Modelling Limited-availability Systems with Multi-service Sources and Bandwidth Reservation

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***Abstract*—The aim of this paper is to present a new analytical calculation method for the occupancy distribution and the blocking probability in the so-called limited-availability group with multi-service sources and reservation mechanisms. The paper considers multi-service limited-availability systems with multi-service sources, in which each single traffic source can generate calls of different traffic classes. To date, only models of multi-service systems with single-service sources, in which a single source of a given class generates always only calls of this particular class have been considered in teletraffic literature. The results of analytical modeling of the limited-availability systems with multi-service sources and reservation mechanisms are compared with simulation data, which confirm a high accuracy of the method. Any possible application of the proposed model can be considered in the context of wireless networks with multi-service sources and reservation mechanisms, as well as in the context of switching networks.**

***Keywords*-limited-availability systems; multi-service networks; multi-service sources; bandwidth reservation.**

I. INTRODUCTION

Cellular networks are one of the most rapidly growing areas of telecommunications and one of the most popular systems of mobile communication. They can be used for voice transmission, but are also very efficient for sending data streams from different applications [1] [2] [3]. Data transmission is a type of service that originally was not handled by cellular networks. Over time, data transmission has become more and more popular in expanding mobile networks. Data transmission services offered by operators include video conferencing services, streaming audio services, electronic mail and large file transmission [4] [5] [6] [7].

The increase in traffic intensity of traffic generated by data transmission services is accompanied by an increase in the requirements with respect to the size of resources offered by networks. This also causes a growing necessity of working out mechanisms that introduce differentiation in Quality of Service (QoS) for particular data classes. The introduction of QoS differentiation mechanisms was conducive in turn to a development of new analytical models for dimensioning of multi-service mobile networks. The initial models of multi-service cellular networks (cell groups models) assumed that a single traffic source of a given class could generate only one, strictly defined, type of the traffic stream (traffic sources class unequivocally determined the nature of a traffic stream). Both cell groups without QoS mechanisms introduced [8], and cell groups with QoS differentiation mechanisms, were considered, including resource reservation mechanisms [9] [10] [11].

With multi-service terminals becoming more and more universal in modern cellular networks, it has become necessary to develop new traffic models. In [12], a model of the multi-service network was presented for the first time, which assumed that a given and defined set of services was related to a single traffic source. The considered system was described as a multi-service system with multi-service sources. The considerations presented in [12] were limited, however, to a model of a single full-availability cell (single resource) without any Quality of Service differentiation mechanisms introduced.

This paper proposes a model of a limited-availability group of resources, in which — to facilitate resource usage — a reservation mechanism has been implemented. The model can be used, similarly as in [12], for modeling cell groups in multi-service networks. In the proposed model, it is taken into consideration that a single terminal can generate various traffic streams corresponding to particular services implemented in the terminal. Additionally, it is assumed that the services cannot be used simultaneously by the terminal. This means that when the terminal is involved in the generation of traffic stream related to one service, it cannot at the same time generate traffic streams related to other services.

The remaining part of the paper is organized as follows. In Section II, the analytical model of the limited-availability systems with multi-service sources and resource reservation mechanism is proposed. In Section III, the results of the blocking probability obtained for three limited-availability systems with multi-service sources and reservation mechanisms are compared with the simulation data. Section IV concludes the paper and presents further work.

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II. Analytical Model of Limited-Availability Group with Multi-service Sources and Reservation Mechanisms

Let us consider a model of the limited-availability group (LAG) with multi-service sources and the capacity V_L, presented in Figure 1. The limited-availability group consists of v identical separated resources (e.g., transmission links) with the capacity equal to f BBUs (basic bandwidth units, i.e., allocation units). The total capacity of the system V_L is equal to $V_L = vf$ BBUs.

