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Modeling and Performance Evaluation of a Cellular Network with OMA and NOMA Users with Batch Arrivals by Means of an $M^{[X]}/M/S/0$ Model

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Abstract: Nowadays, efficient spectrum usage is one of the most important design principles to take into account in wireless communications due to the exponential growth of mobile devices. In that sense, solutions such as Non-Orthogonal Multiple Access (NOMA) and cognitive radio (CR) have been proposed. In essence, NOMA allows some interference level by using non-orthogonal resource allocation with a tolerable increase in receiver complexity employing successive interference cancellation (SIC). In this work, a novel mathematical model of teletraffic for users performing accessment, simultaneously, by means of Orthogonal Multiple Access (OMA) and NOMA, is developed using a Markovian process that considers bursts of arrivals to model the access schemes. This novel procedure implies a closed-form solution of the proposed system compared to other works where these parameters are estimated assuming the moment generating function obtained with approximation models. The model is validated with a discrete event simulator, considering different scenarios and simulation conditions. The simulation results are in agreement with the mathematical solution proposed.

Keywords: blocking probability; NOMA; Markov chain; batch arrivals; next generation

MSC: 60J22

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1. Introduction

The new fifth-generation systems (5G-NR) are driving the massive deployment of cellular networks and leading the way towards the smart cities of tomorrow. City-wide coverage and reliability are vital elements to implement for any successful smart city. Wireless technology is the key and the only viable solution for city-wide deployment. Based on this fact, wireless operators are implementing new systems and internal business processes to meet the challenges of building and managing a 5G network [1].

In the 2017 Ericsson Mobility Report, mobile video traffic was forecast to grow around 50% annually through 2023, representing almost 75% of all mobile data traffic. In addition, it was forecast that social networks would grow 34% annually in the same period of time. Cisco predicted, in its annual Internet report (2018–2023), that by the end of 2023 the number of mobile users would be 13.1 billion and that the number of internet-enabled devices, with an approximate 18.4 billion in 2018, would be 29.3 billion by 2023 [2]. This

growing trend shows no signs of slowing down in the next decade, as this demand is caused by around 70% of the world's population. Therefore, providing massive access is one of the most important goals for next-generation wireless networks.

To implement the Internet of Everything (IoE) and mobile internet, next-generation networks have several performance objectives: **(a)** The maximum data rate must be at least one terabit per second; **(b)** the latency of the air interface must range between 0.01 and 0.1 ms for highly mobile users; **(c)** connection density must be 10 times greater than in current systems; **(d)** Spectral Efficiency (SE) and Energy Efficiency (EE) should be 5–10 and 10–100 times higher than current systems, respectively; and **(e)** reliability must be greater than 99.99999% [3,4].

Industry 4.0 is a business paradigm introduced by the German government that modernizes the way emerging technologies are used in various application domains (such as healthcare, manufacturing, cybersecurity, systems integration, robotics, cloud connectivity, and retail) based on real-time data and connectivity. In Industry 4.0, the Internet of Things (IoT) is the basis for building industrial systems with numerous applications to improve productivity and performance with less human error. IoT is a revolutionary technology that refers to a wireless network of interconnected devices that means the future of communication, computing, and intelligence [5].

The introduction of new communication services with higher bandwidth requirements and better quality of service, the demand for high data transmission rates, and high spectral efficiency are becoming increasingly important in mobile communication systems. A major challenge for new telecommunication technologies is the improvement of spectral efficiency to deliver high data transfer speeds to more smart devices. One option to achieve this improvement is the use of cognitive radio (CR) networks, which require algorithms and protocols for spectrum management based on detection, coordination, and cooperation operations among terminal devices. Another option is to use new multiple access schemes.

An important parameter in wireless communication systems is power control. It is used to compensate for the loss of intensity of the transmitted signal and variations in interference. The user channel quality depends on the SIR, which is a function of the transmission power, channel fading, and interference. In conventional Orthogonal Multiple Access (OMA) schemes, such as Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA), and Orthogonal Frequency Division Multiple Access (OFDMA) used for 1G, 2G, 3G, and 4G, respectively, users are assigned to orthogonal radio resources in the domain of time, frequency, code, or their combinations. Consequently, it remains a challenge for OMA to meet the spectral efficiency and massive 5G connectivity requirements [6].

Recently, Non-Orthogonal Multiple Access (NOMA), also known as the next-generation medium access (NGMA) technique, has emerged as a promising multiple-access technique for next-generation wireless systems [7]. NOMA allows controllable interference for non-orthogonal resource allocation with tolerable increase in receiver complexity. Compared with OMA, the main advantages of NOMA include the following [8]:

- Improvement in spectral efficiency.
- Massive connectivity.
- Low transmission latency and signaling cost.

The NGMA trend is to move from orthogonality to non-orthogonality, that is, serving multiple users by allowing them to share the same resources instead of allocating them to dedicated orthogonal resources. The reason behind this trend can be explained as follows. Orthogonal transmission schemes are strictly suboptimal compared to non-orthogonal transmission schemes, since each user can use only a part of the available resource blocks. On the other hand, given the growth in the number of users in next-generation wireless networks, orthogonal transmission schemes can only support a limited number of users for certain available orthogonal resources. This requires the development of non-orthogonal transmission schemes for NGMA.

The basic idea of NOMA lies in the simultaneous use of the same radio spectrum by multiple users at the cost of causing small interference among users. Networks employing NOMA can serve a greater number of users in the available spectrum bands and can serve individual users with greater bandwidth. One of the key ideas for successful NOMA operation is to form groups of users (exploiting differences in their channel gains) and allow them to transmit on the same radio resource with the appropriate power, and then use SIC (successive interference cancellation) at the receiver(s) to decode the message signal from different users [9].

Figure 1 illustrates the basic NOMA scheme via power domain multiplexing with SIC at the receiver. The SIC receiver is commonly used to perform multi-user detection. For simplicity, the case of a single transmitting antenna and a receiving antenna is assumed. User 2 does not perform interference cancellation since it comes first in the decoding order. First, User 1 decodes User 2 signal and subtracts its component from the received signal. Then, it decodes User 1 signal without interference from User 2 signal.

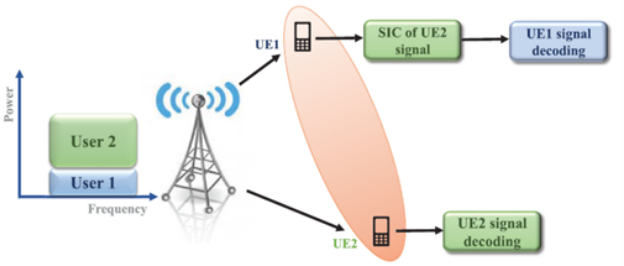


Figure 1. NOMA with SIC in the receiver.

In NOMA, the SIC process is implemented at the receiver. The optimal decoding order is in decreasing order of the channel gain and normalized by the noise and intercell interference power (called simply channel gain). Based on this purpose, it is assumed that any user can correctly decode the signals of other users whose decoding order comes before the corresponding user.

