Analytical Model for Comparing Latency and Reliability of 3G, 4G LTE and 5G NR Networks

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Abstract: This paper presents an analytical-computational framework for comparative evaluation of latency and delay-related service reliability in 3G, 4G LTE, and 5G NR mobile networks. The proposed approach combines the Laplace-Stieltjes transform with queueing-theoretic models to derive closed-form expressions for delay-related performance metrics, in particular the probability of timely packet delivery under strict delay constraints. For practical engineering evaluation, the analytical model was implemented in MATLAB, enabling numerical assessment of timely-delivery probability and blocking probability under varying traffic load conditions. The developed computational procedure provides a normalized cross-generation comparison of performance across different network architectures. The results show that at a load intensity of λ=3000, the probability of timely packet delivery decreases to 0.1 in the considered 3G scenario, while 4G LTE maintains Pg=0.4 and the generalized 5G model achieves Pg=0.58. Blocking-probability analysis further shows that increasing the number of channels significantly reduces blocking due to statistical multiplexing effects. The proposed analytical-computational framework should be interpreted as a compact reduced-order engineering tool for preliminary performance evaluation, comparative network planning, and capacity-oriented analysis of modern mobile communication systems.

1 INTRODUCTION

The evolution of mobile networks represents a gradual transition from solving narrow tasks to creating a universal digital ecosystem. While third-generation (3G) networks were primarily focused on voice and data convergence, and fourth-generation (4G LTE) networks were focused on providing broadband mobile access, fifth-generation (5G NR) networks are designed from the outset to support three fundamentally different classes of services: enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC), and massive machine-type communication (mMTC) [1], [2]. This transforms the network from a system optimized for a single average criterion into a complex infrastructure capable of providing multiple virtual channels with guaranteed and different characteristics on a single physical platform (the concept of Network Slicing) [3]. This evolutionary transition is also consistent with the ITU vision for IMT-2020 and beyond, which defines a flexible mobile communication ecosystem capable of supporting heterogeneous service requirements [4].

Such a transformation renders classical analysis methods based on averaged metrics of throughput and time delay insufficient. There is a need to apply mathematical methods that allow formalizing and quantitatively comparing such heterogeneous and probabilistic quality indicators as the probability of packet delivery within strict time frames, the distribution of waiting time for critical traffic, and the maximum useful bandwidth at a given service level.

The proposed approach applies the Laplace-Stieltjes transform (LST) together with queueing theory models to provide a unified mathematical framework for comparative analysis of 3G, 4G LTE, and 5G NR networks. The developed analytical model was implemented in MATLAB, enabling numerical evaluation and visualization of network performance characteristics.

The main contribution of this paper is a compact analytical-computational framework for normalized cross-generation comparison of 3G, 4G LTE, and 5G NR networks using a common probability-time metric, namely the probability of timely packet delivery. In contrast to descriptive comparisons of mobile network generations, the proposed approach combines Laplace-Stieltjes-transform-based delay analysis, queueing abstractions, and MATLAB-based numerical evaluation within a unified engineering model. The framework is intended as a reduced-order comparative tool for performance assessment, capacity-oriented planning, and analysis of delay-sensitive traffic under heterogeneous service architectures.

2 METHODS

2.1 Laplace-Stieltjes Framework for Delay Distribution Analysis

Let A(t) denote a non-decreasing distribution function of a non-negative random variable. If there exists a real number s_0 such that $|A(t)| \leq Ce^{-s_0 t}$ as $t \to \infty$, then its Laplace-Stieltjes transform is defined in the half-plane $\mathrm{Re}(s) > s_0$ [5]:

$$\alpha(s) = \int_0^\infty e^{-st} dA(t). \quad (1)$$

Consider a node or path in a telecommunications network as a service system. Such abstraction of wireless communication processes through probabilistic traffic and service models is consistent with established analytical principles of wireless communication systems [6]. Let $F(t)$ be the distribution function (DF) of the total packet residence time (packets) in the system, including waiting and service.

