Article

Determination of Traffic Characteristics of Elastic Optical Networks Nodes with Reservation Mechanisms

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Abstract: With the ever-increasing demand for bandwidth, appropriate mechanisms that would provide reliable and optimum service level to designated or specified traffic classes during heavy traffic loads in networks are becoming particularly sought after. One of these mechanisms is the resource reservation mechanism, in which parts of the resources are available only to selected (pre-defined) services. While considering modern elastic optical networks (EONs) where advanced data transmission techniques are used, an attempt was made to develop a simulation program that would make it possible to determine the traffic characteristics of the nodes in EONs. This article discusses a simulation program that has the advantage of providing the possibility to determine the loss probability for individual service classes in the nodes of an EON where the resource reservation mechanism has been introduced. The initial assumption in the article is that a Clos optical switching network is used to construct the EON nodes. The results obtained with the simulator developed by the authors will allow the influence of the introduced reservation mechanism on the loss probability of calls of individual traffic classes that are offered to the system under consideration to be determined.

Keywords: elastic optical networks; frequency slot unit; reservation mechanism; switching networks; traffic management

1. Introduction

The amount of data transmitted over backbone networks is on a continuous increase due to the growing variety and popularity of the services provided in networks of new generation. At present, the significant increase in traffic can be observed for on-line video meeting applications, video conferencing, voice transmission and video streaming [1]. This is caused by the increase in the number of users who make use of the Internet network to interact with others on a daily basis to work, educate and entertain. Each of the services executed in telecommunications networks requires different transmission rates to minimalise the phenomenon of bitrate mismatch between the data stream related to a specific service and the optical layer of the backbone network; it is necessary to appropriately allocate available spectral resources to these services. For this purpose, EONs are used, which have the propriety of elastic bandwidth and adaptive gap between channels [2], and the channel width can be changed dynamically according to the requirements of the transmission bitrate that is necessary for a given service to be executed in the network. This helps improve the spectral efficiency, diminish the wastage of the spectrum and is conducive to better use of spectral resources. As a result, depending on the required bitrate related to a given service class, an appropriate number of spectral units will be assigned. These units are called frequency slots [3]. Other contributing factors to the number of allocated frequency slot units (FSUs) include the modulation technique, distance and the quality of the connection path [3–7].

Over the recent years, the growing number of offered services executed with the application of network resources is clearly observable. Consequently, this causes an increase in network traffic, which in turn defines one of the main traffic problems related to the provision of optimal access to network resources for demands (calls) of different traffic classes. A decision as to the admittance of a new call is made by the call admission control (CAC) function on the basis of the traffic parameters and the demanded QoS (Quality of Service) parameters of both the arriving call and those calls that are already being serviced (Figure 1). The efficiency of the CAC function is associated with the assumed allocation algorithm for the allocation of the network resources to particular calls of different traffic classes. One of the possible and most effective strategies of the CAC function is resource reservation [8–10] for pre-defined traffic classes. As a result, its application can provide appropriate and required service quality for the traffic streams that are related to a given traffic class.
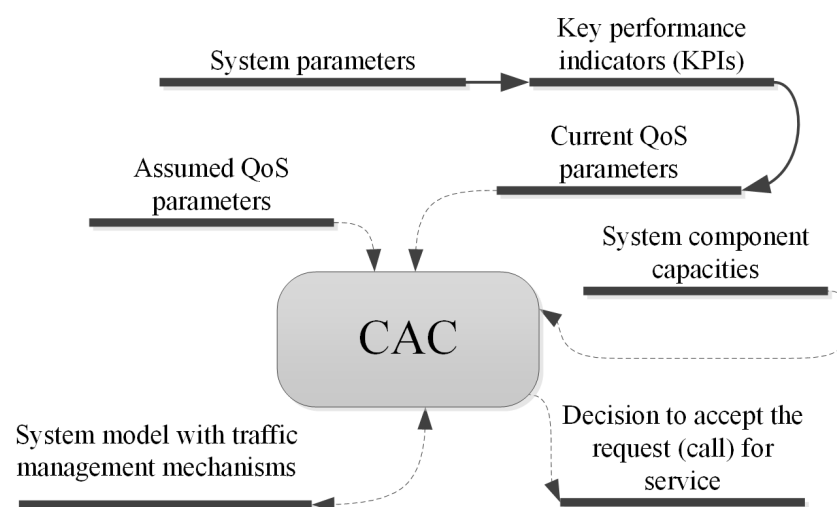

Figure 1. The concept of the CAC function.

When using the reservation mechanism in EONs, it should be stressed that one of the most commonly used structures of switching networks for EONs is the 3-stage W-S-W (wavelength-space-wavelength) switching networks [11–13]. The reservation mechanism introduced in such a network makes decisions on the admittance of a new call for service on the basis of the current load of the system. A determination of traffic characteristics of switching networks for EON aims to verify if the implemented reservation mechanism is managing tasks in the best optimal way and a determination of the influence of the mechanism on the loss probability for individual call classes. This article presents a description of the appropriate simulation program and discusses the results of the loss probabilities for calls of individual traffic classes obtained using the developed simulation program.

The remaining part of the article has the following structure. Section 2 provides a description of the structure of a 3-stage W-S-W network. In Section 3, the structure of traffic offered to the switching network is defined. Section 4 describes the operation of the reservation mechanism. The path selection algorithms for point-to-group and point-to-point connections are presented in Section 5. Section 6 includes a brief description of the simulation program. Section 7 presents the results of the study and their analysis. Finally, Section 8 sums up the article.

2. Structure of W-S-W Network

One of the most widely used structures of switching networks in EONs is the 3-stage W-S-W network with Clos structure (Figure 2). The considered switching network consists of square switches with v inputs and v outputs. Each of the three stages of the network contains v switches. The input, output and inter-stage links of the W-S-W network under consideration have the capacities of f FSUs. In addition, the output links of the switches of

the last stage are grouped into directions. Each direction consists of one output link from each switch of the third stage.
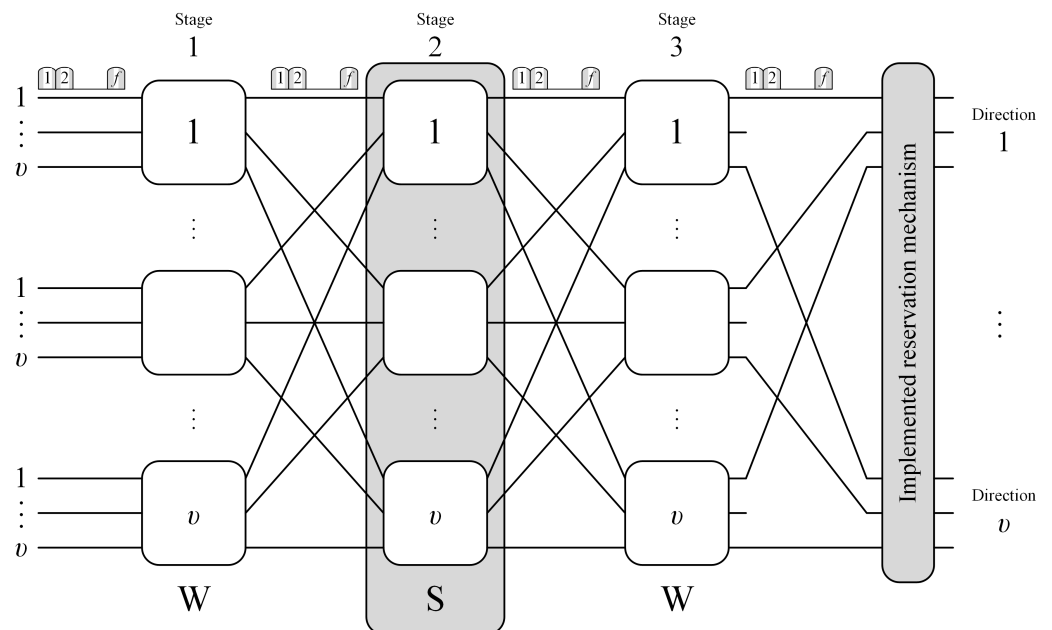

Figure 2. Structure of a switching network with implemented reservation mechanism.