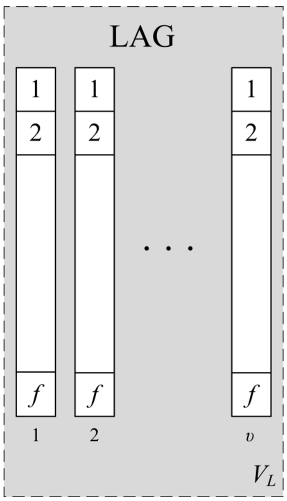

Figure 1. Model of the limited-availability group

In the considered model, m traffic classes that belong to the set $\mathbb{M} = \{1, 2, ..., m\}$ are defined. A given class c requires t_c BBUs to set up a new connection. The service time for class c calls has an exponential distribution with the parameter μ_c (service rate). In the group, the reservation mechanism has been applied. In accordance with the adopted reservation mechanism for a given class c, the reservation limit Q_c is introduced (Q_c is a certain occupancy state of the system, expressed in the number of BBUs being busy). The reservation mechanism can be applied to selected traffic classes from the set $\mathbb{M}$. The classes, in which the reservation limit has been introduced are grouped into a new set of classes $\mathbb{R}$, which is a sub-set of the set $\mathbb{M}$. The parameter R_c that determines the reservation area (a certain number of occupancy states of the system) has also been defined. This parameter can be expressed by the following formula:

$$R_c = V_F - Q_c. \tag{1}$$

The system admits a call of class c that belongs to the set $\mathbb{R}$ for service only when this call can be entirely carried by the resources of an arbitrary single link and when the number of free BBUs in the group is higher or equal to the value of the reservation area R_c. A call of class c that does not belong to the set $\mathbb{R}$ can be serviced when this call can be entirely carried by the resources of an arbitrary single link. This is, thus, an example of a system with a state-dependent service process, in which the state dependence is the result of the structure of the group and the introduced reservation mechanism. An example of the limited-availability group with reservation mechanism applied for only class 1 is presented in Figure 2.

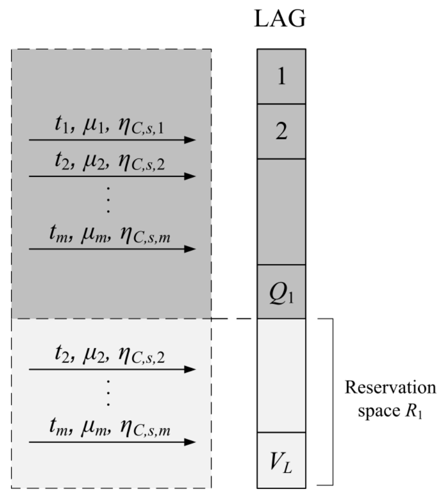

Figure 2. Model of the limited-availability group with reservation mechanisms

The group is offered three types of Erlang (Poisson call streams), Engset (binomial call streams) and Pascal (negative binomial call streams) traffic streams [13]. The selected types of traffic cover three different types of the dependence between the mean arrival rates of calls and the occupancy state of the system: (1) the mean arrival rate of new calls does not depend on the occupancy state of the system (Erlang traffic), (2) the mean arrival rate of new calls decreases with the increase in the occupancy state of the system (Engset traffic), (3) the mean arrival rate of new calls increases with the increase in the occupancy state of the system.

Each traffic stream is generated by sources that belong to the corresponding set of traffic sources $\mathbb{Z}_{C,s}$. In set $\mathbb{Z}_{C,s}$ index C denotes the type of traffic stream generated by sources, which belong to this set and takes the value I for Erlang traffic stream, J for Engset traffic stream and K for Pascal traffic stream, respectively, while index s denotes the number of the set, the sources of which generate a given type of traffic stream. In the system, the s_I sets of traffic sources that generate Erlang traffic streams are defined, as well as s_J sets of traffic sources that generate Engset traffic streams and s_K sets of traffic sources that generate Pascal traffic streams. The total number of the sets of traffic sources is $S = s_I + s_J + s_K$. The sources that belong to the set $\mathbb{Z}_{C,s}$ can generate calls from the set $\mathbb{C}_{C,s} = \{1, 2, ..., c_{C,s}\}$ of traffic classes according to the available set of services.

