Analyzing of Licensed Shared Access Scheme Model with Service Bit Rate Degradation in 3GPP Network

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Abstract. The volume of mobile traffic is growing every year. More and more frequency resources are needed to provide users services with a required level of quality of service (QoS). One of the possible solutions to a problem of radio spectrum shortage is the sharing of spectrum between the owners and LSA licensees. Licensed shared access (LSA) framework gives the owner priority in spectrum access, to the detriment of the secondary user, LSA licensee. If the mobile operator users of both need continuous service without interruptions on the rented part of the spectrum, the rules of shared access should guarantee the possibility of simultaneous access. In this paper we simulate a queuing system and consider a scheme model of LSA framework with the limit power policy. We propose formulas for calculation of main characteristics of the model – a blocking probability and a mean bit rate. These characteristics are very important in teletraffic theory. For example, blocking probabilities help to determine the number of required channels.

Keywords: Queuing system · Licensed shared access · Limit power policy · Blocking probability · Mean bit rate

1 Introduction

Teletraffic theory is a mathematical theory, or one of branches of queueing theory. It is used for studying and designing telecommunication systems (telephony, computer networks, etc.). More generally, one can set the goal of teletraffic theory: construction of mathematical models that map real processes in information

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distribution systems and development of methods for assessing the quality of their functioning [11–13]. The number of user devices connected to a high-speed network as well as the volume of traffic transmitted between them is constantly increasing [1]. Consequently, an increasing amount of resources is needed to provide quality services. The problem of resource shortage could be solved by using the licensed shared access (LSA) framework [2–4]. LSA framework could improve the efficiency of resource usage and ensure the access to a spectrum which otherwise would be underused [5]. By using this framework, the spectrum is shared between the owner (so-called incumbent) and a limited number of LSA licensees (mobile operators). The LSA licensee has access to single-tenant band (the part of the spectrum, belonging only to the mobile operator) and rents the multi-tenant band (the part of the spectrum, belonging to the incumbent and the mobile operator), whereas the incumbent has access only to multi-tenant band. For interference coordination between the incumbent and the LSA licensee three policies [6] are proposed: limit power policy, shutdown policy, and ignore policy. According to the limit power policy [7], there is no interruption of service due to the incumbent accessing spectrum. It implies managing the user equipment power in uplink and eNodeB (eNB) power in downlink. According to shutdown policy [8,9], at any time, LSA spectrum could be used by incumbent or LSA licensees but not together at once. According to ignore policy LSA licensees use the shared spectrum without interference coordination.

In this paper we propose a scheme model of 3GPP wireless network within LSA framework [10]. For efficient interference coordination we consider the limit power policy, which allows us to continue the service of multi-tenant band users, even if the incumbent needs this part of the spectrum. In this case, the service of mobile operator users will not be interrupted, but the service bit rate will be reduced (degraded). At this time, the multi-tenant band goes into the so-called unavailable mode and user's requests arrived on the multi-tenant band continue their service at the degraded bit rate – minimum bit rate. After the incumbent releases the multi-tenant band, the band goes from the unavailable to the operational mode and the service bit rate for the connected mobile network users increases to the maximum value - maximum bit rate. The service on the single-tenant band is always carried out at the maximum bit rate.

This model is an improved version of the model described in [7]. One of the main disadvantages of the previous model was that after the disconnection the band was not recovered which means that even after the band was vacated by the owner, the service continued with degraded quality until all users of multi-tenant band were served. In our model this drawback is eliminated, the band goes into operational mode as soon as the owner frees it, while the quality of user service is increased to the original level.

This paper is organized as follows. In Sect. 2, we propose a mathematical model of the LSA framework with the limit power policy. In Sect. 3, we analyze main characteristics of the model: the blocking probability and the mean bit rate. Finally, we conclude the paper in Sect. 4.

2 Mathematical Model

2.1 General Assumptions and Parameters

We propose a scheme model of a single mobile network cell with LSA framework and limit power policy. We suppose that the mobile operator has access to the single-tenant band with the total capacity of C_1 bandwidth units (b.u.) and rents the multi-tenant band with the total capacity of C_2 b.u. Let the arrival rate λ be Poisson distributed and let the service time be exponentially distributed with mean μ^{-1}. Then, we denote the corresponding offered load as $\rho = \lambda/\mu$.