A more accurate description of the structure of the W-S-W network would reveal that the first and third stages of the network are constructed using Bandwidth-Variable Wavelength converting Switches (BV-WSs) (Figure 3) [11,14], while the second stage of the network is constructed using Bandwidth-Variable wavelength selective Space Switches (BV-SSs) (Figure 4) [11,14].
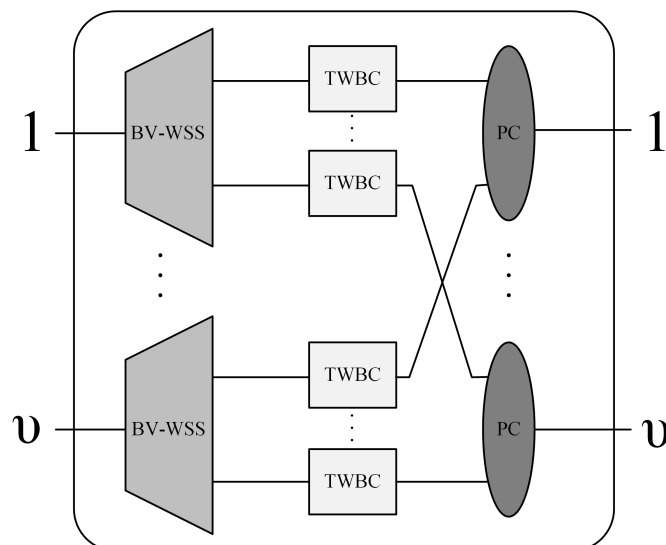

Figure 3. A first/third stage switch. BV-WSS—bandwidth variable wavelength selective switch; TWBC—tunable waveband converter; PC—passive combiner.
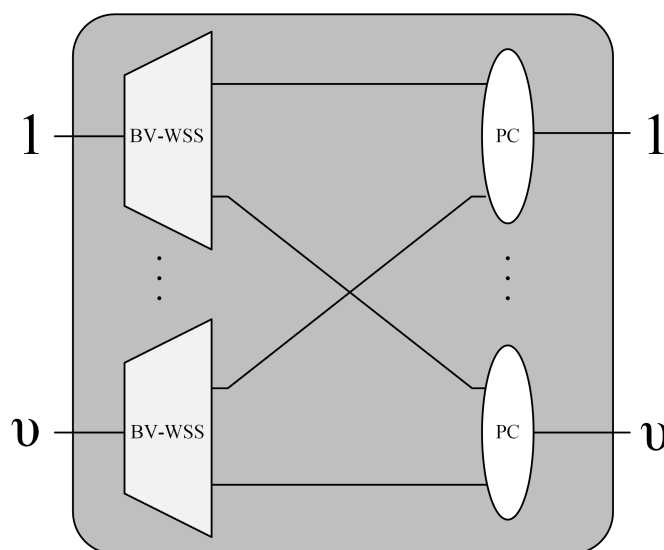
Figure 4. A second stage switch. BV-WSS—bandwidth variable wavelength selective switch; PC—passive combiner.

The switches used to construct the first and third stages have the advantage of changing both the wavelength and the output link (optical fibre). As for the switches of the second stage, only the alternation of the output link is possible, whereas the wavelength remains unchanged at all times.

3. Structure of Traffic Offered to W-S-W Network

The switching network are offered three types of traffic streams (Erlang, Engset and Pascal). Each traffic stream can be generated by calls of several traffic classes that are pre-defined in the system.

Traffic classes for which its sources generate calls that form the Erlang traffic stream are defined by the given parameters:

- Number of traffic classes: C_I;
- Index determining any traffic class: i;
- Intensity of arrival of new calls: $\lambda_1, \lambda_2, \ldots, \lambda_i, \ldots, \lambda_{C_I}$;
- Number of demanded FSUs: $t_1, t_2, \ldots, t_i, \ldots, t_{C_I}$;
- Average service time for calls: $\mu_1^{-1}, \mu_2^{-1}, \ldots, \mu_i^{-1}, \ldots, \mu_{C_I}^{-1}$.

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: $\gamma_1, \gamma_2, \ldots, \gamma_j, \ldots, \gamma_{C_I}$;
- Number of demanded FSUs: $t_1, t_2, \ldots, t_j, \ldots, t_{C_J}$;
- Average service time for calls: $\mu_1^{-1}, \mu_2^{-1}, \ldots, \mu_j^{-1}, \ldots, \mu_{C_J}^{-1}$;
- Number of traffic sources: $S_{1,J} S_{2,J}, \ldots, S_{j,J}, \ldots, S_{C_J,J}$.

For Pascal traffic classes, the parameters that define individual classes are the following:

- Number of traffic classes: C_K;
- Index determining any traffic class: k;
- Intensity of arrival of new classes: $\beta_1, \beta_2, \ldots, \beta_k, \ldots, \beta_{C_I}$;
- Number of demanded FSUs: $t_1, t_2, \ldots, t_k, \ldots, t_{C_K}$;
- Average call service time: $\mu_1^{-1}, \mu_2^{-1}, \ldots, \mu_k^{-1}, \ldots, \mu_{C_K}^{-1}$;
- Number of traffic sources: $S_{1,K}, S_{2,K}, \ldots, S_{k,K}, \ldots, S_{C_K,K}$.

In the case of the Erlang stream, the intensity of new calls does not depend on the occupancy state of the system. In the case of the Engset traffic stream, the intensity of new

calls decreases along with the increase in the system load. In the case of Pascal stream, we observe the opposite situation.

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 the index c will determine any traffic class regardless of the type of traffic stream.

4. Reservation Mechanism

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

5. Path Choice Algorithm in the Switching Network

5.1. Point-Group

Two path selection algorithms were implemented in the switching network: point-to-group and point-to-point. With the point-to-group algorithm, the connection path is set up inside the network between a switch of the first stage at the input of which the call arrived and any switch of the last stage that has free resources in the selected direction. The reservation mechanism for the classes that are in $\mathbb{R}$ implemented in the output directions introduces additional conditions to the determination of a free output link in the demanded direction. In addition to checking whether the output link has t_c free neighbouring FSUs, the current occupancy of the system is also checked. This occupancy must be lower or equal to the reservation threshold R_c. Figure 5 shows a block diagram of the point-to-group algorithm for setting up connections.

