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SIMULATION MODELLING OF MULTISERVICE SWITCHED NETWORKS CARRYING UNICAST AND MULTICAST TRAFFIC WITH PRIORITIES

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Today's computer and telecommunications networks, irrespective of the technical solutions and technologies used to build them, are multi-service in nature. The modelling of networks and nodes in such networks is still an important research problem. The article presents the results of a simulation study of multi-service switching networks in which service-specific priorities are introduced. A specially developed and executed simulation programme was used to carry out the research. In the study, we considered the two most optimal placement of the switching elements performing the functions of multicast traffic splitting in a 3-stages Clos switching network. During the tests, it was assumed that the switching network supported a mixture of multiservice unicast and multicast traffic streams. The aim of the research conducted is to investigate the impact of the introduction of priorities on the loss probability of multicast traffic in a multiservice switching network. The results obtained from the simulation are presented on the graphs in the form of points with confidence intervals.

Keywords: Computer simulation, switching networks, multiservice traffic, multicast, priorities, loss probability

1. Introduction

The ever-expanding network services and the increasing demand for higher data rates, coupled with the rising number of connected devices in the global data transmission network, pose evolving challenges for telecommunications networks. Meeting these demands requires not only improving the throughput of telecommunications links but also accommodating differentiated service quality for diverse traffic streams within network nodes. The switching network is a critical component of multi-service network nodes, making studies on switching networks crucial for addressing contemporary challenges faced by network designers and operators.

The challenges include the evolution of non-blocking network architectures and research into modeling multi-service networks. Notably, the transmission of data, especially high-bit-rate data, places a significant load on network links and nodes, such as routers. Traditionally, resources inside nodes are reserved separately for each stream. However, a newer solution, known as multicast, involves the partial use of individual resources by all data streams only where necessary, thus optimizing resource utilization (Sobieraj *et al.*, 2022; Stasiak *et al.*, 2022; Głąbowski *et al.*, 2022).

Multicasting, implemented in the switching network, is a key aspect of contemporary network nodes. Various proposals for switching networks exist, with Clos field structures being among the highest throughput devices (Yang *et al.*, 2016; Sehery *et al.*, 2016). This article focuses on characterizing traffic attributes in well-established switching networks, particularly in the context of multicast transmissions within Clos networks, which have long been used in nodes with substantial capacities.

The study involves developing and implementing a simulator for multi-service blocking switching networks with the Clos configuration, giving special attention to multicast traffic prioritization and the section in which multicast happens. This configuration is prevalent in modern telecommunication network nodes where prioritization is crucial for traffic management. The research tool enables examining the impact of multicast traffic prioritization on network traffic characteristics and the efficiency of network nodes for various forms of multi-service traffic it also allows for comparison of the effects caused by multicasting in different sections of Clos switching network. The goal of this study is to analyze the impact of multicast traffic prioritization in switching networks, in conjunction with different stages at which multicast split occurs, on the general traffic efficiency of the network. The conducted research is to investigate the impact of the introduction of priorities on the loss probability of multicast traffic in a multiservice switching network.

The article is organized into five sections. Section two outlines the structure of the Clos switching network, with a specific emphasis on multicast traffic handling. Section three details the algorithms and methodologies used to create a simulation environment for node modeling, considering the complexities of multicast data distribution. Section four presents the outcomes of selected simulation experiments, offering insights into the implications of prioritized multicast transmissions within the Clos network. The paper concludes with a concise summary outlining key takeaways from the study and implications for efficient multicast traffic management within the Clos network architecture.

2. Structure of Clos switching network and multicast connections

The central element of a network node consists of the switching network, and this research focuses on nodes constructed using the Clos network architecture (Clos, 1953; Sobieraj, 2014). This network is divisible into stages, with each stage containing several switches. Each switch, the fundamental unit, is equipped with a fixed number of inputs and outputs, facilitating connections between specified inputs and outputs via a network control algorithm. The study examines a 3-stage Clos network, depicted in Figure 1, to illustrate the concept.