Efficient resource allocation is vital for NOMA system performance. In the following, some works in this line of research are mentioned. In [10], the authors propose an implementation of a CR network with NOMA from the operation perspective and compare their proposal with traditional CR. In [11], the authors show a novel two-step random access (RA) procedure using NOMA to increase efficiency and reduce delay. Transmission power levels are a function of probability. The system is evaluated by simulations and Markov Chains. In [12], the authors focus on the resource allocation problem in the power domain. They develop an efficient conjugate gradient-based power allocation technique to solve the power allocation problem in NOMA in the downlink to maximize the sum of user rates. The major feature of this algorithm is that it converges to the global optimal solution. Their results are validated by simulations. In [13], the authors propose optimal solutions for user clustering and power allocation to maximize the system rate sum. The authors develop a closed-form solution using Karush–Kuhn–Tucker (KKT) conditions and Dinkelbach (DKL) and Hungarian (HNG) algorithms. They achieve an improvement of up to 6.7% in the sum of rates and up to 66% in energy efficiency compared to a NOMA scheme with convex scheduling difference (NOMA-DC). In [14], the authors investigate a new strategy for radio resource allocation in NOMA. They propose a hybrid NOMA scheme, where they consider sub-band allocation and transmission power allocation. They use a power allocation technique based on water filling. Its objective is to minimize spectrum use while meeting the data rates requested by users. The results are at the simulation level, achieving a significant increase in spectral efficiency compared to a system based purely on orthogonal or non-orthogonal signaling. In [15], the authors propose a power allocation algorithm in a NOMA scheme that can adapt to channel variations. The shown results are at the simulation level and show that their proposal reduces the bit error rate (BER) of the

system compared to traditional power allocation algorithms. As it can be seen, the vast majority of works reported in the literature are based on the optimal allocation of resources in the power domain. There are few works that carry out resource allocation in the domain of available channels, and they do it at the simulation level.

In [16–20], the channel reservation problem in cognitive radio networks is studied from different perspectives. These models help reduce the interruption probability for secondary users and improve system performance. Resource reservation models are proposed that help improve network performance, considering an OMA access scheme, where a resource can be used by only one user at a time. This paper proposes to develop a model for channel allocation using the Markovian process for a network that considers bursts of arrivals for the OMA and NOMA schemes. This is a novel modeling approach, since other works represent these parameters assuming models based on the moment generating function and approximation models, without obtaining a closed-form solution. The model is validated with a discrete event simulator, considering different scenarios and simulation conditions.

The rest of the paper is organized as follows. In Section 2, the model used for channel allocation in the analysis of OMA and NOMA systems is described. Section 3 shows mathematic and simulated results. The conclusions of this work are presented in Section 4.

2. System Model

In this section, the system operation model is proposed considering the integration of OMA and NOMA. It is assumed that NOMA users arrive in pairs whereas OMA users arrive one by one. The parameters considered in the system are shown in Table 1.

Table 1. System variables.

Variable	Parameter Description
S	Number of channels in the system.
λ_1	Mean arrival rate for OMA users. The time between arrivals of OMA users is distributed with an exponential density function, with parameter λ_1.
λ_2	Mean arrival rate for NOMA users. The time between arrivals of pairs of NOMA users is distributed with an exponential density function, with parameter λ_2.
λ	Total arrival rate ($\lambda = \lambda_1 + \lambda_2$).
μ	Death rate. The service time of the users is distributed with an exponential density function, with parameter μ.

The analysis of the system is carried out through a Markovian process $M^{[X]}/M/S/0$; with S channels, no waiting queue, times between arrivals and service times distributed exponentially, where X is a random variable that represents the size of the arriving batch—for our case, $X = 1$ (OMA), $X = 2$ (NOMA). The proposed system remains Markovian due to the fact that future behavior is a function only of the present and not of the past. A state diagram of the system is depicted in Figure 2.

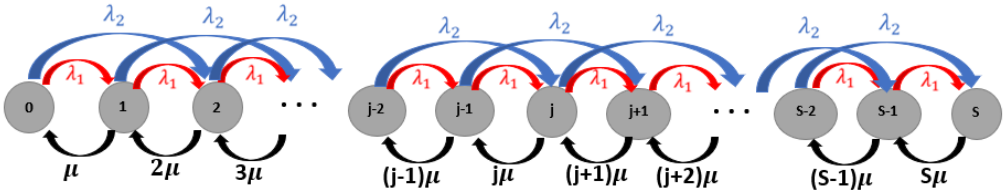


Figure 2. State transition diagram.

In Figure 2, we can see that there are generic states (depicted at the center) and some particular cases at the boundaries. Let j be a state index; then

1. $j = 0$; in this state, only births can occur.
2. $j = 1$; a death can occur, or a birth can arrive from the minor state $(j = 0)$; that is, only one OMA user can arrive.
3. $j = S - 1$; a death may occur, or a birth of an OMA user to the next state $(j = S)$.
4. $j = S$; only deaths can occur.

From Figure 2, the rates among states can be deduced:

$$\lambda_j = \begin{cases} \lambda_1; & \text{for OMA users } (0 \leq j < S) \\ \lambda_2; & \text{for NOMA users } (0 \leq j < S-1) \end{cases} \tag{1}$$

$$\mu_j = \{j\mu; \text{ for } 1 \leq j \leq S \tag{2}$$

We are interested in analyzing the system when it reaches statistical equilibrium. This is achieved when the system has been in operation for a long period of time. When $t \to \infty$, the balance equations provide a "stable" probability of being in each state, independent of time and initial conditions. If we assume that a system is stationary, we take the limit when $t \to \infty$; its differential difference equations become a set of linear difference equations.

In Figure 3, a virtual boundary around the state of interest is represented with a green dashed line. Only the rates involved around the state of interest are shown.

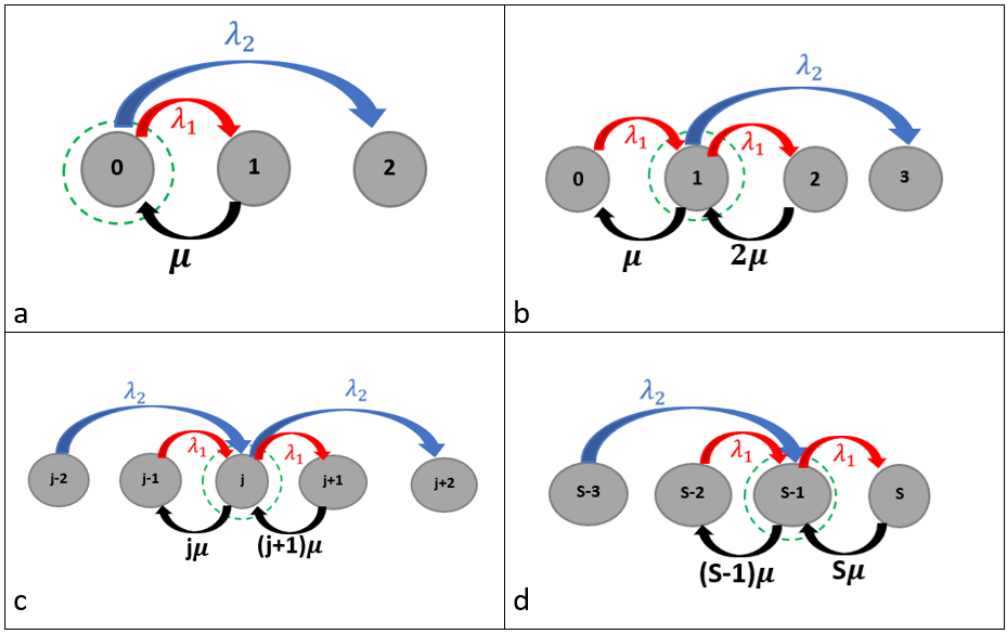


Figure 3. Departure and arrival rates. (**a**) for $j = 0$, (**b**) for $j = 1$, (**c**) for $2 \leq j \leq S$-2, (**d**) for $j = S$-1.

