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Queuing System with Unreliable Servers and Inhomogeneous Intensities for Analyzing the Impact of Non-Stationarity toPerformance Measures of Wireless Network under Licensed Shared Access

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Received: 9 April 2020; Accepted: 12 May 2020; Published: 14 May 2020



Abstract: Given the limited frequency band resources and increasing volume of data traffic in modern multiservice networks, finding new and more efficient radio resource management (RRM) mechanisms is becoming indispensable. One of the implemented technologies to solve this problem is the licensed shared access (LSA) technology. LSA allows the spectrum that has been licensed to an owner, who has absolute priority on its utilization, to be used by other participants (i.e., tenants). Owner priority impacts negatively on the quality of service (QoS) by reducing the data bit rate and interrupting user services. In this paper, we propose a wireless multiservice network scheme model described as a queuing system with unreliable servers and a finite buffer within the LSA framework. The aim of this work is to analyze main system performance measures: blocking probability, average number of requests in queue, and average queue length depending on LSA frequencies' availability.

Keywords: LSA; queuing system; service interruption; radio resources; performance measures

1. Introduction

According to Cisco's latest data, the volume of mobile wireless traffic is expected to increase by almost sixty percent in the next five years, leading to a ten-fold growth of generated traffic in multiservice wireless networks [1]. In connection with that, fourth-generation (4G) wireless networks are facing a problem with the lack of radio resources necessary in the operation of multiservice network technologies such as machine-to-machine (M2M) and device-to-device (D2D) communications [2], the numbers of which are hugely increasing as the smart city vision is taking shape [3]. We remark that all communications are becoming more and more machine-oriented than humans [4].

In this context, the transition to the next fifth-generation (5G) wireless networks, the capacities of which will be higher in comparison with the current 4G wireless networks, seems to be the best solution to this problem. For increasing networks' capacities, researchers are investigating possible ways to extend the radio frequency range with the utilization of high radio frequency spectrum bands (i.e., over 10 GHz) [5] and traditional ones (i.e., under 6 GHz) in more efficient ways. Note that, since radio frequency spectrum bands are all allocated today, there is an urgent need to search for new RRM mechanisms.



For this purpose, different shared access technologies to the radio frequency spectrum bands are being developed [6–9]. We will consider only one of them, namely licensed shared access (LSA) technology, which was developed by ETSI. LSA allows controlled access to spectrum shared between an owner and multiple LSA licensees (i.e., mobile operators) [10]. The owner or incumbent of the LSA band (i.e., multi-tenant band) has absolute priority over its utilization. LSA licensees can access spectrum only when the incumbent's quality of service (QoS) level is not violated. The rules governing the usage of the LSA spectrum are spelled out in a reciprocal agreement that takes into account the necessary QoS requirements. The implementation of these rules is possible through various scenarios that have a different impact on the QoS level of users served on the sharing band.

1.1. Related Works

According to the research conducted, restriction of interference, which is created by users of the LSA licensees in the sharing zone, is usually carried out through two main scenarios (so-called policies of interference coordination). The first is the base station (BS) power limiting (limit power policy) [11–15], and the second is the users' service interruption (shutdown policy) [16–18]. Note that the LSA licensees could have their frequency range, the so-called single-tenant band.

At the moment, the introduction of the LSA framework in wireless multiservice networks is at the development stage. Therefore, this subject is expected to attract the attention of a large number of researchers.

A review of the literature showed that the number of papers devoted to the LSA system simulation is quite large [7,19–24]. For example, in [19], theoretical considerations about various scenarios of network resource management were proposed, but analytical models were not provided. The works in [23,24] offered a mechanism for distributing the LSA frequency spectrum between several LSA band tenants by using a joint auction. This scheme allowed providing unhindered access to the shared spectrum to various LSA licensees that were not related to each other. The BS of the LSA licensees was coordinated by the management organization. However, an analytical model was also not proposed.