Each request processed on the single-tenant band is served at the maximum bit rate $d_{\max}$. Request on the multi-tenant band could be served at the maximum bit rate $d_{\max}$ or at the minimum bit rate $d_{\min}$ depending on the state of the multi-tenant band – operational or unavailable. Figure 1 shows the scheme of the model.

We assume that the multi-tenant band goes into unavailable mode with rate α and recovers into operational mode with rate β. Recovery and failure intervals follow the exponential distribution. All necessary notations are given in Table 1.

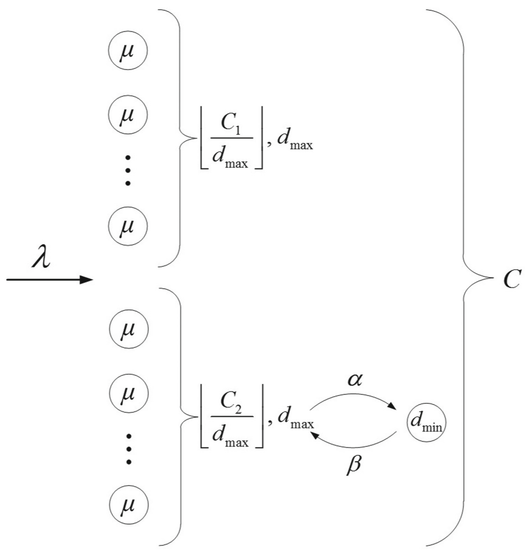

Fig. 1. The scheme of the model.

2.2 Limit Power Policy

Let us consider in more detail the limit power policy. First of all, we determine the rules for accepting requests for service.

When a new request arrives, four scenarios are possible:

Table 1. System parameters

Notation	Parameter description
C_1	Total capacity of the single-tenant band
C_2	Total capacity of the multi-tenant band
λ	Arrival rate
μ^{-1}	Mean service time
$d_{\max}$	Maximum bit rate
$d_{\min}$	Minimum bit rate
α	Rate of a transition the multi-tenant band into unavailable mode
β	Rate of a transition the multi-tenant band into operational mode
n_1	The number of single-tenant band users
n_2	The number of multi-tenant band users
s	The state of the multi-tenant band, s equals to 1 if the band is operational and s equals to 0 if the band is unavailable

- The request will be accepted for service on the single-tenant band, if the single-tenant band has not less than $d_{\max}$ free b.u.
- The request will be accepted for service on the multi-tenant band, if the single-tenant band has less than $d_{\max}$ b.u. free, the multi-tenant band is operational and has not less than $d_{\max}$ b.u. free.
- The request will be blocked, if the single-tenant band has less than $d_{\max}$ b.u. free and the multi-tenant band is unavailable or has less than $d_{\max}$ b.u. free.

Let us note if the owner does not use the frequency spectrum of the multi-tenant band, the data transfer can be carried out at the highest possible rate, which equals to $d_{\max}$, in other case the service bit rate for the mobile operator users is degraded from the maximum $d_{\max}$ to the minimum $d_{\min}$ value. When the multi-tenant band recovers, the bit rates are switched back and all users that have been degraded continue to receive service at bit rate $d_{\max}$.

2.3 System of Equilibrium Equations

The behavior of the system is defined by the Markov process $\mathbf{X}(t) = \{(N_1(t), N_2(t), S(t)), t \geq 0\}$, where $N_1(t)$ is the number of single-tenant band users, $N_2(t)$ is the number of multi-tenant band users, $S(t)$ is the state of the multi-tenant band at the moment $t \geq 0$. Let us denote $N_1 = \left\lfloor \frac{C_1}{d_{\max}} \right\rfloor$ the maximum number of single-tenant band users, $N_2 = \left\lfloor \frac{C_2}{d_{\max}} \right\rfloor$ the maximum number of multi-tenant band users. Then the system state space is the following:

$$\begin{aligned} \mathbf{X} &= \{n_1 = 0, \dots, N_1,\ n_2 = 0, \dots, N_2,\ s = 1 \\ &\vee n_1 = 0, \dots, N_1,\ n_2 = 0, \dots, N_2,\ s = 0\}. \end{aligned} \tag{1}$$

State space (1) could be divided into two subspaces: $\{n_1 = 0, \ldots, N_1, \quad n_2 = 0, \ldots, N_2, \quad s = 1\}$ if the multi-tenant band is operational and requests could be served at the maximum bit rate $d_{\max}$, and $\{n_1 = 0, \ldots, N_1, \quad n_2 = 0, \ldots, N_2, s = 0\}$ if the multi-tenant band is unavailable and requests continue their service at the minimum bit rate $d_{\min}$. Figure 2 shows the structure of the state space, considering the two subspaces.