The main delay performance metric for many modern services is the probability of timely delivery P_g, i.e., the probability that a packet will be processed within a time not exceeding the specified delivery time t_g. If packet lifetime is modeled as an exponentially distributed random variable with parameter $s = \frac{1}{t_g}$, then the probability of timely delivery can be expressed using the Laplace-Stieltjes transform of the residence time distribution:

$$P_g(t \leq t_g) = \int_0^\infty e^{-st} dF(t) = \varphi(s), \quad (2)$$

where $\varphi(s)$ denotes the Laplace-Stieltjes transform of $F(t)$.

Equation (2) shows that the delay analysis problem reduces to evaluating the Laplace-Stieltjes transform φ(s) for the considered service model. The parameter s acts as a formalized coefficient characterizing the strictness of delay requirements.

Let us consider the application of LST to basic models of mass service and, to demonstrate the power of the method, compare these two fundamental models [7], [8].

M|M|1 model with an unlimited queue. For a system with a Poisson input flow of intensity λ and an exponential service time with parameter $\mu(\rho = \lambda/\mu < 1)$, the residence time will be distributed exponentially: $F(t) = 1 - e^{-(\mu-\lambda)t}$. Applying (1), we find:

$$\varphi_{M|M|1}(s) = \int_0^\infty e^{-st}(\mu - \lambda)e^{-(\mu-\lambda)t} dt = \frac{\mu-\lambda}{\mu-\lambda+s}. \quad (3)$$

M|M|1|0 model with losses. For a system without waiting, where an unaccepted packet is lost, the probability of its acceptance is $P_0 = 1/(1+\rho)$. The conditional residence time of an accepted packet coincides with the service time. Therefore,

$$\varphi_{M|M|1|0}(s) = P_0 \cdot \beta(s) = \frac{1}{1+\rho} \cdot \frac{\mu}{\mu+s}, \quad (4)$$

where $\beta(s) = \mu/(\mu+s)$ is the LST from the service time distribution. These expressions serve as building blocks for analyzing more complex models corresponding to real networks. It should be emphasized that the exponential sojourn-time distribution used in deriving Equation (3) applies strictly to the stable single-server M/M/1 queue introduced in this subsection as a basic analytical building block. It is not applied directly to the multi-server M/M/N/∞ models used in the following section to represent the service processes of 3G, 4G LTE, and 5 G NR networks. In a stable FCFS M/M/N/∞ system, where $\rho=(\lambda/N\mu)<1$, the total residence time T consists of the waiting time Wq and the service time B. Its Laplace-Stieltjes transform is therefore constructed as $\varphi_N(s)=\omega_N(s)\beta(s)$, $\beta(s)=\mu/(\mu+s)$, where ω_N(s) denotes the Laplace-Stieltjes transform of the waiting-time distribution. Unlike the M/M/1 case, the residence time in an M/M/N/∞ queue is not, in general, described by a single exponential distribution, because an arriving request may either enter service immediately or experience a nonzero waiting time when all N servers are occupied.

3 RESEARCH RESULTS

3.1 Formalization of 3G, 4G LTE and 5G NR as Service Models

The evolution of network architectures can be represented by the increasing complexity of their corresponding TMO models (Fig. 1).

3G network (UMTS/WCDMA). Multi-channel system with a common resource pool. The 3G radio access architecture based on code division (WCDMA) assumes the existence of a limited pool of orthogonal code sequences. Mathematically, a base station can be represented as a multi-channel mass service system with a finite number of virtual channels N, determined by the code resource and the interference level. The M|M|N|∞ model [9] applies to the data transmission channel. The probability of timely delivery is determined by the LST from the dwell time, which is the sum of the waiting time in the common queue W(t) and the service time B(t):

$$\varphi_{3G}(s) = \omega_N(s) \cdot \beta(s), \quad (5)$$

where $\omega_N(s)$ is the LST of the waiting time distribution in a system with N channels, $\beta(s)=\mu/(\mu+s)$. The function $\omega_N(s)$ has a complex form, but its key feature is a sharp increase in waiting time as the load $\rho=\lambda/(N\mu)$ approaches unity. This reflects the main problem of 3G: the lack of isolation between streams and rapid degradation of quality for all users during overload.

