# A Novel Approach to the Adaptive Allocation of Bandwidth in IP/MPLS Networks in Conditions of Heavy Network Load

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*Abstract* - **In this paper, an algorithm for adaptation layer in order to improve fairness in bandwidth allocation among different traffic classes in IP/MPLS networks under heavy traffic load is proposed. A definition of the blocking frequency of traffic flows at the entry of autonomous network domain and proportional-priority coefficient per traffic class are proposed and used as the input parameters of the adaptation mechanism. In order to evaluate the validity of the proposed algorithm, proper simulation tool is needed and for these purposes OPNET Modeler 14.5 is extended with the modules for adaptation process. Development methodology for the design of modules for adaptation process within network simulators is also proposed. The simulation results proved the hypothesis that with a proper adaptation layer, improvement of the fairness of bandwidth allocation among different traffic classes under heavy network load and at the same time keeps the required QoS conditions in the preferred boundaries is possible.**

***Keywords - Adaptation layer; bandwidth allocation; blocking frequency; LSP; MPLS; NGN; proportional-priority coefficient; RSVP.***

## I. INTRODUCTION

One of the key requirements of the new generation network (NGN) environment is that the network is capable of handling an ever-increasing demand uncertainty, both in volume and time. In such environment, very often the total traffic demands exceed the available network capacity, and the traffic classes with higher priority could occupy the entire network capacity leaving no space for traffic flows with lower priority. Proper adaptation mechanisms could give acceptable results in adequate bandwidth allocation to the traffic variation and in fair treatment of all traffic classes. In the paper [1] was carried out testing of proposed adaptation layer in the case of normal network load. Mechanisms used for bandwidth allocation should be able to manage requests by taking into account at least three parameters: class of service, priority and the requested bandwidth. Several research works in the field of bandwidth management, including [20] [21], have taken in consideration only two parameters out of those three. We used all three parameters in our algorithm, as can be seen in generic architecture of adaptation layer (Fig. 1) and in flow chart (Fig. 2). The fairness in the resource allocation among traffic flows depends on algorithm used during the process of adaptation to the real conditions of traffic load. The fairness of adaptation algorithm represents the ability of the model to distribute available resources in such manner that the probability of traffic blocking for any particular traffic class is the same as the overall blocking probability. We can use ratio $P_i$ of the allocated resources $G_i$ to the requested resources $B_i$ of the particular traffic flow demand $P_i = (G_i / P_i) x 100$ as a measure of the algorithm fairness. Three types of fairness index are possible [15]: balanced fairness, max-min fairness and proportional fairness. Many of researches including [21] [24] used max-min approach as a tool to achieve fair distribution of network resources among traffic classes. Max-min fairness assumes that is not possible to increase rate of any connection without decreasing a rate of maximum value allocated to another connection. According to the results shown in this reference, proportional type of fairness is the most suitable type in the case when the network resources are distributed among different traffic classes and when the adaptive method of resource allocation is used. In the same paper, fairness index J for the proportional type of fairness among n traffic classes is proposed as such:

$$J = \frac{(\sum_{i=1}^{n} P_i)^2}{n \sum_{i=1}^{n} P_i^2} \tag{1}$$

where $P_i$ is the fairness of traffic class i. If the value of the fairness index is equal to 1 (J = 1) there is fairness across all flows. If the value of the fairness index J is higher than 0.9, or in an extreme situation higher than 0.8, one can say that the resource allocation mechanism is fair [3]. Otherwise, variations in resource distribution are significant and blocking percentage of the lower-priority traffic classes is outside of the acceptable margins.

NGN is a packet-oriented network supporting Quality of Service (QoS) based on different type of transport technologies. The most preferred protocol in NGN is IP. There are different approaches for the QoS provisioning in IP based networks: Integrated Services (IntServ), Differentiated Services (DiffServ), combined IntServ/DiffServ, Multiprotocol Label Switching (MPLS), etc. [2]. MPLS is a popular transport technology that uses labels which are imbedded between layer two and layer three headers in order to forward packets. Packets are forwarded by switching packets on the basis of labels and not by

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routing packet based on IP header. One of the major advantages of MPLS networks is the inherent support to traffic engineering. We can also use a combination of MPLS and DiffServ and treat packets of the same Forward Equivalence Class (FEC) in accordance with the DiffServ procedure. Using MPLS Traffic Engineering (MPLS-TE) based on the network state detection we can balance traffic load among different Label Switched Paths (LSPs), but we cannot dynamically change allocated bandwidth to the LSPs [25]. MPLS-TE can be used to shift traffic form overload paths to alternate path with free bandwidth, but it does not contain inherent QoS features. These features should be designed and deployed separately on top of MPLS tunnel (what is subject to adaptation algorithm). Although the MPLS-TE technology uses extension to the RSVP, the MPLS-TE RSVP reservations serve solely as an accounting mechanism. This prevents link oversubscriptions but does not result in any QoS actions.

In order to adapt to dynamics of traffic demands and to allocate sufficient bandwidth to the LSPs, as well as to improve fairness in the resource allocation among traffic flows, we introduce adaptation layer, working in two regimes:

- fuzzy controller regime, when the overall traffic demand is elastic and in average less than network capacity. In this case, the adaptation process is realized by the means of fuzzy logic [19],
- proportional-priority regime, when the overall traffic demand is higher than the network capacity. In this case the adaptation process allocates bandwidth among traffic classes in such a manner that minimal bandwidth is guaranteed to each traffic class and the rest of network capacity is shared on the proportional basis among traffic classes (equation 4).

The adaptation layer supports dynamic exchange between fuzzy controller regime and proportional-priority regime depending on the ratio between traffic load and the network capacity C. When the network load less than its capacity, all requests for bandwidth can be served. With regard to the possible large variation in the intensity of traffic flows, adaptation layer uses fuzzy controller that effectively predicts the variation. When the load is greater than its capacity, large variations in the intensity of traffic flows are not possible. Then there is no need for rapid changes in the allocated bandwidth, and adaptation layer uses a proportional-priority bandwidth allocation regime.