The analytical side of this question has been poorly studied [25–28]. In [25], to obtain a model solution, cognitive radio technology was used. This technology allowed providing dynamic access to the spectrum. The evaluation of the model was carried out by analytical and simulation methods. It should be noted that the performance measures of the analytical models were investigated for stationary mode. Non-stationary mode was considered for the simulation models [29]. However, the models considered in non-stationary mode did not take into account the dependence on the periods of LSA band functioning and non-functioning on time. The methods of non-stationary mode could analyze the dependability on time and its impact on performance metrics. The first papers that examined and studied non-stationary queuing models appeared in the 1970s [30]. In recent years, such models have also been actively studied [31,32]. The research methods that we used in this work were developed in our previous studies [33,34]. This method consists of a complete study of the process X(t) associated with the system and involves: (a) the construction of upper bounds for the rate of convergence to the limit regime, i.e., finding a particular moment, say t^* , starting with which, the probability characteristics of the process X(t) are independent of the initial conditions (with an absolute error); (b) similar lower ratings, which are also very important and guarantee that the moment t^* cannot be taken too small; (c) in the case of an ample state space, the construction of approximations by truncation by similar processes with fewer states and the structure of corresponding error estimates. Finally, applying the results to the system in the case of one-periodic intensities and solving the forward Kolmogorov system with the simplest initial condition corresponding to X(0) = 0 for the truncated process on the interval $[t^*, t^* + 1]$, as a result, we obtain all the main probabilistic characteristics of the process X(t). We also note that only the construction of limiting characteristics, as well as only the determination of the probabilities of the process X(t) are uninformative since they do not provide exhaustive information about when the initial conditions can be ignored and what happens.

1.2. Our Contribution

Let us turn to the task of our paper. The combination of the LSA licensee's frequency ranges (single and multi-tenant bands) using the policies of interference coordination described above makes possible the implementation of various RRM schemes, the analysis of which allows choosing the most effective ones. In this paper, we propose a mathematical model for a radio resources access scheme in a wireless multiservice network within the LSA framework. We consider only the shared frequency spectrum (LSA or multi-tenant band). The RRM mechanism is implemented in such a way that if the incumbent needs his/her frequencies, the band becomes unavailable to the LSA license usage, while the service of tenant users is not interrupted, but goes into standby mode until the LSA band again becomes available. The missed interruptions and the usage of the buffer to serve tenant users, who are in the standby mode of LSA band recovery, are the main features and differences between the considered model and all those previously studied. The model is presented as a queuing system with unreliable servers [35] and a finite buffer and is described by the birth and death process with catastrophes [36]. In contrast to [35], adding a buffer and saving due to this current number of tenant users greatly complicate the task of studying the model. All system parameters are considered as a function of time. In accordance with the above, the main contribution in this paper is an analysis of the mobile network's model within the LSA framework, which is described as a queueing system with unreliable servers and a finite buffer operating in non-stationary mode. To research the model, the queueing theory approach was implemented [37,38].

The paper is organized as follows. In Section 2, the corresponding mathematical model is constructed and the policies for efficient interference coordination are described in terms of queuing theory. Section 3 analyzes the main performance characteristics of the system—blocking probability, the average number of requests in the queue depending on the availability of the LSA band, and the bounds on the rates of convergence to the limiting characteristics of the queue. An analysis of the system transition time to stationary mode is also given. Section 4 concludes the paper by numerical examples aimed at modeling one of the LSA framework application scenarios.

2. Mathematical Model

Let us consider a single cell of the mobile network with an overlaid LSA framework. As a tenant of the shared frequency spectrum, we consider a mobile operator. Let the multi-tenant band have *C* physical resource blocks (RB) and a buffer with size *r* (i.e., r > C). We assume that requests arrive according to the Poissonprocess with rate $\lambda(t)$. For the model tractability and in order not to use approximations, we assume that service time is exponentially distributed with mean $\mu^{-1}(t)$ [39].

The radio access control (RAC) is defined in such a way that, when the user's request arrives in the system, the following outcomes are possible:

- the request always waits first in a buffer when the current number of requests in the buffer is less than r;
- the request's service then starts when the current number of occupied resource blocks is less than *C*;
- the request is blocked otherwise.

