Advanced Considerations Concerning Impact of Applied Call Admission Control Mechanisms on Traffic Characteristics in Elastic Optical Network Nodes

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Abstract — Over the past few years, a significant increase in network traffic volumes has been observed. The ever growing bandwidth demands mean that a reliable and optimum service level needs to be ensured in communication systems for specific traffic categories. Optimal allocation and use of resources may be achieved through the use of call admission control (CAC) mechanisms implemented in network systems. The resource reservation mechanism and the threshold mechanism are two of the most popular CAC methods. In the reservation mechanisms, a certain number of resources is reserved for selected (predefined) services only. In the case of threshold mechanisms, the number of resources allocated to individual traffic classes depends on the network load. This article discusses the results of simulations verifying the impact of applied CAC mechanisms on the traffic characteristics in elastic optical network (EON) nodes with a Clos structure. Loss probability results obtained with the use of the simulator are presented as well.

Keywords — elastic optical networks, frequency slot unit, loss probability, reservation mechanism, threshold mechanism, switching networks, traffic management

1. Introduction

Elastic optical networks (EON) have been proposed as a solution that is capable of meeting the growing demands of bandwidth-intensive applications and services in a flexible and efficient manner [1], [2]. The architecture of an EON network, relying on flexible grid and spectrum allocation, advanced modulation formats, digital signal processing (DSP) techniques, and reconfigurable optical add-drop multiplexers (ROADMs), has been successful in overcoming two major limitations of traditional optical networks: the lack of flexibility in allocating the spectrum and the problem of dynamic bandwidth delivery [3], [4]. The proposed solution was necessary to facilitate further development of information and communication technologies (ICT) networks which are faced with an exponential growth in data volumes and the emergence of new services [2], [5]. The high scalability of EONs [6], [7] allows them also to be used effectively in quality of service differentiating solutions.

Resource management plays a key role in network management, determining whether a new connection or service request can be accepted by the network without degrading the quality of service (QoS) or overloading the resources [8]. Combining resource management with flexible optical networks may lead to efficient resource allocation and bandwidth delivery, while maintaining QoS guarantees.

According to our knowledge, the work performed to date has focused on the development of routing and spectrum assignment (RSA) mechanisms in EONs [9]–[12]. For example, in article [12], the authors addressed the problem of spectrum allocation according to different traffic requirements. Article [12] demonstrates the impact that routing, modulation formats and spectrum assignment schemes exert on the probability of blocking, and the number of transceivers consumed.

RSA mechanisms are accompanied by call admission control mechanisms (CAC) which influence the process of admitting new calls or changing the amount of resources assigned to admitted calls, depending on the current load of the system [13]–[15]. These mechanisms influence the traffic characteristics of both the transmission links and the network nodes (their switches and routers). Each of these devices contains a switching network which is implemented according to a specific switching structure. Studies have shown that appropriately selected CAC mechanisms allow desired traffic characteristics to be achieved by electronic switching networks/fabrics handling streams of multiservice traffic [13], [16]. According to [13], [16], the solutions that reservation and threshold mechanisms are most effective from the point of view of the ability to control the probability of blocking and resource utilization, respectively.

However, in the case of optical switching fabrics used in flexible optical networks, we need to take into account additional constraints affecting the ability to set up connections, including the need to provide contiguous frequency slots. Given the peculiarities of EON networks and switching fabrics in these networks, this article describes a study aiming to determine the impact of known call control algorithms for multiservice traffic streams in EON nodes. This article strives to analyze and compare the results of the loss probability for particular traffic classes in the nodes of EONs, with CAC mechanisms implemented. The impact on the traffic handling ability of network nodes with the Clos structure is investigated as well. The remaining part of the paper is organized as follows. In Section 2 a short review of other works is presented. Section 3 presents the structure of an EON node. The structure of offered traffic, the structure of the switching network, and the selection path algorithms are described therein as well. In Section 4, CAC mechanisms (threshold and reservation mechanisms) are presented. Section 5 describes the simulation environment and the systems studied. Then, in Section 6, the results are discussed and explained. Finally, Section 7 sums up the article.