In order to prove validity of our adaptation layer concept and sustainability of the fairness improvement concept of bandwidth allocation among traffic flows, we need proper simulation tools. Because there are no network simulators supporting the proposed adaptation layer algorithm and dynamics of this algorithm, we established a methodology for development of adaptation layer within network simulators and we also developed the adaptation layer code in C++ within OPNET core structure of node model (Label Edge Router - LER) and within core structure of process model of the Resource Reservation Protocol (RSVP-TE) used in the OPNET modeler.

## II. MECHANISMS AND ARCHITECTURES FOR ADAPTIVE TREATMENT OF TRAFFIC DEMANDS

The goals of adaptive treatment of traffic demand in NGN are to:

- Fulfill QoS requests of any traffic class,
- Reduce drops of any traffic flows,
- Decrease congestion within network,
- Rise efficiency of network capacity.

In order to successfully achieve those goals, appropriate mechanisms for the bandwidth allocation, for the routing optimization and for reaction to the failure conditions are needed. During the research project COST 257 [4], several types of reactive and preventive approaches for network control were investigated:

- the flow control scheme (fluid flow model, discrete-time Markov model or control theory model) for reactive approach,
- the admission control method (Measurement Based Admission Control - MBAC, Traffic Description Based Admission Control - TDBAC, Experience Based Admission Control - EBAC or End-point Admission Control - EAC) for preventive approach,
- the active queue management or fuzzy congestion control as a new control trends.

Preventive controls usually try to limit the number of connections or to enforce connection to use only a limited amount of resources. In IP networks, the specifications of protocols such as RSVP or MPLS make admission control possible. There has been a variety of efforts with regards to admission control [22] [23] [24]. All of them can be categorized into distributed approach or centralized approach. In distributed approach, nodes act independently relying on observed behavior rather than explicit reservation of free resources of the network. This approach leads typically in over-provisioning of the network's capacity in order to bypass imprecision of the probe data. On the other side in centralized approach all new connections must be approved through bandwidth broker. While the centralized approach can offer a precise allocation of resources, it suffers from scalability limitations. We applied an ingress node oriented resource management which combined scalability of distributed approach with the efficiency of centralized approach. MPLS traffic engineering is aimed at optimizing the network path to ensure efficient allocation of network resources, thereby avoiding the occurrence of congestion on the links [2]. During the research project Tequila (Traffic Engineering for QoS in Internet at Large Scale) [6], it was shown that a combination of MPLS and DiffServ could be acceptable solution for load balancing in IP networks when multi-path routing is used. Also, during the research project COST 239 [5] it was shown that, in case of large traffic load, the highest efficiency of the resource usage is in the networks which use border-to-border budget based network admission control (BBB NAC) as a budget-oriented method for allocation of virtual bandwidth. BBB NAC could be realized using RSVP extension for LSP tunnels establishing explicit LSPs with guaranteed bandwidth.

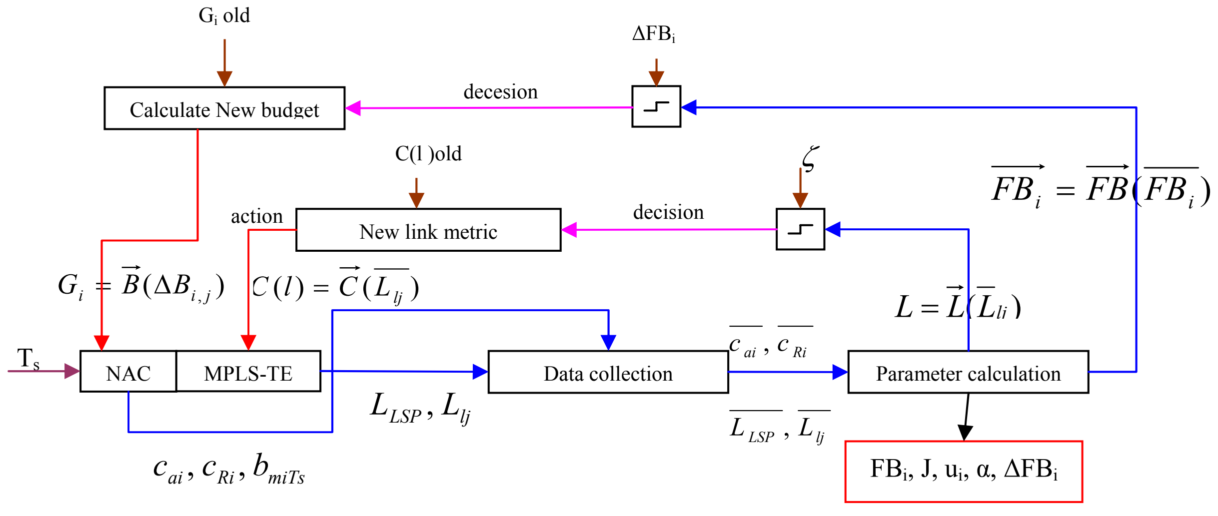

Figure 1. Generic architecture of adaptation layer

Several research projects investigate possible architecture of dynamic provisioning of QoS to the particular traffic flow. The basic result of KING (Key Components for Internet of the Next Generation) project [18] includes development of adaptive architecture in which, by continuous monitoring of network conditions, the network parameters could be adapted to traffic demand.