The incumbent, who has absolute priority over multi-tenant band utilization, uses its shared frequencies with rate $\beta(t)$ and abandons them with rate $\alpha(t)$. In relation to that, the multi-tenant band can be available or not for mobile operators. Note that, when the multi-tenant band goes into unavailable mode, servicing requests are not interrupted and return to the buffer, where they wait for the band to be operational. WE remark that all above-described rates are time-dependent.

Hereby, we simulate the model of the wireless network cell with the LSA framework as a queuing system with *C* unreliable servers and a buffer with size *r*. Unreliable servers are characterized by ON- and OFF-period durations, which are exponentially distributed with rates $\alpha(t)$ and $\beta(t)$, respectively. All *C* servers can go into unavailable mode (fail) only simultaneously, and conversely,

the servers go into operational mode also simultaneously. Requests arrive according to a Poisson process with rate $\lambda(t)$, and if there are free servers, each of them occupies one server for the exponentially distributed time with parameter $\mu(t)$, while keeping its place in the queue. If all the buffer is busy upon the arrival of a request, it is blocked. Upon servers' failure, requests in service are not lost; they return to their places in the queue.

According to the above considerations, we can describe the operation of our queuing model by a Markov process X(t) on the state space (Figure 1):

$$\mathbf{X} = \{0, 1, \dots, n, \dots, 2r+1\},$$
(1)

where n = 0, 2, ..., 2k, ..., 2r are the states in which devices are OFF, n = 1, 3, ..., 2k + 1, ..., 2r + 1 are the states in which devices are ON, and k = 0, 1, ..., r is the number of requests in the system.



Figure 1. State transition diagram of the queuing model with catastrophes and repairs (red—devices are OFF, green—devices are ON).

Therefore, the elements a(n, n') of the transposed infinitesimal generator $\mathbf{A}(t)$ are defined as follows:

$$\begin{array}{ll} \alpha(t), & n' = n - 1, n = 2k + 1, k = 0, \dots, r; \\ \beta(t), & n' = n + 1, n = 2k; \\ \lambda(t), & n' = n + 2, n < 2r; \\ \frac{n - 1}{2}\mu(t), & n' = n - 2, n = 2k + 1, k = 1, \dots, C; \\ C\mu(t), & n' = n - 2, n = 2k + 1, k = C + 1, \dots, r; \\ *, & n' = n; \\ 0, & \text{otherwise;} \end{array}$$
 (2)

where $* = -(\frac{n-1}{2}\mu(t) \cdot I(n = 2k + 1, k = 1, ..., C) + C\mu(t) \cdot I(n = 2k + 1, k = C + 1, ..., r) + \alpha(t) \cdot I(n = 2k + 1) + \beta(t) \cdot I(n = 2k) + \lambda(t) \cdot I(n < 2r)).$

The corresponding matrix $\mathbf{A}(t)$ has a block tridiagonal form:

/

$$\mathbf{A}(t) = \begin{bmatrix} \mathbf{N}_{0}(t) & \mathbf{\Lambda}_{0}(t) & \cdots & \mathbf{0} & \mathbf{0} \\ \mathbf{M}_{1}(t) & \mathbf{N}_{1}(t) & \cdots & \mathbf{0} & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{N}_{r-1}(t) & \mathbf{\Lambda}_{r-1}(t) \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{M}_{r}(t) & \mathbf{N}_{r}(t) \end{bmatrix},$$
(3)

where:

$$\mathbf{\Lambda}_n(t) = \begin{bmatrix} \lambda(t) & 0\\ 0 & \lambda(t) \end{bmatrix}, \quad n = \overline{0, r-1}, \tag{4}$$

$$\mathbf{M}_{n}(t) = \begin{bmatrix} 0 & 0\\ 0 & n\mu(t) \end{bmatrix}, \quad n = \overline{1, C},$$
(5)

$$\mathbf{M}_{n}(t) = \begin{bmatrix} 0 & 0\\ 0 & C\mu(t) \end{bmatrix}, \quad n = \overline{C+1, r}, \tag{6}$$

