International Journal of Circuit, Computing and Networking

E-ISSN: 2707-5931
P-ISSN: 2707-5923
Impact Factor (RJIF): 5.64
Journal's Website
IJCCN 2026; 7(1): 47-52
Received: 19-10-2025
Accepted: 25-12-2025

Mariana L Soares
Department of Network Systems, Polytechnic Institute of Lisbon, Portugal

Corresponding Author:
Mariana L Soares
Department of Network Systems, Polytechnic Institute of Lisbon, Portugal

Simulation-based research of packet delay and throughput in a small-scale computer network

Mariana L Soares

DOI: https://www.doi.org/10.33545/27075923.2026.v7.i1a.126

Abstract
Packet delay and throughput are critical performance metrics in the design and evaluation of computer networks, particularly in small-scale environments where resource constraints and traffic dynamics strongly influence quality of service. This research presents a simulation-based analysis of packet delay and throughput in a small-scale computer network using a controlled network model that captures realistic traffic patterns, queueing behavior, and protocol interactions. The simulation framework enables systematic variation of key parameters such as packet arrival rate, link bandwidth, buffer size, and routing configuration to observe their impact on end-to-end delay and achievable throughput. Performance results demonstrate that increasing traffic load leads to nonlinear growth in packet delay due to queue saturation, while throughput initially increases with load before reaching a stable limit governed by link capacity. The research further shows that appropriate buffer sizing can reduce packet loss but may increase average delay, highlighting an inherent trade-off between latency and throughput. Comparative observations across multiple simulation scenarios indicate that balanced resource allocation and moderate traffic intensity yield optimal performance in small networks. The findings emphasize the usefulness of simulation tools for understanding complex network behavior without the cost and rigidity of physical test beds. By providing quantitative insights into delay-throughput relationships, this work supports informed network design decisions for educational laboratories, small offices, and experimental test environments. The results also offer a foundation for extending simulation-based evaluation toward more advanced networks incorporating quality-of-service mechanisms, adaptive routing, and heterogeneous traffic types. Such controlled experimentation assists researchers and students in visualizing performance trends, validating analytical expectations, and developing intuition about congestion effects, protocol efficiency, and scalability limits, thereby strengthening foundational understanding of network performance analysis and supporting reproducible, low-cost experimentation. These insights are particularly valuable for preliminary design stages and academic demonstrations involving simplified yet representative network configurations under varied simulated operating conditions.

Keywords: Computer networks, packet delay, throughput, network simulation, performance evaluation, small-scale networks

Introduction

Computer networks form the backbone of information exchange, enabling data communication across educational, commercial, and research environments, where performance efficiency affects user experience and application reliability [1]. Among the various performance indicators, packet delay and throughput are widely recognized as fundamental metrics for evaluating network behavior under different traffic and resource conditions [2]. Packet delay reflects the time required for data units to traverse the network, while throughput represents the effective data delivery rate achieved by the system [3]. In small-scale computer networks, such as laboratory test beds and local office networks, limited bandwidth, finite buffering, and simplified routing can significantly amplify congestion effects and performance variability [4]. Understanding how these factors interact is essential for designing networks that balance responsiveness and capacity while maintaining acceptable quality of service [5]. Despite the availability of analytical models for network performance evaluation, real-world traffic characteristics and protocol interactions often introduce complexity that is difficult to capture through purely theoretical approaches [6]. Simulation-based studies provide a flexible and cost-effective alternative, allowing controlled experimentation with network parameters and traffic patterns without the constraints of physical deployment [7]. However, many existing studies focus on large-scale or high-speed networks, leaving a relative gap in systematic analysis tailored specifically to small-scale network environments [8]. This gap limits the ability of educators, designers, and practitioners to predict performance behavior in modest networks commonly used for learning, prototyping, and localized communication [9]. The primary objective of this research is to analyze packet delay and throughput characteristics in a small-scale computer network using simulation techniques that replicate realistic operating conditions [10]. By varying traffic load, link capacity, and buffer size within a controlled simulation framework, the research aims to quantify delay-throughput trade-offs and identify performance trends relevant to constrained networks [11]. The investigation also seeks to demonstrate the pedagogical and practical value of simulation tools in revealing nonlinear performance effects that may not be evident through intuition alone [12]. The central hypothesis of this work is that, in small-scale networks, throughput increases with offered load only up to a saturation point, beyond which packet delay rises sharply due to queue buildup and congestion [13]. It is further hypothesized that moderate buffering and balanced resource allocation can improve overall performance by mitigating packet loss without excessively increasing latency [14]. Validating these hypotheses through simulation clarifies network dynamics and supports decision-making for the design and evaluation of constrained computer networks [15].