We customized this architecture according the requests of the logic of our adaptation algorithm, as shown in Fig 1. The figure shows the following parameters:

- $c_{ai}$ - amount of accepted traffic of i-th traffic class,
- $c_{ri}$ - amount of rejected traffic of i-th traffic class,
- $b_{miTs}$ - number of rejected reservation for i-th traffic class within one sample period,
- $T_s$ - sample time,
- $L_{LSP}$ - LSP traffic load,
- $L_{ij}$ - traffic load of i-th traffic class on j-th link,
- $u_i$ - utility function according equation 6,
- $FB_i$ - blocking frequency of i-th traffic flow,
- $\zeta$ - decision criterion.

We combined the admission control method (MBAC – BBB NAC) with policy based control of adaptation layer to dynamically adapt budget of the NAC in order to decrease blocking frequency and to raise fairness of bandwidth allocation among traffic classes.

## III. DESIGN OF MODEL FOR ADAPTATION PROCESS

### A. *One Possible Solution of Adaptation Layer*

In [11] - [14], an active queue management as network control mechanism is proposed. This approach requires execution of adaptation layer processes at every node in the network, so making it unsuitable for MPLS based networks.

In this paper we use a different approach for solution of the adaptation layer algorithm in order to increase the resource usage efficiency, to provide proper QoS to any traffic class and to improve fairness in bandwidth allocation among traffic flows within MPLS based networks. In the rest of this section we give a brief overview of the solution and corresponding part of pseudo code of algorithm. A full description, that includes a detailed explanation of the algorithm, is given in [16]. In this paper, MPLS is used as a transport technology on the network layer. Network capabilities to provide sufficient resources at a given time for a given traffic class are controlled at ingress node. Instead of assigning bandwidth to a particular link, provisioning of QoS requirements is done by assigning a virtual budget at ingress node for all relations between ingress and egress nodes using BBB NAC. BBB NAC in MPLS for LSP with a guaranteed bandwidth can be established by RSVP extension for LSP tunnels and then managing the right to network access can be made for each stream. Adaptation layer collects statistical data from the network layer and uses that information to generate a global view of the current state in the network. Detection of the current state in the proposed architecture is based on the utilization of the budgets allocated to the NACs, the frequency of blocked reservation (e.g. blocking frequency) and on the utilization of links' capacity. Adaptation process includes adjustment of the amount of available bandwidth for each traffic class separately and optimization of internal routing. For the link metric calculation we use gradient projection algorithm and delay of any (i) traffic class on each (j) link as metrics. But because of results achieved in previous research [5] which shows that the contribution of the link metric changes to the decrease of percentage of blocking traffic is very small and in order to keep our system stable, we switch off the link optimization loop during the simulation.

Adaptation layer follows its own internal strategy and optimization algorithms in order to adapt network performance to the traffic load variations. Adaptation layer has two regimes:

- Fuzzy controller regime, which is realized by means of fuzzy logic, based on the blocking frequency of traffic flows. The adaptation process is executed in discrete cycles. Blocking frequency (FB) measured in particular cycle and difference in blocking frequency (($\Delta$FB) between two cycles are the input variables of triangle fuzzy membership function:

$$\mu(x) = \begin{cases} 0, & x \le b-a, \\ [x-(b-a)]/a, & b-a < x \le b, \\ -[x-(b+a)]/a, & b < x \le b+a, \\ 0, & x > b+a. \end{cases} \quad (2)$$

where the initial values of parameters are a = 2 b = (-6, -5, -4, -3 -2, -1, 0, 1, 2, 3, 4, 5, 6) to obtain 13 different values of the fuzzy variables. The initial design of the network based on the assessment of longer term traffic load and a relatively short period between the two adaptation cycles (15 minutes) significantly limit the value of FB and its fluctuations. This membership function and fuzzy rules, given in [16], are used for determination of the value of proportional coefficient ($n_{ij}$) to the bandwidth increment $\Delta B_i$ of i-th traffic class within j-th cycle. The bandwidth increment $\Delta B_i$ is given in advance for every traffic class. To adjust amount of allocated bandwidth $G_{ij}$ of the i-th traffic class in j-th cycle to the actual traffic demand, adaptation algorithm changes allocated bandwidth of i-th traffic class in j-1st cycle with the value of $n_{ij}$ $\Delta B_i$ in accordance with the following formula:

$$G_{ij} = G_{ij-1} + n_{ij}\Delta B_i \quad (3)$$

- Proportional-priority regime, which is based on minimum bandwidth allocated to the i-th traffic class ($\min_{pi}$) and proportional-priority coefficient $\delta_{ij}$ of the i-th traffic class in j-th cycle, performs its functions in accordance with the following formula:

$$G_{ij} = \min\nolimits_{pi} + \delta_{ij}(C - \sum_{i=1}^{n} \min\nolimits_{pi}) \quad (4)$$

The criterion for switching between the two regimes is fulfilled when the sum of requested capacity of traffic classes $B_i$ is bigger than network capacity (C):

$$\sum_{i=1}^{n} B_i > C \quad (5)$$

In the previous studies [17], behavior of the overall system, which performs its control functions automatically, autonomously and in an adaptive manner, is usually described by means of the following parameters:

- blocking frequency of traffic flows (FB),
- fairness of the allocation of resources to the traffic flows (P, J),
- utility function of network capacity ($u_i$)

$$u_i = \frac{\sum_{i=1}^{n} G_i}{C} \quad (6)$$

Blocking frequency of traffic flows (FB), we used as a key parameter for adaptation process, is defined as the total number of the rejected resource reservation ($b_{miTN}$) in all n classes of traffic within the determined time interval k. Measurement of rejected traffic flow is performed at the NAC any time new traffic flow (c($f^{new}_{v,w}$ ) added to the existing traffic flows (c(f)) requests capacity which is higher than the available capacity (C(BBB)). of the given resources between nodes v and w. While the frequency of blocking can be defined as the maximum blocking probability or a relative ratio of blocked and offered traffic, this definition of blocking frequency, which treats all traffic classes simultaneously and only at the input node, is simple to measure and easy to calculate:

$$FB = \sum_{i=1}^{n} FB_i, \quad FB_i = \sum_{T_N=1}^{k} b_{miT_N} \quad (7)$$

$$b_{miT_N} = countif\left\{\left[c(f^{new}{}_{v,w}) + \sum c(f)\right] > C(BBB)\right\}$$