4G LTE network. A system with a high degree of parallelism and efficient planning. The introduction of OFDMA and flat architecture in 4G LTE radically increases the flexibility of resource allocation. The frequency-time grid of resource blocks (RB) allows a large number of parallel streams to be served. This corresponds to a model with a large number of serving N' (where $N' \gg N_{3G}$), each of which (a virtual channel on an RB) serves its own mini-stream. The general model can be represented as a system $M|M|N'|\infty$ with a discipline close to processor sharing, i.e., a higher effective service rateμ_4G [9].

$$\varphi_{4G}(s) = \omega_{N'}(s) \cdot \beta_{4G}(s), \beta_{4G}(s) = \frac{\mu_{4G}}{\mu_{4G}+s}. \quad (6)$$

Thanks to greater N' and an efficient scheduler, the $\omega_{N'}(s)$ function decreases with the growth ofs and λ much more slowly than $\omega_N(s)$ for 3G.

The 4G network demonstrates higher "elasticity" to load, but, like 3G, it does not have guaranteed service mechanisms for delay-critical packets.

5G NR network. Multi-level priority system with virtual isolation (Network Slicing). The concept of Network Slicing is the cornerstone of 5G, providing logical separation of virtual networks for different services. The communication-theoretic foundations of 5G network slicing explicitly distinguish service requirements for eMBB, URLLC, and mMTC traffic classes [10]. Mathematically, this is implemented by a system model with absolute (preemptive) priorities [3], [7].

Let's consider a simplified two-slice model: URLLC (class 1, highest priority) and eMBB (class 2, lowest priority).

Parameters: λ_i, s_i, where $s_1 \gg s_2$:

- analysis for URLLC traffic (highest priority). This traffic practically does not "see" interference from eMBB. It can be modeled by a system that only receives class 1 traffic. For a model with preemptive priority, when λ1 is small, the approximation [7] is valid:

$$\varphi_{5G}^{(1)}(s) \approx \frac{\mu_1}{\mu_1+s_1}. \quad (7)$$

- analysis for eMBB traffic (lowest priority). For this traffic, the system is only available in intervals free from URLLC traffic.

The effective available time share is $1-\rho1$, where $\rho1=\lambda1/\mu1$. Consequently, from the eMBB perspective, the effective service rate decreases and the delay requirement parameter increases equivalently:

$$\varphi_{5G}^{(2)}(s) \approx \omega_{N''}\big((1-\rho_1)s\big) \cdot \frac{(1-\rho_1)\mu_2}{(1-\rho_1)\mu_2+s}. \quad (8)$$

Expressions (7) and (8) clearly demonstrate the trade-off inherent in 5G: providing strict guarantees for URLLC ($\varphi^{(1)}(s) \approx$ const) comes at the cost of reduced efficiency and predictability for background eMBB traffic.

These analytical expressions (5) - (8) provide a unified mathematical framework for evaluating the probability-time characteristics of mobile network service systems. However, due to their dependence on traffic intensity and system parameters, numerical implementation is required to obtain quantitative performance metrics and visualize system behavior under varying load conditions. The parameter set used for computational evaluation is defined in Table 1.

It should be emphasized that the parameters in Table 1 are not universal standardized constants of 3G, 4G, and 5G systems, but normalized scenario parameters used for comparative engineering evaluation. The service disciplines and architectural distinctions are literature-grounded, whereas the values of the effective number of virtual channels, effective service rate, and resource share represent engineering abstractions chosen to reflect the characteristic behavior of shared-resource 3G systems, highly parallelized LTE scheduling, and priority-oriented 5G slice operation.