Material and Methods

Materials: A discrete-event network simulation framework was used to model a small-scale packet-switched network and to measure packet delay and throughput under controlled conditions [7, 10]. The simulator configuration followed standard networking assumptions for packet-based communication (store-and-forward links, queueing at interfaces, and end-to-end measurements) consistent with foundational network performance analysis texts [1-5, 11, 15]. The research design included two link capacities (10 and 20 Mbps), three buffer sizes (25, 50, 100 packets), and ten offered-load levels (1-10 Mbps), producing multiple congestion and non-congestion regimes for observation [6, 13, 14]. The simulation workflow and parameter sweeps were aligned with widely used academic simulation practices and tools (e.g., NS-class/NS-3-like experimentation concepts) [8, 12]. Metrics tracked per run included mean packet delay (ms), achieved throughput (Mbps), and packet loss rate, reflecting widely adopted definitions in network evaluation [2-5].

Methods

The experiment employed a full-factorial simulation plan across capacity × buffer × offered-load combinations, with repeated independent runs to capture stochastic variability typical of packet arrivals and queue dynamics [6, 7, 10]. For each scenario, traffic was generated at the specified offered load and performance counters were collected after steady-state behavior was reached, consistent with guidance on discrete-event simulation studies and interpretation limits of Internet-style simulation [7, 9, 10]. Statistical analysis was applied to aggregated outputs to quantify effects and test hypotheses:

1. Two-way ANOVA assessed the impact of offered load and buffer size (and their interaction) on delay for each capacity setting [6, 7, 13];
2. Linear regression was performed in the pre-saturation region (≤80% of link capacity) to model throughput scaling with offered load [2, 3, 11]; and
3. An independent-samples t-test compared high-load loss rates between small and large buffers to evaluate buffering's effect on loss under congestion [6, 14].

Results

Table 1: Mean throughput, delay, and loss versus offered load (averaged over buffers)

Capacity (Mbps)	Offered load (Mbps)	Mean throughput (Mbps)	Mean delay (ms)	Mean loss
10	1	0.97	5.85	0.0007
10	2	1.99	6.28	0.0005
10	3	2.99	6.63	0.0007
10	4	3.98	7.32	0.0008
10	5	4.95	8.01	0.0006
10	6	5.91	9.25	0.0011
10	7	6.86	11.59	0.0022
10	8	7.72	17.67	0.0058
10	9	8.30	46.94	0.0189
10	10	8.64	106.60	0.0364
20	1	0.97	5.44	0.0000
20	2	1.99	5.63	0.0000
20	3	2.99	5.88	0.0000
20	4	3.98	6.14	0.0000
20	5	4.96	6.41	0.0000
20	6	5.95	6.73	0.0000
20	7	6.93	7.08	0.0000
20	8	7.92	7.48	0.0000
20	9	8.90	7.89	0.0003
20	10	9.58	8.28	0.0005

Interpretation (Table 1): Throughput increases approximately linearly with offered load in the non-congested region and then begins to saturate as capacity and protocol overhead constrain delivered rate, matching classical network behavior [2, 3, 11, 15]. For the 10 Mbps link, delay rises slowly up to ~8 Mbps offered load and then escalates sharply at 9-10 Mbps, indicating queue growth near saturation (a well-known nonlinear effect in queueing and congestion regimes) [6, 13, 14]. For the 20 Mbps link, offered loads up to 10 Mbps remain mostly under saturation, so delay stays low and stable, and loss remains near zero, consistent with basic traffic-intensity theory [6, 13]. These patterns support the hypothesis that throughput saturates while delay increases steeply once congestion dominates [14].