2. State of the Art

EONs have been the subject of many scientific studies. The considerations concerned the structures of network nodes, non-blocking conditions, simulators and analytical models. Research on the combinatorial aspects of EONs concentrates primarily on the non-blocking conditions of switching fabric architectures employed within EON nodes [17]–[19]. These conditions hinge on the inter-stage link capacities, typically quantified in frequency slot units (FSUs) [18]. Novel contributions include the introduction of a routing algorithm reliant on fixed slot assignments in inter-stage links, significantly impacting non-blocking conditions [17], and explorations into how the quantity of switches at individual network stages influences non-blocking parameters [19]. Research on the combinatorial properties of non-blocking switching networks is of great importance for optimizing the structures of blocking switching networks, because it can be a starting point for their effective construction.

Concurrently, there is a growing body of research addressing blocking switching networks accommodating multi-service traffic [20]–[22]. The development of an EON node simulator predicated on the Clos structure [21] is one of the noteworthy aspects, with its authors presenting loss probability outcomes for various call classes directed to the switching fabric. Such analyses are instrumental in the correct dimensioning of EON nodes. Furthermore, [20] unveiled a pioneering analytical model for multi-service, multi-stage blocking switching networks utilized in EON nodes, facilitating an understanding of how the traffic characteristics of these networks influence operational effectiveness of nodes.

A central theme in EON research pertains to the core technology underpinning resource scheduling – specifically, routing and spectrum assignment (RSA) – with a special emphasis on resolving the RSA conundrum. RSA is critical in EONs, as it allows the establishment of light paths for traffic demands by judicious route selection and allocation of contiguous, non-overlapping frequency slot units (FSUs) [23]–[25]. Innovative solutions, such as the genetic algorithm (GA) for near-optimal RSA problem-solving [23] and a state-of-the-art algorithm hinging on the deep reinforcement learning (DRL) framework, specifically the Deep Q-Network (DQN) [25], have been proposed. RSA algorithms do not solve the problems addressed by this paper; it is the problem of calculating the blocking probability in EON switching networks being offered various mixtures of multi-service traffic stream.

To sum up, the topic of EONs is very important and complex, making it a popular theme in the literature dealing with the subject.

3. Structure of EON Node

3.1. Structure of Offered Traffic

Each service rendered with the use of telecommunications networks requires different bit rates to minimize the phenomenon of bit-rate mismatch between the data stream related to a specific service and the optical layer of the backbone network. Therefore, the most important task is to appropriately allocate the available spectral resources to these specific services. EONs are used for this purpose. EONs are characterized by their elastic bandwidth and an adaptive gap between channels [26], where channel width may be dynamically changed according to transmission speed-related requirements. This helps improve spectral efficiency, diminishes spectrum wastage, and is conducive to better use of spectral resources. Consequently, depending on the bit rate required for a given service class, an appropriate number of spectral units is assigned. These units are called frequency slots [3]. Other factors contributing to the number of allocated frequency slots (FSUs) include the following: modulation technique, distance, and quality of the connection path [27]–[30].

Furthermore, in order to describe the traffic streams offered to modern telecommunications networks, including EONs, it is necessary to consider changes in the intensity of the traffic streams offered, depending — inter alia – on the number of traffic sources of a given class being served, occupancy status of the system, etc. To this end, the article assumes that three typical types of traffic streams, i.e., Erlang, Engset and Pascal multiservice traffic streams, will be considered at the flow level. Each traffic stream can be generated by calls of particular traffic classes available in the system [31]–[34].

In the case of Erlang traffic streams, the system is offered C_{I} independent classes of Poisson's call streams. The intensity of new requests does not depend on the system's load state. Thus, it is an example of a system with a state-independent process of incoming new calls. Traffic classes whose sources generate calls that form Erlang traffic streams are defined by the following parameters:

- number of traffic classes C_{I},
- index determining any traffic class i,
- intensity of arrival of new calls $\lambda_1, \lambda_2, \ldots, \lambda_i, \ldots, \lambda_{C_{\mathrm{I}}}$,
- average service time for calls: $\mu_1^{-1}, \mu_2^{-1}, \ldots, \mu_i^{-1}, \ldots, \mu_{C_{\mathrm{I}}}^{-1}$.