The corresponding Markov process $\mathbf{X}(t)$, which representing the system's states, is described by the following system of equilibrium equations

$$\begin{aligned} & p(n_1, n_2, s)\left[\lambda \cdot \mathrm{I}(n_1 < N_1) + \lambda \cdot \mathrm{I}(n_1 = N_1,\ n_2 < N_2,\ s = 1)\right. \\ & \left. +\ (n_1 + n_2)\mu + \alpha \cdot \mathrm{I}(s = 1) + \beta \cdot \mathrm{I}(s = 0)\right] \\ & = p(n_1 + 1, n_2, s)\left[(n_1 + 1)\mu \cdot \mathrm{I}(n_1 < N_1)\right] \\ & + p(n_1, n_2 + 1, s)\left[(n_2 + 1)\mu \cdot \mathrm{I}(n_2 < N_2)\right] \\ & + p(n_1 - 1, n_2, s)\left[\lambda \cdot \mathrm{I}(n_1 > 0)\right] \\ & + p(n_1, n_2 - 1, 1)\left[\lambda \cdot \mathrm{I}(n_1 = N_1,\ n_2 > 0,\ s = 1)\right] \\ & + p(n_1, n_2, 1)\left[\alpha \cdot \mathrm{I}(s = 0)\right] + p(n_1, n_2, 0)\left[\beta \cdot \mathrm{I}(s = 1)\right], \quad (n_1, n_2, s) \in X, \end{aligned} \tag{2}$$

where $(p(n_1, n_2, s))_{(n_1, n_2, s) \in X} = \mathbf{p}$ is the stationary probability distribution.

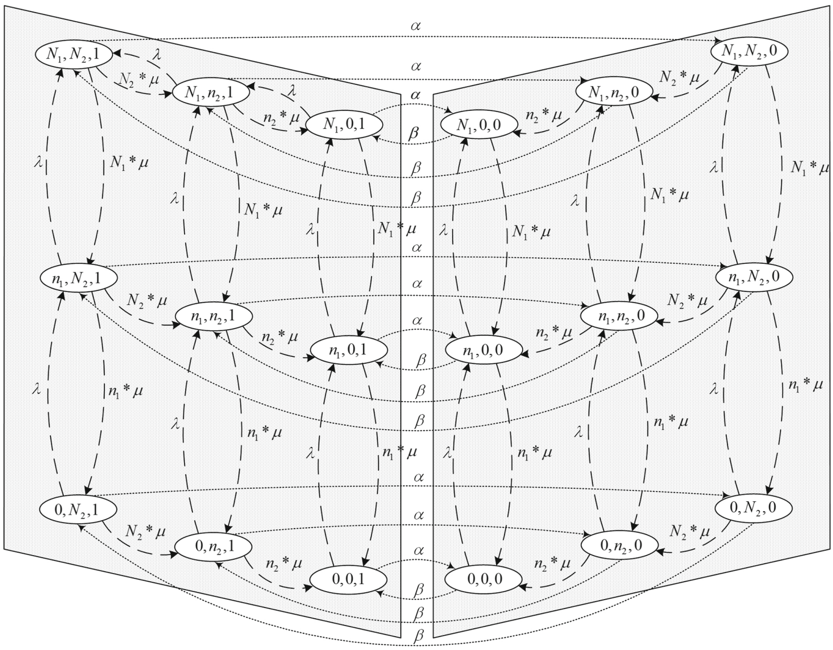

Fig. 2. The state space.

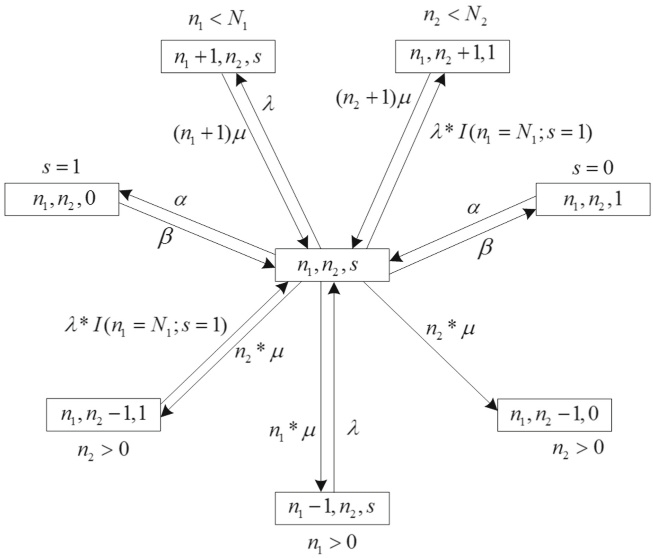

Fig. 3. Central state.