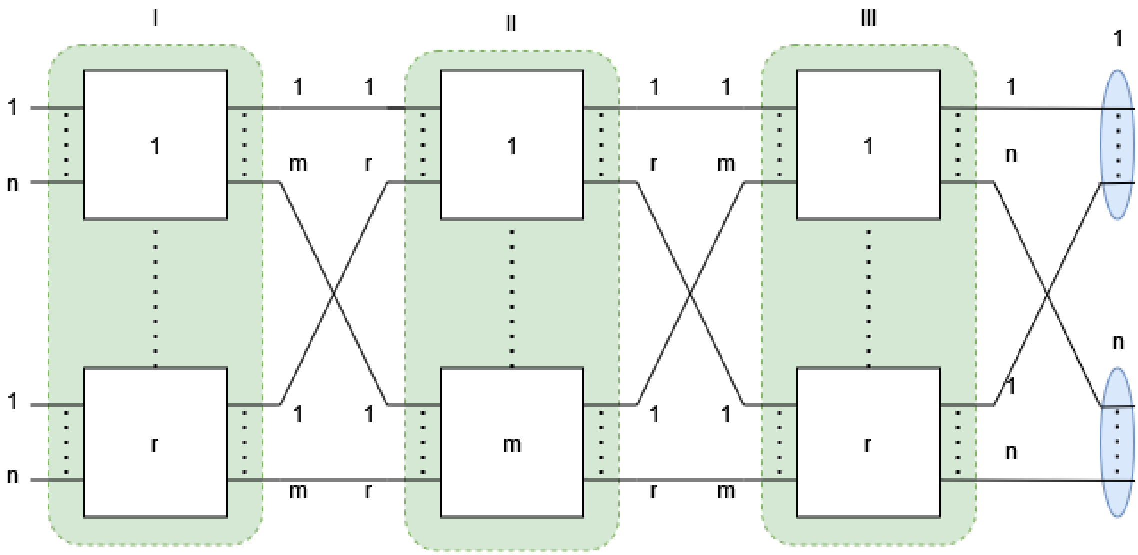


Figure 1. Structure of three-stage Clos network

Figure 1 demonstrates the structure of the three-stage Clos network, with the following notations:

- n – the number of inputs, outputs and output directions,
- I, II, III – stage identifier,
- r – the number of switches in stage I and III,
- m – the number of switches in stage II.

The availability of an unoccupied connection pathway is imperative for establishing a connection. In this study, only a version of the point-to-group selection algorithm was employed. If the switches in the final stage don't have sufficient available resources in the requested multicast directions, the call is terminated due to external blocking. If an unoccupied connection pathway cannot be identified within the network, the call is rejected due to internal blocking (Sobieraj, 2014). It's crucial to emphasize that all evaluations of resource availability adhere to the prioritized traffic regulations detailed later in this section.

Exploring further, within the domain of multicast operations in the Clos network, involves efficiently transmitting data to multiple recipients concurrently. Unlike unicast, which entails point-to-point communication, multicast facilitates delivering information to numerous destinations simultaneously, serving as a foundational mechanism for distributing data efficiently among various users in the network. When considering prioritized multicast within the Clos network, the process becomes more complex, requiring meticulous management to ensure the prompt delivery of crucial data to recipients while optimizing resource usage. Prioritizing multicast traffic becomes vital to guarantee timely delivery of high priority information, even under conditions of high traffic volume. This delicate balance between effective data distribution and resource management underscores the importance of well-designed algorithms and strategies, as discussed in the article. By accounting for priorities associated with different multicast streams, the algorithm dynamically allocates resources, ensuring efficient delivery of higher-priority multicast data to target recipients while optimizing resource utilization. This approach enhances overall network efficiency, enabling seamless transmission of critical data to multiple nodes concurrently. Figure 2 illustrates a multicast connection with the split in the third stage of the Clos network. Figure 3 shows multicast connection with the split in the second stage.

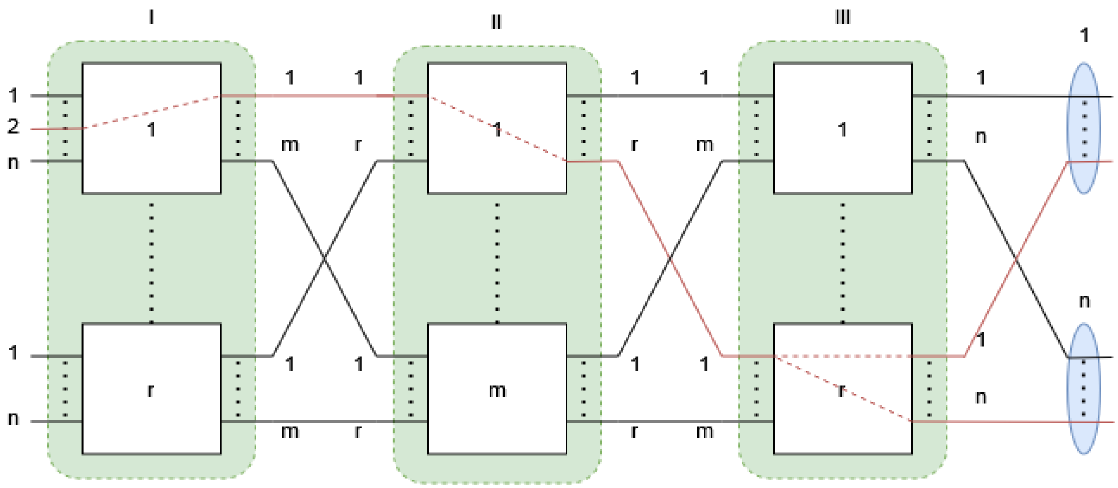


Figure 2. Three stage Clos network servicing a multicast connection with a split in third stage. Red lines represent connection paths