5.2. Point-to-Point

With the point-to-point path choice algorithm, a connecting path is set up between a switch of the first stage at the input of which a new call has appeared and a selected switch of the last stage that has a free output link in the required direction. In the implemented reservation mechanism in the output directions, a free output link in the demanded direction for a call of class c is such a call that has at least t_c free, neighbouring FSUs and, additionally in the case of the classes that belong to $\mathbb{R}$, the current occupancy state of the system has to be no greater than the reservation threshold R_c. The block diagram of the point-to-point algorithm is presented in Figure 6.
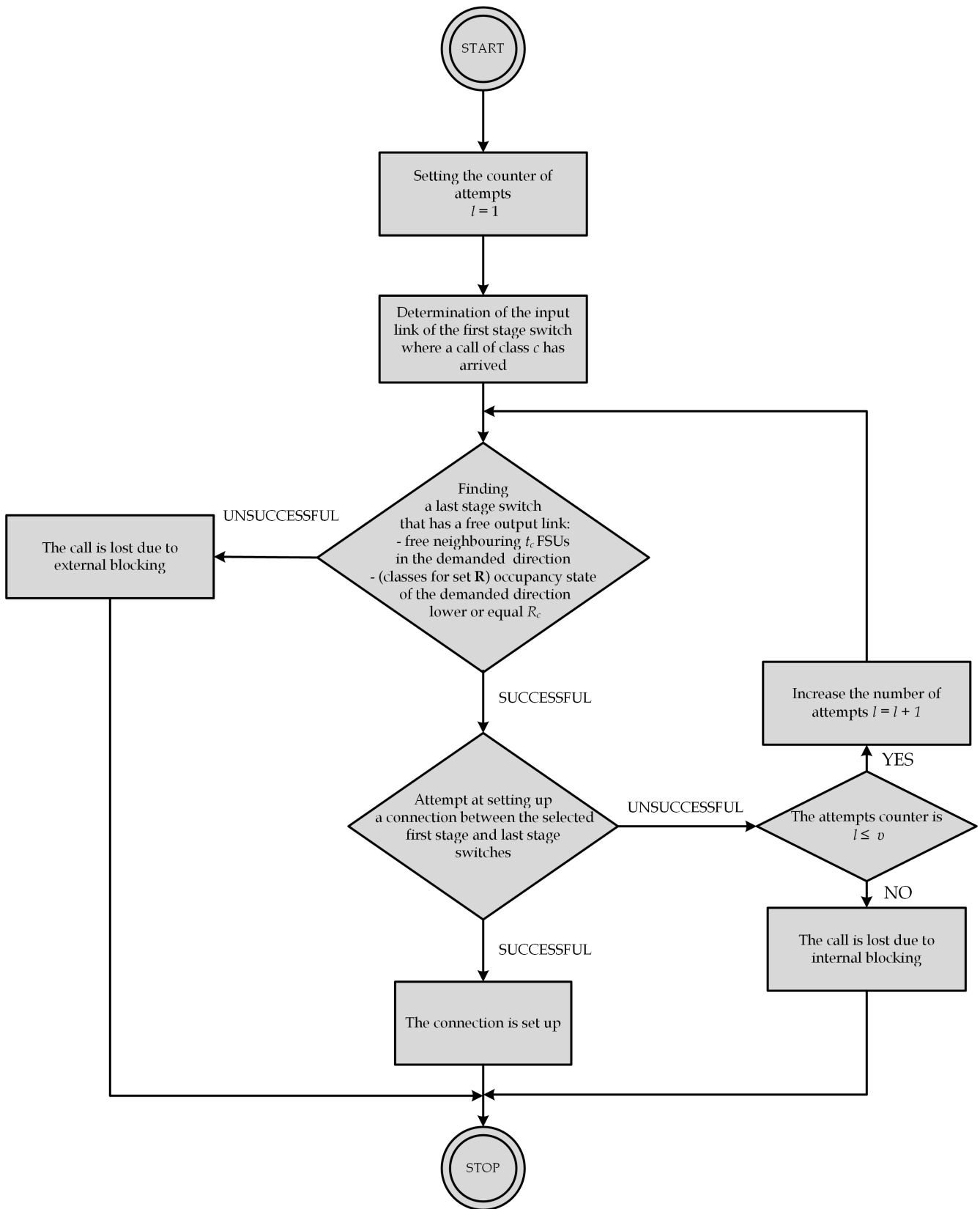
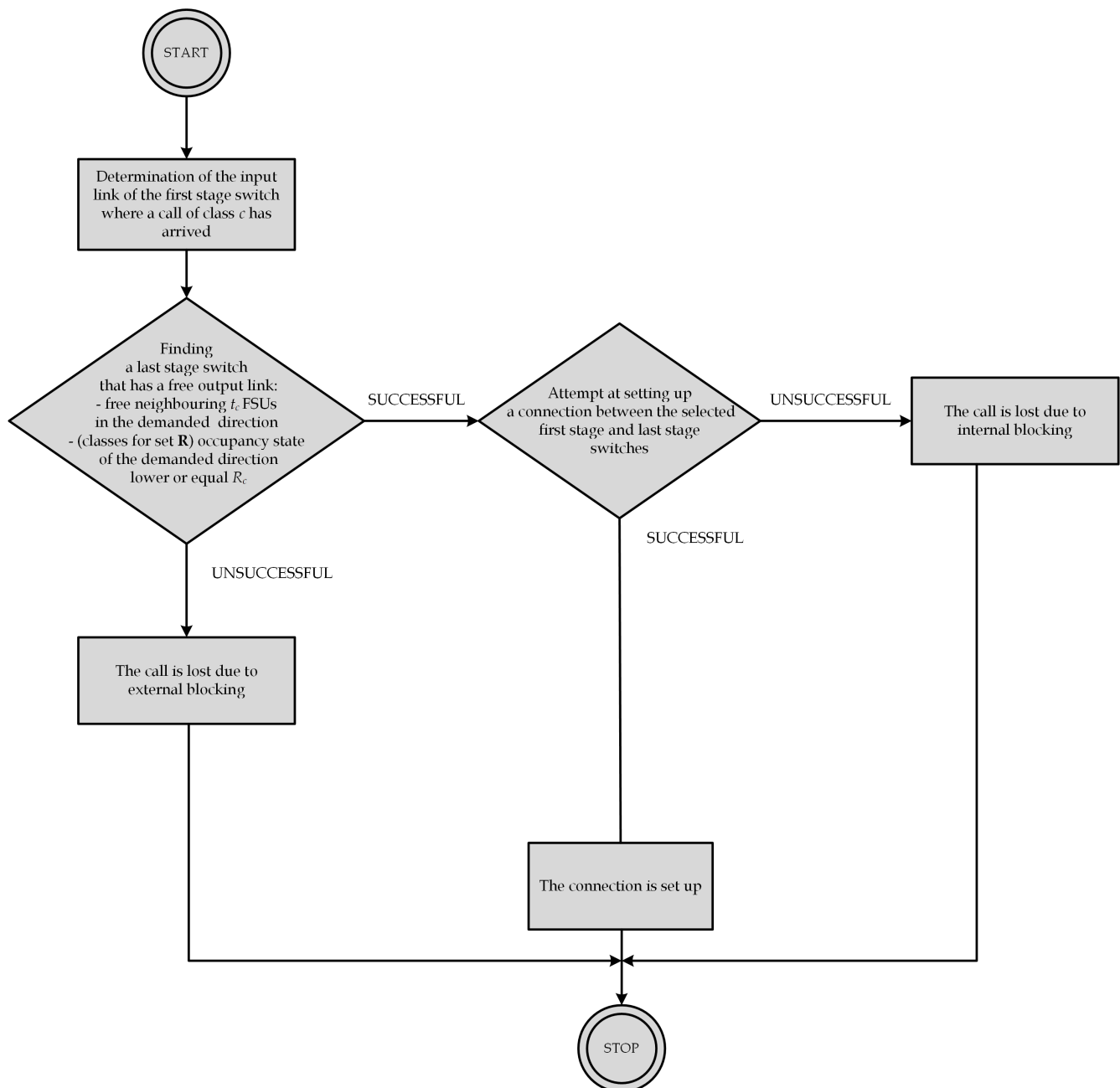**Figure 5.** Point-to-group path choice algorithm.

Figure 6. Point-to-point path choice algorithm.