For $j = 0$ (see Figure 3a),

$$(\lambda_1 + \lambda_2)P_0 = \mu P_1. \tag{3}$$

With $\lambda = \lambda_1 + \lambda_2$,

$$\lambda P_0 = \mu P_1. \tag{4}$$

$$P_1 = \frac{\lambda P_0}{\mu}. \tag{5}$$

For $j = 1$ (see Figure 3b),

$$(\lambda_1 + \lambda_2 + \mu)P_1 = 2\mu P_2 + P_0\lambda_1. \tag{6}$$

With $\lambda = \lambda_1 + \lambda_2$,
Solving by recurrence

$$(\lambda + \mu)P_1 = 2\mu P_2 + P_0\lambda_1. \tag{7}$$

$$(\lambda + \mu)\left(\frac{\lambda P_0}{\mu}\right) - P_0\lambda_1 = 2\mu P_2. \tag{8}$$

Substituting $\lambda_1 = \lambda - \lambda_2$,

$$\left(\frac{\lambda^2}{\mu}\right)P_0 + \lambda P_0 - \lambda P_0 + \lambda_2 P_0 = 2\mu P_2. \tag{9}$$

Solving for P_2,

$$P_2 = \frac{\lambda^2}{2\mu^2}P_0 + \frac{\lambda_2}{2\mu}P_0. \tag{10}$$

Figure 3c shows the rates at which the system leaves states $E_{(j-2)}$ and $E_{(j-1)}$ towards a higher state and the rate at which the system leaves the state $E_{(j+1)}$ towards a lower state. And the system balance equation, Equation (11), can be obtained from Figure 3c.

$$0 = -(\lambda + j\mu)P_j + (j+1)\mu P_{j+1} + \sum_{k=1}^{L} P_{j-k}\lambda_k. \tag{11}$$

For our case ($L = 2$), Equation (12) looks like this:

$$0 = -(\lambda + j\mu)P_j + (j+1)\mu P_{j+1} + P_{j-1}\lambda_1 + P_{j-2}\lambda_2. \tag{12}$$

where the first term on the right side of the equation corresponds to the system being in E_j and remains in the same state (nothing happens), the second term is in $E_{(j+1)}$ and a death occurs, and the third and fourth terms correspond to the system being in state $E_{(j-1)}$ and a birth of an OMA user occurs or is in state $E_{(j-2)}$ and a birth of NOMA users occurs.
For $j = 2$ (see Figure 3c), substituting in (12),

$$3\mu P_3 = \lambda P_2 + 2\mu P_2 - \lambda_1 P_1 - \lambda_2 P_0. \tag{13}$$

Substituting P_2 in (13),

$$3\mu P_3 = \frac{\lambda^3}{2\mu^2}P_0 + \frac{\lambda\lambda_2}{2\mu}P_0 + \frac{\lambda_2}{\mu}P_0 + \lambda_2 P_0 - \lambda_1 P_1 - \lambda_2 P_0. \tag{14}$$

Substituting P_1 in (14),

$$3\mu P_3 = \frac{\lambda^3}{2\mu^2}P_0 + \frac{\lambda\lambda_2}{2\mu}P_0\frac{\lambda_2}{\mu}P_0 + \lambda_2 P_0 - \lambda_1\frac{\lambda}{\mu}P_0 - \lambda_2 P_0. \tag{15}$$

Substituting $\lambda_1 = \lambda - \lambda_2$ and solving for P_3,

$$P_3 = \frac{\lambda^3}{6\mu^3}P_0 + \frac{\lambda\lambda_2}{2\mu^2}P_0. \tag{16}$$

Proceeding by recurrence, we obtain the rest of the probabilities. As an example of this, Table 2 shows the first 10 steady-state probabilities.

Table 2. State probabilities.

State	Probability
$j = 0$	$P_1 = \frac{\lambda P_0}{\mu}$
$j = 1$	$P_2 = \frac{\lambda^2}{2\mu^2} P_0 + \frac{\lambda_2}{2\mu} P_0$
$j = 2$	$P_3 = \frac{\lambda^3}{6\mu^3} P_0 + \frac{\lambda\lambda_2}{2\mu^2} P_0$
$j = 3$	$P_4 = \frac{\lambda^4}{24\mu^4} P_0 + \frac{\lambda^2\lambda_2}{4\mu^3} P_0 + \frac{\lambda_2^2}{8\mu^2} P_0$
$j = 4$	$P_5 = \frac{\lambda^5}{120\mu^5} P_0 + \frac{\lambda^3\lambda_2}{12\mu^4} P_0 + \frac{\lambda\lambda_2^2}{8\mu^3} P_0$
$j = 5$	$P_6 = \frac{\lambda^6}{720\mu^6} P_0 + \frac{\lambda^4\lambda_2}{48\mu^5} P_0 + \frac{\lambda^2\lambda_2^2}{16\mu^4} P_0 + \frac{\lambda_2^3}{48\mu^3} P_0$
$j = 6$	$P_7 = \frac{\lambda^7}{5040\mu^7} P_0 + \frac{\lambda^5\lambda_2}{240\mu^6} P_0 + \frac{\lambda^3\lambda_2^2}{48\mu^5} P_0 + \frac{\lambda\lambda_2^3}{48\mu^4} P_0$
$j = 7$	$P_8 = \frac{\lambda^8}{40320\mu^8} P_0 + \frac{\lambda^6\lambda_2}{1440\mu^7} P_0 + \frac{\lambda^4\lambda_2^2}{192\mu^6} P_0 + \frac{\lambda^2\lambda_2^3}{96\mu^5} P_0 + \frac{\lambda_2^4}{384\mu^4} P_0$
$j = 8$	$P_9 = \frac{\lambda^9}{362880\mu^9} P_0 + \frac{\lambda^7\lambda_2}{10080\mu^8} P_0 + \frac{\lambda^5\lambda_2^2}{960\mu^7} P_0 + \frac{\lambda^3\lambda_2^3}{288\mu^6} P_0 + \frac{\lambda\lambda_2^4}{384\mu^5} P_0$
$j = 9$	$P_{10} = \frac{\lambda^{10}}{3628800\mu^{10}} P_0 + \frac{\lambda^8\lambda_2}{80640\mu^9} P_0 + \frac{\lambda^6\lambda_2^2}{5760\mu^8} P_0 + \frac{\lambda^4\lambda_2^3}{1152\mu^7} P_0 + \frac{\lambda^2\lambda_2^4}{768\mu^6} P_0 + \frac{\lambda_2^5}{3840\mu^5} P_0$

Following the behavior of the probabilities, we can obtain a generalized expression for the state probability. This is shown in Equation (17).

$$P_j = \sum_{k=0}^{\left\lfloor \frac{j}{2} \right\rfloor} \frac{1}{(j-2k)!2^k k!} \frac{\lambda^{j-2k}\lambda_2^k}{\mu^{j-k}} P_0; \quad 0 \le j \le S, \tag{17}$$

where $\lfloor X \rfloor$ represents the integer part less than or equal to X.