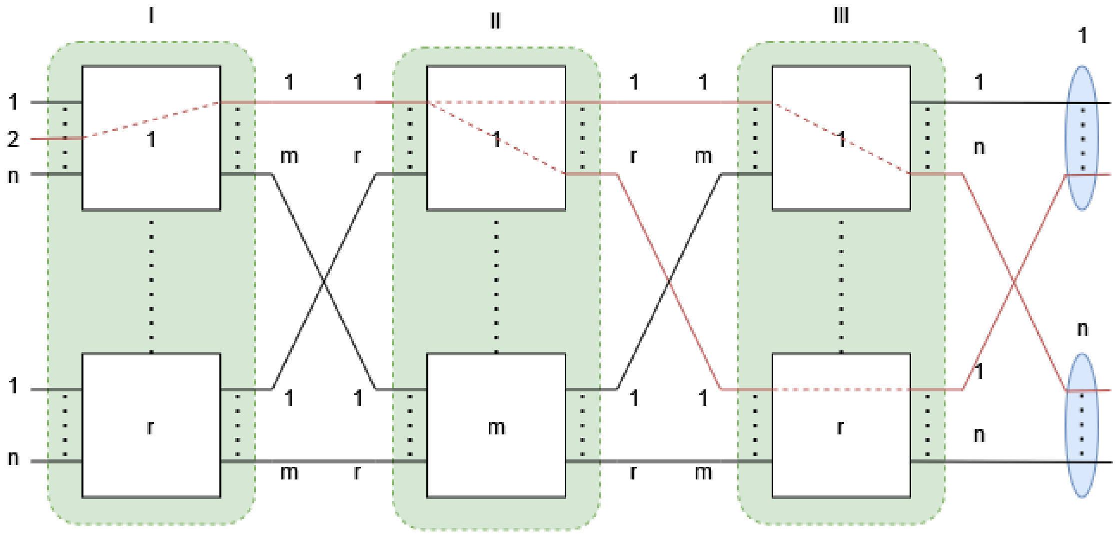


Figure 3. Three stage Clos network servicing a multicast connection with a split in second stage. Red lines represent connection paths

Even though in both cases (Figure 2 and Figure 3) the effect is the same - input number 2 of the first switch in the first stage is connected with first output direction and n-th output direction there are some key differences when comparing. In case of split in the last section there are fewer links occupied by serviced calls in the network when compared to splitting in the second section. Third stage split requires five free links while second stage split requires six. This inherently increases the load on the network. The second main difference is that in the case of third section split, the last stage switch needs to provide free links in the demanded output directions alone. In the case of the second section split K switches of the third section are selected, where K is the number of demanded directions, which leaves more flexibility for assembling the connections path.

In the simulation environment outlined in this article, the management of multicast traffic within the Clos network is guided by principles aimed at efficiently allocating resources according to the priorities assigned to various multicast streams and ensuring their precedence over lower priorities. Prioritized traffic adheres to following rules (Nowak *et al*., 2020):

- All call classes possess assigned priorities.
- Service of low-priority calls does not impact the blocking probability of high-priority calls.
- Absence of free resources prompts the termination of service for lower-priority calls upon the arrival of a higher-priority call.

3. Simulation algorithms and methodologies

The discrete-event (Tyszer, 1999) simulation for the three-stage Clos network, which supports:

- third or second section multicast
- multi-service traffic with prioritization
- reduction of evicted calls (Nowak, 2022)
- random multicast output directions requested by calls

was implemented using the C# programming language. The path-finding algorithm utilized a version of the point-to-group algorithm, later extended to handle call priorities and minimize the set of calls to be evicted.

The resulting simulator enables the exploration of a diverse mix of multi-class traffic with varying demands, multicast destination directions, and associated priorities. Within this simulation environment, various traffic types, such as Binominal, Poisson, and Pascal traffic (referred to as BPP traffic - Binominal, Poisson, Pascal), are settable (Sobieraj *et al.*, 2021a, Sobieraj *et al.*, 2021b).

The input data for the simulator includes:

- the parameters of the three-stage Clos network (Figure 1):
  - m – the number of switches of the second stage,
  - n – the number of input fibers of the switches of the first stage and output fibers in the switches of the third stage,
  - r – the number of switches of the first and third stages;
- f - capacity of a single fiber;
- list of traffic classes with defined type (Poisson, Binominal, Pascal) and, where necessary, the number of traffic classes n - $C_{i,\{P,B_n,P_n\}}$
- d - number of random directions requested by given traffic class
- list of resources demanded by each of the classes - t_i;
- priority for each of the classes - p_i ;
- a – average intensity per allocation unit.

Two key events within the simulation were defined:

- connection request,
- end of connection.

Upon receiving a connection request, the network evaluates resource availability considering the path selection algorithm. If there aren't enough resources to handle the incoming call, the simulator imposes prioritization, potentially displacing lower-priority calls currently being serviced. Identified connections at risk are marked for possible termination. If designated connections are utilizing sufficient resources such that terminating them would enable the acceptance of higher priority calls, they are then terminated, allowing the higher priority call to be serviced. Termination of lower priority calls involves selecting as few calls as possible starting from the lowest priority so that any unnecessary termination does not take place. If termination of lower priority calls wouldn’t provide enough resources for the incoming higher priority call the call is lost. The system schedules the next event regardless of whether the call was accepted for service or not. When a connection ends, network resources are released, indicating completion. The detailed simulation algorithm is illustrated in Figure 4 and Figure 5, showing the complex dynamics of managing prioritized multicast data in the Clos network.