6. Simulation Program

6.1. Implementation and Application

The simulator of EONs with the introduced reservation mechanisms was implemented in the C++ programming language using the object-oriented programming technique and the process-interaction method [15]. Thus, the developed simulator has the advantage of providing the possibility to set the value of the loss probability in optical switching networks with point-to-group and point-to-point selection, in which resource reservation mechanisms have been implemented. In the future, this simulator will be used to verify and validate analytical models that would make it possible to find traffic characteristics of optical switching networks with resource reservation mechanisms. In addition, the same simulator can be used as a tool in the optimisation of introduced CAC mechanisms. In the immediate future, the authors' intend to develop and publish methods that would make it possible to analytically determine the loss probability for individual call classes.

6.2. Input Data

The following parameters are given as input data to the simulation program:

- Number of input links, output switches: v;
- Capacity of input links and output switches: f FSUs;
- Number of classes of Erlang traffic: C_{I};
- Number of classes of Engset traffic: C_{J};
- Number of classes of Pascal traffic: C_{K};
- For each class i from among C_{I} Erlang classes:
  - Number of demanded FSUs: t_i;
  - Average service time: μ_i^{-1};
- For each class j from among C_{J} Engset classes:
  - Number of demanded FSUs: t_j;
  - Average service time: μ_j^{-1};
  - Number of traffic classes: $S_{j,\mathrm{J}}$;
- For each class k from among C_{K} Pascal classes:
  - Number of demanded FSUs: t_k;
  - Average service time: μ_k^{-1};
  - Number of traffic classes: $S_{k,\mathrm{K}}$;
- Set $\mathbb{R}$ of traffic classes;
- Reservation threshold R_c for classes from set $\mathbb{R}$;
- Traffic value a offered to a single FSU.

On the basis of data given to the simulator, the intensities of the arrival of new calls λ_i, γ_j and β_k can be determined as follows.

$$\sum_{i=1}^{C_{\mathrm{I}}} \lambda_i / \mu_i t_i + \sum_{j=1}^{C_{\mathrm{J}}} \gamma_j S_{j,\mathrm{J}} / \mu_j t_j + \sum_{k=1}^{C_{\mathrm{K}}} \beta_k S_{k,\mathrm{K}} / \mu_k t_k = avvf. \tag{2}$$

6.3. Simulation Algorithm

While implementing the simulator using the process interaction method, two events were defined: *arrival of a new call* and *termination of call service*. With the case of the event *arrival of a new call*, it is checked whether a new call can be admitted for service. If this is possible, the resources of the system become occupied; if not, the call is lost. The event *termination of call service* means that the service of a given call has terminated and the resources of the system are to be released. The execution of the handling of these events in the simulation program is realised by using designated functions. These functions are presented in detail in other publications [16,17], while the general block diagram of the simulation algorithm is shown in the Figure 7.
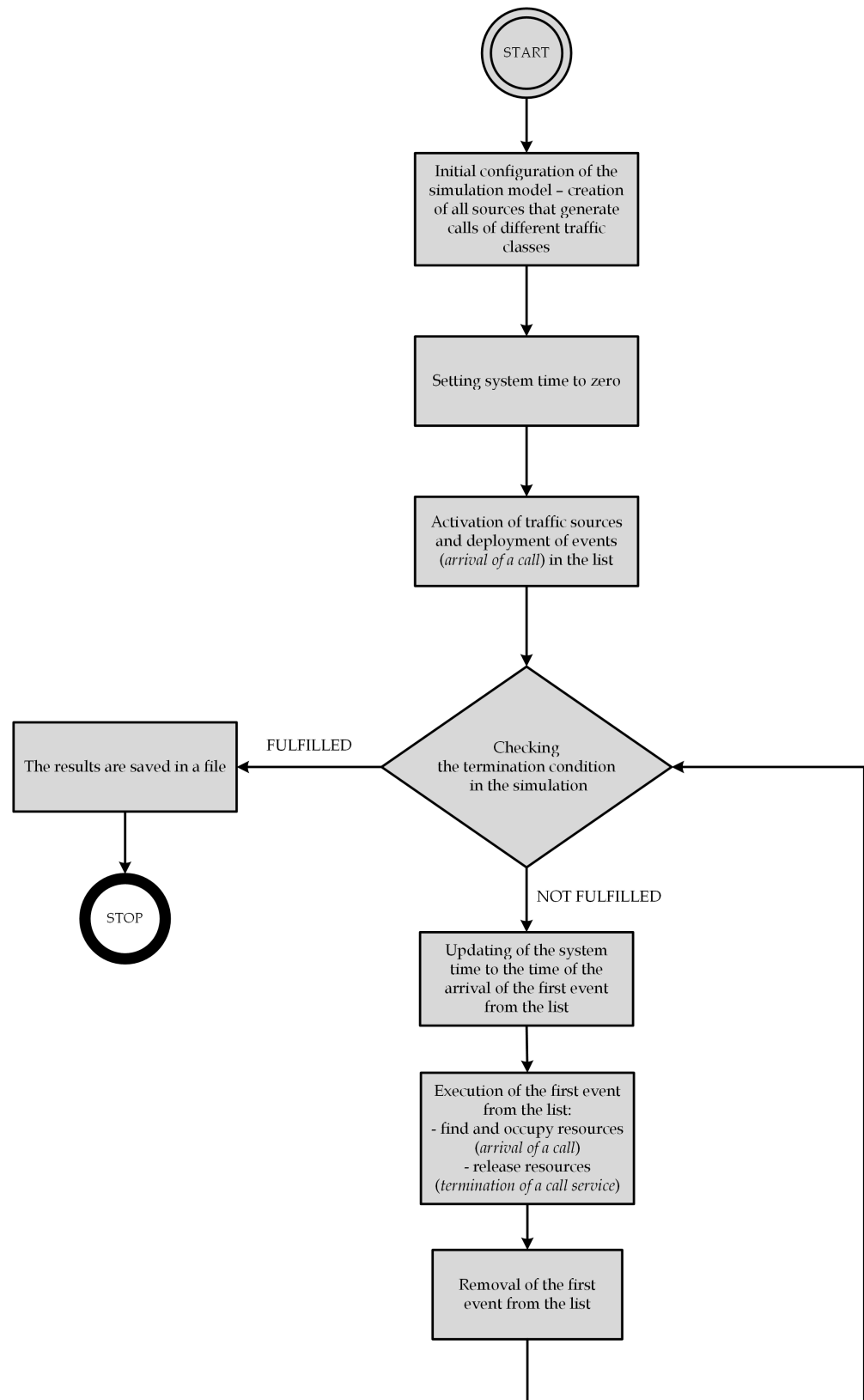
Figure 7. Simulation algorithm.

6.4. Termination Condition

The simulation program permits the determination of the loss probability, which is calculated as the quotient of two determinants: the number of lost calls and the number of generated calls. Accordingly, the number of generated calls of the least active class, i.e.,

the class whose calls are generated with the least intensity, was adopted as the termination condition. The final result for a given set of input parameters can be determined as the arithmetic mean calculated from five series of simulations. The 95% confidence intervals are also determined, which in practice do not exceed 5% of the average value. For this purpose, the maximum of 1,000,000 calls of the class with the least call intensity are to be generated.

7. Numerical Results

The simulation study was conducted for systems for which its parameters are presented in Table 1. In addition, a study on the dependence of the loss probability for calls of individual traffic classes on the value of the reservation threshold was also performed.

Table 1. Parameters of the systems under investigation.

	System 1	System 2
Structure of switching network	$v = 4, f = 320$ FSUs	$v = 4, f = 320$ FSUs
Path choice algorithm	point-to-group	point-to-point
Number of traffic classes	3	4
Number of required FSUs	$t_1 = 5$ (Erlang)	$t_1 = 5$ (Erlang)
	$t_2 = 10$ (Engset)	$t_2 = 10$ (Erlang)
	$t_3 = 20$ (Pascal)	$t_3 = 15$ (Engset)
		$t_4 = 30$ (Pascal),
Classes in $\mathbb{R}$ set	1, 2	1, 2
Reservation threshold	$R_1 = 960$ FSUs	$R_1 = 960$ FSUs
	$R_2 = 960$ FSUs	$R_2 = 960$ FSUs

The choice of appropriate number of demanded FSUs was performed on the basis of the data included in Table 2.