In the case of Engset traffic streams, the call stream is generated by a finite number of traffic sources. The intensity of new calls appearing in the system decreases as the system's occupancy state (load) increases. This is an example of a system with a state-dependent process for generating new calls.

Traffic classes within the Engset stream can be defined by the following parameters:

- number of traffic classes C_{J},
- index determining any traffic class j,
- intensity of arrival of new calls $\gamma_1, \gamma_2, \ldots, \gamma_j, \ldots, \gamma_{C_{\mathrm{I}}}$,
- average service time for calls $\mu_1^{-1}, \mu_2^{-1}, \ldots, \mu_j^{-1}, \ldots, \mu_{C_{\mathrm{J}}}^{-1}$.
- number of traffic sources $S_{1,\mathrm{J}}, S_{2,\mathrm{J}}, \ldots, S_{j,\mathrm{J}}, \ldots, S_{C_{\mathrm{J}},\mathrm{J}}$.

Pascal traffic streams are also generated by a finite number of traffic sources. In this case, the intensity of appearance of new calls increases with the growing occupancy state of the system. This is also an example of a system with a state-dependent process for new incoming calls. For Pascal traffic classes, the parameters that define the individual classes include the following:

- number of traffic classes C_{K},
- index determining any traffic class k,
- intensity of arrival of new classes $\beta_1, \beta_2, \ldots, \beta_k, \ldots, \beta_{C_{\mathrm{I}}}$,
- average call service time $\mu_1^{-1}, \mu_2^{-1}, \ldots, \mu_k^{-1}, \ldots, \mu_{C_{\mathrm{K}}}^{-1}$.
- number of traffic sources $S_{1,\mathrm{K}}, S_{2,\mathrm{K}}, \ldots, S_{k,\mathrm{K}}, \ldots, S_{C_{\mathrm{K}},\mathrm{K}}$.

Consequently, the sum of all classes offered to the switching network can be expressed by the following formula:

$$C = C_{\mathrm{I}} + C_{\mathrm{J}} + C_{\mathrm{K}} \ . \tag{1}$$

The additional assumption in the present considerations is that index c will determine any traffic class regardless of the type of the traffic stream concerned.

3.2. Structure of 3-stage W-S-W Switching Network

The structures of EON networks can assume different forms and types. One of the most common structures of switching networks, within which connections in the nodes of EONs are executed, is a three-stage W-S-W network with a Clos structure (Fig. 1) [18], [35], [36]. The switching network under consideration is composed of a number of square switches with n inputs and n outputs. In each of the 3 stages of the considered network, there are n switches. The input, output and inter-stage links of the considered W-S-W network have their capacities equal to f FSUs each [3], [27]–[28]. For the first and third stages, the individual switches allow us to change both the wavelength (frequency slot) and the output fiber. That operation performed by the switches requires specific components, such as a bandwidth variable waveband selective switch (BV-WSS) [35], [37], a bandwidth variable transceiver, and a bandwidth variable tunable waveband converter (TWBC) [35], [38]–[40]. In the case of switches of the second stage, it is only possible to change the output fiber. It follows that TWBC elements were not used in the construction of these switches. In addition, output links of the switches of the last stage are organized in directions. A direction includes one link of each output link of each third stage switch.

3.3. Path Selection Algorithms

The considered switching network may work with one of two selection path algorithms: point-to-group (Algorithm 1) and point-to-point (Algorithm 2) [32]–[34].

Path-choice algorithms make it possible to find those elements of the network that have the required resources to service a new call that has arrived at the network's input point. When it is not possible to find free resources in the links outgoing from the network, external blocking follows, whereas when resources necessary to set up a connection path in the network cannot be found, internal blocking takes place.

