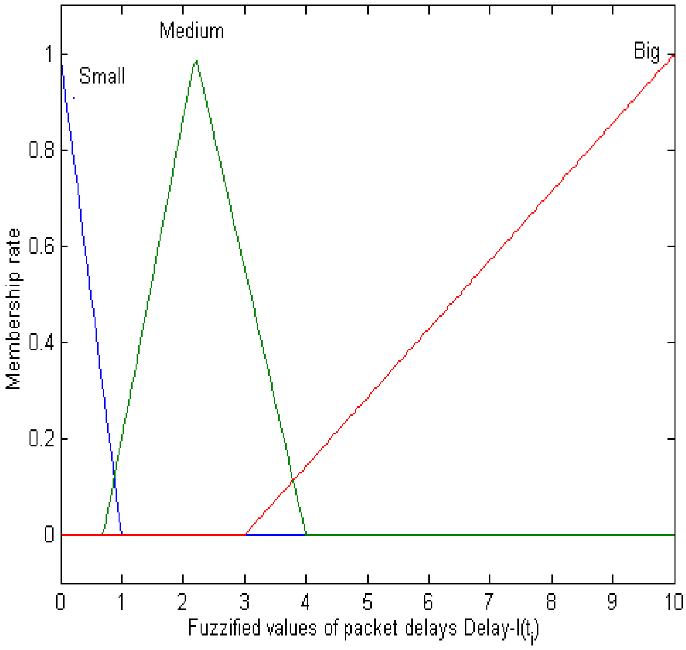

Figure 36 Membership functions of the linguistic input variable $Delay\_l(t_l)$ after modification

As a result, most fuzzified values of input variable $Delay\_l(t_l)$ at the moment of fuzzy interference were classified as *large*. It means that IF-THEN rules, which provide the response of the fuzzy algorithm when $Delay\_l(t_l)$ are large, become determinative at the moment of decision making.

The variable $Delay\_l(t_l)$ was selected for the analysis, since it has the highest influence on the IF-THEN rule base of the fuzzy system, and displays very clearly how the applied changes influence the general effectiveness of the fuzzy inference system.

Figs. 37-38 show the decision surfaces produced by the modified fuzzy inference system before and after modifying the membership functions of linguistic variables.

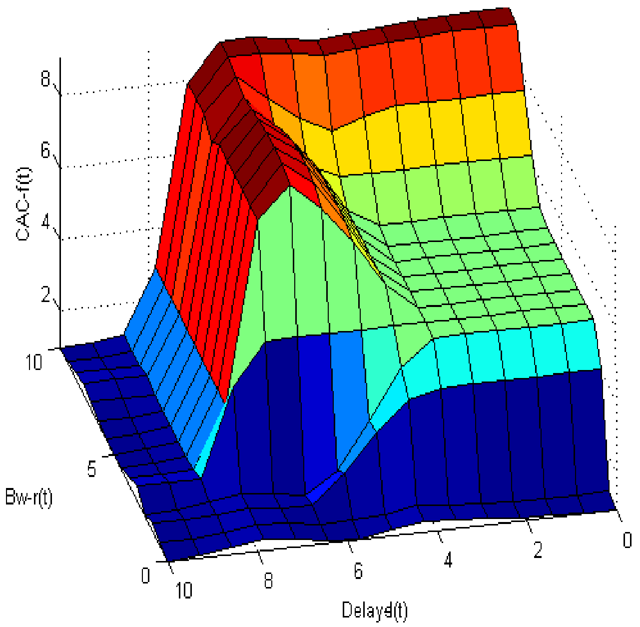

Figure 37 Fuzzy-CAC decision-making surface of input variables $\mathrm{Delay\_l}(t_1)$ and $\mathrm{Bw\_r}(t_1)$ prior to modifying the membership functions of the linguistic input variable $\mathrm{Delay\_l}(t_1)$

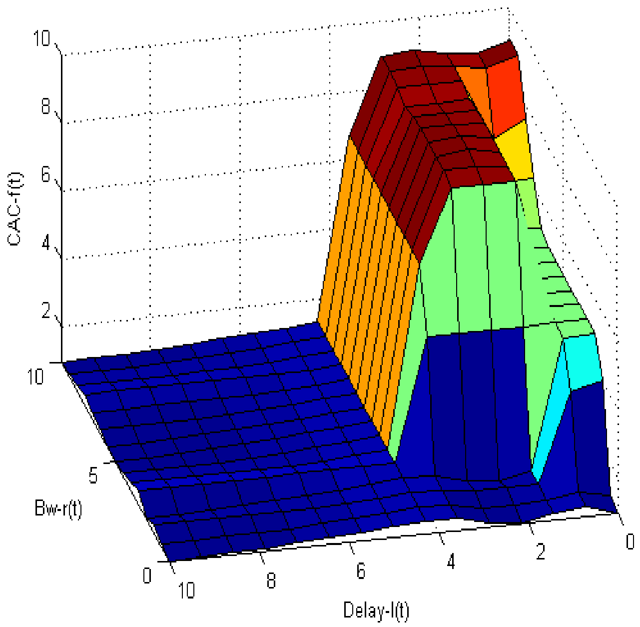

Figure 38 Fuzzy-CAC decision-making surface of input variables $\mathrm{Delay\_l}(t_1)$ and $\mathrm{Bw\_r}(t_1)$ after modifying the membership functions of the linguistic input variable $\mathrm{Delay\_l}(t_1)$