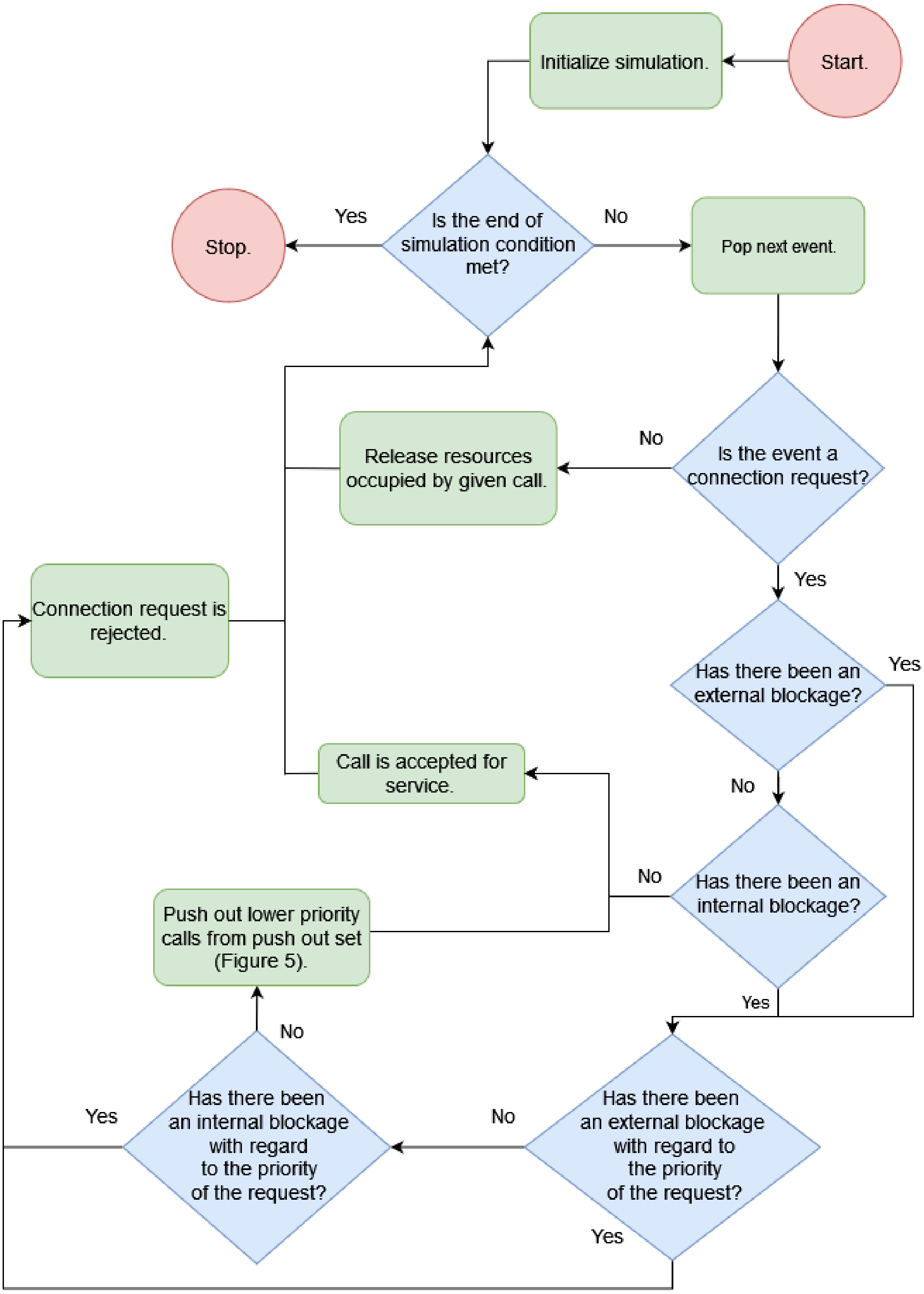


Figure 4. General algorithm for the simulation of the switching network with prioritized and multicast traffic classes

When faced with the need to remove calls from the connection pathway, the difficulty lies in identifying which specific calls should be terminated in favor of higher priority calls. The approach outlined in (Nowak, 2022), aimed at minimizing push out losses, is implemented to address this challenge. The approach is to select calls, starting from lowest priority, that are being serviced in as many as possible links in the chosen path so that it's not needed to terminate different calls in each intersection link. A compacted version of said algorithm is shown in Figure 5.