Algorithm 1. Point-to-group algorithm

```
1:  Random selection of the input on which class c call will
    appear
2:  Random selection of the outgoing direction
3:  Set the iteration counter to l = 1
4:  Find the last stage switch which has a t_c free neighboring
    FSUs in the required direction
5:  if successful then
6:      Try to set up the connection between
        the first and the last stage switch
        via one of the middle stage switches
7:      if successful then
8:          Set up the connection path via selected switches
9:          Go to step 21
10:     else
11:         if l < v then
12:             Increase iteration counter to l = l + 1
13:             Go to step 4
14:         else
15:             The connection is lost due to an
                internal blocking
16:         end if
17:     end if
18: else
19:     The connection is lost due to an external blocking
20: end if
21: Stop the algorithm
End
```

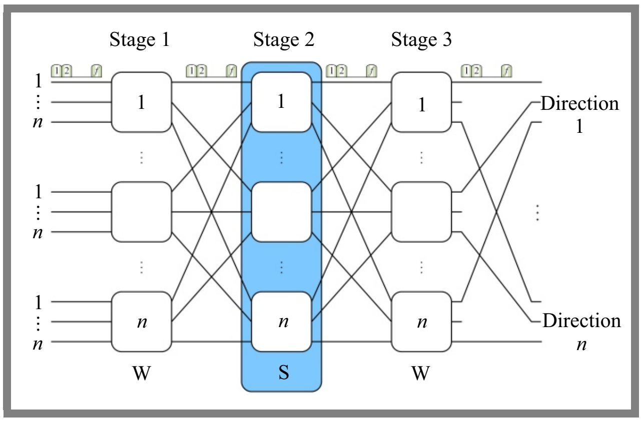

Fig. 1. Structure of a 3-stage Clos switching network.

Algorithm 2. Point-to-point algorithm

```
1:  Random selection of the input on which class c call will
    appear
2:  Random selection of the outgoing direction
3:  Find the last stage switch which has a t_c free neighboring
    FSUs in the required direction
4:  if successful then
5:      Try to set up the connection between
        the first and the last stage switch
        via one of the middle stage switches
6:      if successful then
7:          Set up the connection path via selected switches
8:          Go to step 15
9:      else
10:         The connection is lost due to an internal blocking
11:     end if
12: else
13:     The connection is lost due to an external blocking
14: end if
15: Stop the algorithm
```

4. CAC Mechanisms

4.1. Reservation Mechanism

A reservation mechanism has been implemented in the W-S-W network under consideration. The reservation mechanism was introduced to those classes that belonged to the $\mathbb{R}$ set. For a given class c that belonged to the $\mathbb{R}$ set, a reservation threshold R_c was introduced to specify the system occupancy value (expressed percentage-wise) above which calls of class c could not be serviced. This means that all resources of the system will be available for the remaining traffic classes. In the case of the switching network under consideration, the reservation threshold determines the load of the output directions. From the QoS perspective, classes for which no reservation mechanism has been introduced (i.e., those that belong to set $\mathbb{R}$) are deemed to be privileged.

4.2. Threshold Mechanism

The essential feature of the threshold mechanism introduced to the network consists in managing the admission of new calls by limiting the number of FSUs allocated to them, based on the current occupancy state of the system. The lower the load, the higher the number of allocated FSUs, while changes in the number of allocated FSUs occur in jumps and depend on the threshold of system's load [13]. The introduced threshold mechanism defines the thresholds as a percentage value of the system's load. The threshold mechanism is applied to a given set of traffic classes $\mathbb{T}$ that is a subset of all call classes offered to the switching network. Each class c, belonging to set $\mathbb{T}$, is defined by a the following parameters:

- Threshold values $\{Q_{c,1}, Q_{c,2}, \ldots, Q_{c,q_c}\}$, where index c of each of the elements defines the call class number, whereas the other index defines the number of the threshold, and q_c specifies the number of thresholds for class c.

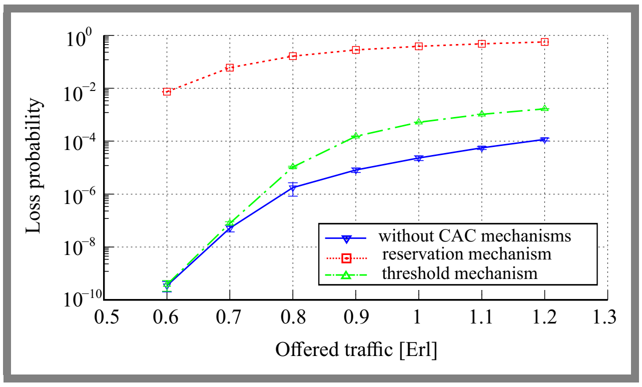

Fig. 2. Loss probability for class 1 in system 1 with different CAC mechanisms.