Table 2. Number of FSUs in different connections depending on required bitrate and modulation format [7].

Number of FSUs	Bitrate (Gb/s)	Modulation Format
1	40	64-QAM
1	40	32-QAM
1	40	16-QAM
2	40	QPSK
2	100	64-QAM
2	100	32-QAM
3	100	16-QAM
5	100	QPSK
3	160	64-QAM
4	160	32-QAM
4	160	16-QAM
8	160	QPSK
7	400	64-QAM
8	400	32-QAM
10	400	16-QAM
20	400	QPSK
10	600	64-QAM
12	600	32-QAM
15	600	16-QAM
30	600	QPSK

The results of the simulation (Figures 8–18) are presented in graphs in the form of plotted points with the confidence intervals calculated on the basis of the Student's t-

distribution (with 95% confidence level) for five series with 1,000,000 calls (of the least active class) each. The confidence intervals were determined based on the following formula:

$$\left(\bar{X} - t_\alpha \frac{\sigma}{\sqrt{d}} ; \bar{X} + t_\alpha \frac{\sigma}{\sqrt{d}} \right) \tag{3}$$

where $\bar{X}$ is the arithmetic mean calculated from d results (simulation runs), t_α is the value of the Student's t-distribution for $d - 1$ degrees of freedom. The parameter σ, which determines the standard deviation, is then determined by using the following equation:

$$\sigma^2 = \frac{1}{d-1} \sum_{s=1}^{d} x_s^2 - \frac{d}{d-1} \bar{X}^2, \tag{4}$$

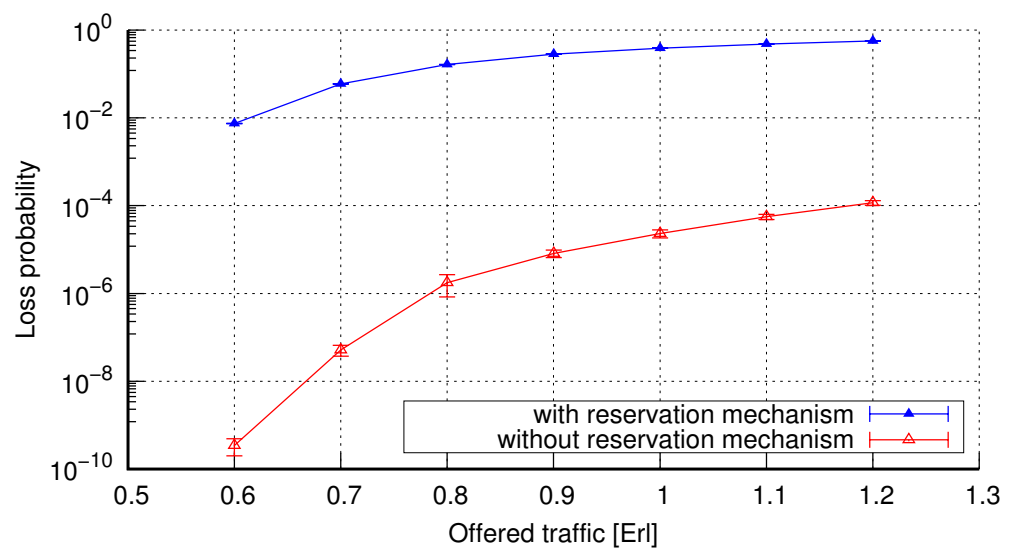where x_s is the result obtained in the s-th run of the simulation.

Figure 8. Loss probability for calls of class 1 (non-privileged class) in System 1.
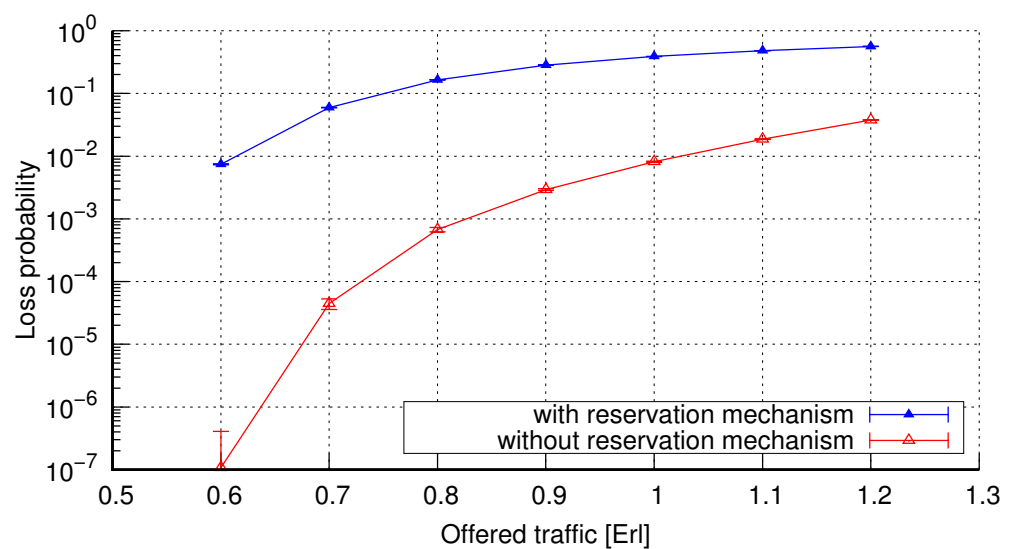

Figure 9. Loss probability for calls of class 2 (non-privileged class) in System 1.

Figures 8–14 show the values of the loss probability for calls of 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 system with introduced reservation mechanism and the system

without reservation mechanism are compared. It is observable that in the case of the classes that belong to the set $\mathbb{R}$, the values of the loss probability increase (in the case of the system with reservation) as compared to the values of the loss probability in the system without reservation (Figures 8, 9, 11 and 12). In the case of the classes that do not belong to the set $\mathbb{R}$ (privileged classes in the system with reservation), we can observe a decrease in the loss probability as compared to the values obtained for the same classes in the system without reservation (Figures 10, 13 and 14).
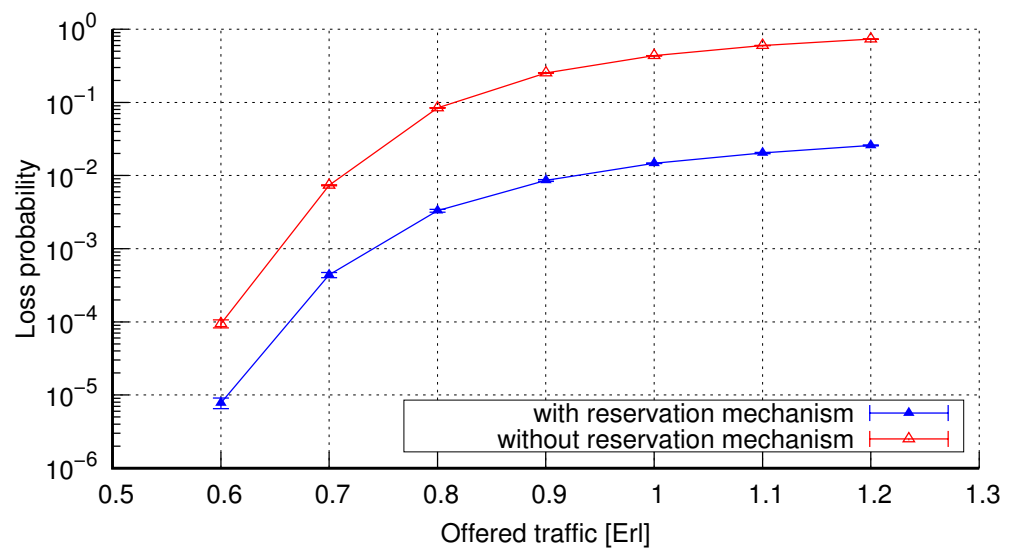

