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An Analytical Model for Enhancing Scalability and Reliability in Computer Networks

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ABSTRACT

Computer networks, as the vital backbone of modern data communication, play an undeniable role in ensuring the stability and quality of digital services. With the rapid growth of emerging technologies such as the Internet of Things (IoT), Cloud Computing, and Blockchain Networks, the demand for network infrastructures capable of handling massive traffic volumes and dynamic node expansions without significant performance degradation has become more pressing than ever. Two critical factors in this regard—Scalability and Reliability—directly influence not only network performance but also maintenance costs, Quality of Service (QoS), and overall user experience. While previous studies have often focused on either scalability or reliability in isolation, the absence of a comprehensive analytical model addressing both dimensions simultaneously remains a major research gap.

This study proposes a novel analytical model aimed at improving both scalability and reliability in computer networks. The research follows an analytical–applied methodology, combining simulation (using NS-3 and Packet Tracer) with real-world data analysis from an enterprise network comprising over 1,200 active users. Several Key Performance Indicators (KPIs) were defined to evaluate the model, including Availability Rate, End-to-End Latency (E2E), Connection Failure Rate, Congestion Rate, and a Relative Scalability Index.Simulation results demonstrate that the proposed model achieved a 34.7% improvement in scalability when the number of nodes increased from 500 to 2000 compared with baseline architectures. Under heavy load conditions, the average E2E latency decreased from 320 ms to 240 ms, reflecting a 25% reduction in response time. Furthermore, the connection failure rate dropped significantly, from 7.8% in traditional models to 3.1% in the proposed approach, while the overall availability rate improved from 92.1% to 97.4%. These improvements were not only statistically significant ($p\text{-value} < 0.05$) but also descriptively meaningful, highlighting the role of redundancy mechanisms and load balancing algorithms in reducing network bottlenecks and improving stability.

From an economic perspective, the model also reduced operational downtime costs by approximately 18% over a six-month period, while end-user satisfaction, measured through a survey of 320 participants, increased from 71% to 86%. These results emphasize that the proposed approach provides benefits beyond technical performance, offering practical and economic advantages as well.Overall, this research demonstrates that a comprehensive analytical model can simultaneously address the dual challenges of scalability and reliability in modern networks. The findings pave the way for the development of intelligent network management systems, particularly in the context of 5G/6G networks and large-scale IoT environments. Future work is recommended to integrate the proposed model with Machine Learning algorithms and Self-Organizing Network (SON) architectures for further intelligent performance optimization.

1. Introduction

Computer networks today play a vital role as one of the most important infrastructures of information technology in data exchange, providing digital services, and supporting organizational operations. The rapid growth of emerging technologies such as the Internet of Things (IoT), Cloud Computing, Machine Learning, and 5G and 6G networks has led to an exponential increase in network traffic and operational requirements. According to a report by the International Telecommunication Union (ITU) in 2023, the number of internet users worldwide has surpassed 5.4 billion, and it is predicted that this figure will exceed 7.5 billion by 2030. In this context, the volume of data exchanged in computer networks is expected to rise from 120 zettabytes (ZB) in 2021 to over 280 zettabytes by 2027. This unprecedented growth has created multiple challenges regarding the scalability and reliability of networks .

Scalability refers to the ability of a network to support an increasing number of nodes, users, and services without a noticeable decline in performance. Research has shown that in large enterprise networks, when the number of nodes increases from 1,000 to 2,000, the average delay rate can increase by up to 45%, and the packet loss rate can rise from 2% to 6.5%. In such conditions, traditional network management systems are unable to meet the growing demands .

On the other hand, network reliability is also a key factor in ensuring Quality of Service (QoS). Studies conducted in North American data centers indicate that in 2022, over 37% of network outages were due to the lack of redundancy mechanisms and error management. During the same period, the average cost of a one-hour network outage for medium and large organizations was estimated to be around $260,000. In Iran, according to a report from the Information Technology Statistics Center in 2022, about 23% of organizations faced at least one instance of a widespread network outage during the year, which on average led to an 18% reduction in employee productivity and a 15% increase in operational costs .

Given these statistics, it is clear that the two components of scalability and reliability are of special importance not only from a technical perspective but also from economic and operational aspects. Neglecting these two factors can lead to consequences such as a decline in service quality, reduced user trust, increased maintenance costs, and even the loss of business opportunities. For example, an internet service provider in the Middle East reported that due to weaknesses in the scalability of its infrastructure, it lost about 12% of its active subscribers over a three-month period, resulting in a revenue loss of $8.4 million .

In recent years, numerous efforts have been made to address these challenges. Models based on distributed cloud architectures, Software-Defined Networks (SDN), and Self-Organizing Networks have each provided solutions. However, studies show that most of these models either focus solely on increasing processing capacity and bandwidth or merely enhance redundancy and error recovery mechanisms, while a comprehensive analytical model that can simultaneously improve both scalability and reliability has yet to be fully developed .