2.4 Infinitesimal Generator

The system probability distribution is calculated as the numerical solution of the system of equilibrium equations $\mathbf{p}\cdot\mathbf{A} = \mathbf{0}$, $\mathbf{p}\cdot\mathbf{1}^T = 1$, where $\mathbf{A}$ is the infinitesimal generator of Markov process $\mathbf{X}(t)$. Let us denote $n = \overline{0,\ N_1 + N_2}$ – the number of users.

The infinitesimal generator $\mathbf{A}$ has a block tridiagonal form

$$\mathbf{A} = \begin{bmatrix} \mathbf{N}_0 & \mathbf{\Lambda}_0 & \cdots & 0 & 0 \\ \mathbf{M}_1 & \mathbf{N}_1 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & \mathbf{N}_{N_1+N_2-1} & \mathbf{\Lambda}_{N_1+N_2-1} \\ 0 & 0 & \cdots & \mathbf{M}_{N_1+N_2} & \mathbf{N}_{N_1+N_2} \end{bmatrix}.$$

Blocks $\mathbf{\Lambda}_n$, $n = \overline{0,\ N_1\ N_2 - 1}$ have the sizes

$$\dim \mathbf{\Lambda}_n = \begin{cases} (2n+2)\times(2n+4), & n = \overline{0,\ N_2 - 1}, \\ (2N_2+2)\ \times(2N_2+2), & n = \overline{N_2,\ N_1 - 1}, \text{ if } N_1 > N_2, \\ (2\,(N_1 + N_2 - n) + 2) & \\ \times\ (2\,(N_1 + N_2 - n)), & n = \overline{N_1,\ N_1 + N_2 - 1}. \end{cases}$$

and the following form:

(1) $n = \overline{0,\, N_2 - 1}$

$$\mathbf{\Lambda}_n = \begin{bmatrix} \lambda & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & \lambda & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & \lambda & 0 & 0 & 0 \\ 0 & 0 & \cdots & 0 & \lambda & 0 & 0 \end{bmatrix},$$

(2) $n = \overline{N_2,\, N_1 - 1}$, if $N_1 > N_2$

$$\mathbf{\Lambda}_n = \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & \lambda & \cdots & 0 & 0 & 0 & 0 \\ \lambda & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & \lambda & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & \lambda & 0 & 0 & 0 \\ 0 & 0 & \cdots & 0 & \lambda & 0 & 0 \end{bmatrix},$$

(3) $n = \overline{N_1,\, N_1 + N_2 - 1}$

$$\mathbf{\Lambda}_n = \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 \\ 0 & \lambda & \cdots & 0 & 0 \\ \lambda & 0 & \cdots & 0 & 0 \\ 0 & \lambda & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & \lambda & 0 \\ 0 & 0 & \cdots & 0 & \lambda \end{bmatrix}.$$

Blocks $\mathbf{M}_n$, $n = \overline{1,\, N_1 + N_2}$ have the sizes

$$\dim \mathbf{M}_n = \begin{cases} (2n+2) \times 2n, & n = \overline{1,\, N_2}, \\ (2N_2+2) \times (2N_2+2)\,, & n = \overline{N_2 + 1,\, N_1}, \text{ if } N_1 > N_2, \\ (2\,(N_1 + N_2 - n) + 2) & \\ \times\ (2\,(N_1 + N_2 - n) + 4)\,, & n = \overline{N_1 + 1,\, N_1 + N_2}. \end{cases}$$

and the following form:

(1) $n = \overline{1, N_2}$

$$\mathbf{M}_n = \begin{bmatrix} n\mu & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & n\mu & 0 & 0 & \cdots & 0 & 0 \\ \mu & 0 & (n-1)\mu & 0 & \cdots & 0 & 0 \\ 0 & \mu & 0 & (n-1)\mu & \cdots & 0 & 0 \\ 0 & 0 & 2\mu & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & 2\mu & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & \mu & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & \mu \\ 0 & 0 & 0 & 0 & \cdots & n\mu & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & n\mu \end{bmatrix},$$