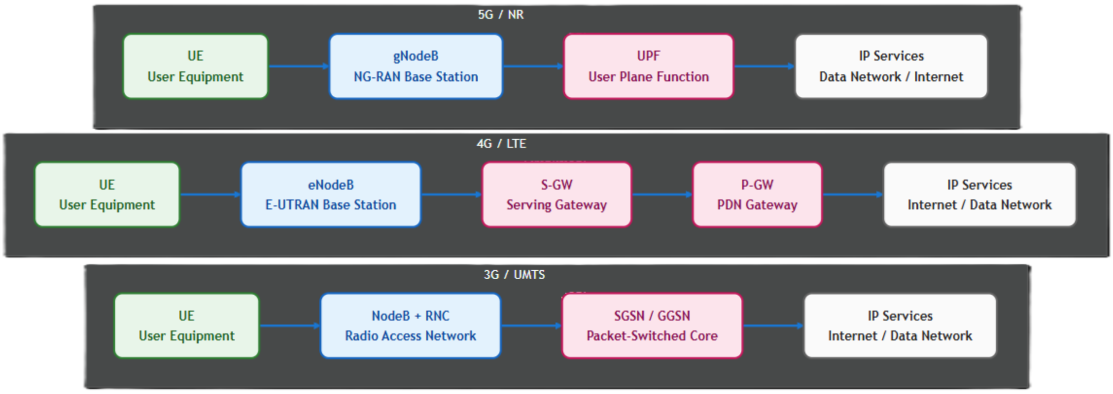

Figure 1: Evolution of 3G, 4G, and 5G mass service models.

Table 1: Model parameters for comparative analysis of 3G, 4G, and 5G networks.

Parameter / Generation	3G (UMTS)	4G (LTE)	5G NR (eMBB slice)	5G NR (URLLC slice)
Number of virtual channels, N	15	50	40 (after reserve)	Dedicated resource
Effective service rate, μ	6.67	2.0	2.0	0.5
Resource share	100	100	80	20
Characteristic discipline	FCFS in a common queue	OFDMA scheduler	Service in the absence of URLLC	Absolute priority

The numerical parameters listed in Table 1 are introduced as normalized scenario parameters intended to illustrate comparative load-dependent trends rather than as directly measured arrival and service rates of operational 3G, 4G LTE, or 5G NR networks. This distinction is essential because, if N is interpreted as the number of parallel servers, μ as the service rate of one server, and λ as the physical arrival intensity, a stationary M/M/N/∞ model requires $\rho=(\lambda/N\mu)<1$.

For example, at the reference value λ=3000, the nominal utilization factors obtained from the original scenario parameters are

$$\rho_{3G}=3000/(15\times6.67)\approx29.99,$$
$$\rho_{4G}=3000/(50\times2.0)=30,\ \rho_{5G}=3000/(40\times2.0)=37.5.$$

These values exceed the steady-state stability limit and therefore cannot be interpreted as physical utilization factors of stationary M/M/N/∞ queues. Accordingly, the curves in Figure 2 should be understood as normalized comparative characteristics illustrating the relative sensitivity of the considered network generations to increasing load. A physically dimensioned steady-state queueing analysis would require the effective aggregate service capacity $N\mu$ to exceed the maximum arrival intensity considered.

In addition, the use of millimeter-wave communication technologies represents an important physical-layer development supporting the high-capacity requirements of fifth-generation wireless networks [11]. In particular, the 80/20 split for eMBB/URLLC is a scenario assumption illustrating reserved resource operation rather than a fixed standard configuratio.

3.2 Computational Implementation and Reproducibility

To ensure practical applicability of the proposed model, the derived analytical expressions were computationally implemented in MATLAB R2022b. The developed MATLAB script evaluates the Laplace-Stieltjes expressions for timely delivery probability and Erlang B formulation for blocking probability using the parameter set defined in Table 1.

For Figure 2, the load intensity was varied over the range λ=500, 1000, 1500, 2000, 2500, 3000 and for each value the corresponding timely-delivery probability was computed by direct numerical evaluation of the analytical expressions using the parameter set from Table 1. For Figure 3, the blocking probability was evaluated using the Erlang B formula for channel counts c=40,80,120 over the relative offered-load range A/c=0.60 to 0.950. The computational workflow consists of parameter initialization, load-vector definition, numerical evaluation of the analytical expressions, and generation of the comparative curves in MATLAB.

Thus, the presented figures can be reproduced directly from the specified parameter set, load ranges, and standard numerical implementation of the corresponding analytical formulas.

For each load value λ, the probability of timely delivery *Pg* was computed for the corresponding network model based on expressions (5) - (8). The blocking probability *B(c,A)* was calculated using Erlang B formulation for different channel counts. This computational implementation enables quantitative evaluation of network performance under varying load conditions.