Table 4

Parameter Means – 3,000 Cases Considered		
Parameter	Fuzzy-CAC before modification	Fuzzy-CAC after modification
Average link utilization (the resources reserved by the RSVP-TE)	**0.82**	**0.79**
Packet loss, %	**3.90**	**0.15**
Jitter, ms	**1.3**	**0.6**
Buffer utilization, packets	**14**	**5**
Packet delay, ms	**46**	**29**

Making the analysis of the number of rejected flows (Table 5), we can see that the fuzzy-CAC solution increases the number of rejected flows for about 17 per cent as a result of modifying the membership functions of the linguistic variable $\mathrm{Delay\_l}(t_1)$.

Table 5

Number of Rejected LSP Flows		
Number of Decisions	Fuzzy-CAC before modification	Fuzzy-CAC after modification
500	**312**	**378**
1000	**679**	**769**
2000	**1348**	**1583**
3000	**1987**	**2343**

Table 6 characterizes the performance of the fuzzy-CAC algorithm admitting the LSP flows with reserving some additional resources. The fuzzy-CAC solution after the modification of membership functions of linguistic variables $Delay\_l(t_l)$ decreases the number of LSP flows admitted with additional bandwidth reservation for 55 per cent. The increased admission selectivity of LSP flows increases the number of rejected LSP flows and decreases the number of LSP flows required by QoS. Therefore, the parameters of QoS sustain at the acceptable level.

Table 6

LSP Flows of the fuzzy-CAC algorithm admitted with additional resource reservation		
Number of Decisions	Fuzzy-CAC before modification	Fuzzy-CAC after modification
500	**19**	**10**
1000	**32**	**17**
2000	**67**	**41**
3000	**98**	**54**

Modification of the Decision-Making Threshold

This approach can be considered as the method of response post-processing and does not influence in a direct way the structure of a fuzzy system. While the author failed to find this approach for post-processing the response of the fuzzy-CAC inference system in scientific literature, it still, in author's opinion, allows providing the real-time adaptation of the fuzzy-CAC algorithm to unstable transmission conditions in fast and efficient manner. Thus, it is possible to change the general traffic management policy instantly without changing the operation of the fuzzy-CAC inference system.

The simulation results produced for 3,000 fuzzy-CAC decision cases, changing the value of the symmetric threshold s, in the case of optimistic scenario, are shown in Fig. 39. In turn, Fig. 40 summarizes the simulation results in the case of pessimistic scenario.

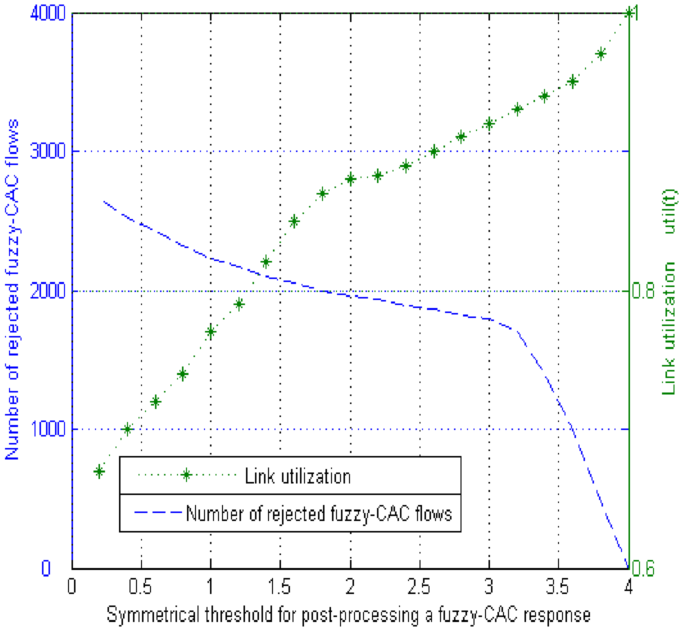

Figure 39 Link utilization and the number of rejected fuzzy-CAC flows against the values of a post-processing threshold (optimistic scenario)