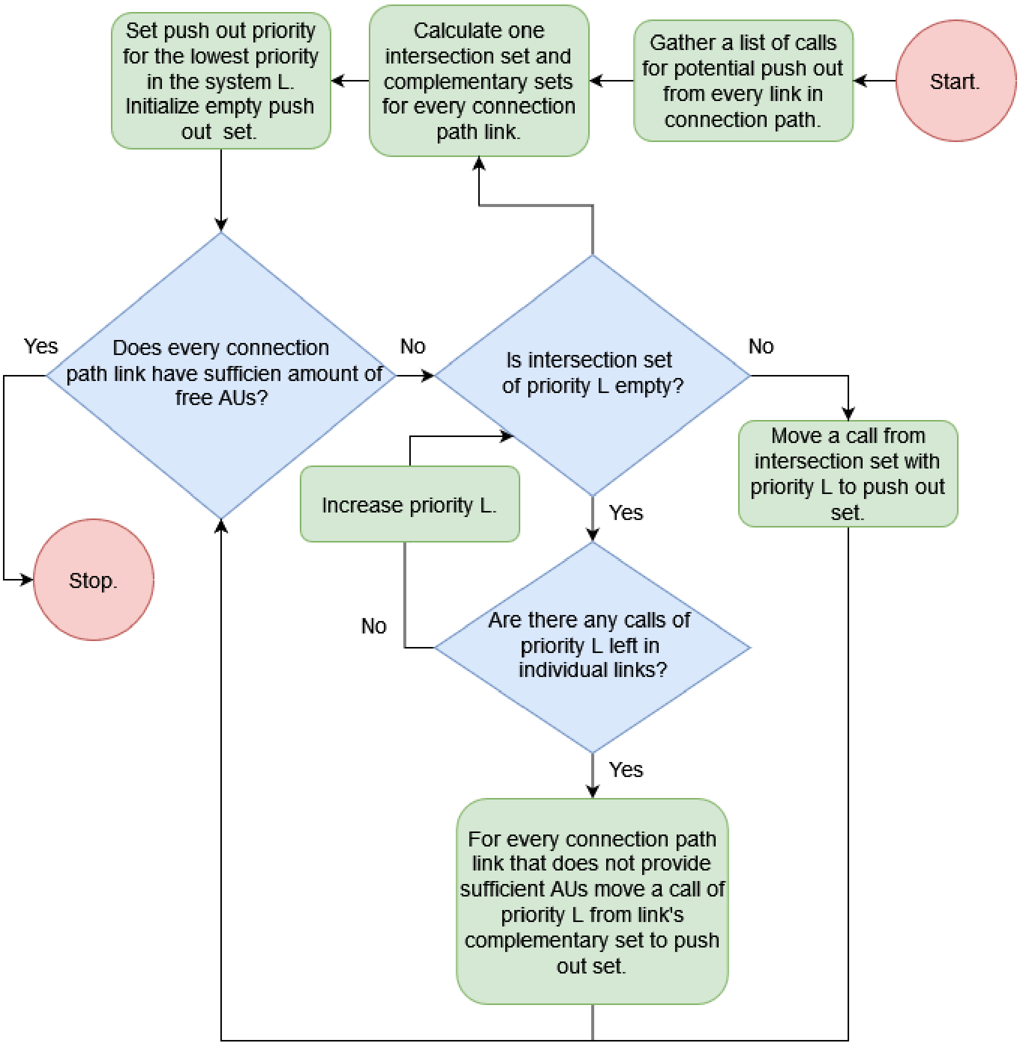


Figure 5. Compacted version of algorithm typing calls to be pushed out in favor of incoming higher priority calls

When considering multicast traffic, it is essential to grasp that at each stage of the Clos network, connections are divided to reach multiple destinations (multicast directions), as illustrated in Figures 2 and 3. At each step outlined in Figure 4, which assesses the availability of resources for incoming connections, the connection is evaluated against all multicast directions it requires. This may lead to a mandatory necessity that could terminate numerous existing connections currently being serviced, particularly if the incoming connection possesses significant priority and the division occurs at earlier stages of the Clos network.

Simulation results are stored in files. These files contain data on internal, external, and overall losses. Internal losses occur when a connection path required to service a specific call cannot be established within the network. External losses result from the lack of available resources in the designated output links of the network. Total losses include both types of losses mentioned above, along with losses from terminating lower priority connections, offering a comprehensive understanding of the effects on calls within the network.

4. Simulation experiment and example results

The simulation was performed on a three-stage Clos network. The simulator can handle a variety of traffic characteristics, including multiple traffic classes, priorities, demanded resource levels, types and relevant parameters specific to a three-stage Clos network. Multicast splitting occurs in either the second or third stage of the network, with each class being assigned a specific number of uniformly distributed output directions.

The research proposed a network setup consisting of four switches per stage ($m = r = 4$), each with 4 inputs and outputs ($n = 4$) and an allocation capacity of 48 units for each input/output ($f = 48\,AU$). Additionally, it assumed that the establishment of connections in the network was governed by the point-to-group selection algorithm.

In the study, we considered the two most optimal distributions of switching elements performing the traffic splitting function in a 3-stages Clos switching network[1]. For each of them, we chose two traffic scenarios. The first scenario assumes that all traffic classes are handled with the same priority in the system, while the second scenario assumes that each class is handled with a different priority. The set of traffic classes and the number of required output directions and allocation units were chosen as examples. This method of defining the test scenarios makes it possible to see both the effect of the placement of the splitter elements on the values of the probabilities of internal and external loss of calls in the switching network and the effect that the introduction of the priority mechanism has on these values.

Thus finally, the simulation study was divided into four scenarios. The difference between said scenarios is the stage at which the multicast split occurs and setting of priorities. Offered traffic consisted of three Poisson classes:

- Poisson class C_0 , demanding 3 allocation units ($t_0 = 3$), demanding 2 directions,
- Poisson class C_1 , demanding 6 allocation units ($t_1 = 6$), demanding 2 directions,
- Poisson class C_2 , demanding 12 allocation units ($t_2 = 12$), demanding 1 direction,

and as mentioned:

- Scenario 1 - multicast split in the second stage, priorities setting: all classes equal.
- Scenario 2 - multicast split in the second stage, priorities setting: C_0 - highest, C_0 - medium, C_0 - lowest.
- Scenario 3 - multicast split in the third stage, priorities setting: all classes equal.
- Scenario 4 - multicast split in the third stage, priorities setting: C_0 - highest, C_0 - medium, C_0 - lowest.