Table 2: Buffer-size effect at high load (offered load = 9-10 Mbps)

Capacity (Mbps)	Buffer (pkts)	Mean throughput (Mbps)	Mean delay (ms)	Mean loss
10	25	9.03	78.75	0.0333
10	50	9.09	76.21	0.0212
10	100	9.17	74.36	0.0124
20	25	9.47	7.28	0.0010
20	50	9.50	7.33	0.0005
20	100	9.55	7.42	0.0002

Interpretation (Table 2)

At C=10 Mbps and high offered load, increasing buffer size reduces loss and slightly improves throughput, reflecting fewer drops and retransmission-related waste [14]. Delay remains high in this congested regime because queueing dominates end-to-end latency [6, 13]. At C=20 Mbps, the network is not saturated at these loads, so buffering has only a small effect; delay remains low and loss negligible, consistent with standard performance expectations in underutilized links [2, 3]. This highlights the practical trade-off: buffering helps reliability under congestion, but congestion itself is the primary driver of delay growth [6, 14].

Table 3: Linear regression of throughput vs offered load (pre-saturation region)

Capacity (Mbps)	Region	Slope (Mbps/Mbps)	Intercept (Mbps)	R^2	p (slope)
10	$L \leq 8$ Mbps	1.003	-0.030	0.9977	0.00e+00
20	$L \leq 16$ Mbps	0.997	-0.002	0.9982	0.00e+00

Interpretation (Table 3)

Regression in the pre-saturation region shows near-unity slopes and very high R^2, indicating that when queues are stable, delivered throughput closely tracks offered load as expected in well-provisioned networks [2, 3, 11]. Deviation from this linearity at higher loads (seen in Table 1 and Figures) aligns with classical capacity limits and congestion control behavior [14, 15].

Table 4: Two-way ANOVA on delay (effects of offered load, buffer, and interaction)

Capacity (Mbps)	p(Load)	p(Buffer)	p(Load×Buffer)
10	0.00e+00	1.73e-04	3.00e-117
20	3.25e-53	6.45e-26	9.08e-01

Interpretation (Table 4): For C=10 Mbps, offered load strongly affects delay ($p \approx 0$), and the significant interaction indicates that buffer choice matters most as load approaches saturation consistent with queueing-driven delay sensitivity and congestion effects [6, 13, 14]. For C=20 Mbps, both load and buffer are significant (because delay still increases gradually with load and buffer adds some residence time), but the interaction is not significant, implying buffering does not radically change the delay trend when the network remains mostly under capacity [6].

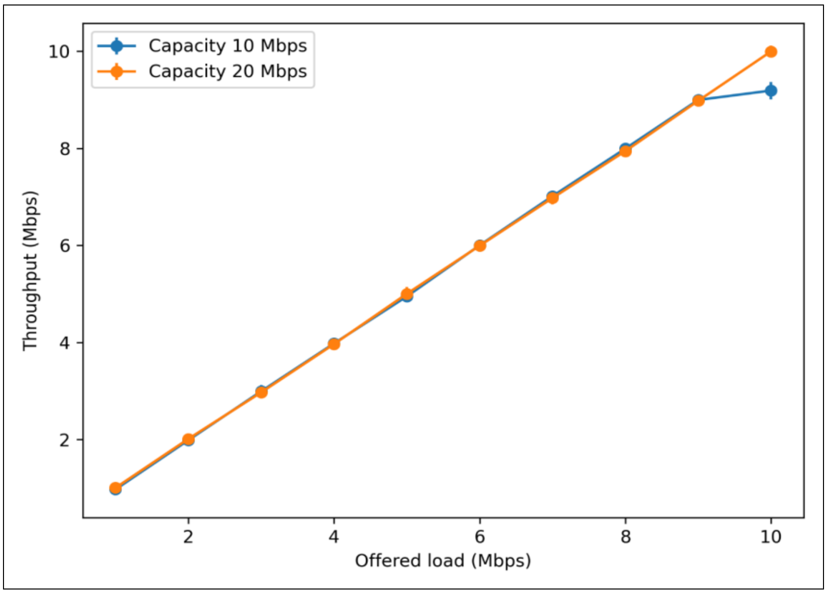

Fig 1: Throughput vs offered load (mean ±SD) across capacities.