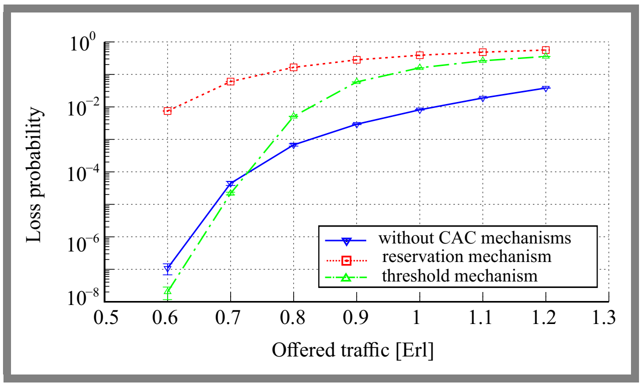

Fig. 3. Loss probability for class 2 in system 1 with different CAC mechanisms.

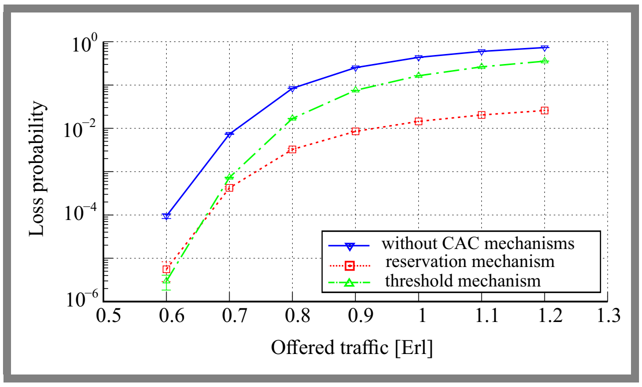

Fig. 4. Loss probability for class 3 in system 1 with different CAC mechanisms.

- The numbers of FSUs allocated to the call in particular threshold areas $t_{c,0}, t_{c,1}, \ldots, t_{c,q_c}$.
- The average service times for the call in particular threshold areas $\mu_{c,0}^{-1}, \mu_{c,1}^{-1}, \ldots, \mu_{c,q_c}$.

The dependencies between specific parameters describing traffic class c are described in detail in [33].

5. Results

5.1. Simulation Environment

All simulation experiments were carried out using a simulation program developed by the authors. The simulator of

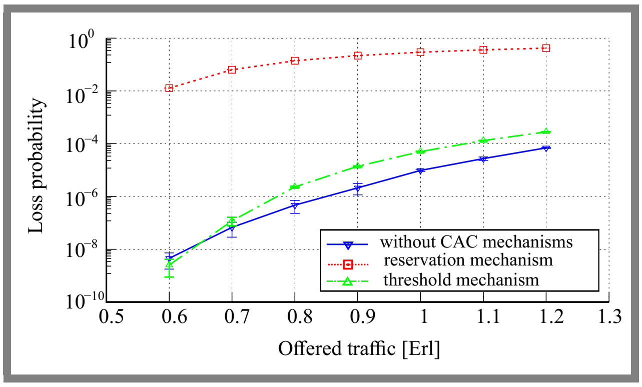

Fig. 5. Loss probability for class 1 in system 2 with different CAC mechanisms.

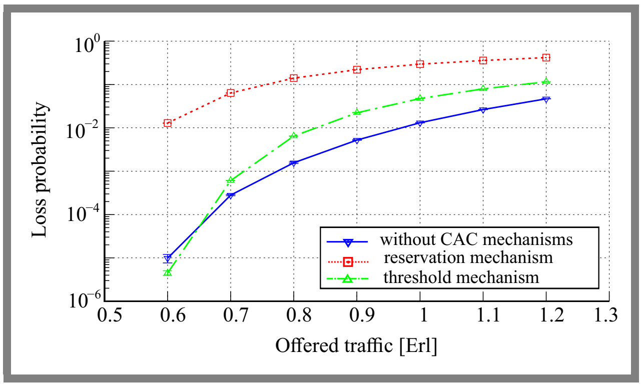

Fig. 6. Loss probability for class 2 in system 2 with different CAC mechanisms.