Each simulation trial underwent 7 repetitions, resulting in a 95% confidence interval for 7 sets of simulations, calculated using Formula (Durka, 2003):

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

where X represents the mean value computed from d repeats of the simulation, t_α is the quantile value for the t-Student distribution for d-1 degrees of freedom, whereas σ^2 is the variance of the distribution. The number 7 has been chosen based on statistical considerations, aiming to strike a balance between computational resources and statistical accuracy.

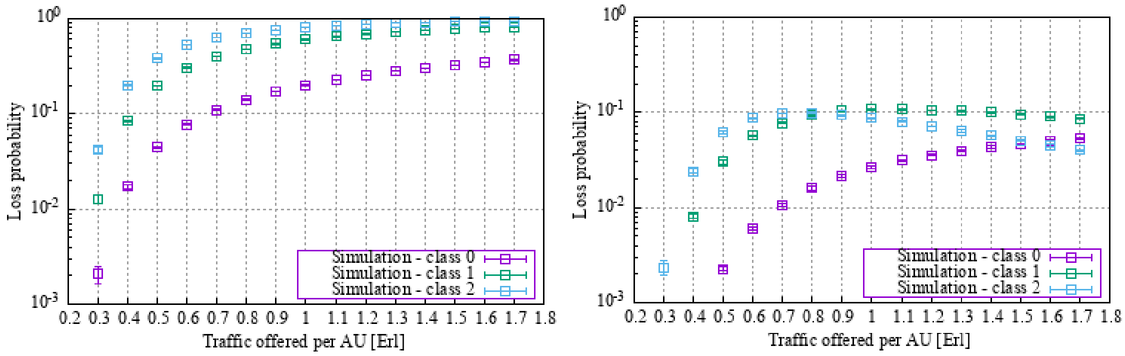
A singular simulation extended over 150,000 time units, with the initial series spanning 500 time units. For previously described scenarios, with consideration of simulation events frequency, these time spans assure analysis of steady state and very high degree of accuracy. The outcomes of each simulation are illustrated through graphs below depicting the relationship between loss probabilities and intensity per allocation unit in the system (a), as defined by the following formula:

$$a = \sum_{i=0}^{2} \frac{a_i \cdot t_i}{n \cdot m \cdot f},$$

i represents the class index, a_i, t_i denote the intensity and number of requested resources for class i, respectively. Additionally, n stands for the number of inputs of the first-stage switch, m represents the number of switches in the first stage, and f signifies the capacity of a single link. Results for scenario 1 are shown in Figures 6 and 7, results for scenario 2 are shown in Figures 8 and 9 and Table 1. Results for scenario 3 are shown in Figure 10, results for scenario 4 are shown in Figure 11 and Table 2. Results presented in Tables are based on calculating the push out losses formula which states that push out losses are equal to total losses reduced by internal and external losses:

$$E_p = E_t - E_{in} - E_{ex}.$$

[1]These conclusions follow, among other things, from the authors' previous studies published i.a. in Stasiak *et al*. (2022).



(a) (b)

Figure 6. External (a) and internal (b) losses probability for scenario 1

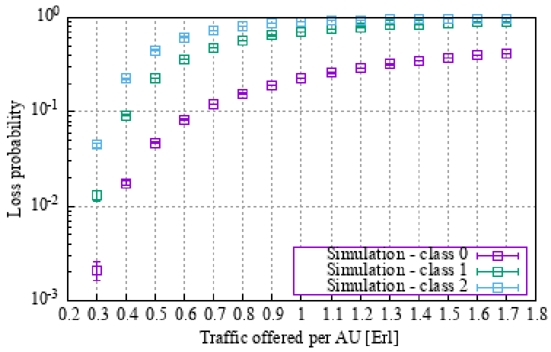
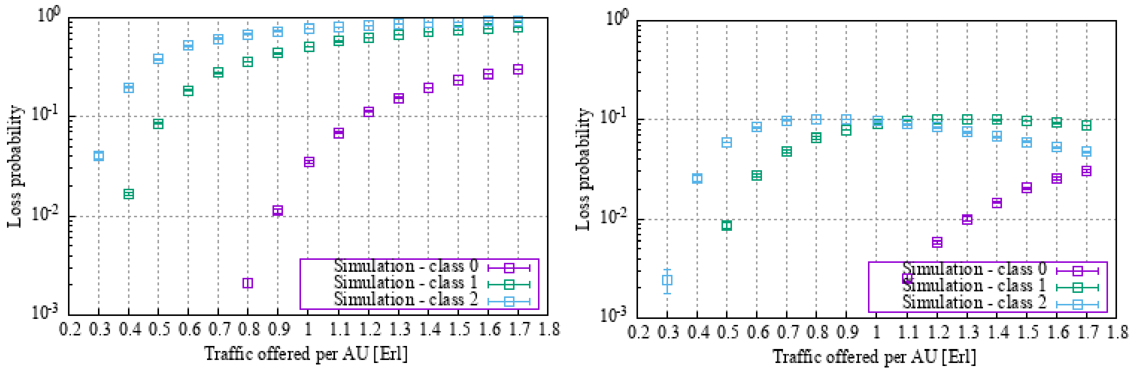