Fairness of resource allocation between traffic classes depends on the resource (bandwidth) allocation algorithm used during the process of adaptation to the actual traffic demands. Consideration of fairness makes sense only if the total amounts of requested resources exceed the capacity of available network resources. Otherwise, the problem boils down to utilization of network resources and to load balancing in order to assess the cost of depreciation and to even utilization of network resources. Fairness of the adaptive algorithm is the ability of the model to distribute the available resources in such a way that any traffic class does not give preference outside of the defined priority mechanism. The main goal of equitable allocation of resources assessment includes quantification of differences in distribution of resources between traffic classes by measuring variations in the ratio of allocated resources. We used equation 1 to evaluate fairness of proposed adaptation algorithm. We also compare the same fairness index achieved in the network architectures operating in adaptation mode and in the network architecture operating in non-adaptation mode to evaluate improvement in fairness.

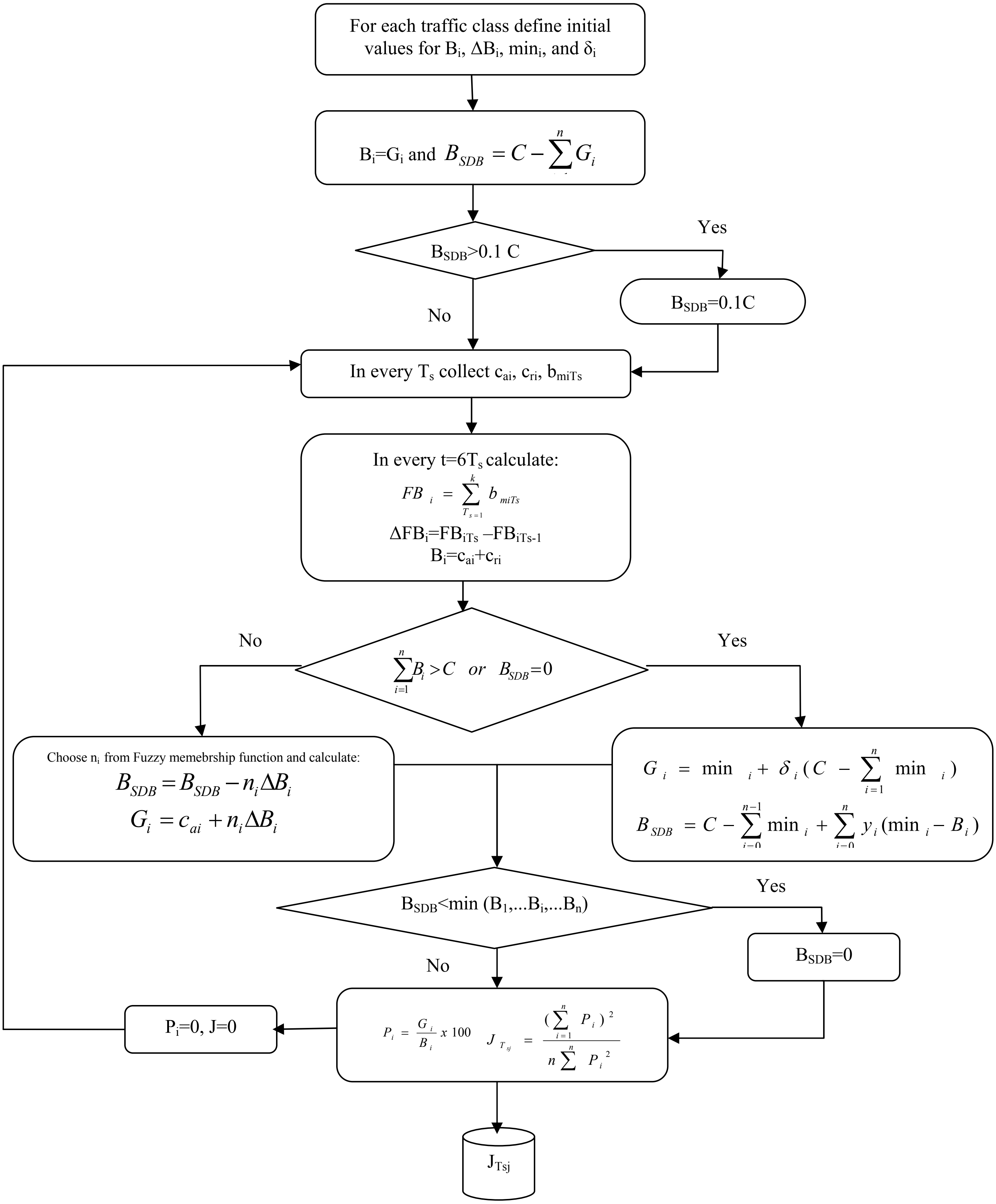

Figure 2. Flow chart of adaptation layer

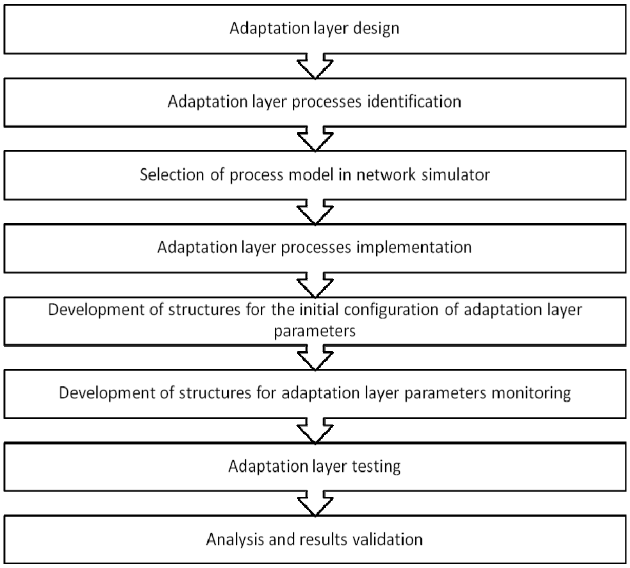

Figure 3. Development methodology of adaptation layer

Simulation model of network architecture we used consists of the adaptation and network layers. The adaptation layer performs a calculation of the new bandwidth budget for network admission controllers (NAC) and a calculation of new metrics on the links in order to adapt network performance to the actual traffic conditions. Measurements of blocking frequency (FB), accepted traffic ($c_{ai}$), rejected traffic ($c_{ri}$) and LSP load are performed in the regular time intervals at the ingress node in order to provide input data for operation of adaptation layer. The network layer autonomously executes forwarding functions of the packets and ensures QoS requirements using the capabilities of existing technologies and protocols. This type of network architecture represents the optimal set of available technologies with flexible topological landscape. Admission control functions, based on timely adjusted allocated bandwidth and load balancing functions by means of MPLS traffic engineering capabilities, are executed only at the ingress node of the autonomous network domain.

### *B. Looking for a Simulation Tool for Validation of Designed Model*

The adaptation processes are capable of a continuous monitoring of the network parameters and performing their adaptation in accordance to the ever-changing traffic demands. Possible solution for such structure of adaptation process could be an active resource allocation based on the dynamic monitoring of their availability and of their sustainability to effectively transfer traffic.

The efficiency of such structures should be evaluated and an adequate simulation model which can adequately represent mechanisms and architecture for adaptive treatment of traffic demand is needed. Therefore, in this section we investigated possibilities of existing network simulators to support structure of adaptation algorithm we used in this paper. The analysis is based on a review of scientific studies in this field and documentation available for the network simulators.

In [8], a scheme for an adaptive bandwidth reservation in wireless multimedia networks was examined. For the purpose of validation of the proposed solution, necessary module for network simulator OPNET (Modeler 8.0) was developed. However, examination of the latest available version of the network simulator OPNET (Modeler 14.5) showed that these modules are not supported by the simulator manufacturers and as such is not included in the set of available modules. In [9], a solution for the adaptive bandwidth allocation in MPLS networks using a control with one-way feedback was given. The proposed solution was tested in a network