$$\mathbf{N}_{n}(t) = \begin{bmatrix} -(\beta(t) + \lambda(t)) & \beta(t) \\ \alpha(t) & -(n\mu(t) + \alpha(t) + \lambda(t)) \end{bmatrix}, \quad n = \overline{0, C},$$
(7)

$$\mathbf{N}_{n}(t) = \begin{bmatrix} -(\beta(t) + \lambda(t)) & \beta(t) \\ \alpha(t) & -(C\mu(t) + \alpha(t) + \lambda(t)) \end{bmatrix}, \quad n = \overline{C + 1, r - 1}, \quad (8)$$

$$\mathbf{N}_n(t) = \begin{bmatrix} -\beta(t) & \beta(t) \\ \alpha(t) & -(C\mu(t) + \alpha(t)) \end{bmatrix}, \quad n = r.$$
(9)

Let us denote the probability that there are *n* requests in the system (where some of them are in service, and others are waiting for a service to start or resume) $p_n(t) = P\{X(t) = n\}, 0 \le n \le 2r + 1$. It will be the probability that the continuous-time Markov chain X(t) is in state *n* at time *t*, and denote by $\mathbf{p}(t) = (p_0(t), p_1(t), p_2(t), \dots, p_{2r+1}(t))^T$ the probability distribution vector at time *t*.

Then, the corresponding Kolmogorov forward equations could be written as follows:

$$p'_{n}(t) = \lambda(t) \cdot I(n > 1)p_{n-2}(t) + \beta(t) \cdot I(n = 2k + 1)p_{n-1}(t) + \alpha(t) \cdot I(n = 2k)p_{n+1}(t) + C\mu(t) \cdot I(n = 2k + 1, k = C, ..., r - 1) \cdot p_{n+2}(t) + \frac{n+1}{2}\mu(t) \cdot I(n = 2k + 1, k = 0, ..., C - 1)p_{n+2}(t) - [\lambda(t) \cdot I(n < 2r) + \alpha(t) \cdot I(n = 2k + 1) + \beta(t) \cdot I(n = 2k) + \frac{n-1}{2}\mu(t) \cdot I(n = 2k + 1, k = 1, ..., C) + C\mu(t) \cdot I(n = 2k + 1, k = C + 1, ..., r)] \cdot p_{n}(t),$$

$$(10)$$

where $n \in X, k = 0, ..., r$.

Further, we proceed to estimate the boundaries of the rates of convergence to the limiting probability distribution.

3. Bounds on the Rates of Convergence

3.1. Bounds' Defining

Let us consider the forward Kolmogorov system (10) for the process describing the number of requests in the system.

Recall that a Markov chain X(t) is called weakly ergodic, if $||\mathbf{p}^*(t) - \mathbf{p}^{**}(t)|| \to 0$ as $t \to \infty$ for any initial conditions $\mathbf{p}^*(0)$, $\mathbf{p}^{**}(0)$, where $\mathbf{p}^*(t)$ and $\mathbf{p}^{**}(t)$ are the corresponding solutions of (10), where $|| \bullet ||$ denotes the l_1 -norm (or distance in total variation).

The fact of the weak ergodicity of the chain X(t) follows from our previous results; see the references in [40,41]. It is important to note that to calculate the main limiting characteristics of the process and the possibility of their practical use, we need not the fact of weak ergodicity, but the bounds of the rate of convergence. Unfortunately, the structure of the intensity matrix of the model under consideration is such that the application of the logarithmic norm cannot give us explicit estimates in the same way as in [40–42]. Therefore, it is necessary to apply less obvious research paths. Firstly, consider the logarithmic norm γ of transposed intensity matrix A(t); we have $\gamma(A(t)) = \max_j \left(a_{jj}(t) + \sum_{i \neq j} a_{ij}(t) = 0\right)$ for any $t \ge 0$; hence, $\|\mathbf{p}^*(t) - \mathbf{p}^{**}(t)\| \to 0$ in total variance distance decreases. Therefore, if this norm is less than ϵ for some t_0 , then it is less than ϵ for any $t \ge t_0$.