To calculate P_0, the normalization equation is used, given by Equation (18).

$$\sum_{j=0}^{S} P_j = 1. \tag{18}$$

Developing the normalization equation, we obtain

$$P_0 + P_1 + P_2 + \cdots + P_{S-1} + P_S = 1. \tag{19}$$

Using Equation (19), we can express each state probability in terms of P_0, and thus factor and solve P_0, remaining as Equation (20).

$$P_0 = \left[\sum_{k_2=0}^{S} \sum_{k=0}^{\left\lfloor \frac{k_2}{2} \right\rfloor} \frac{1}{(k_2-2k)!2^k k!} \frac{\lambda^{(k_2-2k)}\lambda_2^k}{\mu^{k_2-k}} \right]^{-1}. \tag{20}$$

Therefore, Equation (17) can be written as shown in Equation (21).

$$P_j = \frac{\sum_{k=0}^{\left\lfloor \frac{j}{2} \right\rfloor} \frac{1}{(j-2k)!2^k k!} \frac{\lambda^{(j-2k)}\lambda_2^k}{\mu^{j-k}}}{\left[\sum_{k_2=0}^{S} \sum_{k=0}^{\left\lfloor \frac{k_2}{2} \right\rfloor} \frac{1}{(k_2-2k)!2^k k!} \frac{\lambda^{(k_2-2k)}\lambda_2^k}{\mu^{k_2-k}} \right]}. \tag{21}$$

To calculate the blocking probability, P_B, we evaluate Equation (21) in $j = S$.

$$P_B = \frac{\sum_{k=0}^{\lfloor \frac{S}{2} \rfloor} \frac{1}{(S-2k)!2^k k!} \frac{\lambda^{(S-2k)} \lambda_2^k}{\mu^{S-k}}}{\left[\sum_{k_2=0}^{S} \sum_{k=0}^{\lfloor \frac{k_2}{2} \rfloor} \frac{1}{(k_2-2k)!2^k k!} \frac{\lambda^{(k_2-2k)} \lambda_2^k}{\mu^{k_2-k}}\right]}. \tag{22}$$

Therefore, to calculate the blocking probability, we use Theorem 1.

Theorem 1. *Given a system that represents birth and death processes, there are births with two user types, OMA users with λ_1 rate and NOMA users with λ_2 rate (two users per resource). Users leave the system with μ rate. When there are S users in the system and a user that wants to send the information, the call is considered blocked. With this model, we can obtain the probability of being in any state of the system, as shown in Equation (23),*

$$P_j = \sum_{k=0}^{\lfloor \frac{j}{2} \rfloor} \frac{1}{(j-2k)!2^k k!} \frac{\lambda^{j-2k} \lambda_2^k}{\mu^{j-k}} P_0; \quad 0 \leq j \leq S, \tag{23}$$

where $\lfloor X \rfloor$ represents the integer part less than or equal to X.

Proof. Considering the initial conditions, shown in the Equation (24),

$$P_{-1} = P_{-2} = 0, \tag{24}$$

from Equation (12),

$$\begin{aligned} 0 = &-(\lambda + j\mu)P_j + (j+1)\mu P_{j+1} \\ &+ Pj - 1\lambda_1 + P_{j-2}\lambda_2. \end{aligned} \tag{25}$$

Solving for P_{j+1},

$$\begin{aligned} P_{j+1} = &\frac{1}{(j+1)\mu}\left[(\lambda + j\mu)P_j - \lambda_1 P_{j-1}\right. \\ &\left.-\lambda_2 P_{j-2}\right]. \end{aligned} \tag{26}$$

We know that $\lambda_1 = \lambda - \lambda_2$. Substituting, we obtain Equation (27):

$$\begin{aligned} P_{j+1} = &\frac{1}{(j+1)\mu}\left[(\lambda + j\mu)P_j - (\lambda - \lambda_2)P_{j-1}\right. \\ &\left.-\lambda_2 P_{j-2}\right]. \end{aligned} \tag{27}$$

Evaluating for $n = j + 1$,

$$\begin{aligned} P_n = &\frac{1}{n\mu}[(\lambda + (n-1)\mu)P_{n-1} - (\lambda - \lambda_2)P_{n-2} \\ &-\lambda_2 P_{n-3}]. \end{aligned} \tag{28}$$

From Equation (23), we have

$$q_n = \sum_{k=0}^{\lfloor \frac{n}{2} \rfloor} \frac{1}{(n-2k)!2^k k!} \frac{\lambda^{n-2k} \lambda_2^k}{\mu^{n-k}} P_0. \tag{29}$$

Evaluating Equation (28) for $n = 1$ and using the initial conditions,

$$\begin{aligned} P_1 &= \frac{1}{(1)\mu}[(\lambda)P_0 - (\lambda - \lambda_2)P_{-1} - \lambda_2 P_{-2}] \\ &= \frac{\lambda}{\mu}P_0. \end{aligned} \tag{30}$$

Evaluating Equation (29) for $n = 1$,

$$\begin{aligned} q_1 &= \sum_{k=0}^{\lfloor \frac{1}{2} \rfloor} \frac{1}{(1-2k)!2^k k!} \frac{\lambda^{1-2k}\lambda_2^k}{\mu^{1-k}} P_0 \\ &= \sum_{k=0}^{0} \frac{1}{(1-2k)!2^k k!} \frac{\lambda^{1-2k}\lambda_2^k}{\mu^{1-k}} P_0 \\ &= \frac{1}{(1)!2^0 0!} \frac{\lambda^{1-2(0)}\lambda_2^0}{\mu^{1-0}} P_0 \\ &= \frac{\lambda}{\mu}P_0. \end{aligned} \tag{31}$$

$\therefore P_1 = q_1$
Evaluating Equation (28) for $n = 2$, using the initial conditions and substituting P_1,

$$\begin{aligned} P_2 &= \frac{1}{2\mu}[(\lambda + \mu)P_1 - (\lambda - \lambda_2)P_0 - \lambda_2 P_{-1}] \\ &= \frac{1}{2\mu}\left[(\lambda + \mu)\left(\frac{\lambda}{\mu}P_0\right) - \lambda P_0 + \lambda_2 P_0\right] \\ &= \frac{\lambda^2}{2\mu^2}P_0 + \frac{\lambda}{2\mu}P_0 - \frac{\lambda}{2\mu}P_0 + \frac{\lambda_2}{2\mu}P_0 \\ &= \frac{\lambda^2}{2\mu^2}P_0 + \frac{\lambda_2}{2\mu}P_0. \end{aligned} \tag{32}$$

Evaluating Equation (29) for $n = 2$,

$$\begin{aligned} q_2 &= \sum_{k=0}^{\lfloor \frac{2}{2} \rfloor} \frac{1}{(2-2k)!2^k k!} \frac{\lambda^{2-2k}\lambda_2^k}{\mu^{2-k}} P_0 \\ &= \sum_{k=0}^{\lfloor 1 \rfloor} \frac{1}{(1-2k)!2^k k!} \frac{\lambda^{1-2k}\lambda_2^k}{\mu^{1-k}} P_0 \\ &= \frac{1}{(2)!2^0 0!} \frac{\lambda^{2-2(0)}\lambda_2^0}{\mu^{2-0}} P_0 + \frac{1}{(0)!2^1 1!} \frac{\lambda^{2-2}\lambda_2^1}{\mu^{2-1}} P_0 \\ &= \frac{\lambda^2}{2\mu^2}P_0 + \frac{\lambda_2}{2\mu}P_0. \end{aligned} \tag{33}$$

$\therefore P_2 = q_2$
We assume that it is true for all $k \leq n$, i.e., $P_k = q_k$. So, we proceed to $n = n + 1$.
Evaluating Equation (28) for $n = n + 1$,

$$\begin{aligned} P_{n+1} = &\frac{1}{(n+1)\mu}[(\lambda + n\mu)P_n - (\lambda - \lambda_2)P_{n-1} \\ &-\lambda_2 P_{n-2}]. \end{aligned} \tag{34}$$