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The participation of class c (from the set $\mathbb{M}$) in the traffic structure of traffic generated by sources from the set $\mathbb{Z}_{C,s}$ is determined by the parameter $\eta_{C,s,c}$, which, for particular sets of Erlang, Engset and Pascal traffic sources, satisfies the following dependencies:

$$\sum_{c=1}^{c_{I,i}} \eta_{I,i,c} = 1, \qquad \sum_{c=1}^{c_{J,j}} \eta_{J,j,c} = 1, \qquad \sum_{c=1}^{c_{K,k}} \eta_{K,k,c} = 1. \tag{2}$$

To determine the value of traffic $A_{I,i,c}$ offered by Erlang sources that belong to the set $\mathbb{Z}_{I,i}$ as well as the traffic value $A_{J,j,c}(n)$ offered by Engset sources from the set $\mathbb{Z}_{J,j}$ and traffic $A_{K,k,c}(n)$ offered by Pascal sources from the set $\mathbb{Z}_{K,k}$ that generate calls of class c in the state of n busy BBUs, we use the following formulas [12]:

$$A_{I,i,c} = \eta_{I,i,c}\lambda_{I,i}/\mu_c. \tag{3}$$

$$A_{J,j,c}(n) = \eta_{J,j,c}N_{J,j}\alpha_{J,j}\sigma_{J,j,c,T}(n), \tag{4}$$

$$A_{K,k,c}(n) = \eta_{K,k,c}S_{K,k}\beta_{K,k}\sigma_{K,k,c,T}(n), \tag{5}$$

$$\sigma_{J,j,c,T}(n) = [\eta_{J,j,c}N_{J,j} - y_{J,j,c}(n)]/\eta_{J,j,c}N_{J,j}, \tag{6}$$

$$\sigma_{K,k,c,T}(n) = [\eta_{K,k,c}S_{K,k} + y_{K,k,c}(n)]/\eta_{K,k,c}S_{K,k}, \tag{7}$$

where:

- $\lambda_{I,i}$ – the mean arrival rate of new calls generated by a single Poisson source that belongs to the set $\mathbb{Z}_{I,i}$
- $\eta_{J,j,c}$ – the parameter that determines the participation of calls of class c in traffic generated by sources that belong to the set $\mathbb{Z}_{J,j}$,
- $\eta_{K,k,c}$ – the parameter that determines the participation of calls of class c in traffic generated by sources that belong to the set $\mathbb{Z}_{K,k}$,
- $N_{J,j}$ – the number of Engset traffic sources that belong to the set $\mathbb{Z}_{J,j}$,
- $S_{K,k}$ – the number of Pascal traffic sources that belong to the set $\mathbb{Z}_{K,k}$,
- $y_{J,j,c}(n)$ – the average number of calls of class c generated by Engset sources that belong to the set $\mathbb{Z}_{J,j}$ currently serviced in the system in the occupancy state n,
- $y_{K,k,c}(n)$ – the average number of calls of class c generated by Pascal sources that belong to the set $\mathbb{Z}_{K,k}$ currently serviced in the system in the occupancy state n,
- $\alpha_{J,j}$ – the average traffic intensity of traffic generated by a single Engset source that belongs to the set $\mathbb{Z}_{J,j}$, determined by the following formula:

$$\alpha_{J,j} = \sum_{c=1}^{c_{J,j}} \eta_{J,j,c}\frac{\gamma_{J,j}}{\mu_c}, \tag{8}$$

  where $\gamma_{J,j}$ – the mean arrival rate of new calls generated by a single Engset source that belongs to the set $\mathbb{Z}_{J,j}$,
- $\beta_{K,k}$ – the average traffic intensity of traffic generated by a single Pascal source that belongs to the set $\mathbb{Z}_{K,k}$, defined by the following formula:

$$\beta_{K,k} = \sum_{c=1}^{c_{K,k}} \eta_{K,k,c}\frac{\gamma_{K,k}}{\mu_c}, \tag{9}$$

  where $\gamma_{K,k}$ – the mean arrival rate of new calls generated by a single Pascal source that belongs to the set $\mathbb{Z}_{K,k}$.