Figure 7. Total losses probability for scenario 1



(a) (b)

Figure 8. External (a) and internal (b) losses probability for scenario 2

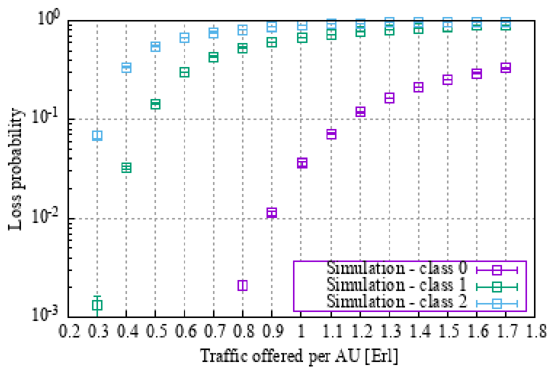
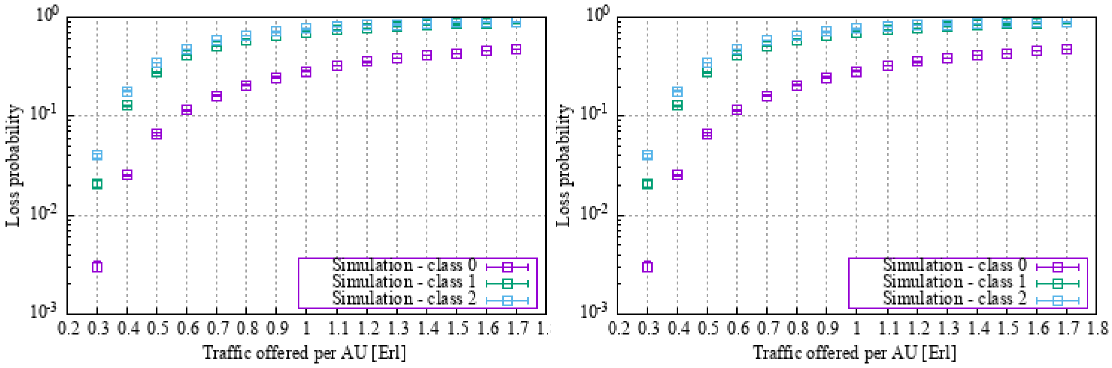


Figure 9. Total losses probability for scenario 2

Table1. Push-out losses for scenario 2

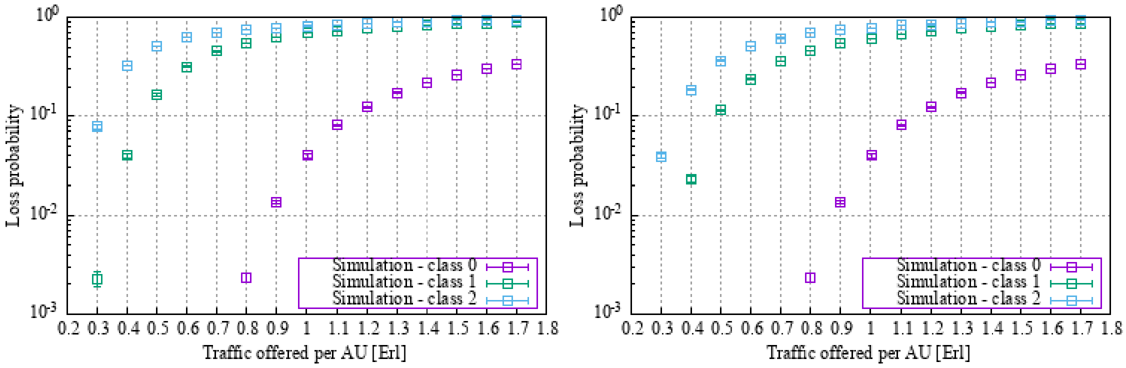
a	C_0	C_1	C_2
0.3	0	0.0009567658	0.0264733195
0.4	0	0.0149688025	0.1146292198
0.5	0	0.0498662696	0.1150528885
0.6	0	0.0865162577	0.0767434592
0.7	0	0.1073232865	0.0468810759
0.8	0	0.111387653	0.0289212109
0.9	0	0.1030536294	0.0177304689
1	0	0.0833792286	0.0104282624
1.1	0	0.0630391237	0.0061182784
1.2	0	0.0451307533	0.003609491
1.3	0	0.0319001471	0.0020915909
1.4	0	0.0223601891	0.0012341026
1.5	0	0.0155603882	0.0007448258
1.6	0	0.0109973306	0.0004435966
1.7	0	0.0080022914	0.0002974288

Internal losses for scenarios 3 and 4 were omitted because of their insignificance. Their peak was observed for class 2 at $a = 0.5$ with value of $E_{in,C_2} \approx 6 \cdot 10^{-6}$. For all other classes the internal losses were equal to zero at every point.