simulator ns-2.27. But this solution is dedicated for particular problem and only in ns 2-27. Because of that it is inflexible for usage in general. Elwalid et al. [10] discussed adaptive traffic engineering in MPLS networks and their effort to develop their own simulator is the significant sign that there is a poor support for the dynamic adaptation structures in the available network simulators. Reviewing the documentation about the available network simulators we determined that none of those network simulators have built-in support for the dynamic adaptation structures. As the available simulators have no appropriate support for dynamic adaptation structures, and the same is necessary to test proposed structures, one of the objectives of this paper is to establish the methodological approach to development of adaptation layer in the network simulator. This methodology will be used for development of the adaptive layer modules within a chosen network simulator.

## IV. DEVELOPMENT METHODOLOGY OF AN ADAPTATION LAYER WITHIN NETWORK SIMULATOR

In order to develop an adaptation layer which is independent of the adaptation mechanism of the used technology or of the network simulator, it is necessary to define a development methodology. We established a development methodology of an adaptation layer within network simulator which has eight steps shown in Fig. 3. Each of those steps will be explained in this section.

### *A. Design of the Adaptation Layer*

In the section III we explained the basic functions and principles of our adaptation layer. The detailed design of adaptation layer with adaptation algorithm, input and output variables, decision criteria and pseudo code of the adaptation layer components are given in [16].

### *B. Adaptation Layer Processes Identification*

For the purpose of execution of adaptation layer functions we identify next three processes:

- measurement of input variables,
- adaptation, and
- output parameters control.

The first process is deterministic and it is performed in regular time intervals ($T_N$). The task of this process is measurement of flow intensity of each traffic class and a measurement of blocking frequency at the entry into the MPLS domain.

The process of adaptation is also deterministic, and it is performed in regular time intervals determined by the duration of discrete cycle of adaptation. The task of this process is to calculate a new budget based on input variables.

The last process is a stochastic process and its execution is caused by the decision results of adaptation process. The task of this process is to allocate a new budget to the network admission controller.

### *C. Selection of Process Model in Network Simulator*

A number of network simulators are available today. Some of them, used in scientific researches, are ns-2/3, OPNET, OmNet++, GloMoSim, Nets, etc. Selection of adequate network simulator should be based on the characteristics of the simulators corresponding to the needs of adaptation layer developed as the target platform. We choose OPNET Modeler 14.5 as a proper network simulator considering next properties of the chosen simulator:

- simulation is based on the discrete network states (FSM-based approach),
- it supports traffic profile we intend to use during a simulation,
- it supports the network technologies and protocols we selected for a simulation model,
- it is suitable for prototype research such as this simulation model,
- it is easy to configure,
- it has relatively good documentation and support,
- it can be extended for adaptation layer (supports C-scripting language).

Since the proposed adaptive layer is a prototype of generic adaptation layer and as such does not exist in the selected network simulator, the whole adaptation layer should be developed based on the pseudo code given in [16], taking into account the constraints of simulator architecture. The architecture of the network simulator OPNET Modeler 14.5, extended with necessary modules for adaptation layer, is presented in Fig. 4.