We can notice that – according to Formulas (6) and (7) – with the case of Engset sources, the mean arrival rate of new calls of individual traffic classes decreases with the increase in the occupancy state of the system, whereas in the case of Pascal sources the mean arrival rate of new calls of individual traffic classes increases with the increase in the occupancy state of the system.

Taking into consideration the influence of the specific structure of the limited-availability group on the process of a determination of the occupancy distribution using Kaufman-Roberts recursion, in [14] the use of conditional coefficients of passing $\sigma_{c,S}(n)$, was proposed. The value of the parameter $\sigma_{c,S}(n)$ does not depend on incoming call process and can be determined as follows [14]:

$$\sigma_{c,S}(n) = \frac{F(V_L - n, \upsilon, f, 0) - F(V_L - n, \upsilon, t_c - 1, 0)}{F(V_L - n, \upsilon, f, 0)}, \tag{10}$$

where $F(x, \upsilon, f, t)$ is the number of arrangement of x free BBUs in υ links, calculated with the assumption that capacity of each link is equal to f BBUs and each link has at least t free BBUs:

$$F(x, \upsilon, f, t) = \sum_{r=0}^{\left\lfloor \frac{x-\upsilon t}{f-t+1} \right\rfloor} (-1)^r \binom{\upsilon}{r} \binom{x - \upsilon(t-1) - 1 - r(f-t+1)}{\upsilon - 1}. \tag{11}$$

Observe that in the case of the considered model of the limited-availability group with multi-service traffic sources and reservation the operation of the reservation mechanism introduces an additional dependence between the service stream in the system and the current state of the system. To determine this dependence, the parameter $\sigma_{c,R}(n)$ is introduced. The parameter $\sigma_{c,R}(n)$ can be calculated using the following formula:

$$\sigma_{c,R}(n) = \begin{cases} 1 & \text{for } n \leqslant Q_c \wedge c \in \mathbb{R}, \\ 0 & \text{for } n > Q_c \wedge c \in \mathbb{R}, \\ 1 & \text{for } c \notin \mathbb{R}. \end{cases} \tag{12}$$

The reservation mechanism is introduced to the group regardless of its structure, which allows us to carry on with product-form determination of the total coefficient of passing (transition coefficient) $\sigma_{c,\text{Tot}}(n)$ in the limited-availability group:

$$\sigma_{c,\text{Tot}}(n) = \sigma_{c,S}(n) \cdot \sigma_{c,R}(n). \tag{13}$$

Having the values of offered traffic $A_{I,i,c}$, $A_{J,j,c}(n)$, $A_{K,k,c}(n)$ and the total coefficient of passing $\sigma_{c,\text{Tot}}(n)$ at our disposal, we are in position to modify the original Kaufman-Roberts formula [15] [16] in order to determine the occupancy distribution in the limited-availability group with multi-service traffic sources and the reservation mechanism:

$$\begin{aligned} n[P_n]_{V_L} &= \sum_{i=1}^{s_I}\sum_{c=1}^{c_{I,i}} A_{I,i,c}\sigma_{c,\text{Tot}}(n-t_c)t_c[P_{n-t_c}]_{V_L} + \\ &+ \sum_{j=1}^{s_J}\sum_{c=1}^{c_{J,j}} A_{J,j,c}(n-t_c)\sigma_{c,\text{Tot}}(n-t_c)t_c[P_{n-t_c}]_{V_L} + \\ &+ \sum_{k=1}^{s_K}\sum_{c=1}^{c_{K,k}} A_{K,k,c}(n-t_c)\sigma_{c,\text{Tot}}(n-t_c)t_c[P_{n-t_c}]_{V_L}, \end{aligned} \tag{14}$$

where $[P_n]_{V_L}$ is the occupancy distribution (the probability of n busy BBUs) in a system with the capacity V_L, and the parameter $\sigma_{c,\text{Tot}}(n)$ determines the additional dependence between the service stream and the current state of the system resulting from the specific structure of the group and the applied reservation mechanism.