(a) (b)

Figure 10. Total(a) and external(b) losses probability for scenario 3



(a) (b)

Figure 11. Total(a) and external(b) losses probability for scenario 4

Table 2. Push-out losses for scenario 4

a	C_0	C_1	C_2
0.3	0	0.0015716941	0.0380742068
0.4	0	0.0164272503	0.1395386243
0.5	0	0.0505737603	0.1488674951
0.6	0	0.0792565411	0.1139619115
0.7	0	0.095342018	0.0810561014
0.8	0	0.0976420538	0.0573452271
0.9	0	0.0916934666	0.0414279807
1	0	0.0786695036	0.0300668358
1.1	0	0.0627218652	0.0219673018
1.2	0	0.0495861057	0.0163519887
1.3	0	0.0374257392	0.0116951933
1.4	0	0.0286160611	0.0087050043
1.5	0	0.0220029133	0.0064429856
1.6	0	0.0170216476	0.0047257772
1.7	0	0.0134065083	0.0036686534

Scenarios 1 and 3 serve as reference points for scenarios 2 and 4. They present the same systems but without imposed priorities the only difference is the section in which multicast occurs. The purpose of scenario 1 and 3 is to show the impact of imposing priorities. Comparing scenarios 1 and 3 with 2 and 4 shows standard behavior when applying priorities (Nowak and Zwierzykowski, 2022). The service level of the highest priority class improves greatly, the service level of the middle class improved noticeably while the service level of the lowest priority class is decimated.

When analyzing results from scenarios 2 and 4 some key observations emerge. When multicast split occurs in the last stage the internal loss probability is close to non-existent. On the other hand, when the split takes place in the second stage internal losses account for a significant portion of total losses. This observation is directly linked to the fact that splitting in the last section inherently does not affect any additional inter-section links. Moreover, in the case of the last section split, splitting connections in N directions increases the resource occupancy in output links by N-fold when compared to connections without multicast. It is crucial to notice that these resources are going to be occupied only in the output links, not inter section links. This leads to a substantial occupation of output links and minimal occupation of links in other sections, resulting in a notable increase in external losses compared to servicing calls without multicast, and near eradication of internal losses. In the case of second stage split inter section links are also going to be affected by the split. As a result, significant internal losses can be observed.

When looking at overall efficiency it can be observed that when the network splits connection in the second stage the overall performance is worse and the network becomes congested at lower offered traffic values. Only the highest priority class losses remain almost unchanged. This is due to the fact mentioned in the first section of this article. The earlier, section-wise, the network splits connection the more links in total it's going to occupy thus reducing network performance. The call should be split as late as possible to avoid unnecessary occupation of resources while still providing a given multicast connection.

Analysis of the push out probability of given traffic classes shows that the highest priority class indeed hasn't experienced any terminations. As for other classes, push out losses are a significant portion of their total losses. It is worth noting that when the offered traffic is high enough the lower priority class can experience smaller push out losses than higher priority class. This is due to the fact that at these levels of traffic the lower priority class doesn't even enter the network therefore it cannot be pushed out. As a result, the class with the next higher priority, which gets to be accepted in the network, will experience terminations to give a way in for higher priority classes.

5. Conclusions

The article introduces a network node simulator handling multicast traffic featuring a built-in mechanism for prioritizing services. Through this simulator, one can assess the loss probability for distinct traffic classes within a switching network employing point-to-group selection. The conducted simulation studies validated the viability of utilizing the traffic prioritization mechanism for traffic management within network nodes. Similar to the dynamic reservation mechanism (Sobieraj *et al.*, 2021a) or the threshold mechanism (Sobieraj *et al.*, 2021b), this mechanism enables the differentiation of service quality among various traffic classes and can be used as a CAC mechanism. Its optimal utilization is assumed with classes requiring lower bit rates and typically associated with minimal traffic volumes, such as maintenance, monitoring, or emergency services. However, employing it to prioritize high-volume traffic may significantly diminish the quality of service for other classes. Furthermore, prioritization can act preventively, activating when specific types of traffic necessitate optimal quality handling within the network. In case of practical implementation, numerous challenges may emerge. Neglecting careful prioritization without prior simulation could result in severe repercussions for certain less prioritized services, potentially leading to substantial traffic loss during peak periods. It is generally recommended, as mentioned, to assign the highest priorities to categories with lower volume, such as emergency calls. Another challenge could be the time needed for the algorithm to enforce and handle priorities, potentially introducing additional latency. Future research is planned to analyze efficiency in systems with dynamic multicast split section i.e. systems that try to split connections as far away from the source as possible to avoid unnecessary network congestion. Moreover, direct comparison of various aspects of prioritization and other CAC mechanisms such as reservation is planned. The main result of the conducted research, elements of which are presented in the article, is the confirmation that the traffic prioritization mechanism can also be successfully used to differentiate the quality of service of multiservice traffic using split connections. At the same time, this traffic is more sensitive to the operation of the prioritization mechanism than unicast traffic. Therefore, the introduction of a prioritization mechanism in such switching networks requires detailed validation tests, taking into account the expected types of traffic to be served. Particularly important is to verify the association of priorities with multicast traffic, the purpose of which will be to confirm whether, for a given field structure and serviced traffic mixture, the switching network will allow the carrying of traffic with an assumed level of loss probability that the resulting amount of traffic serviced of each traffic class will be at an acceptable level.

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