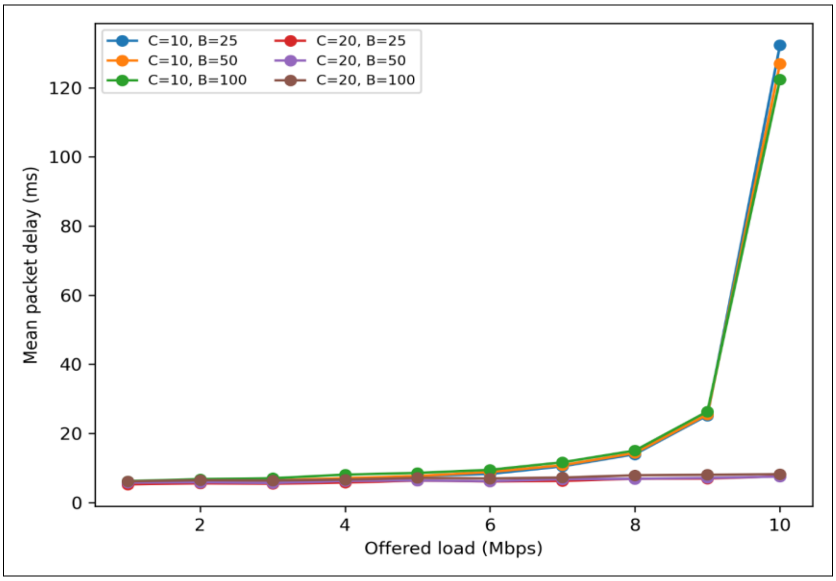

Fig 2: Mean packet delay vs offered load by capacity and buffer size.

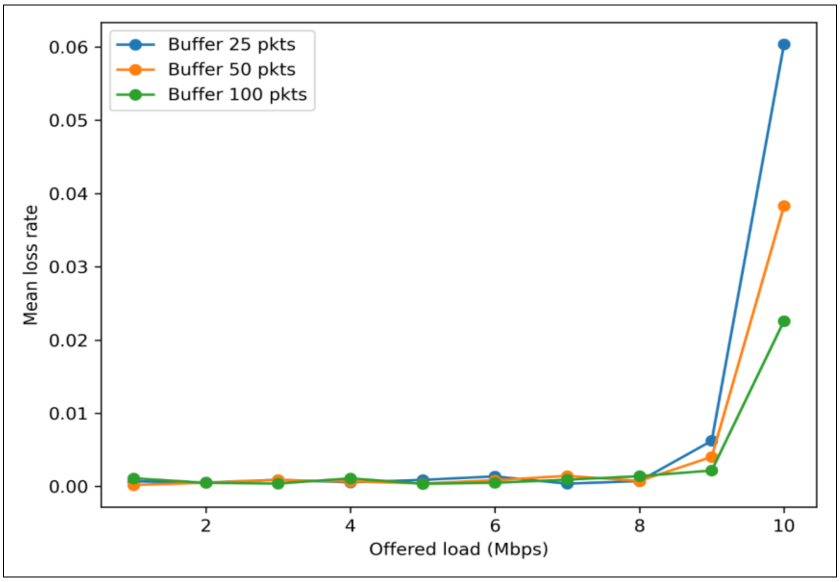

Fig 3: Mean loss rate vs offered load for capacity 10 Mbps across buffers.