Having the values of individual state probabilities $[P_n]_{V_L}$, determined on the basis of Formula (14), we are in position to determine the average number of serviced calls of class c, generated by sources that belong to the sets $\mathbb{Z}_{J,j}$ (Engset) and $\mathbb{Z}_{K,k}$ (Pascal sources). For this purpose, we use the following formulas:

$$y_{J,j,c}(n) = \begin{cases} A_{J,j,c}(n-t_c)\sigma_{c,\text{Tot}}(n-t_c)[P_{n-t_c}]_{V_L}/[P_n]_{V_L} & \text{for } n \leqslant V_L, \\ 0, & \text{for } n > V_L. \end{cases} \tag{15}$$

$$y_{K,k,c}(n) = \begin{cases} A_{K,k,c}(n-t_c)\sigma_{c,\text{Tot}}(n-t_c)[P_{n-t_c}]_{V_L}/[P_n]_{V_L} & \text{for } n \leqslant V_L, \\ 0, & \text{for } n > V_L. \end{cases} \tag{16}$$

The knowledge of the occupancy $[P_n]_{V_L}$ is required to determine the parameters $y_{J,j,c}(n)$ and $y_{K,k,c}(n)$. Whereas, to determine the occupancy $[P_n]_{V_L}$ it is necessary to know the values of the parameters $y_{J,j,c}(n)$ and $y_{K,k,c}(n)$. Equations (15), (16) and (14) form thus a set of confounding equations. To solve a given set of confounding equations it is necessary to employ iterative methods [17] [18].

Assuming that the distribution $[P_n^{(l)}]_{V_L}$ is the occupancy distribution, determined in the l-th iteration, while $y_{J,j,c}^{(l)}(n)$ and $y_{K,k,c}^{(l)}(n)$ define the average number of serviced calls of class c generated by traffic sources that belong respectively to the sets $\mathbb{Z}_{J,j}$ and $\mathbb{Z}_{K,k}$, we can write:

$$y_{J,j,c}^{(l+1)}(n) = \begin{cases} A_{J,j,c}^{(l)}(n-t_c)\sigma_{c,\text{Tot}}(n-t_c)[P_{n-t_c}^{(l)}]_{V_L}/[P_n^{(l)}]_{V_L} & \text{for } n \leqslant V_L, \\ 0, & \text{for } n > V_L. \end{cases} \tag{17}$$

$$y_{K,k,c}^{(l+1)}(n) = \begin{cases} A_{K,k,c}^{(l)}(n-t_c)\sigma_{c,\text{Tot}}(n-t_c)[P_{n-t_c}^{(l)}]_{V_L}/[P_n^{(l)}]_{V_L} & \text{for } n \leqslant V_L, \\ 0, & \text{for } n > V_L. \end{cases} \tag{18}$$

The iteration process, involving Formulas (14), (17) and (18), terminates when the assumed accuracy ϵ of the iteration process is reached:

$$\forall_{0 \le n \le V} \left| \frac{y_{J,j,c}^{l-1}(n) - y_{J,j,c}^{(l)}(n)}{y_{J,j,c}^{(l)}(n)} \right| \leqslant \epsilon, \tag{19}$$

$$\forall_{0 \le n \le V} \left| \frac{y_{K,k,c}^{l-1}(n) - y_{K,k,c}^{(l)}(n)}{y_{K,k,c}^{(l)}(n)} \right| \leqslant \epsilon. \tag{20}$$

Subsequently, we are in position to determine the blocking probability for calls of class c that belong to the set $\mathbb{M} = \{1, 2, ..., m\}$:

$$E_c = \sum_{n=0}^{V_L} [P_n]_{V_L} \left[1 - \sigma_{c,\text{Tot}}(n)\right]. \tag{21}$$

III. Numerical Results

The presented method for a determination of the blocking probability in systems with multi-service traffic sources and reservation mechanisms is an approximate method. In order to confirm adopted assumptions, the results of the analytical calculations were compared with the simulation data. The research was carried for three systems, which are described below:

1) Limited-availability system No. 1
   - Capacity: $v = 2$, $f = 20$ BBUs, $V_L = 40$ BBUs,
   - Number of traffic classes: 3
   - Structure of traffic: $t_1 = 1$ BBU, $\mu_1^{-1} = 1$, $t_2 = 2$ BBUs, $\mu_2^{-1} = 1$,$t_3 = 6$ BBUs, $\mu_3^{-1} = 1$, $R_1 = R_2 = 33$ BBUs
   - Sets of sources: $\mathbb{C}_{I,1} = \{1,2\}$, $\eta_{I,1,1} = 0.6$, $\eta_{I,1,2} = 0.4$, $\mathbb{C}_{J,2} = \{2,3\}$, $\eta_{J,2,2} = 0.7$, $\eta_{J,2,3} = 0.3$, $N_2 = 60$
2) Limited-availability system No. 2
   - Capacity: $v = 2$, $f = 30$ BBUs, $V_L = 60$ BBUs,
   - Number of traffic classes: 3
   - Structure of traffic: $t_1 = 1$ BBU, $\mu_1^{-1} = 1$, $t_2 = 3$ BBUs, $\mu_2^{-1} = 1$,$t_3 = 7$ BBUs, $\mu_3^{-1} = 1$, $R_1 = R_2 = 51$ BBUs
   - Sets of sources: $\mathbb{C}_{I,1} = \{1\}$, $\eta_{I,1,1} = 1.0$, $\mathbb{C}_{J,2} = \{1,2\}$, $\eta_{J,2,1} = 0.6$, $\eta_{J,2,2} = 0.4$, $N_2 = 50$,

$\mathbb{C}_{K,3} = \{2,3\}$, $\eta_{K,3,2} = 0.7$, $\eta_{K,3,3} = 0.3$, $S_3 = 50$

3) Limited-availability system No. 3
   - Capacity: $\upsilon = 4$, $f = 20$ BBUs, $V_L = 80$ BBUs,
   - Number of traffic classes: 4
   - Structure of traffic: $t_1 = 1$ BBU, $\mu_1^{-1} = 1$, $t_2 = 2$ BBUs, $\mu_2^{-1} = 1$,$t_3 = 4$ BBUs, $\mu_3^{-1} = 1$, $t_4 = 9$ BBUs, $\mu_4^{-1} = 1$, $R_1 = R_2 = R_3 = 63$ BBUs
   - Sets of sources: $\mathbb{C}_{I,1} = \{1,2\}$, $\eta_{I,1,1} = 0.6$, $\eta_{I,1,2} = 0.4$, $\mathbb{C}_{J,2} = \{2,3\}$, $\eta_{J,2,2} = 0.7$, $\eta_{J,2,3} = 0.3$, $N_2 = 70$, $\mathbb{C}_{K,3} = \{2,3,4\}$, $\eta_{K,3,2} = 0.3$, $\eta_{K,3,3} = 0.2$, $\eta_{K,3,4} = 0.5$, $S_3 = 140$

The results of the research study are presented in Figures 3-5, depending on the value of traffic a offered to a single BBU. The mean value of offered traffic a can be calculated using following equation:

$$a = \left[\sum_{i=1}^{s_I} \lambda_{I,i} \sum_{c=1}^{c_{I,i}} t_c\eta_c \sum_{c=1}^{c_{I,i}} \eta_c/\mu_c + \right. \\ + \sum_{j=1}^{s_J} \gamma_{J,j} N_{J,j} \sum_{c=1}^{c_{J,j}} t_c\eta_c \sum_{c=1}^{c_{J,j}} \eta_c/\mu_c + \\ \left. + \sum_{k=1}^{s_K} \gamma_{K,k} S_{K,k} \sum_{c=1}^{c_{K,k}} t_c\eta_c \sum_{c=1}^{c_{K,k}} \eta_c/\mu_c \right] /V_L. \quad (22)$$

The results of the simulation are shown in the charts in the form of marks with 95% confidence intervals that have been calculated according to the t-Student distribution for the five series with 1,000,000 calls of each class. For each of the points of the simulation, the value of the confidence interval is at least one order lower than the mean value of the results of the simulation. In many a case, the value of the simulation interval is lower than the height of the sign used to indicate the value of the simulation experiment.