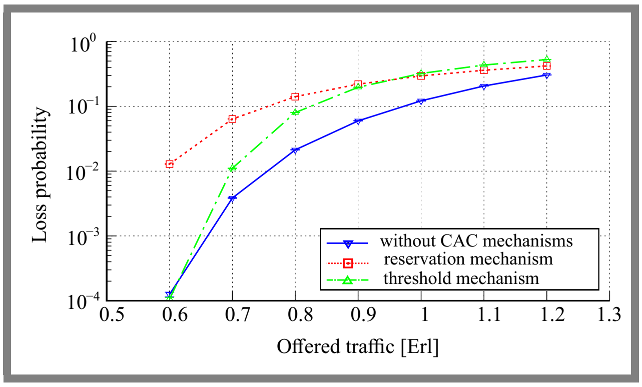

Fig. 7. Loss probability for class 3 in system 2 with different CAC mechanisms.

EONs, with the CAC mechanisms introduced, was written using the C++ programming language and relied on the object-oriented programming technique and the process-interaction method [41]. The simulator makes it possible to determine the traffic characteristics of EONs, including the loss probability for particular traffic classes in switching networks with CAC mechanisms implemented. The simulator may be also used as an optimization tool. Detailed information on the simulator can be found in [32], [33], where the implemented algorithms and call servicing functions are described as well.

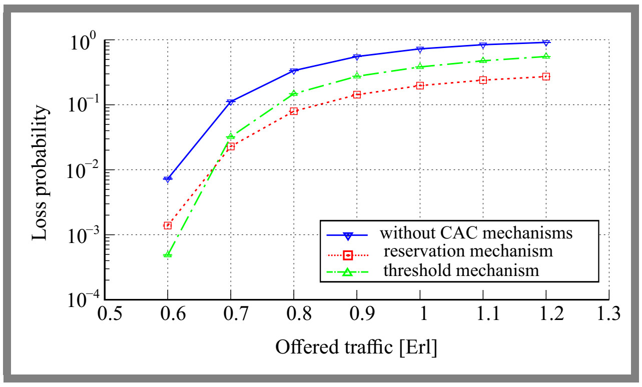

Fig. 8. Loss probability for class 4 in system 2 with different CAC mechanisms.

5.2. Systems Under Consideration

The simulation study was carried out for systems whose parameters are presented in Tab. 1.

The choice of a suitable number of FSUs demanded by particular traffic classes was made on the basis of the data included in [30].

The results of the simulation are presented on graphs, in the form of plotted points, with confidence intervals calculated based to the t-Student distribution (with a 95% confidence level) for 5 series with 1,000,000 calls (of the least active class) each. The confidence intervals were determined on the basis of the following formula:

$$\left(\bar{X} - t_\alpha \frac{\sigma}{\sqrt{d}}; \bar{X} + t_\alpha \frac{\sigma}{\sqrt{d}}\right) , \tag{2}$$

where $\bar{X}$ is the arithmetic mean calculated from d results (simulation runs), t_α is the value of the t-Student distribution for $d-1$ degrees of freedom. Parameter σ determining the standard deviation, is then calculated using:

$$\sigma^2 = \frac{1}{d-1}\sum_{s=1}^{d} x_s^2 - \frac{d}{d-1}\bar{X}^2, \tag{3}$$

where x_s is the result obtained in the s-th run of the simulation.

Figures 2-8 show the values of the loss probability for calls belonging to individual traffic classes in relation to the traffic value a offered to a single FSU. In the graphs, the values of the loss probability in the systems with CAC mechanisms introduces and the system without the CAC mechanism are compared.

Figures 9-10 show changes in the value of loss probability for particular traffic classes depending on the reservation threshold. Reservation thresholds are expressed as a percentage of the total system capacity. In the considered system with a reservation mechanism, reservation thresholds ranging from 60% to 100% were taken into account. 100% means a system with no reservation mechanism introduced.

Figures 11-12 show changes in the value of loss probability for individual traffic classes depending on the threshold values. Threshold values are expressed as a percentage of the total system capacity. Threshold values ranging from 10% to 90% of the system capacity were considered.