(2) $n = \overline{N_2 + 1, N_1}$, if $N_1 > N_2$

$$\mathbf{M}_n = \begin{bmatrix} \mu & 0 & N_1\mu & 0 & \cdots & 0 & 0 \\ 0 & \mu & 0 & N_1\mu & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & \mu & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & \mu \\ 0 & 0 & 0 & 0 & \cdots & n\mu & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & n\mu \end{bmatrix},$$

(3) $n = \overline{N_1 + 1, N_1 + N_2}$

$$\mathbf{M}_n = \begin{bmatrix} (n-N_1)\mu & 0 & N_1\mu & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & (n-N_1)\mu & 0 & N_1\mu & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & N_2\mu & 0 & (n-N_2)\mu & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & N_2\mu & 0 & (n-N_2)\mu \end{bmatrix}.$$

Blocks $\mathbf{N}_n$, $n = \overline{0, N_1 + N_2}$ have the sizes

$$\dim \mathbf{N}_n = \begin{cases} (2n+2) \times (2n+2), & n = \overline{0, N_2 - 1}, \\ (2N_2+2) \times (2N_2+2), & n = \overline{N_2, N_1 + N_2 - 2}, \\ (2(N_1+N_2-n)+2) & \\ \times\ (2(N_1+N_2-n)+2), & n = \overline{N_1+N_2-1, N_1+N_2}. \end{cases}$$

and the following form:

(1) $n = \overline{0, N_1 - 1}$

$$\mathbf{N}_n = \begin{bmatrix} -(\lambda+n\mu+\beta) & \beta & \cdots & 0 & 0 \\ \alpha & -(\lambda+n\mu+\alpha) & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & -(\lambda+n\mu+\beta) & \beta \\ 0 & 0 & \cdots & \alpha & -(\lambda+n\mu+\alpha) \end{bmatrix},$$

(2) $n = \overline{N_1, N_1 + N_2 - 1}$

$$\mathbf{N}_n = \begin{bmatrix} -(n\mu+\beta) & \beta & \cdots & 0 & 0 \\ \alpha & -(\lambda+n\mu+\alpha) & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & -(\lambda+n\mu+\beta) & \beta \\ 0 & 0 & \cdots & \alpha & -(\lambda+n\mu+\alpha) \end{bmatrix},$$

(3) $n = N_1 + N_2$

$$\mathbf{N}_n = \begin{bmatrix} -(n\mu+\beta) & \beta \\ \alpha & -(n\mu+\alpha) \end{bmatrix}.$$

3 Numerical Analysis

3.1 Performance Measures

Having found the probability distribution $p(n_1, n_2, s)$, $(n_1, n_2, s) \in X$, one may compute performance measures of the considered scheme:

- Blocking probability

$$B = \sum_{i=0}^{N_2} p(N_1, i, 0) + p(N_1, N_2, 1); \tag{3}$$

- Mean bit rate

$$\overline{d} = \frac{\sum_{(n_1, n_2, s) \in X/(0,0,0),(0,0,1)} \frac{n_1 d_{\max} + n_2 d_{\max} \cdot \mathrm{I}(s=1) + n_2 d_{\min} \cdot \mathrm{I}(s=0)}{n_1 + n_2} \cdot p(n_1, n_2, s)}{\sum_{(n_1, n_2, s) \in X/(0,0,0),(0,0,1)} p(n_1, n_2, s)}; \tag{4}$$

- Mean bit rate on the multi-tenant band

$$\overline{d}(C_2) = \frac{\sum_{(n_1, n_2, s) \in X: n_2 \neq 0} (d_{\max} \cdot p(n_1, n_2, 1), + d_{\min} \cdot p(n_1, n_2, 0))}{\sum_{(n_1, n_2, s) \in X: n_2 \neq 0} p(n_1, n_2, s)}. \tag{5}$$

3.2 Numerical Example

Let us assume that users view short video in high quality at a bit rate $d_{\max}$= 1 Mbps. If a part of the frequency band has to be returned, the bit rate decreases to $d_{\min}$= 0.5 Mbps. So the users continue watching video but in a lower quality. The multi-tenant band goes into unavailable mode every hour (3600 s) or every four