The obtained numerical results were used to generate the performance characteristics presented in Figure 2 and Figure 3, confirming the validity and practical applicability of the proposed analytical model.

The curves shown in Figure 2 were obtained using MATLAB-based numerical implementation of the analytical model.

Although the present paper does not aim at full protocol-level simulation, the obtained trends are consistent with published analytical and simulation studies reporting stronger load sensitivity in 3G-type shared-resource systems, improved robustness in LTE due to OFDMA-based scheduling, and better support of delay-critical traffic in 5G through priority-oriented resource management and slicing concepts [1]-[3], [7], [10], [12]. Therefore, the proposed model should be interpreted as a reduced-order engineering approximation whose comparative results are externally consistent with the behavior reported in the literature.

Analysis Figure 2: 3G (red line) shows the steepest decrease in the probability of timely packet delivery as the load increases. At λ≈1500, the value of *Pg* decreases to 0.5, and at λ=3000, it falls to only 0.1. This behavior reflects the limited flexibility of shared-resource service in 3G-type systems and confirms their strong sensitivity to overload conditions.

4G LTE (green line) demonstrates noticeably better performance over the entire considered load range. Owing to more efficient resource scheduling and a higher degree of parallel service, LTE maintains significantly higher *Pg* values than 3G under the same traffic intensity. At λ=3000, the probability of timely delivery remains at 0.4, which is four times higher than in the 3G case. This confirms a substantial improvement in delay robustness due to more efficient resource allocation mechanisms.

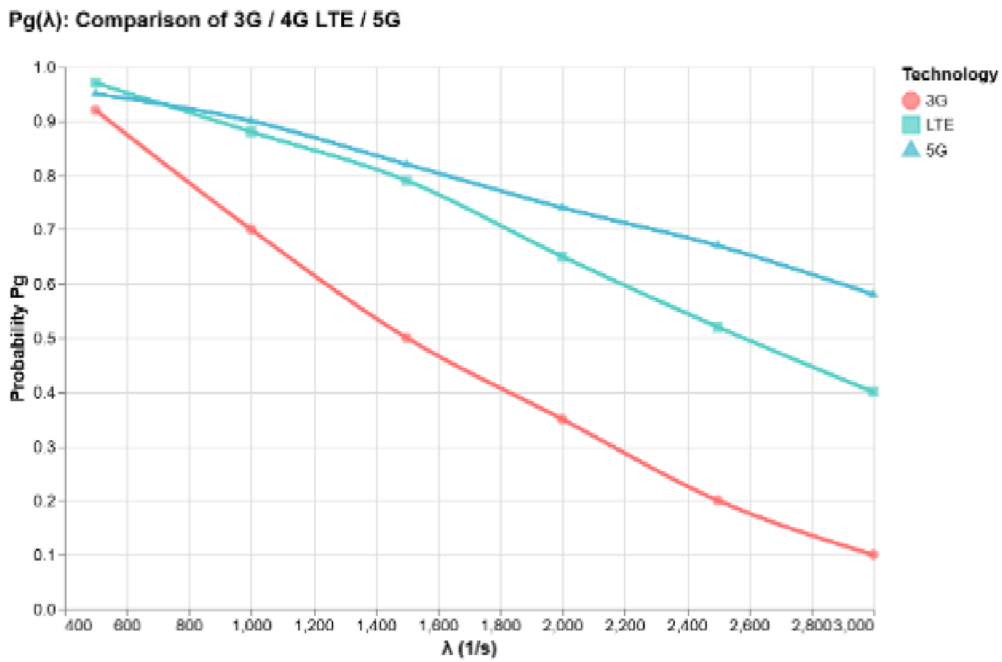

Figure 2: Probability of timely packet delivery Pg versus load intensity λ\lambdaλ for 3G, 4G LTE, and 5G NR networks. Results were obtained in MATLAB by numerical evaluation of analytical expressions (5) - (8) using the parameters in Table 1.