By hypothesis, we have

$$P_n = \sum_{k=0}^{\lfloor \frac{n}{2} \rfloor} \frac{1}{(n-2k)!2^k k!} \frac{\lambda^{n-2k}\lambda_2^k}{\mu^{n-k}} P_0. \tag{35}$$

$$P_{n-1} = \sum_{k=0}^{\lfloor \frac{n-1}{2} \rfloor} \frac{1}{(n-1-2k)!2^k k!} \frac{\lambda^{n-1-2k}\lambda_2^k}{\mu^{n-1-k}} P_0. \tag{36}$$

$$P_{n-2} = \sum_{k=0}^{\lfloor \frac{n-2}{2} \rfloor} \frac{1}{(n-2-2k)!2^k k!} \frac{\lambda^{n-2-2k}\lambda_2^k}{\mu^{n-2-k}} P_0. \tag{37}$$

Substituting (35), (36), and (37) in (34),

$$\begin{aligned}
P_{n+1} &= \frac{P_n}{(n+1)\mu}(\lambda + n\mu) - \frac{(\lambda-\lambda_2)(P_{n-1})}{(n+1)\mu} - \frac{(\lambda_2)(P_{n-2})}{(n+1)\mu} \\
&= \frac{1}{(n+1)\mu}(\lambda + n\mu) \sum_{k=0}^{\lfloor \frac{n}{2} \rfloor} \frac{1}{(n-2k)!2^k k!} \frac{\lambda^{n-2k}\lambda_2^k}{\mu^{n-k}} P_0 \\
&\quad - \frac{(\lambda-\lambda_2)}{(n+1)\mu} \sum_{k=0}^{\lfloor \frac{n-1}{2} \rfloor} \frac{1}{(n-1-2k)!2^k k!} \frac{\lambda^{n-1-2k}\lambda_2^k}{\mu^{n-1-k}} P_0 \\
&\quad - \frac{\lambda_2}{(n+1)\mu} \sum_{k=0}^{\lfloor \frac{n-2}{2} \rfloor} \frac{1}{(n-2-2k)!2^k k!} \frac{\lambda^{n-2-2k}\lambda_2^k}{\mu^{n-2-k}} P_0 \\
&= \sum_{k=0}^{\lceil \frac{n}{2} \rceil} \frac{1}{(n+1)(n-2k)!2^k k!} \frac{\lambda^{n+1-2k}\lambda_2^k}{\mu^{n+1-k}} P_0 \\
&\quad + \sum_{k=0}^{\lfloor \frac{n}{2} \rfloor} \frac{n}{(n+1)(n-2k)!2^k k!} \frac{\lambda^{n-2k}\lambda_2^k}{\mu^{n-k}} P_0 \\
&\quad - \sum_{k=0}^{\lfloor \frac{n-1}{2} \rfloor} \frac{1}{(n+1)(n-1-2k)!2^k k!} \frac{\lambda^{n-2k}\lambda_2^k}{\mu^{n-k}} P_0 \\
&\quad + \sum_{k=0}^{\lfloor \frac{n-1}{2} \rfloor} \frac{1}{(n+1)(n-1-2k)!2^k k!} \frac{\lambda^{n-1-2k}\lambda_2^{k+1}}{\mu^{n-k}} P_0 \\
&\quad - \sum_{k=0}^{\lfloor \frac{n-2}{2} \rfloor} \frac{1}{(n+1)(n-2-2k)!2^k k!} \frac{\lambda^{n-2-2k}\lambda_2^{k+1}}{\mu^{n-1-k}} P_0.
\end{aligned} \tag{38}$$

Continuing with development,

$$\begin{aligned}
P_{n+1} = {} & \frac{1}{(n+1)!}\frac{\lambda^{n+1}}{\mu^{n+1}}P_0 + \frac{1}{(n+1)(n-2)!}\frac{\lambda^{n-1}\lambda_2}{\mu^n}P_0 \\
& + \sum_{k=2}^{\lfloor \frac{n}{2} \rfloor} \frac{1}{(n+1)(n-2k)!2^k k!}\frac{\lambda^{n+1-2k}\lambda_2^k}{\mu^{n+1-k}}P_0 \\
& + \frac{n}{(n+1)!}\frac{\lambda^n}{\mu^n}P_0 \\
& + \sum_{k=1}^{\lfloor \frac{n}{2} \rfloor} \frac{n}{(n+1)(n-2k)!2^k k!}\frac{\lambda^{n-2k}\lambda_2^k}{\mu^{n-k}}P_0 \\
& - \frac{1}{(n+1)(n-1)!}\frac{\lambda^n}{\mu^n}P_0 \\
& - \sum_{k=1}^{\lfloor \frac{n-1}{2} \rfloor} \frac{1}{(n+1)(n-1-2k)!2^k k!}\frac{\lambda^{n-2k}\lambda_2^k}{\mu^{n-k}}P_0 \\
& + \frac{1}{(n+1)(n-1)!}\frac{\lambda^{n-1}\lambda_2}{\mu^n}P_0 \\
& + \sum_{k=1}^{\lfloor \frac{n-1}{2} \rfloor} \frac{1}{(n+1)(n-1-2k)!2^k k!}\frac{\lambda^{n-1-2k}\lambda_2^{k+1}}{\mu^{n-k}}P_0 \\
& - \sum_{k=0}^{\lfloor \frac{n-2}{2} \rfloor} \frac{1}{(n+1)(n-2-2k)!2^k k!}\frac{\lambda^{n-2-2k}\lambda_2^{k+1}}{\mu^{n-1-k}}P_0.
\end{aligned} \tag{39}$$

Making a variable change,

$$\begin{aligned}
P_{n+1} = {} & \frac{1}{(n+1)!}\frac{\lambda^{n+1}}{\mu^{n+1}}P_0 + \frac{1}{(n+1)(n-2)!2}\frac{\lambda^{n-1}\lambda_2}{\mu^n}P_0 \\
& + \sum_{r=0}^{\lfloor \frac{n}{2} \rfloor - 2} \frac{1}{(n+1)(n-4-2r)!2^{r+2}(r+2)!}\frac{\lambda^{n-3-2r}\lambda_2^{r+2}}{\mu^{n-1-r}}P_0 \\
& + \frac{n}{(n+1)!}\frac{\lambda^n}{\mu^n}P_0 \\
& + \sum_{r=0}^{\lfloor \frac{n}{2} \rfloor - 1} \frac{n}{(n+1)(n-2-2r)!2^{r+1}(r+1)!}\frac{\lambda^{n-2-2r}\lambda_2^{r+1}}{\mu^{n-1-r}}P_0 \\
& - \frac{1}{(n+1)(n-1)!}\frac{\lambda^n}{\mu^n}P_0 \\
& - \sum_{r=0}^{\lfloor \frac{n-1}{2} \rfloor - 1} \frac{1}{(n+1)(n-3-2r)!2^{r+1}(r+1)!}\frac{\lambda^{n-2-2r}\lambda_2^{r+1}}{\mu^{n-1-r}}P_0 \\
& + \frac{1}{(n+1)(n-1)!}\frac{\lambda^{n-1}\lambda_2}{\mu^n}P_0 \\
& + \sum_{r=0}^{\lfloor \frac{n-1}{2} \rfloor - 1} \frac{1}{(n+1)(n-3-2r)!2^{r+1}(r+1)!}\frac{\lambda^{n-3-2r}\lambda_2^{r+2}}{\mu^{n-1-r}}P_0 \\
& - \sum_{r=0}^{\lfloor \frac{n-2}{2} \rfloor} \frac{1}{(n+1)(n-2-2r)!2^r r!}\frac{\lambda^{n-2-2r}\lambda_2^{r+1}}{\mu^{n-1-r}}P_0.
\end{aligned} \tag{40}$$