Secondly, since the state space (from zero to S = 2r + 1) is finite and not too large, we can find the exact (at least with any practically necessary accuracy) solution of the forward Kolmogorov system with any initial condition X(0) = i (which corresponds to $p(0) = e_i$) on an arbitrary finite interval [0, l]. Now, having found the norms of the difference between all pairs of such solutions and then choosing in the set of all solutions those for which the "extreme" initial conditions X(0) = 0 and X(0) = S, we come to a value l such that for $t \ge l$, the norms of the corresponding differences will be sufficiently small. Then, the solution with initial condition X(0) = 0 gives us the periodic limiting behavior with the required accuracy on the interval [l; l + T] (and all characteristics in which one is interested).

3.2. Performance Measures

Let us consider the main performance measures of the system from the LSA licensee's, i.e., mobile operator's, point of view. The most interesting queuing system limiting characteristics are listed below.

• The blocking probability B(t), i.e., the probability that a new user's request will be dropped:

$$B(t) = \sum_{i=0}^{1} p_{2r+i}(t) = p_{2r}(t) + p_{2r+1}(t).$$
(11)

• The average number of requests in the queue Q(t), i.e., the number of requests awaiting in the buffer when the service will be started:

$$Q(t) = \sum_{k=1}^{r} k p_{2k}(t) + \sum_{k=C+1}^{r} (k-C) p_{2k+1}(t).$$
 (12)

• The average queue length, when the LSA band is operational $Q_{on}(t)$, i.e., the number of requests waiting when the current number of occupied resource blocks will be less than C:

$$Q_{on}(t) = \sum_{k=C+1}^{r} (k-C) p_{2k+1}(t).$$
(13)

• The average queue length, when the LSA band is unavailable $Q_{off}(t)$, i.e., the number of requests waiting when devices will be ON and the current number of occupied resource blocks will be less than *C*:

$$Q_{off}(t) = \sum_{k=1}^{r} k p_{2k}(t).$$
(14)

• The resource utilization factor, *UTIL*(*t*), is given by:

$$UTIL(t) \cdot C = \sum_{k=1}^{r} k p_{2k}(t) + \sum_{k=1}^{r} k p_{2k+1}(t).$$
(15)

4. Numerical Analysis

We remark that, with the increase of the number of M2M communications due principally to smart city technology development, data traffic in modern wireless networks will grow dramatically. This technology is an example of the M2M communication paradigm in 5G networks. Due to the fact that most smart city applications are machine-oriented [4,40], the interconnected sensors may become an integral part of this environment, especially in the vehicle-to-everything (V2X) scenario [41], which we consider in this section.

For the numerical analysis, we considered the case when the LSA spectrum incumbent in an urban area requires its frequency resources only occasionally, namely every 20 or 30 min, in small and

localized portions. In this way, we assumed that the LSA band goes into unavailable mode every 20 or 30 min, i.e., $\alpha^{-1} = 1200$ or 1800 s. The network operator can request an underused spectrum each 20 s, i.e., $\beta^{-1} = 20$ s. Let us note that these rates do not depend on the time of the day. Furthermore, we assume that one cell of the wireless network can simultaneously serve 30 sensors, and the average duration of service is equal to 0.1 s.

To get the values of the arrival rate $\lambda(t)$, let us consider the source [42] (Figure 2).



Figure 2. Application traffic daily profile in Central and Eastern Europe (TB) [42].

The data presented in Figure 2 allow us to describe the number of sensor requests for data transmission by a function of *t*. For this purpose, based on Figure 2, we can form Table 1, which shows the application traffic daily profile as a percentage.