Network simulator OPNET Modeler 14.5 is hierarchically organized. A network model is located at the highest level of hierarchy. The network model is composed of nodes and links connecting the nodes. Each node is defined by the node model (workstation, switch, router, server, etc.). Node model consists of processors that are described in process models. Process models are described in FSM's (Finite State Machine) and transfer functions written in C++ programming language. Transfer functions rely on the core functions of the simulator. The core simulator consists of pre-compiled libraries, whose source code is not available. The kernel is based on discrete event simulation.

Node at which network admission control functions are performed is the ingress LER of the MPLS domain. Bandwidth control at the entry of the network is ensured by establishing an explicit path with guaranteed bandwidth. The protocol that is responsible for setting up LSPs is RSVP-TE.

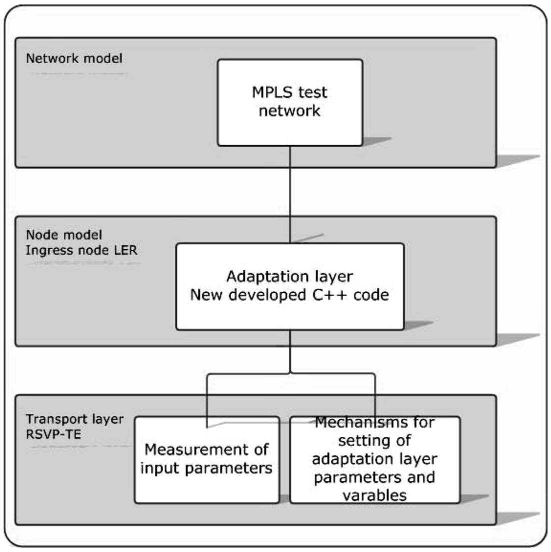

Figure 4. Hierarchical architecture of OPNET simulator

Therefore, the logical choice of process model within the simulator is RSVP process model. We used the network model which consists of five traffic sources nodes, the ingress edge router, four core MPLS routers, the egress edge router and five traffic destination nodes.

### *D. Adaptation Layer Processes Implementation*

Ingress LER node model (Cisco 7600) consists of processors and queues associated with packet or statistic wires. We introduce the new statistical flows between the MAC (Media Access Control) queues and RSVP process model in order to take periodical measurements of the input variables, such as the mean intensity of flows, number of the rejected reservations, etc.

Process models in the OPNET network simulator are based on FSM. Passing from one state to another is initiated by different types of interruptions (packet arrival, arrival of new statistics value, user-defined stop, etc.).

During the transition stage different functions could be called. Besides the FSMs, the main components of a process model are the state variables, temporary variables, function block with headers, block functions, block for debugging and scheduling process block. Each process model also has attributes, interfaces, local and global statistics. Attributes and statistics can be promoted to a higher level, i.e. at the level of the node model.

### *E. Initial Configuration of Adaptation Layer Parameters*

The initial parameters of adaptation layer, such as initial bandwidth per each traffic class ($B_i$), minimal bandwidth per traffic class ($min_{pi}$,), proportional-priority coefficient ($\delta_i$), bandwidth increment ($\Delta B_i$), are defined in [16]. Those initial parameters are subject to changes during the exploitation period (if the traffic environment changes dramatically) or during the simulation process (to be able to perform different simulation scenarios). For this purpose we need a proper structure within a simulator which offers changeability of the

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initial configuration settings and changeable setting of its parameters. The development process of that structure has the following steps:

- definition of the adaptation layer attributes within the set of the existing process model attributes,
- promotion of the attributes from a process model level to the level of the node model,
- coding the input function in C++ to retrieve attributes when the simulation starts.

### *F. Monitoring of Adaptation Layer Parameters*

In Sections I and III, we defined parameters which should be monitored such as blocking frequency (FB), fairness index (J), difference of blocking frequency (ΔFB) used as input variable for fuzzy membership function, etc. Those parameters should be measurable and monitored in order to qualify adaptation process execution and to use them as the input parameters to the adaptation layer. For this purpose we need a structure within simulator which offers a possibility to measure and monitor the values of the adaptation layer parameters. The development process of that structure has the following steps:

- definition of the local statistics in the process model,
- promotion of statistics on the level of the node model,
- coding of the function in C++ to record statistics.

### *G. Testing, Analysis and Result Validation*

Those two steps of the development methodology are explained in Section V.

## V. THE SIMULATION RESULTS

The simulation model created for testing purposes of adaptation layer is shown in Fig. 5 below. All nodes in the access part of the network are connected using 10 Gbps links, while the core routers are connected using 1 Gbps links. OSPF protocol is used as an IGP, and RSVP-TE protocol is used for establishment of LSPs. Between the LERs is 10 tunnels configured (two for each of five traffic classes). Traffic mapping at ingress LER is done using five different FEC based on the address of the traffic source. Traffic of each FEC is transmitted through two LSP (the first has an explicit route LER1-LSR1-LSR4-LER2, and the second-LER1 LSR1-LSR3-LER2).

For testing of adaptation layer, two scenarios are proposed:

- average load is 80% of network capacity,
- average load is 100% of network capacity.

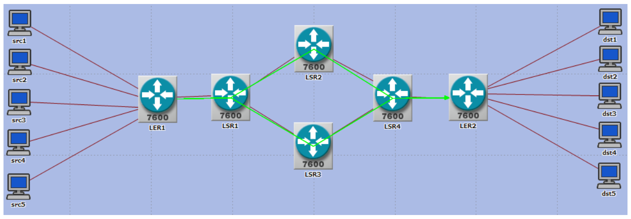

Figure 5. Simulation model for adaptation layer testing

The detailed dynamics of traffic demand of traffic classes for both scenarios, used during a simulation process, are given in the thesis [16]. In the first scenario the traffic generators are configured so that the average network load is 80%. The network capacity is 2 Gbps. The peak load of the network is about 2.5 Gbps. The initial values for those traffic classes, in the case that average network load is 80% of the network capacity, are given in Table 1 below.