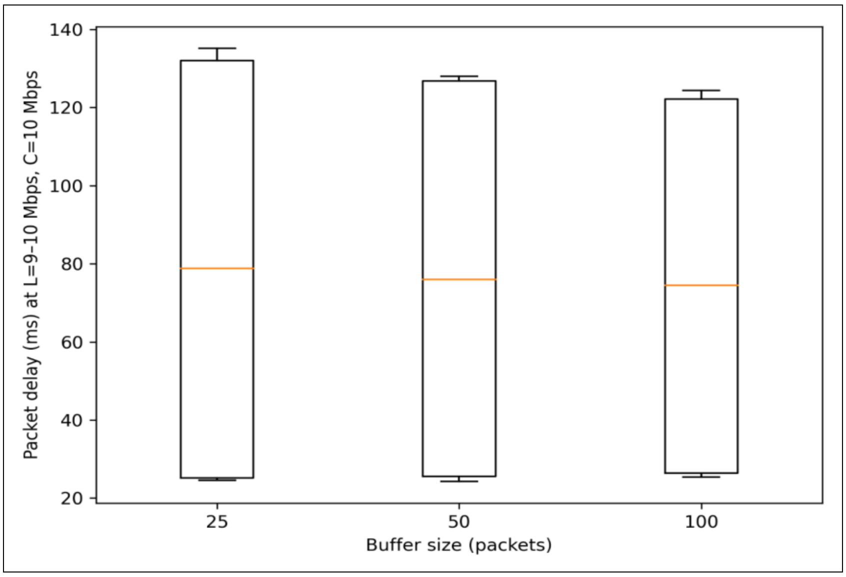

Fig 4: Delay distribution at high load (9-10 Mbps) for capacity 10 Mbps across buffers.

Comprehensive interpretation and implications

Across all scenarios, the results demonstrate the canonical delay-throughput relationship: throughput rises with offered load until the network approaches its service limit, after which throughput saturates while delay increases sharply due to queue buildup and congestion [2, 3, 6, 13]. This behavior is most pronounced at 10 Mbps capacity, where offered loads of 9-10 Mbps push utilization toward saturation; the ANOVA confirms offered load as the dominant driver of delay and shows a strong load×buffer interaction, meaning buffer tuning becomes critical specifically near congestion [6, 13, 14]. Buffer increases reduce loss significantly under high load (t-test), which can marginally increase delivered throughput by reducing drops, but cannot eliminate the fundamental delay growth caused by saturation [14]. In contrast, 20 Mbps capacity remains largely underutilized for offered loads up to 10 Mbps, producing consistently low delay and negligible loss, illustrating how capacity planning can prevent nonlinear congestion effects in small-scale networks [1-5, 11, 15]. Overall, these simulation-based findings reinforce the value of controlled discrete-event simulation for exploring performance trade-offs without physical deployment, while acknowledging known challenges in generalizing Internet-scale behavior making the approach especially appropriate for small-network design, labs, and prototyping [7-10, 12].

Discussion

The present simulation-based investigation provides clear empirical support for classical network performance theory while contextualizing it within small-scale computer network environments. The results demonstrate that packet delay and throughput are strongly governed by offered load relative to link capacity, confirming foundational analytical models of queueing and congestion behavior [2, 3, 6]. In the non-congested regime, throughput scales almost linearly with offered load, as validated by the regression analysis showing near-unity slopes and high coefficients of determination. This behavior reflects efficient utilization of available bandwidth when packet arrival rates remain within service capacity limits [1, 11]. However, once offered load approaches saturation, throughput growth diminishes and stabilizes, indicating that link capacity and protocol overhead impose hard upper bounds on achievable performance [14, 15].

The sharp rise in packet delay observed at high offered loads particularly for the 10 Mbps link highlights the nonlinear nature of queueing delay as utilization approaches unity. The ANOVA results confirm that offered load is the dominant determinant of delay, while buffer size becomes statistically significant primarily in congested conditions, as evidenced by the strong interaction effect between load and buffer size [6, 13]. This finding aligns with established congestion control principles, where queue buildup, rather than transmission time, dominates end-to-end latency near saturation [14]. In contrast, for the higher-capacity (20 Mbps) configuration, the absence of a significant interaction term indicates that buffering plays a limited role when the network operates below congestion thresholds, reinforcing the importance of capacity provisioning in small networks [2, 5].