$$
\begin{aligned}
P_{n+1} = {} & \frac{1}{(n+1)!}\frac{\lambda^{n+1}}{\mu^{n+1}}P_0 + \left[\frac{\lambda^{n-1}\lambda_2 P_0}{(n+1)(n-2)!2} + \frac{n\lambda^n P_0}{(n+1)!}\right. \\
& \left. - \frac{\lambda^n P_0}{(n+1)(n-1)!} + \frac{\lambda^{n-1}\lambda_2 P_0}{(n+1)(n-1)!}\right]\frac{1}{\mu^n} \\
& + \sum_{r=0}^{S}\left[\frac{\lambda^{n-3-2r}\lambda_2^{r+2}P_0}{(n-4-2r)!2^{r+2}(r+2)!} + \right. \\
& \frac{n\lambda^{n-2-2r}\lambda_2^{r+1}P_0}{(n-2-2r)!2^{r+1}(r+1)!} - \frac{\lambda^{n-2-2r}\lambda_2^{r+1}P_0}{(n-3-2r)!2^{r+1}(r+1)!} + \\
& \frac{\lambda^{n-3-2r}\lambda_2^{r+2}P_0}{(n-3-2r)!2^{r+1}(r+1)!} - \\
& \left.\frac{\lambda^{n-2-2r}\lambda_2^{r+1}P_0}{(n-2-2r)!2^r r!}\right]\frac{1}{(n+1)\mu^{n-1-r}} + \xi,
\end{aligned}
\tag{41}
$$

where $S =$ minimum value $\left\{\left\lfloor\frac{n}{2}\right\rfloor - 2, \left\lfloor\frac{n}{2}\right\rfloor - 1, \left\lfloor\frac{n-1}{2}\right\rfloor - 1, \left\lfloor\frac{n-2}{2}\right\rfloor\right\} = \left\lfloor\frac{n}{2}\right\rfloor - 2.$

$$
\begin{aligned}
P_{n+1} = {} & \frac{1}{(n+1)!}\frac{\lambda^{n+1}}{\mu^{n+1}}P_0 + \frac{1}{(n-1)!2}\frac{\lambda^{n-1}\lambda_2}{\mu^n}P_0 \\
& + \sum_{r=0}^{S}\frac{\lambda^{n-3-2r}\lambda_2^{r+1}P_0}{(n+1)\mu^{n-1-r}}\left[\frac{\lambda_2}{(n-4-2r)!2^{r+2}(r-2)!}\right. \\
& + \frac{n\lambda}{(n-2-2r)!2^{r+1}(r+1)!} - \frac{\lambda}{(n-3-2r)!2^{r+1}(r+1)!} \\
& \left. + \frac{\lambda_2}{(n-3-2r)!2^{r+1}(r+1)!} - \frac{\lambda}{(n-2-2r)!2^r r!}\right] + \xi.
\end{aligned}
\tag{42}
$$

But

$$
\begin{aligned}
0 = {} & \frac{n\lambda}{(n-2-2r)!2^{r+1}(r+1)!} \\
& - \frac{\lambda}{(n-3-2r)!2^{r+1}(r+1)!} \\
& - \frac{\lambda}{(n-2-2r)!2^r r!} \\
0 = {} & \frac{n\lambda - \lambda(n-2-2r) - 2\lambda(r+1)}{(n-2-2r)!2^{r+1}(r+1)!}.
\end{aligned}
\tag{43}
$$

$$
\begin{aligned}
\therefore P_{n+1} = {} & \frac{1}{(n+1)!}\frac{\lambda^{n+1}}{\mu^{n+1}}P_0 + \frac{1}{(n-1)!2}\frac{\lambda^{n-1}\lambda_2}{\mu^n}P_0 \\
& + \sum_{r=0}^{S}\frac{\lambda^{n-3-2r}\lambda_2^{r+2}P_0}{(n+1)\mu^{n-1-r}}\left[\frac{1}{(n-4-2r)!2^{r+2}(r+2)!}\right. \\
& \left. + \frac{1}{(n-3-2r)!2^{r+1}(r+1)!}\right] + \xi \\
= {} & \frac{1}{(n+1)!}\frac{\lambda^{n+1}}{\mu^{n+1}}P_0 + \frac{1}{(n-1)!2}\frac{\lambda^{n-1}\lambda_2}{\mu^n}P_0 \\
& + \sum_{r=0}^{S}\frac{\lambda^{n-3-2r}\lambda_2^{r+2}P_0}{(n-3-2r)!2^{r+2}(r+2)!\mu^{n-1-r}} + \xi.
\end{aligned}
\tag{44}
$$

Consequently,

$$\begin{aligned} P_{n+1} &= \frac{1}{(n+1)!}\frac{\lambda^{n+1}}{\mu^{n+1}}P_0 + \frac{1}{(n-1)!2}\frac{\lambda^{n-1}\lambda_2}{\mu^n}P_0 \\ &\quad + \sum_{k=2}^{\lfloor \frac{n}{2} \rfloor} \frac{\lambda^{(n+1)-2k}\lambda_2^k P_0}{((n+1)-2k)!2^k k!\mu^{(n+1)-k}} + \xi \\ &= \sum_{k=0}^{\lfloor \frac{n+1}{2} \rfloor} \frac{1}{((n+1)-2k)!2^k k!}\frac{\lambda^{(n+1)-2k}\lambda_2^k}{\mu^{(n+1)-k}}P_0 \\ &= q_{n+1}. \end{aligned} \tag{45}$$

$$\therefore P_n = \sum_{k=0}^{\lfloor \frac{n+1}{2} \rfloor} \frac{1}{(n-2k)!2^k k!}\frac{\lambda^{(n-2k)}\lambda_2^k}{\mu^{(n-k)}}P_0 \quad \forall n \in \mathbb{N}. \tag{46}$$

	$n = 2m$	$n = 2m+1$
$\lfloor \frac{n}{2} \rfloor - 2$	$m-2$	$m-2$
$\lfloor \frac{n}{2} \rfloor - 1$	$m-1$	$m-1$
$\left\lfloor \frac{n-1}{2} \right\rfloor - 1$	$m-2$	$m-1$
$\lfloor \frac{n-2}{2} \rfloor$	$m-1$	$m-1$

If n is even, with $n = 2m$, we have

$$\begin{aligned} \xi &= \frac{m\lambda_2^m P_0}{m!(1+2m)2^{m-1}\mu^m} - \frac{\lambda_2^m P_0}{(1+2m)(m-1)!2^{m-1}\mu^m} \\ &= \frac{-\lambda_2^m P_0}{(1+2m)2^{m-1}\mu^m}\left[\frac{1}{(m-1)!} - \frac{1}{(m-1)!}\right] \\ &= 0. \end{aligned} \tag{47}$$