TABLE I. INITIAL VALUES OF TRAFFIC SOURCES FOR $1^{ST}$ SCENARIO

| **Traffic class** | **Initial BW kbps** | **Minimal BW kbps** | **Maximal BW kbps** | **BW incr. ΔBi** | **Proportional-priority coefficient δi** |
|---|---|---|---|---|---|
| EF | 8,270 | 5,990 | 14,000 | 125 | $1.2\frac{B_{ij}}{\sum B_{ij}}$ |
| AF1 | 465,110 | 319,760 | 700,000 | 10,000 | $\frac{B_{ij}}{\sum B_{ij}}$ |
| AF2 | 586,390 | 403,140 | 800,000 | 22,000 | $0.9\frac{B_{ij}}{\sum B_{ij}}$ |
| AF3 | 5,690 | 3,850 | 14,000 | 200 | $0.9\frac{B_{ij}}{\sum B_{ij}}$ |
| BE | 431,310 | 286,528 | 700,000 | 6,000 | $0.8\frac{B_{ij}}{\sum B_{ij}}$ |

During the simulation process we observe a distribution of requested bandwidth per each traffic class $B_i$ and distribution of allocated bandwidth per each traffic class $G_i$ in the same time window. We perform those observations in the adaptation mode of network architecture and in non-adaptation mode of the same network architecture in order to validate the accurate of the adaptation layer processes and to evaluate improvement in resource utilization as well as in QoS satisfaction of the requests of any traffic class.

We also observe values and distribution of fairness index (J) in both modes of network operation and values and distribution of ratio of the allocated resources to the requested bandwidth per each traffic class, in order to evaluate improvement of fairness in adaptation mode of network operation compared to the non-adaptation mode of operation. During the simulation process we take measures every 10 seconds and average those measurement values in time window of one minute, using those average values to calculate parameters which are needed for adaptation process of our adaptation algorithm.

By means of Figures 6 to 8 below, as a part of simulation results, we will show the outcomes of proposed adaptation algorithm, as well as of the extension of the OPNET structure. The whole scope of simulation results, from which we proof our entire concept, can be seen in [16].

From the Fig. 6, we can see that allocated bandwidth G for EF traffic class pretty well follows the required bandwidth B. This confirms that the adaptation layer functions properly and accurately. We can see the same results for other traffic classes and for average load of 80%.

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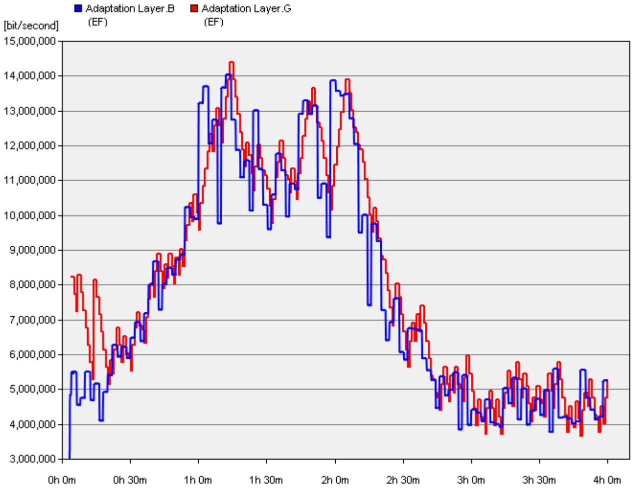

Figure 6. Requested and allocated bandwidth for EF traffic class

Fig. 7 shows us that introduction of adaptation layer improves the fairness of resource allocation in the network. During the non-adaptive mode, the ratio (P) of the allocated resources to the requested resources for EF class was unstable and goes up to 200%, while during the adaptive mode of network operation this percentage was stabilized and dropped to 100%, as is the preferred value for all traffic classes.

Fairness index (Fig. 8) is, in the adaptation mode of network operation, maintained above 0.96 with brief outages of up to 0.8, while the same index, in non-adaptation mode, is very unstable and drops up to 0.5.

Fig. 9 shows that the adaptation layer is stable structure. Blocking frequency stabilizes after a certain time on the value 10.

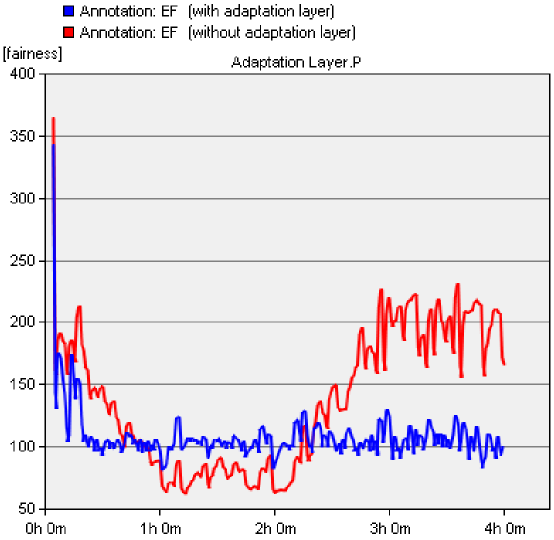

Figure 7. Ratio of the allocated resources for the EF traffic class (first scenario)

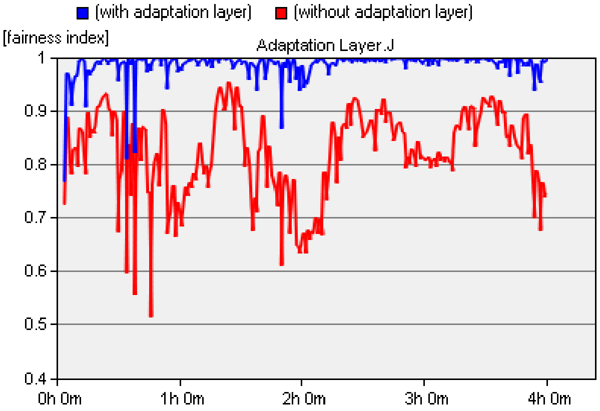

Figure 8. Fairness index (first scenario)