Hours	Application Traffic (%)							
110410	Streaming	Computing	Storage	Gaming	Communicating			
12:00 a.m.	58.15217	54.97835	57.86164	57.73381	57.54098			
01:00 a.m.	34.78261	33.11688	38.57442	36.33094	36.06557			
02:00 a.m.	21.19565	20.12987	27.67296	25.35971	24.7541			
03:00 a.m.	15.48913	15.15152	24.73795	22.30216	21.31148			
04:00 a.m.	12.22826	12.55411	23.68973	21.22302	20			
05:00 a.m.	12.5	14.06926	25.78616	23.20144	21.63934			
06:00 a.m.	19.29348	23.80952	35.63941	32.73381	30.32787			
07:00 a.m.	41.57609	48.2684	59.32914	57.19424	52.62295			
08:00 a.m.	55.16304	64.50216	74.00419	74.10072	68.68852			
09:00 a.m.	57.06522	68.61472	76.72956	75.35971	71.63934			
10:00 a.m.	61.95652	74.24242	80.92243	76.61871	75.2459			
11:00 a.m.	63.58696	76.40693	82.18029	75.89928	76.22951			
12:00 p.m.	63.8587	76.83983	81.97065	74.82014	75.7377			
01:00 p.m.	65.21739	77.92208	82.38994	75.17986	75.57377			
02:00 p.m.	66.57609	79.43723	83.43816	76.07914	76.22951			
03:00 p.m.	67.3913	80.95238	84.48637	76.97842	76.55738			
04:00 p.m.	67.66304	81.38528	84.90566	77.69784	76.55738			
05:00 p.m.	72.01087	84.19913	87.21174	80.7554	79.5082			
06:00 p.m.	75.54348	85.28139	88.05031	82.3741	81.14754			
07:00 p.m.	82.06522	88.52814	90.56604	85.61151	84.09836			
08:00 p.m.	90.21739	93.72294	94.54927	90.64748	90.16393			
09:00 p.m.	100	100	100	100	100			
10:00 p.m.	98.36957	95.88745	95.59748	99.64029	99.01639			
11:00 p.m.	83.42391	79.22078	79.87421	83.63309	82.29508			

Table 1. Application traffic daily profile in Central and Eastern Europe (%).

The Fourier 2 transform can approximate the dependencies obtained in Table 1 into the function $\lambda(t) = a_0 + a_1 \cos(w \cdot t) + b_1 \sin(w \cdot t) + a_2 \cos(2w \cdot t) + b_2 \sin(2w \cdot t)$. Table 2 summarizes the initial data for the considered example. Table 3 contains the coefficients that are necessary for calculating the arrival rate $\lambda(t)$.

Notation	Value
С	30
r	50
α^{-1}	1200, 1800 s
eta^{-1}	20 s
$\lambda(t)$	$a_0 + a_1 \cos(w \cdot t) + b_1 \sin(w \cdot t) + a_2 \cos(2w \cdot t) + b_2 \sin(2w \cdot t)$
μ^{-1}	0.1 s

Table 2. Main framework notations.

Table 3. Arrival rate	$\lambda(t$) b	y using	traffic	daily	profile a	approximation	n (Fourier	: 2)	•
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<i>a</i> ₀	<i>a</i> ₁	b_1	<i>a</i> ₂	b_2	w		
Streaming traffic							
57.78	-5.188	-29.19	3.973	-20.11	0.2601		
Computing traffic							
63.72	-13.39	-30.77	3.483	-19.45	0.2605		
Storage traffic							
69.18	-14.16	-25.95	1.884	-18.02	0.2605		
Gaming traffic							
v 65.92	-11.25	-24.58	1.679	-20.26	0.2601		
Communicating traffic							
64.71	-11.1	-25.62	2.983	-19.66	0.26		

We further focused on the following set of metrics of interest: the blocking probability B(t) and the average number of requests in the queue Q(t), based on the arrival rate $\lambda(t)$.

For this purpose, first of all, we considered the data corresponding to the first type of traffic (streaming traffic) presented in Table 3. Next, we define a time interval (Figure 3) on which the system ceases to depend on the selected initial conditions, the first of which X(0) = 0 corresponds to the fact that the system is empty and the second X(0) = 101 to the fact that the system is filled.

According to Figure 3, the system ceases to depend on the selected initial conditions, starting with the value of 150 s. From this point onwards, a complete coincidence of the curves is observed. A similar situation occurs for the case of $\alpha^{-1} = 1800$ s. Note that the obtained interval is suitable for estimating the other considering the queuing system's limiting characteristics. Let us pass to an estimation of their limiting values.