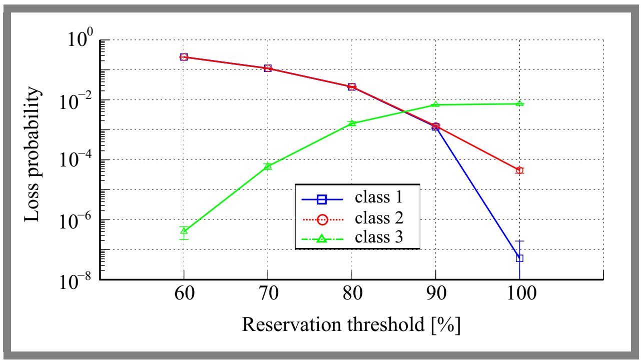

Fig. 9. Changes in loss probability depending on the reservation threshold in system 3 for $a = 0.7$ Erl.

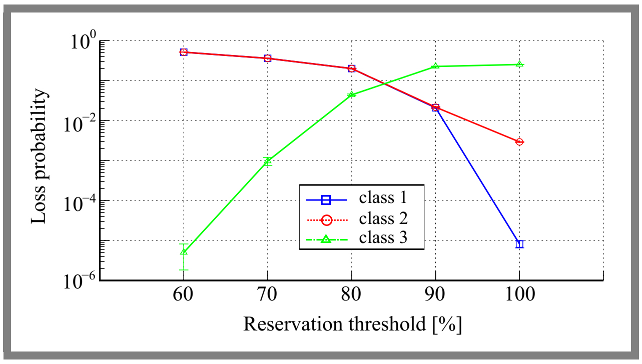

Fig. 10. Changes in loss probability depending on the reservation threshold in system 3 for $a = 0.9$ Erl.

6. Discussion

The presented results show that in the case of classes belonging to the $\mathbb{T}$ set and for the classes for which the reservation mechanism has not been introduced (classes not belonging to the $\mathbb{R}$ set), the loss probability value decreases (Figs. 4 and 8) at the expense of a decrease in the loss probability for the remaining traffic classes (Figs. 2-3 and Figs. 5-7). We observe more rapid changes in loss probabilities if the reservation mechanism is introduced. Therefore, in order to reduce the loss probability for certain traffic classes, it is possible to introduce a reservation threshold for other traffic classes, thus reducing the number of available resources (for classes belonging to the $\mathbb{R}$ set). Alternatively, by introducing a threshold mechanism, one may reduce the number of allocated resources and potentially extend the call service time (for classes belonging to the $\mathbb{T}$ set).

Figures 9-10 also show the dependence of loss probability on set reservation threshold set. As one may see, with a decrease in the reservation threshold value, and thus an increase in the reservation area, the loss probability increases for classes from the $\mathbb{R}$ set (subject to the reservation mechanism), and decreases for the remaining classes. An important observation is also that with the appropriate selection of the reservation threshold value, it is possible to equalize loss probabilities for all traffic classes (the intersection point of the lines in Figs. 9-10). A similar behavior of the system is observed for different load values a. In the case of Figs. 11-12, we can observe the impact of the threshold value on the loss probability of traffic class in a system with threshold mechanisms implemented. We can see that along with an increase in the threshold value, the loss probability for traffic classes from set $\mathbb{T}$ (in the considered system for class 3) increases as well. For the remaining traffic classes, a decrease the loss probability is observed. By observing changes in the loss probability value depending on the threshold value, we can set an optimal threshold value enabling to optimize the use of resources.

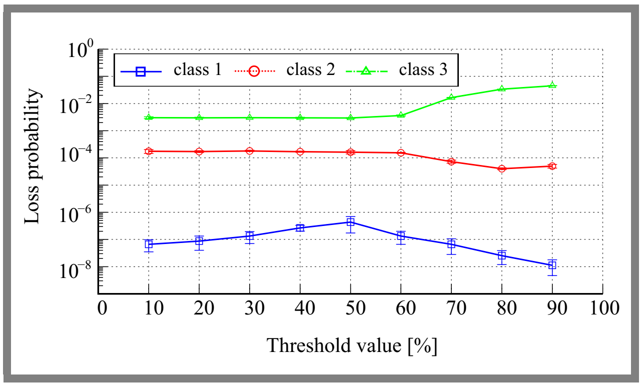

Fig. 11. Changes in loss probability depending on the threshold value in system 3 for $a = 0.7$ Erl.