Also: $\lfloor \frac{n}{2} \rfloor = \left\lfloor \frac{n+1}{2} \right\rfloor$
If n is odd, with $n = 2m+1$, we have

$$\begin{aligned} \xi &= \frac{\lambda_2^{(m+1)}P_0}{(m+1)m!2^{m+1}\mu^{m+1}} + \frac{\lambda[m(-1+m)! - m!]\lambda_2^m P_0}{(1+m)(m-1)!m!\mu^{m-1}} \\ &= \frac{1}{(m+1)!2^{m+1}}\frac{\lambda_2^{(m+1)}P_0}{\mu^{m+1}} \\ &= \frac{1}{\left(n-2\left\lfloor \frac{n+1}{2} \right\rfloor\right)!2^{\lfloor \frac{n+1}{2} \rfloor}\left(\left\lfloor \frac{n+1}{2} \right\rfloor\right)!}\frac{\lambda^{n-2\lfloor \frac{n+1}{2} \rfloor}\lambda_2^{\lfloor \frac{n+1}{2} \rfloor}}{\mu^{n-\lfloor \frac{n+1}{2} \rfloor}}P_0. \end{aligned} \tag{48}$$

Also: $\lfloor \frac{n}{2} \rfloor + 1 = \left\lfloor \frac{n+1}{2} \right\rfloor = m+1$
This completes the proof. □

3. Analytical and Simulated Results

To check and validate the mathematical proof provided in the previous section of what was found, a discrete event simulator was developed, simulating 1,000,000 arrivals for a traffic value for OMA users and a traffic value for NOMA users. In Figure 4, a flowchart of the discrete event simulator is shown. The results for the blocking probability for different values of servers with a comparison of the analytical solution and simulation results from the discrete event simulator are shown in Figure 5.

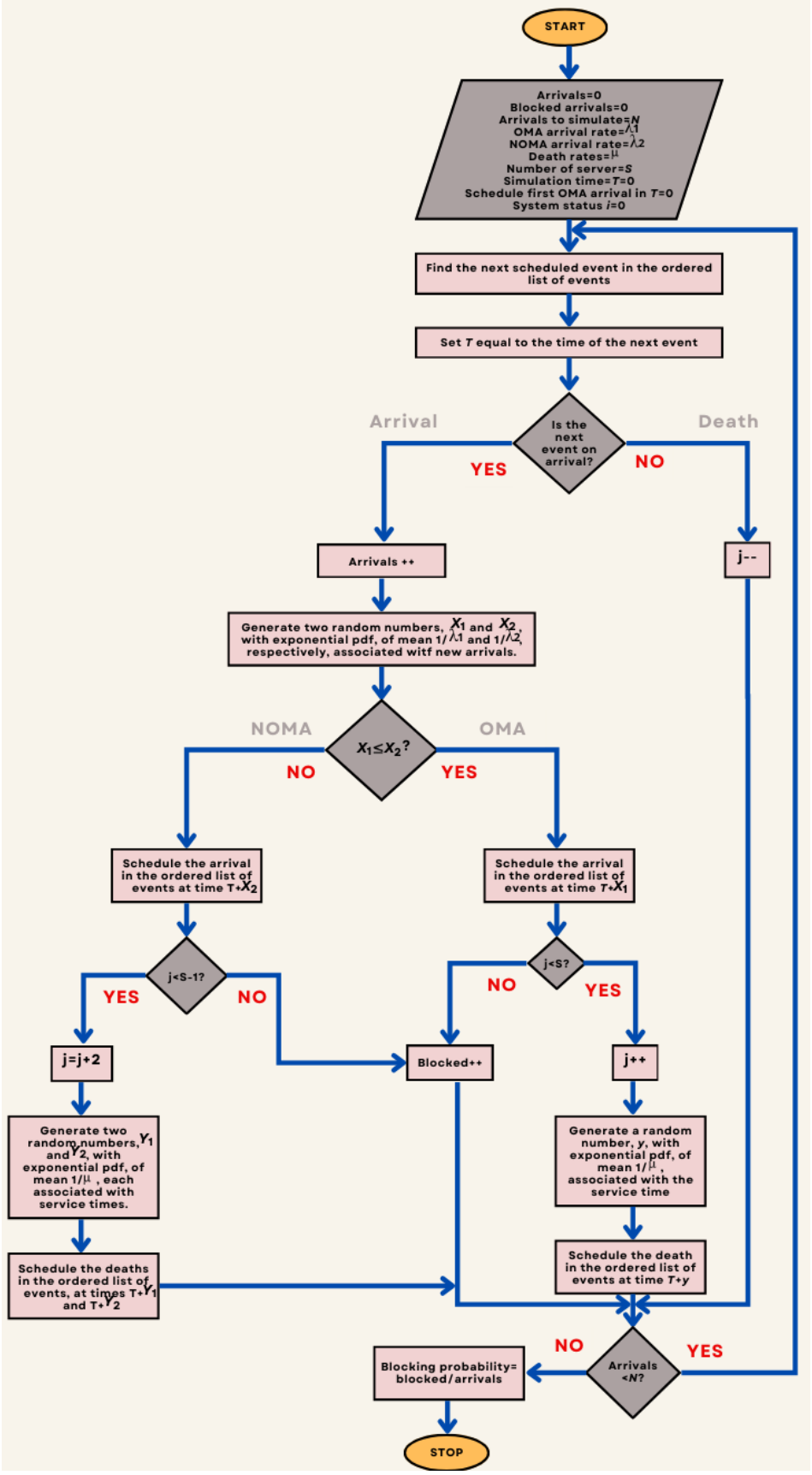


Figure 4. Flowchart.

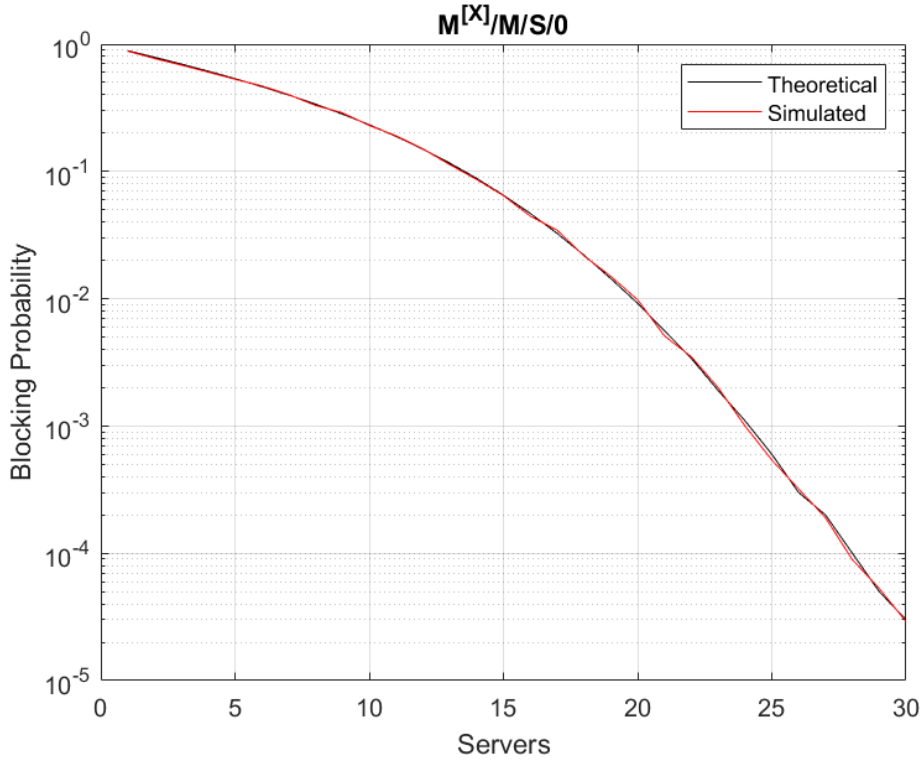


Figure 5. Comparison: analytical vs. simulated.