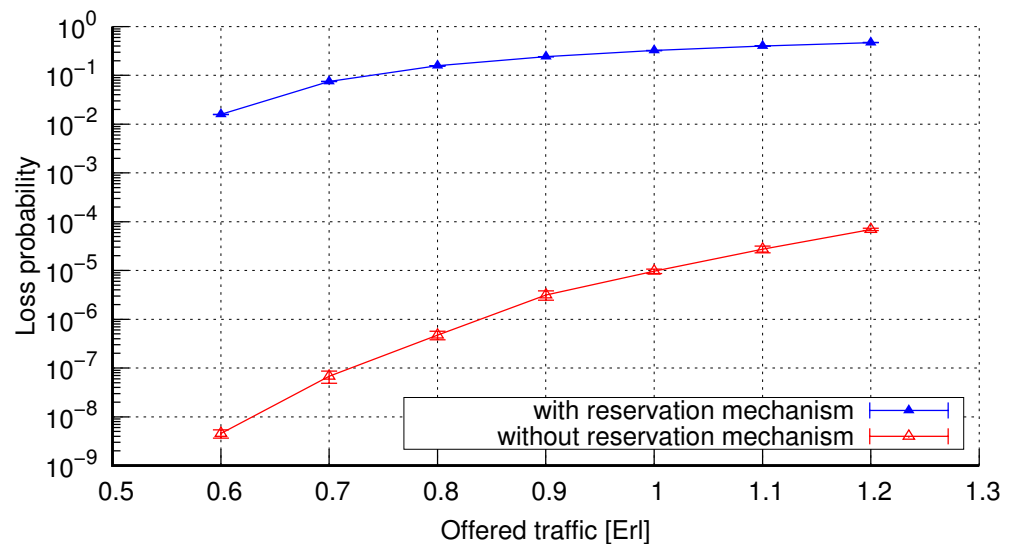**Figure 10.** Loss probability for calls of class 3 (privileged class) in System 1.

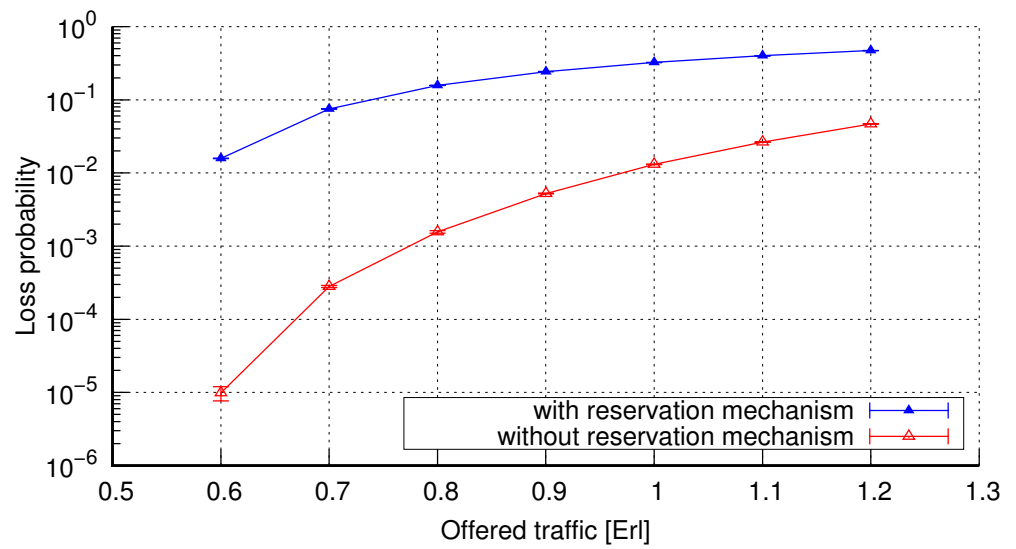**Figure 11.** Loss probability for calls of class 1 (non-privileged class) in System 2.

Figure 12. Loss probability for calls of class 2 (non-privileged class) in System 2.
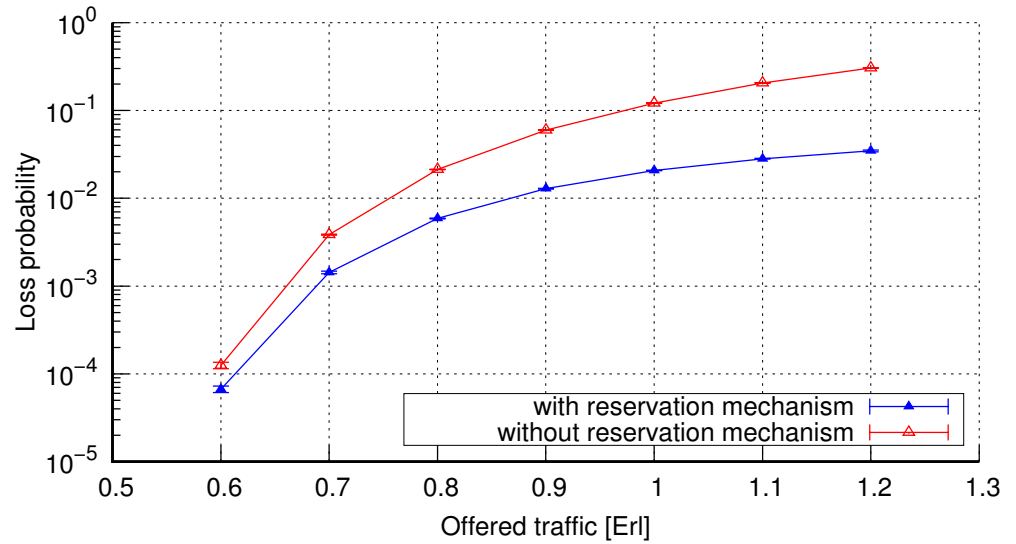

Figure 13. Loss probability for calls of class 3 (privileged class) in System 2.
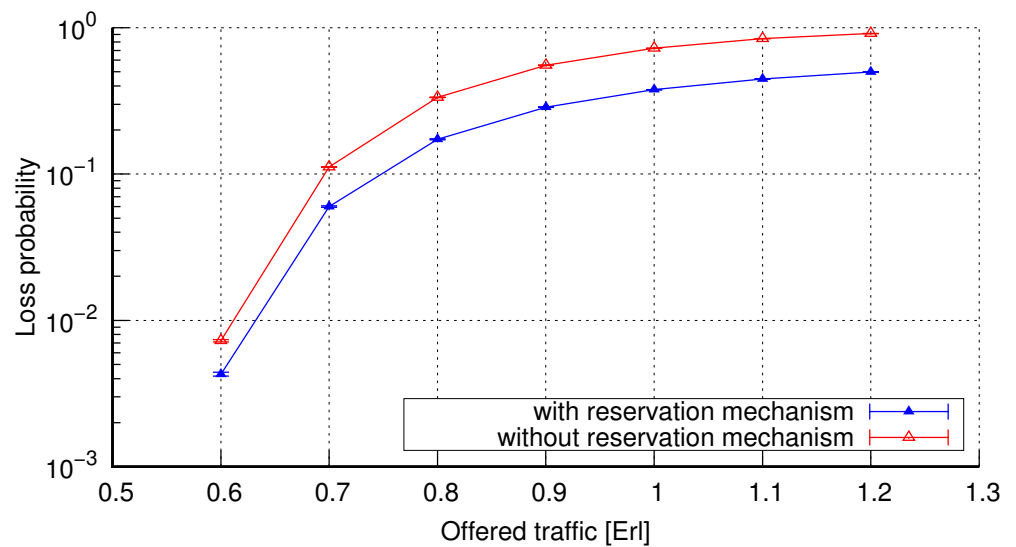

Figure 14. Loss probability for calls of class 4 (privileged class) in System 2.