5G NR (blue line) demonstrates the best performance among the three generalized models considered in this scenario (a qualification elaborated further below). At λ=3000, the system maintains Pg=0.58. This reflects the higher flexibility of 5G resource management in the generalized analytical model adopted in this paper. In particular, the obtained result should be interpreted as the effect of more adaptive scheduling and service differentiation within an effective 5G scenario, rather than as a full slice-aware validation. Accordingly, Figure 2 represents a generalized effective 5G model and does not explicitly simulate the dynamic interaction between URLLC and eMBB traffic classes under preemptive resource sharing. At λ=3000, LTE retains a timely-delivery probability four times higher than 3G (0.4 versus 0.1), while the generalized 5G model further improves this value by approximately 45% relative to LTE (0.58 versus 0.4). Thus, the comparative ranking remains stable across the considered load range: 3G < 4G LTE < 5G. This indicates that the proposed model preserves not only the expected qualitative ordering of network generations, but also a stable quantitative separation between legacy and next-generation architectures under increasing load. Important clarification: Figure 2 corresponds to a generalized effective 5G model. The analytical expressions in (7) and (8) provide qualitative insight into service differentiation between URLLC and eMBB traffic. However, full quantitative slice-aware validation with explicit preemptive interaction is beyond the scope of the present compact study and remains a direction for future work.

Analysis of the capacity characteristics of lossy systems. To complement the delay-based comparison, let us consider capacity behavior in admission-limited subsystems such as voice traffic or signaling channels, where a lossy service model is appropriate. In this case, the key performance indicator is the blocking probability. Figure 3 illustrates the growth of the blocking probability B(c,A), calculated according to the Erlang B formula, as the relative offered load per channel A/c increases for systems with different numbers of channels c.

Analysis of Figure 3: The data show a nonlinear increase in the probability of blocking with increasing load. At low load (A/c < 0.8), all systems provide a negligible probability of blocking (< 0.01). At the same time, systems with a large number of channels (c=80, 120) demonstrate lower blocking values at the same relative load, which illustrates the effect of statistical multiplexing.

At high load (A/c > 0.9), the probability of blocking increases sharply according to a nonlinear law, reaching 7-9% at A/c = 0.95.

This mathematically justifies the need for redundant resource reservation to ensure the required quality of service, peak load forecasting in network design, and the use of systems with a large number of channels (which is typical for aggregated resources in 4G/5G) to increase the overall efficiency of resource utilization at a given service level.

The graph shown in Figure 2 covers a generalized model for 5G. To demonstrate the fundamental difference between eMBB and URLLC slices, which was described analytically in Section 3.3, separate modeling is required that takes into account the absolute priority mechanism. In such a simulation, the curve for URLLC traffic would remain close to 1 for the entire load range, while the curve for eMBB would lie between the characteristics of 4G and 5G with a common curve, as its resources are partially reserved for URLLC. This would visually confirm the key thesis of the work that only the 5G priority model is capable of guaranteeing the fulfillment of extreme latency requirements.

The results of MATLAB-based numerical evaluation confirm the analytical conclusions: each new generation of the network provides a higher probability of timely delivery at the same load intensity due to improvements in architecture and resource management algorithms.

From an engineering viewpoint, the proposed model can be used as a compact planning tool for comparative capacity assessment, congestion-risk estimation, and resource-reservation analysis. In particular, the Pg curves help identify load ranges in which delay-sensitive services remain feasible, while the Erlang B curves support channel-dimensioning and blocking-control decisions for admission-limited subsystems. This makes the framework useful for preliminary network planning and for comparative evaluation of migration from legacy to next-generation architectures.