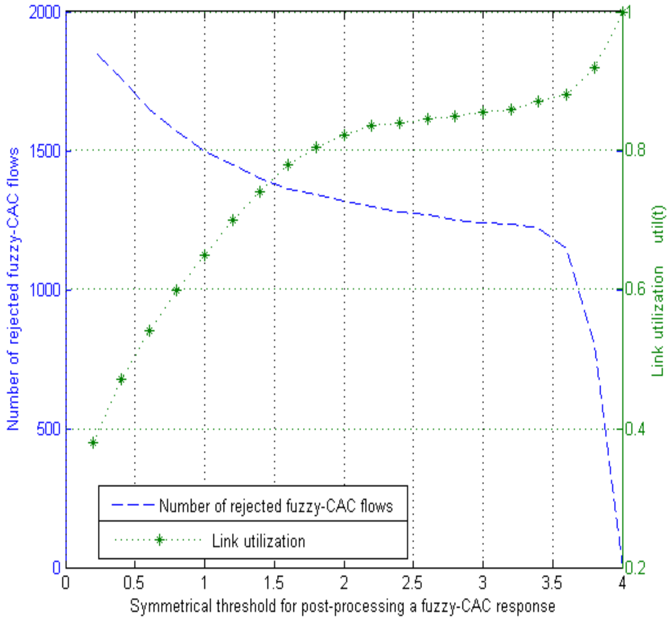

Figure 40 Link utilization and the number of rejected fuzzy-CAC flows against the values of a post-processing threshold (pessimistic scenario)

It is necessary to mention that the results produced by modifying a post-processing threshold will be unique for each particular fuzzy inference system as well as network specification and traffic type. The management of the fuzzy-CAC system has to be based on something similar to codec packs used in personal computers to enable some multimedia applications. The results shown in Figs. 39-40 can serve as the basis of a management card, which provides the instantaneous system adaptation to external conditions, and in this way, does not allow uncontrolled degradation of QoS parameters.

However, it is worth emphasizing that these post-processing methods can be only considered as the short-term performance tools, which are fast and do not require any direct modifications of the fuzzy inference system. Such methods can be applied in the case of short-term bursts of traffic flows, decreasing rapidly the number of connected LSP flows to preserve the QoS parameters within the accepted limits. In order to provide the long-term performance of the fuzzy-CAC algorithm, it is necessary to formulate the traffic management policy within the fuzzy inference system, which can be preserved and modified in routing equipment and applied taking into account the demands of an external environment.

MAIN RESULTS OF THE PROMOTION THESIS

While developing the promotion thesis, the following main results were obtained:

1. It was proved that if the CAC decision-making policy of the RSVP-TE protocol in the MPLS-TE networks is based solely on the available bandwidth of a link, then the traffic management of the MPLS-TE networks is ineffective. The thesis introduces the alternative CAC-management approach, which is based on the fuzzy-logic decision-making mechanism and enables the simultaneous analysis of multiple QoS parameters at the decision-making moment. This ensures the selective setup of LSP channels, which takes into account the QoS requirements on the application side and the QoS parameters of a network. At the same time, the QoS parameters are sustained within accepted limits.
2. The CAC solution based on fuzzy logic decreases the number of rejections of LSP flows as well as increases the number of connections of high-level QoS, sustaining the QoS parameters within accepted limits.
3. The fuzzy-CAC solution with three CAC decisions, which include admitting the LSP connection with additional resource reservation, ensures proactive traffic management by developing the so called “safety cushion” for LSP channels, the “size” of which is directly proportional to the admitted high-priority LSP flows and ensures sustaining the QoS parameters within accepted limits.
4. The estimation of performance of the fuzzy-CAC algorithm of the MPLS-TE experimental network, which reserves the resources of the RSVP-TE protocol at the moment of setting LSP channels, shows that even in the case of an overloaded network characterized by “bursty” traffic, the fuzzy-CAC enables the selective control of LSP flows and lighter degradation of QoS parameters.
5. It was proved that it is possible to perform fast post-processing of the responses of the fuzzy decision-making algorithm by applying a threshold parameter to the fuzzy-CAC responses. This enables an instantaneous change of the policy of the fuzzy-CAC algorithm without changing the membership functions of linguistic input variables and / or the base of IF-THEN rules.
6. While analyzing the fuzzy-CAC real-time decision-making adaptive methods, it was proved that such methods of output de-fuzzification of membership functions as SOM, MOM un LOM decrease the volume of information about the decisions made by the IF-THEN rules and disable the effective post-processing of the fuzzy-CAC responses.

To summarize the promotion thesis, the author would like to emphasize that the results are very promising. They show that the fuzzy-CAC solution for the management of the RSVP-TE protocol of MPLS-TE networks is capable of providing a dynamic and proactive management of the LSP setup, while sustaining the QoS parameters within accepted limits. The fuzzy-CAC management solution proposed by the author is practically implemented in the MPLS-TE routing device, developing an experimental product.

The author of the thesis highlights the following topics for future research:

- fuzzy-CAC for multi-agent connections
- fuzzy-CAC adaptation methods
- automatic generation of the fuzzy-CAC inference system
- automatic development of the IF-THEN rule-base for the fuzzy-CAC inference system.

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