Table 2. System parameters

Parameter description	Notation	Value
Total capacity of the single-tenant band	C_1	10 Mbps
Total capacity of the multi-tenant band	C_2	10 Mbps
Mean service time of one user	μ^{-1}	30 s
Mean time when multi-tenant band is available	α^{-1}	3540 s, 14340 s
Mean time when multi-tenant band is unavailable	β^{-1}	60 s
Maximum bit rate	$d_{\max}$	1 Mbps
Minimum bit rate	$d_{\min}$	0.5 Mbps
Offered load	ρ	$0 \div 30$

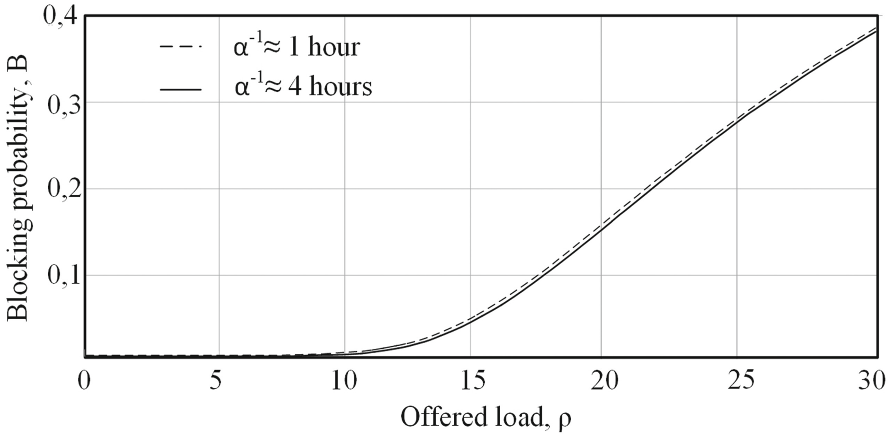

Fig. 4. Blocking probability B for different α^{-1}.

hours (14400 s) and the recovery takes around one minute. Table 2 summarizes the initial data of the example.

The figures below show the behavior of each characteristic – blocking probability B (Fig. 4), mean bit rates $\overline{d}$ and $\overline{d}\,(C_2)$ (Fig. 5) – for different values of α^{-1} (the mean time when the multi-tenant band is available). All figures show that the less multi-tenant band goes into unavailable mode, the better the performance metrics, namely, the blocking probability is lower, whereas the mean bit rate is higher.

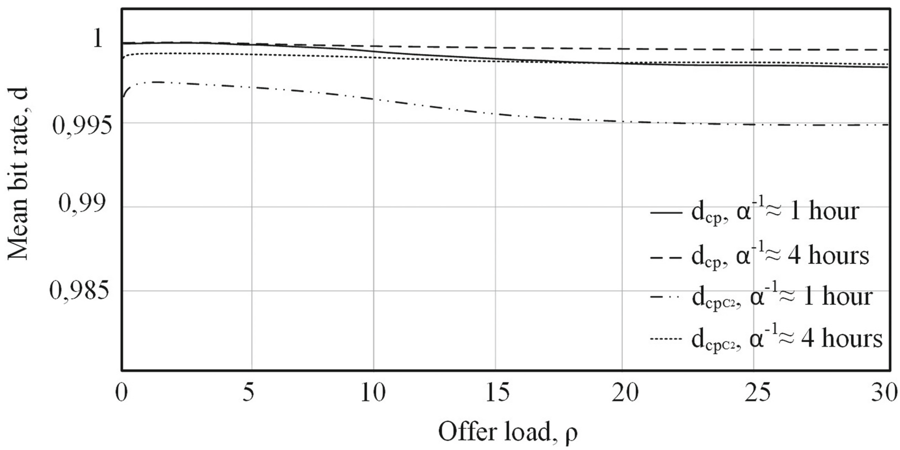

Fig. 5. Mean bit rates $\overline{d}$ and $\overline{d}\,(C_2)$ for different α^{-1}.

4 Conclusion

We have presented the scheme model for analyzing the simultaneous access to spectrum in 3GPP cellular network within LSA framework for intolerant to delay traffic under the limit power policy. This policy is based on the implementation of a mechanism the service bit rate degradation for the mobile operator users on multi-tenant band, if it is necessary to release the resources of this band for the owner. We have obtained the infinitesimal generator as a block tridiagonal matrix, what is required for the numerical solution of the equilibrium equations system and the calculation of the performance metrics for the considered queuing system that characterize the impact of LSA on the QoS – the blocking probability and the mean bit rate.

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