Additionally, a study on the influence of the value of the reservation threshold on the values of the loss probability obtained for calls of particular traffic classes in the switching network with reservation was performed. The results of the study are presented in Figures 15–18. The analysis of obtained results shows that the values of the loss probability for privileged classes (i.e., those that do not belong to the set $\mathbb{R}$) increase with the increase in the value of the reservation threshold. The increase in the value of the reservation threshold involves a decrease in the volume of resources reserved for privileged classes. On the other hand, in the case of the classes that belong to the set $\mathbb{R}$, we can observe a decrease in the loss probability with the increase in the value of the reservation threshold. It is also possible to find such a value of the reservation threshold for which equalisation of the value of the loss probability for calls that belong to the set $\mathbb{R}$ with one privileged class occurs. In addition, it should be added that in Figures 15–18, the value of the reservation threshold that is equal to 100% means that each traffic class has access to all resources of the system (as if it was a system without reservation).
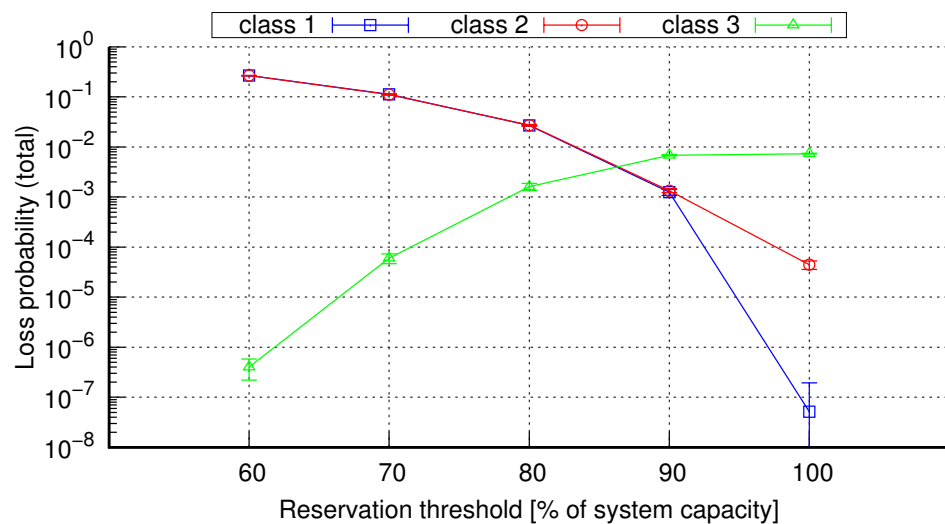

Figure 15. Changes in the loss probability for calls of individual traffic classes in System 1 in relation to the value of reservation threshold. The results are presented for the value $a = 0.7$ Erl of traffic offered to a single FSU.

Figure 16. Changes in the loss probability for calls of individual traffic classes in System 1 in relation to the value of reservation threshold. The results are presented for the value $a = 0.9$ Erl of traffic offered to a single FSU.
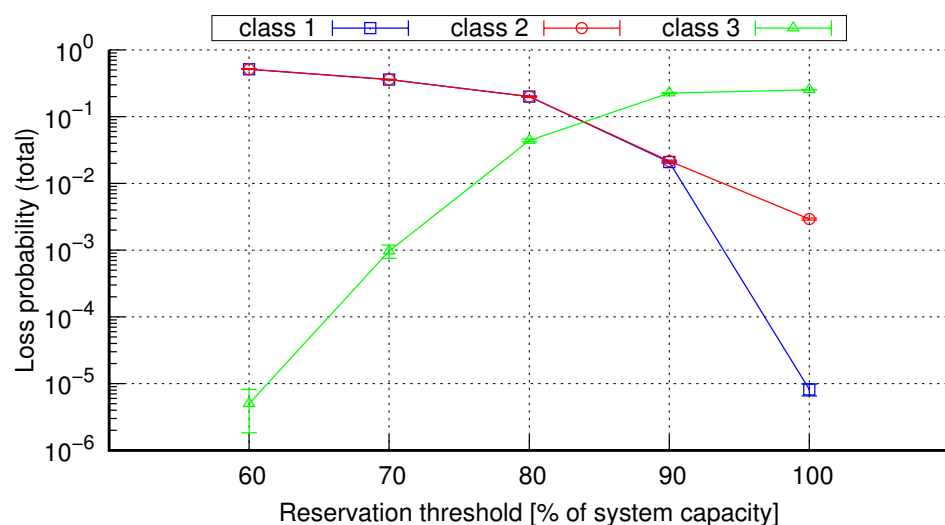
Figure 17. Changes in the loss probability for calls of individual traffic classes in System 2 in relation to the value of reservation threshold. The results are presented for the value $a = 0.7$ Erl of traffic offered to a single FSU.