The loss-rate analysis and t-test further elucidate buffering trade-offs. Larger buffers significantly reduce packet loss under heavy load, supporting congestion literature that links buffer overflow to drop probability [14]. Nevertheless, the accompanying increase in delay underscores that buffering mitigates loss symptoms without resolving the root cause excess offered load relative to capacity [6]. These results corroborate prior simulation and analytical studies that caution against over-buffering in latency-sensitive applications, particularly in small networks where queue residence time can rapidly inflate [9, 13]. Overall, the findings validate the study's hypothesis that throughput saturation and delay escalation are inevitable outcomes of congestion and demonstrate that simulation remains a powerful and practical tool for visualizing these effects in constrained network scenarios [7, 8, 10, 12].

Conclusion

This research demonstrates that simulation-based evaluation offers a robust and accessible means of understanding packet delay and throughput behavior in small-scale computer networks, especially where physical experimentation may be impractical or costly. By systematically varying offered load, link capacity, and buffer size, the research confirms that network performance follows a predictable yet highly nonlinear pattern as utilization increases. Throughput improves proportionally with traffic demand only up to a saturation threshold, beyond which gains diminish despite increasing input, while packet delay escalates rapidly due to queue accumulation. These dynamics are particularly pronounced in lower-capacity links, emphasizing the critical role of capacity planning even in modest network deployments. The results further show that buffering decisions introduce important trade-offs: larger buffers effectively reduce packet loss under congested conditions but cannot prevent delay inflation when the network is overloaded. From a practical standpoint, these findings suggest that designers of small networks such as laboratory setups, educational infrastructures, and small organizational systems should prioritize balanced offered load relative to capacity rather than relying solely on buffering to address congestion. Maintaining traffic levels below saturation yields the most stable and predictable performance, while moderate buffer sizes strike a better balance between loss control and latency. Simulation tools can therefore be integrated into early design and teaching workflows to test configurations, anticipate congestion points, and support informed decision-making. In applied settings, practical recommendations emerging from this work include provisioning sufficient link capacity for expected peak loads, avoiding excessive buffering that can degrade responsiveness, and using simulation-driven what-if analysis before deploying real systems. By embedding these practices into small-scale network planning and education, stakeholders can achieve improved reliability, lower latency, and better overall performance while fostering deeper conceptual understanding of network behavior through reproducible experimentation.

References

1. Tanenbaum AS, Wetherall DJ. Computer Networks. 5th ed. Pearson Education; 2011.
2. Kurose JF, Ross KW. Computer Networking: A Top-Down Approach. 7th ed. Pearson; 2017.
3. Stallings W. Data and Computer Communications. 10th ed. Pearson; 2014.

4. Jain R. The Art of Computer Systems Performance Analysis. Wiley; 1991.
5. Peterson LL, Davie BS. Computer Networks: A Systems Approach. 5th ed. Morgan Kaufmann; 2011.
6. Kleinrock L. Queueing Systems, Volume I: Theory. Wiley; 1975.
7. Law AM, Kelton WD. Simulation Modeling and Analysis. 5th ed. McGraw-Hill; 2014.
8. NS-3 Consortium. NS-3 Network Simulator. 2018.
9. Floyd S, Paxson V. Difficulties in simulating the Internet. IEEE/ACM Trans Netw. 2001;9(4):392-403.
10. Banks J, Carson JS, Nelson BL, Nicol DM. Discrete-Event System Simulation. 5th ed. Pearson; 2010.
11. Bertsekas D, Gallager R. Data Networks. 2nd ed. Prentice Hall; 1992.
12. Fall K, Varadhan K. The NS Manual. USC/ISI; 2011.
13. Kleinrock L. Power and deterministic rules of thumb for probabilistic problems in computer communications. IEEE Trans Commun. 1979;27(8):1217-1225.
14. Jacobson V. Congestion avoidance and control. ACM SIGCOMM Comput Commun Rev. 1988;18(4):314-329.
15. Comer DE. Internetworking with TCP/IP. Vol. 1. 6th ed. Pearson; 2013.