In Figure 5, it can be seen that the results of the analytical solution are similar to the simulation solution, thus verifying the validity of the proposed model. From Figure 2, Section 2, it can be seen that when the arrival rate for NOMA users is zero ($\lambda_2 = 0$), the model reduces to the Erlang-B model. These results are shown in Figure 6.

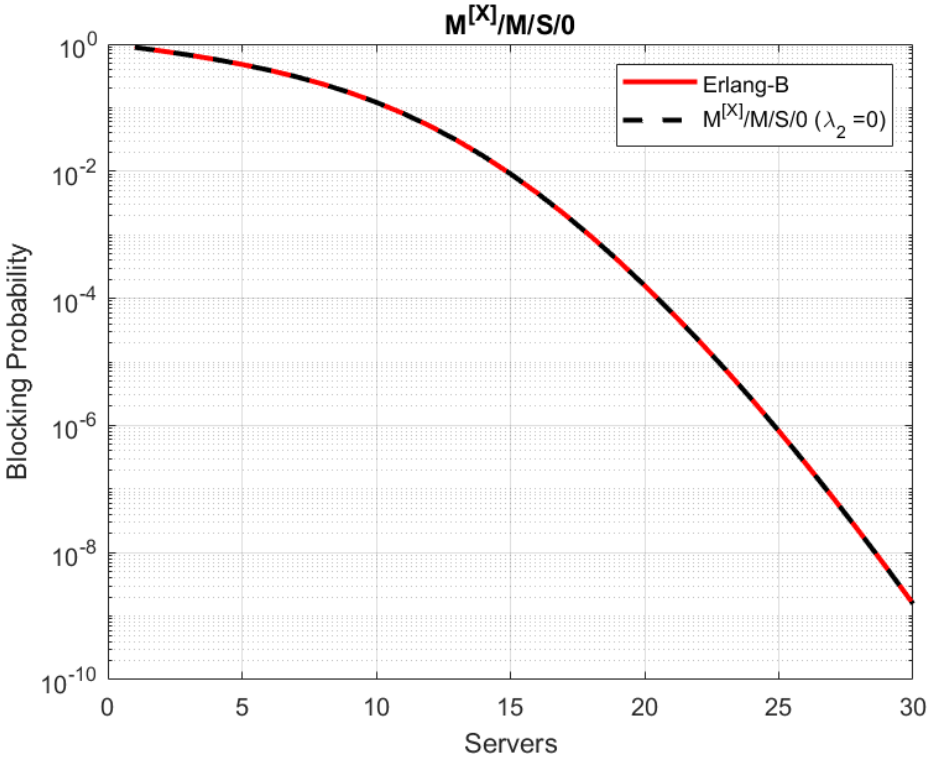


Figure 6. Comparison with $\lambda_2 = 0$.

Figure 7 shows a comparison when OMA user traffic ($\alpha_{OMA} = \frac{\lambda_1}{\mu}$) is greater than NOMA user traffic ($\alpha_{NOMA} = \frac{\lambda_2}{\mu}$), and the opposite case. We can observe that when NOMA arrival traffic is greater, the system has greater blocking probability, given that the number of users doubles. This is shown in Figure 7.

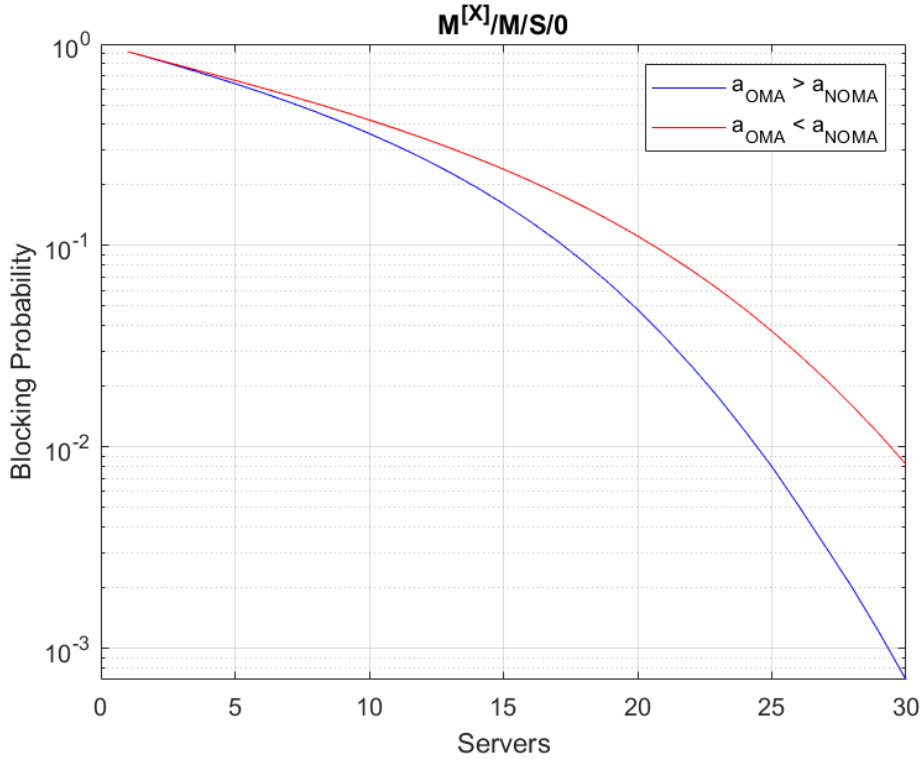


Figure 7. Model evaluation.

4. Conclusions

In this work, we develop a closed-form mathematical model through teletraffic analysis to evaluate the behavior of a cellular network considering non-orthogonal multiple access (NOMA) and orthogonal multiple access (OMA). The model is developed using a Markovian process considering batch arrivals. This procedure has not been published before, since other works represent these parameters assuming models based on the moment generating function and approximation models, without obtaining a closed-form solution. The main contribution of the work is development of an analytical model to find a closed-form mathematical solution to calculate the state probability and the blocking probability of the system. A discrete event simulator is also developed for a cellular network that operates with the OMA and NOMA access techniques. In this simulator, it is possible to evaluate the operation of the system considering different scenarios and obtain quality of service parameters such as the blocking probability of the system. The simulation results are compared with the analytical results found, and both converge. It can be seen that the development of the simulator is complex and computationally demanding, so with the closed-form mathematical solution found, we can evaluate the behavior of the system in a simpler and faster way. Due to the precision of the mathematical model presented, the calculation of a realistic system for different scenarios can be performed in a few seconds compared to simulations and approximation models, where the results take a long time to obtain.

The developed model can be used to evaluate the performance of future communication networks, where new media access schemes are used to increase the capacity of users in the networks and serve different types of services. It can also be used to evaluate cognitive radio networks, for example, a real case in health emergencies, where there are

primary and secondary users, depending on the severity of the patient. It can also be used for mission-critical networks, such as earthquakes, floods, hurricanes, etc., where messages are classified depending on the severity of the scenario.

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Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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

Abbreviations

The following abbreviations are used in this manuscript:

5G-NR	New Fifth-Generation Systems
CDMA	Code Division Multiple Access
CR	Cognitive Radio
EE	Energy Efficiency
FDMA	Frequency Division Multiple Access
IoE	Internet of Everything
IoT	Internet of Things
NGMA	Next-Generation Medium Access
NOMA	Non-Orthogonal Multiple Access
OFDMA	Orthogonal Frequency Division Multiple Access
OMA	Orthogonal Multiple Access
SE	Spectral Efficiency
SIC	Succesive Interference Cancellation
TDMA	Time Division Multiple Access

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