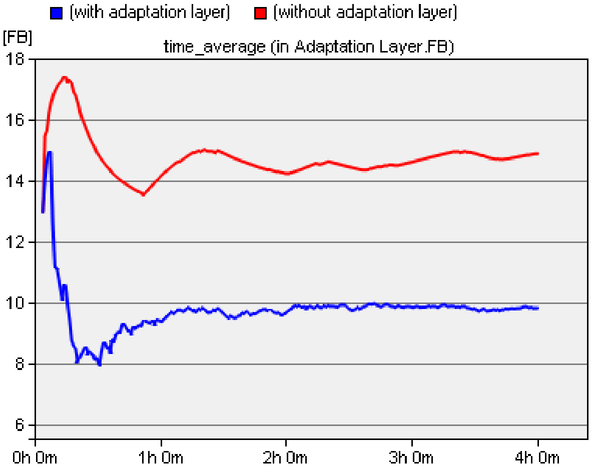

Figure 9. Blocking frequency (first scenario)

In the second scenario, the traffic generators are configured so that the average network load is 100%. The network capacity is 2 Gbps. The peak load of the network is about 3.125 Gbps.

To justify the results of simulation process we repeated the simulation and the same measurements and observations in the case that the average network load is 100% of the network capacity.

Fig. 10 shows that introduction of adaptation layer improves the fairness of resource allocation in the network even in conditions of heavy network load.

Fairness index (Fig. 11) is, in the adaptation mode of network operation, maintained above 0.8 with brief outages of up to 0.76, while the same index, in non-adaptation mode, is very unstable and drops up to 0.5.

Fig. 12 shows that the adaptation layer is stable structure - blocking frequency stabilizes after a certain time on the value 12.

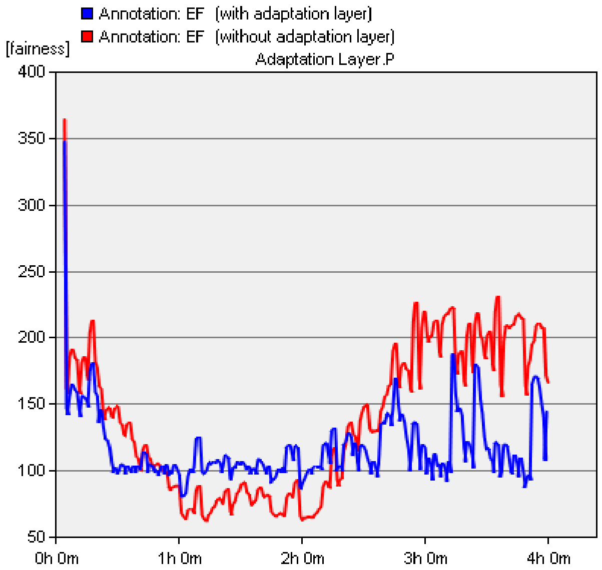

Figure 10. Ratio of the allocated resources for the EF traffic class (second scenario)

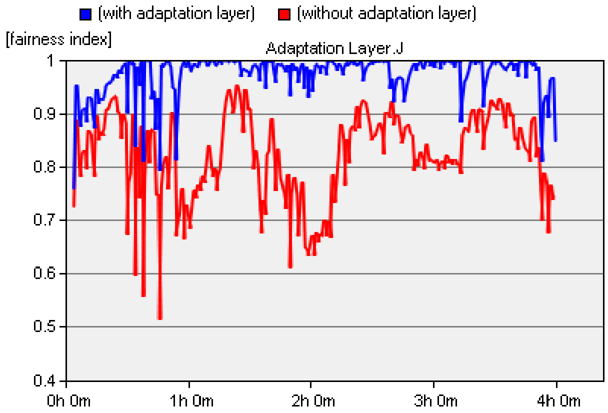

Figure 11. Fairness index (second scenario)

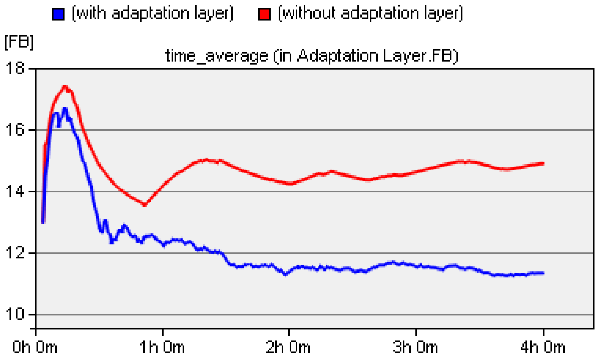

Figure 12. Blocking frequency (second scenario)

These results give us the proof of our hypothesis that with a proper adaptation layer we can improve the fairness of bandwidth allocation among different traffic classes under heavy network load and at the same time keep the required QoS conditions in the preferred boundaries. We can also conclude that the proposed adaptation algorithm behaves properly.

## VI. CONCLUSION AND FUTURE WORK

The simulation results have shown that the proposed adaptation algorithm can significantly improve the fairness of bandwidth allocation among different traffic classes under a heavy traffic load in IP/MPLS networks, while keeping the required QoS conditions to any traffic class within the boundaries as preferred. The bandwidth allocated to any traffic class follows the required one, and in the case of a sufficient bandwidth, the QoS requests are guaranteed.

We see future work in researching the impact of different fuzzy algorithms and membership functions in the adaptation layer. It would also be interesting to analyze and discuss the required computational power and the protocol overhead in case of heavy network load, as well as ways of adaptation layer integration into existing network management systems.

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