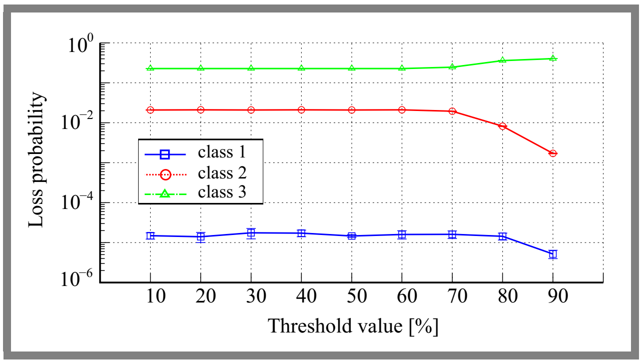

Fig. 12. Changes in loss probability depending on the threshold value in system 3 for $a = 0.9$ Erl.

7. Conclusions

The results of a study aiming to determine the loss probability for calls of traffic classes offered in EONs with CAC mechanisms implemented have been presented in this paper. The analysis conducted will make it possible to choose the correct CAC mechanism and the optimal threshold value. In the future, the authors intend to develop analytical methods that would determine loss probabilities in EON networks with a Clos structure and CAC mechanisms, while the developed simulator would be used as a tool enabling suitable verification and validation of these methods.

Acknowledgements

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Tab. 1. Parameters of the tested systems

Traffic classes	**Structure of switching network**
System 1	
Erlang: $t_1 = 5$ FSUs, $\mu_1^{-1} = 1$, Engset: $t_2 = 10$ FSUs, $\mu_2^{-1} = 1$, Pascal: $t_3 = 20$ FSUs, $\mu_3^{-1} = 1$	$f = 320$ FSUs, $n = 4$
System 2	
Erlang: $t_1 = 5$ FSUs, $\mu_1^{-1} = 1$, Erlang: $t_2 = 10$ FSUs, $\mu_2^{-1} = 1$, Engset: $t_3 = 15$ FSUs, $\mu_3^{-1} = 1$, Pascal: $t_4 = 30$ FSUs, $\mu_4^{-1} = 1$	$f = 320$ FSUs, $n = 4$
System 3	
Erlang: $t_1 = 5$ FSUs, $\mu_1^{-1} = 1$, Erlang: $t_2 = 10$ FSUs, $\mu_2^{-1} = 1$, Erlang: $t_3 = 30$ FSUs, $\mu_3^{-1} = 1$	$f = 320$ FSUs, $n = 4$
Threshold mechanism	**Reservation mechanism**
System 1	
$\mathbb{T} = \{3\}, Q_{3,1} = 75\%$ $t_{3,0} = t_3, \mu_{3,0}^{-1} = \mu_3^{-1}$ $t_{3,1} = 10$ FSUs, $\mu_{3,1}^{-1} = 2$	$\mathbb{R} = \{1, 2\}$, $R_1 = R_2 = 75\%$
System 2	
$\mathbb{T} = \{4\}, Q_{4,1} = 50\%$, $Q_{4,2} = 75\%$, $t_{4,0} = t_4, \mu_{4,0}^{-1} = \mu_4^{-1}$, $t_{4,1} = 20$ FSUs, $\mu_{4,1}^{-1} = 1.5$, $t_{4,2} = 15$ FSUs, $\mu_{4,2}^{-1} = 2$	$\mathbb{R} = \{1, 2, 3\}$, $R_1 = R_2$ $= R_3 = 75\%$
System 3	
$\mathbb{T} = \{3\}, Q_{3,1} = 10 - 90\%$ $t_{3,0} = t_4, \mu_{3,0}^{-1} = \mu_4^{-1}$, $t_{3,1} = 15$ FSUs, $\mu_{3,1}^{-1} = 2$	$\mathbb{R} = \{1, 2\}$, $R_1 = R_2$ $= 60 - 100\%$

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