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Development of Radio Admission Scheme Model for 5G Network Slicing Framework as a Retrial Queue

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Abstract

To improve the efficiency of using network resources, fifth-generation 5G networks propose to use the technology of network slicing. This feature consists of creating multiple logical, self-contained networks on top of a common shared physical infrastructure, and, therefore, it can be used to support multi-tenancy on the 5G network. Each of these logical networks is referred to as a network slice and can be tailored to provide a particular system behavior to best support specific service/application domains. This work is devoted to the development of a mathematical model of resource allocation in network slicing. Using the first-order asymptotic analysis method, we will find basic numerical and probabilistic characteristics.

Keywords: access control, radio resource slicing, performance measure, queuing system

1. Introduction

Network slicing is defined as one of the main components of fifth-generation mobile communications that can solve the problem of colossal growth in data volume traffic in cellular networks [1, 2]. The key feature of network slicing for ensuring performance and high quality of service is isolation, which limits the influence of slices on each other. Isolation is a fundamental property of network slicing that

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provides performance and security guarantees for each client when different clients use network segments for services with conflicting performance requirements [3]. Using isolation and resource sharing strategies on the radio interface is a rather entangled process [4].

The paper proposes one of the possible schemes for dividing radio resources on a single slice between two arrival processes. To describe and analyze the efficiency indicators of the proposed scheme, a retrial queueing system was used.

2. Mathematical Model

Consider one network segment receiving two arrival processes of service requests. Let two Poisson processes, corresponding to requests for data transmission from users of two different slices, arrive at the retrial queueing system (RQ system).The total capacity of the system is C resource units. The arrivals intensities are constant and equal to λ_1 and λ_2, respectively. Each request arriving from the k-process, $k = 1, 2$, requires b_k resource units to serve. If there is enough free resource in the system, then the request gets up for service, the duration of which is exponentially distributed with the parameter μ_k. If the free resource in the system turns out to be insufficient for servicing, then the request goes to the orbit, where it carries out an exponentially distributed random delay with the parameter σ_k, after which it makes the next attempt to get up for service. The orbits for each of the incoming streams are independent and have unlimited capacity.

We define a stochastic process $\mathbf{X}(t) = \{N_1(t), N_2(t), I_1(t), I_2(t)\}$, where $N_k(t)$ is the customers number of the k-process in the service at the time t, $t > 0$, and $I_k(t)$ is the customers number of the k-process in the orbit at the time t, $t > 0$, $k = 1, 2$. Then the states space of the process has the form:

$$\mathbb{X} = \{(n_1, n_2, i_1, i_2) : b_1 n_1 + b_2 n_2 \leq C,\, i_k \geq 0,\, k = 1, 2\},$$

where n_k is current state of the process $N_k(t)$, i_k is current state of the process $I_k(t)$.

The state spaces of customers blocking (i.e. the arrivals go to the orbit): $\mathbb{B}_1 = \{(n_1, n_2, i_1, i_2) : b_1(n_1+1)+b_2 n_2 \geq C\}$, $\mathbb{B}_2 = \{(n_1, n_2, i_1, i_2) : b_1 n_1+b_2(n_2+1) \geq C\}$, accordingly, the state spaces of accepting customers are $\tilde{\mathbb{B}}_k = \mathbb{X} \backslash \mathbb{B}_k$.

The condition for the existence of a steady-state regime in the system under consideration has the form:

$$\frac{\lambda_1}{\mu_1} b_1 + \frac{\lambda_2}{\mu_2} b_2 < C.$$

3. System of Equilibrium Equations

Let us write a system of equilibrium equations to obtain the stationary probability distribution of states $P(n_1, n_2, i_1, i_2)$, $(n_1, n_2, i_1, i_2) \in \mathbb{X}$ of the process $\mathbf{X}(t)$:

$$
\begin{gathered}
[\lambda_1+\lambda_2+n_1\mu_1+n_2\mu_2+i_1\sigma_1\cdot I(b_1(n_1+1)+b_2n_2\le C,i_1>0)+\\
+i_2\sigma_2\cdot I(b_1n_1+b_2(n_2+1)\le C,i_2>0)]\cdot P(n_1,n_2,i_1,i_2)=\\
=\lambda_1\cdot I(n_1>0)\cdot P(n_1-1,n_2,i_1,i_2)+\lambda_2\cdot I(n_2>0)\cdot P(n_1,n_2-1,i_1,i_2)+\\
+\lambda_1\cdot I(b_1(n_1+1)+b_2n_2>C,i_1>0)\cdot P(n_1,n_2,i_1-1,i_2)+\\
+\lambda_2\cdot I(b_1n_1+b_2(n_2+1)>C,i_2>0)\cdot P(n_1,n_2,i_1,i_2-1)+\\
+(n_1+1)\mu_1\cdot P(n_1+1,n_2,i_1,i_2)\cdot I(b_1(n_1+1)+b_2n_2\le C)+\\
+(n_2+1)\mu_2\cdot P(n_1,n_2+1,i_1,i_2)\cdot I(b_1n_1+b_2(n_2+1)\le C)+\\
+(i_1+1)\sigma_1\cdot I(n_1>0)\cdot P(n_1-1,n_2,i_1+1,i_2)+\\
+(i_2+1)\sigma_2\cdot I(n_2>0)\cdot P(n_1,n_2-1,i_1,i_2+1).
\end{gathered}
$$

At the next step, we write separately the form of the system of equilibrium equations for the subsets of states:

- $(1): b_1n_1+b_2n_2=0$, when the system is empty,
- $(2): (b_1(n_1+1)+b_2n_2\le C)\cap(b_1n_1+b_2(n_2+1)\le C)$, when it is possible to accept customers from both processes,
- $(3): (b_1(n_1+1)+b_2n_2>C)\cap(b_1n_1+b_2(n_2+1)>C)$, when it is not possible to accept customers from both processes,
- $(4): (b_1(n_1+1)+b_2n_2>C)\cap(b_1n_1+b_2(n_2+1)\le C)$, when it is not possible to accept customers from 1-process, but possible for 2-process,
- $(5): (b_1(n_1+1)+b_2n_2\le C)\cap(b_1n_1+b_2(n_2+1)>C)$, when it is possible to accept customers from 1-process, but not possible for 2-process.

4. Partial Characteristic Functions

Then, we introduce the partial characteristic functions:

$$
H(n_1,n_2,u_1,u_2)=\sum_{i_1=0}^{\infty}\sum_{i_2=0}^{\infty}e^{ju_1i_1}e^{ju_2i_2}P(n_1,n_2,i_1,i_2),\ \text{where } j=\sqrt{-1},
$$

and rewrite the system for partial characteristic functions for subsets of states. Then, we denote $\mathbf{H}(u_1,u_2)$ as matrix of functions $H(n_1,n_2,u_1,u_2)$ and rewrite the system as operator equation:

$$
\begin{gathered}
(\mathbf{A}+\lambda_1e^{ju_1}\mathbf{B_1}+\lambda_2e^{ju_2}\mathbf{B_2})\mathbf{H}(u_1,u_2)+\\
+j\sigma_1(\mathbf{C_1}-e^{-ju_1}\mathbf{D_1})\frac{\partial\mathbf{H}(u_1,u_2)}{\partial u_1}+j\sigma_2(\mathbf{C_2}-e^{-ju_2}\mathbf{D_2})\frac{\partial\mathbf{H}(u_1,u_2)}{\partial u_2}=0, \qquad (1)
\end{gathered}
$$

where $\mathbf{A}, \mathbf{B_1}, \mathbf{B_2}, \mathbf{C_1}, \mathbf{C_2}, \mathbf{D_1}, \mathbf{D_2}$ are operators, which are specified in the following form:

$$\mathbf{B_1 H}(u_1,u_2)=\begin{cases} 0, (1), (2), (5) \\ H(n_1,n_2,u_1,u_2), (3), (4) \end{cases} \quad \mathbf{B_2 H}(u_1,u_2)=\begin{cases} 0, (1), (2), (4) \\ H(n_1,n_2,u_1,u_2), (3), (5) \end{cases}$$

$$\mathbf{C_1 H}(u_1,u_2) = \begin{cases} H(n_1,n_2,u_1,u_2), & (1),(2),(5) \\ 0, & (3),(4) \end{cases}$$

$$\mathbf{C_2 H}(u_1,u_2) = \begin{cases} H(n_1,n_2,u_1,u_2), & (1),(2),(4) \\ 0, & (3),(5) \end{cases}$$

$$\mathbf{D_1 H}(u_1,u_2) = \begin{cases} 0, & (1) \\ H(n_1-1,n_2,u_1,u_2), & (2)-(5) \end{cases}$$

$$\mathbf{D_2 H}(u_1,u_2) = \begin{cases} 0, & (1) \\ H(n_1,n_2-1,u_1,u_2), & (2)-(5) \end{cases}$$

$$\mathbf{AH}(u_1,u_2) = \begin{cases} -(\lambda_1+\lambda_2)H(n_1,n_2,u_1,u_2)+\mu_1 H(n_1+1,n_2,u_1,u_2)+ & \\ +\mu_2 H(n_1,n_2+1,u_1,u_2), & (1) \\ -(\lambda_1+\lambda_2+n_1\mu_1+n_2\mu_2)H(n_1,n_2,u_1,u_2)+ & \\ +\lambda_1 H(n_1-1,n_2,u_1,u_2)+\lambda_2 H(n_1,n_2-1,u_1,u_2)+ & \\ +(n_1+1)\mu_1 H(n_1+1,n_2,u_1,u_2)+ & \\ +(n_2+1)\mu_2 H(n_1,n_2+1,u_1,u_2), & (2) \\ -(\lambda_1+\lambda_2+n_1\mu_1+n_2\mu_2)H(n_1,n_2,u_1,u_2)+ & \\ +\lambda_1 H(n_1-1,n_2,u_1,u_2)+\lambda_2 H(n_1,n_2-1,u_1,u_2), & (3) \\ -(\lambda_1+\lambda_2+n_1\mu_1+n_2\mu_2)H(n_1,n_2,u_1,u_2)+ & \\ +\lambda_1 H(n_1-1,n_2,u_1,u_2)+\lambda_2 H(n_1,n_2-1,u_1,u_2)+ & \\ +(n_2+1)\mu_2 H(n_1,n_2+1,u_1,u_2), & (4) \\ -(\lambda_1+\lambda_2+n_1\mu_1+n_2\mu_2)H(n_1,n_2,u_1,u_2)+ & \\ +\lambda_1 H(n_1-1,n_2,u_1,u_2)+\lambda_2 H(n_1,n_2-1,u_1,u_2)+ & \\ +(n_1+1)\mu_1 H(n_1+1,n_2,u_1,u_2), & (5) \end{cases}$$

Let us define $\mathbf{E}$ as an operator that sums functions overall available values of n_1, n_2 and represents the following additional scalar equation:

$$\mathbf{E}(\lambda_1(e^{ju_1}-1)\mathbf{B_1}+\lambda_2(e^{ju_2}-1)\mathbf{B_2})\mathbf{H}(u_1,u_2)+ \\ +j\sigma_1(1-e^{-ju_1})\mathbf{ED_1}\frac{\partial \mathbf{H}(u_1,u_2)}{\partial u_1}+j\sigma_2(1-e^{-ju_2})\mathbf{ED_2}\frac{\partial \mathbf{H}(u_1,u_2)}{\partial u_2}=0. \qquad (2)$$