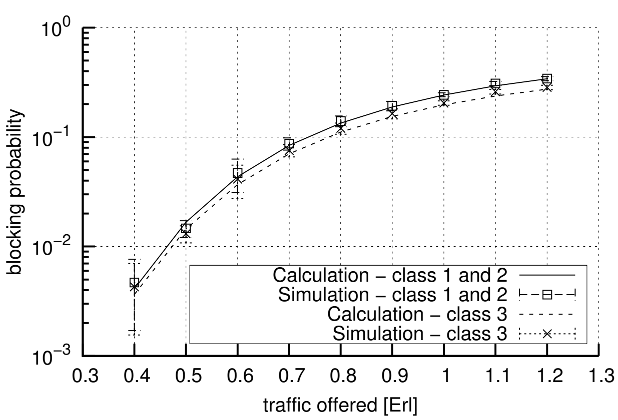

Figure 3. Blocking probability in the limited-availability group No. 1 with reservation mechanism; the reservation mechanism equalizes the blocking probability for calls of class 1 and 2

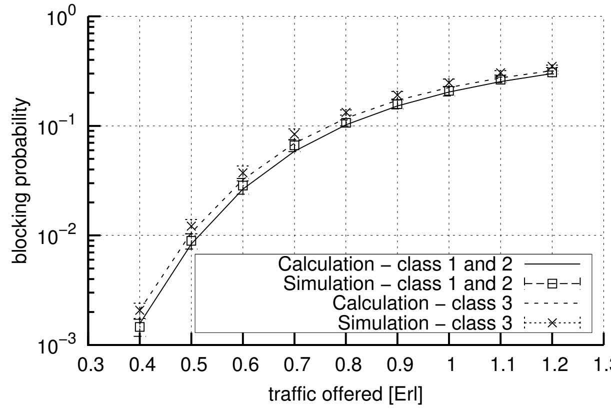

Figure 4. Blocking probability in the limited-availability system No. 2 with reservation mechanism; the reservation mechanism equalizes the blocking probability for calls of class 1 and 2

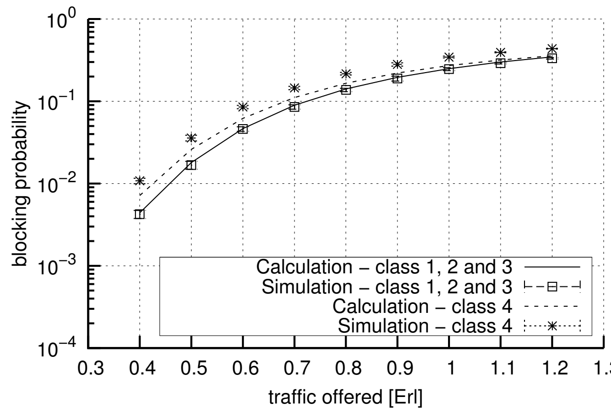

Figure 5. Blocking probability in the limited-availability system No. 3 with reservation mechanism; the reservation mechanism equalizes the blocking probability for calls of class 1, 2 and 3

IV. Conclusion and Further Work

This paper proposes a new method for a calculation of the occupancy distribution and the blocking probability in limited-availability systems with multi-service traffic sources and reservation mechanisms. The method can be used in modeling connection handoff between cells in cellular systems [8], as well as in modeling outgoing directions of switching networks [19]. The proposed method is based on the iterative algorithm for a determination of the average value of traffic sources being serviced in particular states of the system. The results of analytical calculations were compared with the simulation data, which confirmed high accuracy of the proposed method. The proposed method is not complicated and can be easily implemented.

In the further work we plan to develop analytical models of the multi-service systems with multi-service sources, in which different call admission control mechanisms will be applied, i.e., an analytical model of multi-service networks with threshold mechanisms and multi-service sources, and a model of multi-service systems with hysteresis and multi-service sources.

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