Figure 4 shows that frequent LSA band transitions into unavailable mode lead to the blocking probability B(t) (Figure 4a) and the average queue length Q(t) (Figure 4b) increasing. In particular, with $\alpha^{-1} = 1200$ s, the performance measures of the system are almost one and a half times worse than for $\alpha^{-1} = 1800$ s, namely the limiting values of the blocking probability and the average queue length for $\alpha^{-1} = 1200$ approximately equal 0.016 and 0.82, and for $\alpha^{-1} = 1800$, they approximately equal 0.011 and 0.55, respectively.

Furthermore, Figure 4 allows selecting a more accurate interval, suitable for analyzing the system performance measures, namely the time interval from 270 to 300 s, at which the system goes to steady-state. We used this interval to perform a comparative analysis of the system performance measures, which worked with different types of traffic. Namely, consider the dependence of the

blocking probability (Figure 5a) and the average queue length (Figure 5b) on the types of traffic generated in the system. Let us recall that the data for carrying out such an analysis are presented in Table 3.

According to the obtained results, the maximum blocking probability and the queue length were reached when traffic of type "storage" was transmitted. The minimal blocking probability and the queue length were reached when traffic of type "streaming" was transmitted. Note that the numerical analysis presented the results that allowed us to estimate only the average length of the queue Q(t), which did not depend on the state of the LSA band. This was due to the fact that the value of Q(t) practically coincided with the value of performance measure $Q_{on}(t)$ (average queue length, when the LSA band was operational) and was slightly larger than the value of $Q_{off}(t)$.

 $\begin{array}{c} & & & & \\ & & & & \\ & & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ & & & \\ &$

This allowed us to obtain an upper bound for these three characteristics.

Figure 3. Estimating the time interval for blocking probability B(t) analysis.



Figure 4. Estimating of limiting values for blocking probability (a) and average queue length (b).



Figure 5. Blocking probability (a) and average queue length (b) depending on traffic type.

5. Conclusions

In the conditions of the rapid growth of data traffic volume, which is generated in modern multiservice networks, the LSA framework becomes one of the possible solutions to the frequency range shortage problems, which arises in this case. In this paper, we described a characteristic urban LSA use case, where the spectrum license owner in a smart city used its frequency resources only occasionally. We analyzed the LSA usage for the V2X scenario, within the framework of the smart city concept. For the analysis, we considered the case when the LSA licensee did not have its frequency range and he/she had access only to the LSA band. This access was modeled as a queuing system with the queue, catastrophes, and repairs. To assess the model performance measures, we analyzed the bounds on the rates of convergence to limiting characteristics: the blocking probability, the average number of requests in the queue, the average queue length, when the LSA band was operational and unavailable based on the arrival rate, which depended on the time of the day and type of generated traffic.

In this work, we considered a case of the non-stationarity of different types of rates (intensities). The corresponding mathematical method could only be applied for specific types of one-dimensional stochastic processes. For calculating delay metrics, we plan to use the apparatus of the embedded Markov chain (EMC) (as Little's law in the form $\lambda(1 - B(t))W(t) \neq Q(t)$ cannot be applied due to the service unreliability). After, a novel approach for analyzing non-stationarity, EMC should be developed. As the first step of further work, we plan to simulate the system to calculate the expected waiting time for data in the queue and total queuing delay. Since in this paper, we considered a kind of M/M/m/mqueueing model to describe the RAC scheme with exponentially distributed service times, we further plan to consider a more complex type of queueing model, for example G/G/m, which will make the model more realistic.

Author Contributions: Conceptualization, A.Z.; software, E.M.; investigation, E.M. (Sections 1 and 4), Y.S. (Sections 2 and 3), I.K. (Sections 2 and 3), and A.Z. (Sections 2 and 3); writing, original draft preparation, E.M., A.S., Y.S., and I.K.; writing, review and editing, A.Z. All authors read and agreed to the published version of the manuscript.

Funding: Sections 2 and 3 were written by Satin, Zeifman, and Kochetkova under the support of the Russian Science Foundation, Project 19-11-00020. The publication has been prepared with the support of the "RUDN University Program 5-100" (recipient Markova, Sections 1 and 4).

Conflicts of Interest: The authors declare no conflict of interest.

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