Figure 18. Changes in the loss probability for calls of individual traffic classes in System 2 in relation to the value of reservation threshold. The results are presented for the value $a = 0.9$ Erl of traffic offered to a single FSU.
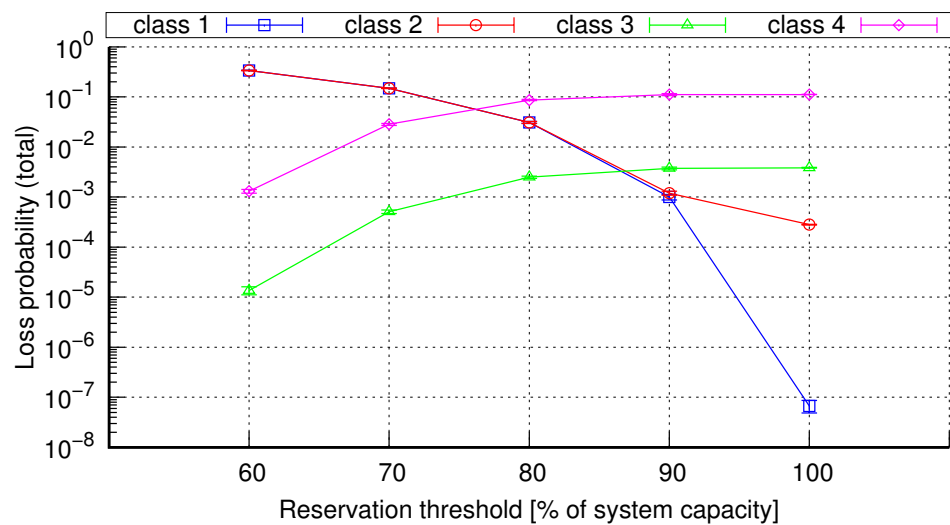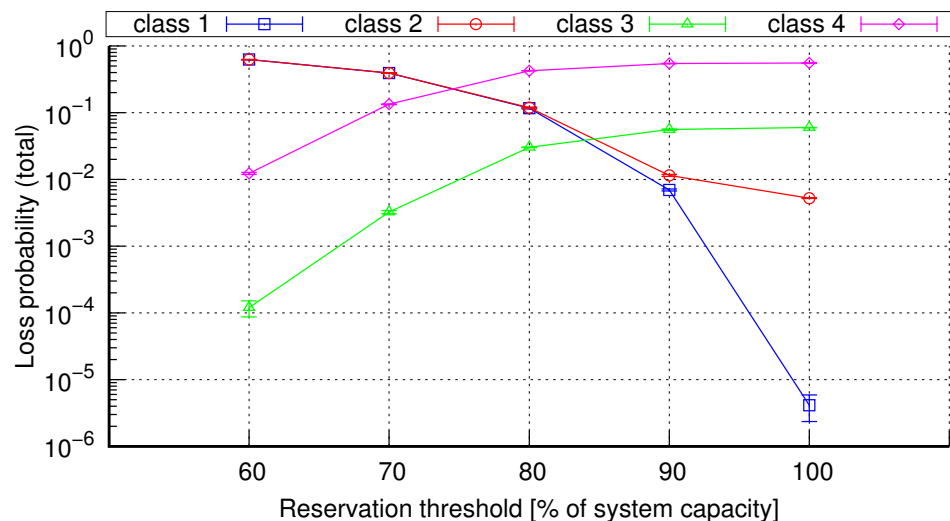
Yet another study was also conducted to examine the dependence between the duration of a single simulation run and the number of traffic classes offered to the switching network. The network under investigation was a network with the point-to-group structure with the following structure: $v = 4$ and $f = 320$ FSUs. The traffic classes offered to the system were defined by the following parameters: $t_1 = 1$ FSU, $\mu_1^{-1} = 1$, $t_2 = 2$ FSUs, $\mu_1^{-1} = 2$, $t_3 = 3$ FSUs, $\mu_3^{-1} = 1$, $t_4 = 4$ FSUs, $\mu_4^{-1} = 1$, $t_5 = 5$ FSUs, $\mu_5^{-1} = 1$. All traffic classes generated calls that formed Erlang traffic streams. The network was offered 3, 4 and 5 traffic classes, respectively. To ensure credibility of obtained results, in each case the aggregate number of calls generated by all traffic classes offered to the switching network was 7,000,000. The simulations were run on a server platform with Intel Xeon X5670 processor and 32 GB RAM memory. The results are shown in Figure 19 in the form of a bar graph. It is observable that the number of traffic classes offered to the system has only slight influence on the duration of a simulation run. The differences in time do not exceed 10%.
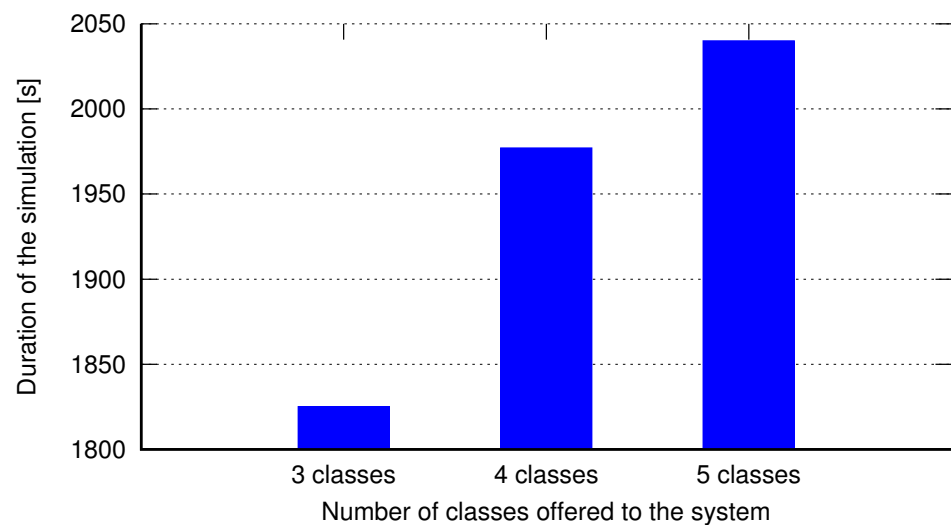
Figure 19. Duration of simulation in relation to the number of classes offered to the system.

An analysis of the length of the simulation program (of one simulation run) in relation to the required number of generated calls of the least active class was also performed. The results are presented in Figure 20 in the form of a bar chart. The study was performed for the systems presented in Table 1 and the value $a = 0.7$ of traffic is offered to a single FSU. The analysis of the results reveals that along with the increase in the number of generated calls, the duration time of the simulation also significantly increases.
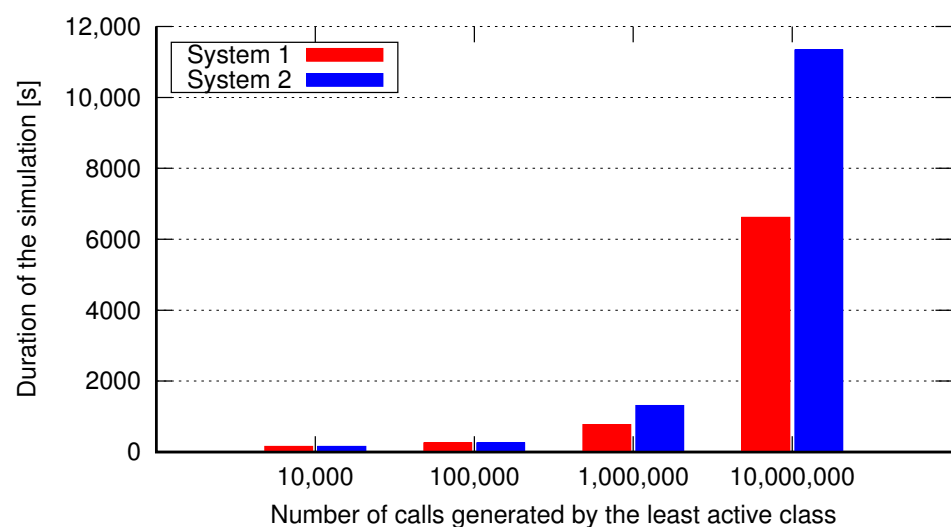

Figure 20. Duration of one simulation run in relation to the required number of generated calls of the least active class.

8. Conlusions

This article shows the results of a study on the determination of the loss probability for calls of traffic classes offered in EON networks with implemented reservation mechanisms. The authors also performed an analysis of the influence of the value of the reservation threshold on the obtained values of the loss probability. As a result, the analysis will make it possible to adjust the choice of the value of the reservation threshold with the most optimal method. The article also presents the analysis of the influence of the number of the classes offered to the switching network with reservation mechanism and the number of calls generated by the least active class on the duration time of the simulation program. In the future, the authors intend to develop analytical methods that would determine loss probabilities in EON networks with Clos structure and introduced reservation mechanisms,

while the developed simulator would be used as an appropriate tool for verification and validation of these methods.

Author Contributions: Conceptualization, M.S. and P.Z.; methodology, P.Z.; software, M.S.; validation, E.L., M.S. and P.Z.; formal analysis, E.L.; investigation, M.S.; resources, E.L.; writing—original draft preparation, M.S. and P.Z.; writing—review and editing, M.S.; visualization, M.S.; supervision, P.Z.; project administration, E.L.; funding acquisition, P.Z. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to the project limitation.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

QoS	Quality of Service;
CAC	Call Admission Control;
EON	Elastic Optical Networks;
FSU	Frequency Slot Unit;
W-S-W	Wavelength-Space-Wavelength;
BV-WSS	Bandwidth-Variable Wavelength Selective Switch;
BV-SS	Bandwidth-Variable wavelength selective Space Switch;
BV-WS	Bandwidth-Variable Wavelength converting Switch;
PC	Passive Converter;
TWBC	Tunable Waveband Bandwidth Converter;
QAM	Quadrature Amplitude Modulation;
QPSK	Quadrature Phase-Shift Keying.

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