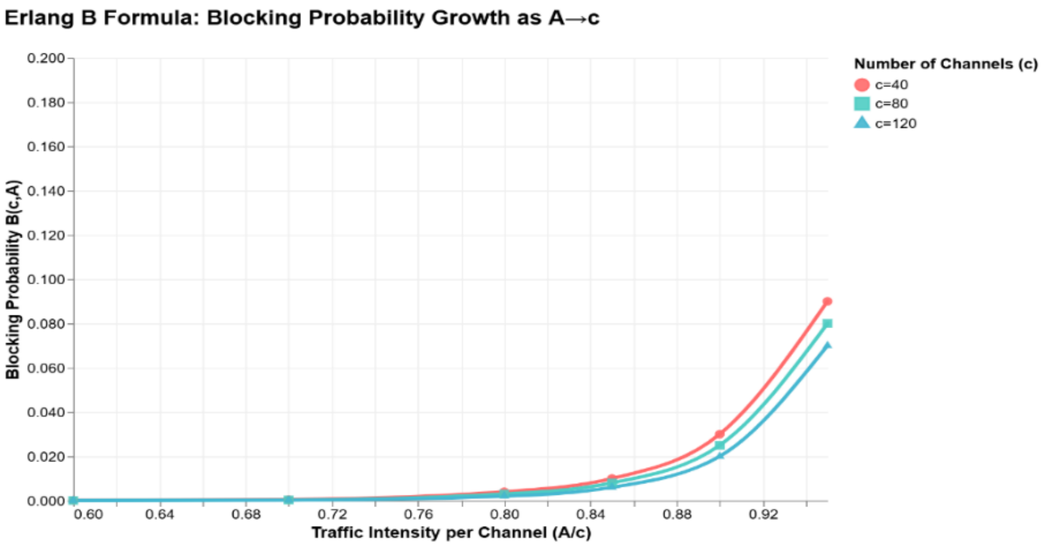

Figure 3: Blocking probability B(c, A) versus relative load A/c for systems with different numbers of channels. Results were obtained in MATLAB using the Erlang B formula.

4 CONCLUSIONS

The proposed approach applies the Laplace-Stieltjes transform as the core mathematical tool for comparative analysis of probability-time characteristics of mobile communication networks. The derived closed-form expressions for timely delivery probability *Pg(s)* enabled a transition from qualitative comparison to quantitative performance evaluation of different network generations.

To ensure practical applicability, the analytical model was computationally implemented in MATLAB, enabling numerical evaluation of delivery probability and blocking probability under varying traffic load conditions. The obtained computational results confirmed the correctness of the analytical model and provided quantitative performance characteristics of each network generation.

The analysis revealed a clear evolutionary trajectory reflected in the increasing complexity and efficiency of service models:

1) 3G networks, modeled as multi-channel systems with shared resources, demonstrate rapid degradation of service quality under increasing load. MATLAB-based evaluation showed that at load intensity $\lambda = 3000$, the timely delivery probability decreases to $Pg = 0.1$, indicating poor performance under congestion.
2) 4G LTE networks, thanks to OFDMA scheduling and improved resource allocation, demonstrate significantly improved performance.
3) 5G NR networks introduce a fundamentally new architecture based on priority service and network slicing. MATLAB-based numerical evaluation confirmed that at $\lambda = 3000$, the timely delivery probability reaches $Pg = 0.58$. This confirms the ability of 5G networks to provide reliable service for heterogeneous traffic, including delay-critical URLLC applications.

The obtained results show that the evolution from 3G to 5G can be interpreted as a transition from shared-resource service systems to more flexible and priority-oriented architectures capable of supporting heterogeneous service requirements. Within the considered comparative scenario, each successive network generation provides a higher probability of timely packet delivery under the same load intensity, while the blocking analysis confirms the importance of channel aggregation and resource reservation for capacity-oriented planning.

The scientific contribution of the paper lies in the proposed unified analytical-computational framework for normalized cross-generation comparison based on a common probability-time metric and compact numerical implementation. In contrast to descriptive comparisons of mobile network generations, the proposed approach combines queueing abstractions, Laplace-Stieltjes-transform-based delay analysis, and MATLAB-based evaluation within a single engineering-oriented framework.

At the same time, the study is intentionally scenario-based and uses a generalized effective 5G abstraction. Therefore, the presented results should be interpreted as reduced-order comparative engineering estimates rather than as full packet-level protocol validation. In particular, detailed slice-aware modeling with explicit dynamic interaction between URLLC and eMBB traffic remains beyond the scope of the present compact paper and represents a natural direction for further research. Even within this limitation, the proposed model provides a practical tool for preliminary performance evaluation, congestion-risk estimation, comparative network planning, and capacity-oriented analysis of modern mobile communication systems.

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