5. First Order Approximation

We find the solution of (1)–(2) using the asymptotic analysis [5] under the condition of proportional to the increasing delay time in orbits (i.e. $\sigma_k = \sigma \cdot \gamma_k$, $\sigma \to 0$, $k = 1, 2$). As a result of first order asymptotic analysis we obtain the first order approximation of matrix characteristic function:

$$\mathbf{H}(u_1, u_2) = \mathbf{R} \cdot \exp\left\{ju_1\frac{x_1}{\sigma} + ju_2\frac{x_2}{\sigma}\right\},$$

where $\mathbf{R}$ is a matrix of elements $R(n_1, n_2)$ – a stationary joint probability distribution of the two-dimensional process $\{N_1(t), N_2(t)\}$, and x_1, x_2 are the normalized customers numbers means in orbits. The parameters are defined from:

$$[(\mathbf{A} + \lambda_1\mathbf{B_1} + \lambda_2\mathbf{B_2}) - x_1\gamma_1(\mathbf{C_1} - \mathbf{D_1}) - x_2\gamma_2(\mathbf{C_2} - \mathbf{D_2})]\,\mathbf{R} = 0,$$

$$\mathbf{E}\,[\lambda_1\mathbf{B_1} - x_1\gamma_1\mathbf{D_1}]\,\mathbf{R} = 0, \quad \mathbf{E}\,[\lambda_2\mathbf{B_2} - x_2\gamma_2\mathbf{D_2}]\,\mathbf{R} = 0, \quad \mathbf{ER} = 1.$$

At this step, we obtain the marginal probability distribution of customers number in the service $\mathbf{R}$ and the means of customers number in the orbits $\frac{x_k}{\sigma}$, $k = 1, 2$.

6. Numerical Example

We can calculate the main numerical characteristics of system performance. Let the system parameters has the form: $C = 5$, $\lambda_1 = \lambda_2 = 2$, $\mu_1 = \mu_2 = 2$, $\sigma_1 = \sigma_2 = 3 \cdot \sigma\,(\sigma \to 0)$, $b_1 = 1$, $b_2 = 2$. Figure 1 shows the changes in means of customers' numbers in the orbits and their relative errors with simulation mean. Other characteristics can be easily calculated using the stationary probability distribution:

- probability that arrival goes to the orbit (probabilistic characteristic)

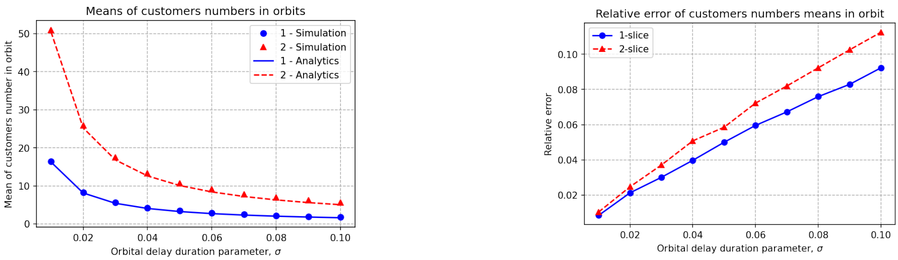
$$p_k = \sum_{(n_1,n_2,i_1,i_2)\in\mathbb{B}_k} R(n_1, n_2),\ k = 1, 2,$$

- means of the total resource amounts occupied (numerical characteristic)

$$\mathrm{E}[B_k] = \sum_{(n_1,n_2,i_1,i_2)\in\mathbb{X}} b_k n_k R(n_1, n_2),\ k = 1, 2,$$

- utility coefficient (numerical characteristic)

$$R = (\mathrm{E}[B_1] + \mathrm{E}[B_2])/C.$$



(a) Means of customers numbers in orbits

(b) Relative error

Fig. 1. Visualization of approximation accuracy

7. Conclusion

In this paper, we formalized the mathematical model of resource allocation in network slicing. Using the first-order asymptotic analysis method, we found basic numerical and probabilistic characteristics. Next, we plan to perform a second-order asymptotic analysis to obtain a four-dimensional probability distribution that will allow us to calculate a wider range of performance metrics for network slicing technology. In addition, it is necessary to consider a model with three or more arrival processes (slices).

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