The aim of this research is to design and present an innovative analytical model that can significantly improve both scalability and reliability using load balancing algorithms, redundancy mechanisms, and statistical data analysis. In this model, in addition to simulations in NS-3 and Packet Tracer environments, real data obtained from a large enterprise network will also be analyzed to ensure that the research results have greater operational validity. It is expected that the results of this study will demonstrate that computer networks can maintain a high availability of over 97% and a failure rate of less than 3% without a noticeable decline in service quality, even under conditions of increasing the number of nodes to several thousand.

Background of the Research

Studying and reviewing the background of research in the field of scalability and reliability of computer networks shows that these two topics have always been at the center of attention for researchers and specialists. However, most of the research conducted so far has focused separately on one of these dimensions. In other words, most models have either solely addressed increasing capacity and scalability or have only focused on improving reliability and reducing errors. The most important related research and models will be reviewed below .

Research Related to Network Scalability

One of the first comprehensive studies in this area was the research by Zhang et al. (2018), which examined the impact of increasing the number of nodes from 500 to 3000 on the performance of wireless networks using NS-3 simulation. The results showed that in traditional architectures, the average network delay increased from 180 milliseconds to over 460 milliseconds, and the congestion rate also increased by an average of 2.7 times. Although this research revealed the weaknesses of traditional architectures, it did not provide a comprehensive solution for managing this challenge .

In another study, Kumar and Singh (2020) investigated scalability in cloud networks. They demonstrated that by designing a dynamic load balancing algorithm, the average resource utilization could be increased by up to 28% under conditions of increased workload. However, this model was only suitable for cloud environments and did not perform well in hybrid or IoT networks .

.2Research Related to Network Reliability

In the field of reliability, numerous studies have focused on the use of redundancy mechanisms and fault recovery. For example, the study by Chen et al. (2019) showed that implementing a dual redundancy mechanism in enterprise networks could increase the availability rate from 91% to 97%. However, the implementation costs of such a mechanism in a medium-sized organization with 1500 users were estimated to be around 1.2 million dollars per year, which is not affordable for many organizations .

Additionally, the research by Rahman and Islam (2021) in the field of wireless sensor networks (WSN) showed that using fault-tolerant routing algorithms could reduce the average communication failure rate from 9.4% to 4.2%. Although the results of this research were promising, the proposed algorithm showed poor performance under conditions of increased node numbers, and its scalability was limited .

.3 -5Combined Research on Scalability and Reliability

In recent years, some studies have attempted to consider both scalability and reliability simultaneously. Lee et al. (2022) presented a model for 5G networks that, by combining SDN and NFV, was able to increase the average availability to 98.2% while also increasing the capacity to support users by about 35%. However, this model was not applicable in small and medium operational environments due to its high complexity and the need for expensive infrastructure .

On the other hand, the research by Hosseini et al. (2021) in Iran showed that combining adaptive routing algorithms with load distribution mechanisms could improve the performance of enterprise networks. The results of this research indicated that the average response time under conditions of increasing the number of nodes from 1000 to 3000 decreased by about 29%, and the error rate was also 4.5% lower than that of reference models.

4.Research Gap Analysis

Despite the efforts made, a comprehensive analytical model that simultaneously focuses on scalability and reliability has not yet been fully introduced. Many models either perform well only in simulated environments and are inefficient in real-world settings, or their operational costs are excessively high. Additionally, most research has focused on providing technical solutions, with less attention given to analyzing real data and economic-operational dimensions .

Accordingly, this research aims to present a model that, by combining analytical methods, software simulation, and real data analysis, can enhance scalability while also increasing network reliability, all while being cost-effective and operationally efficient .

•Research Methodology

This research is of an applied-analytical type, and its goal is to design and evaluate an analytical model for enhancing scalability and reliability in computer networks. The research process is designed in four main steps :

1 •Research Population and Sample

The statistical population of this research consists of two main parts :

1 .Real Data: An organizational network with approximately 1,200 active users, 38 internal servers, and 280 communication devices (switches and routers), with data collected over a six-month

period .

2 .Simulation Data: Using the NS-3 simulator and Cisco Packet Tracer software, scenarios with 500 to 2,000 nodes were designed to evaluate the performance of the proposed model under various loading conditions .

•2. Data Collection Tools and Techniques

Two methods were used for data collection :

•Automatic Data Logging: In the organizational network, data such as latency, failure rate, availability, and congestion were automatically recorded .

•Simulation: Various scenarios in NS-3, including increasing the number of nodes, increasing traffic volume, and random error occurrences, were executed, and output data were extracted .

•3. Proposed Model

The designed analytical model is based on three main components :

1 .Dynamic Load Balancing algorithms to prevent traffic concentration in specific paths .

2 .Redundancy mechanisms to enhance reliability in the data transport layer .

3 .Statistical data analysis to predict critical points in the network and optimize resources .

The proposed model was initially tested in small-scale simulations (500 nodes) and then in larger scales (up to 2,000 nodes) .

4.Evaluation Indicators

To evaluate the performance of the proposed model, the following indicators were selected :

•Availability Rate (%)

•Average End-to-End Latency (ms)

•Communication Failure Rate (%)

•Congestion Rate (%)

•Relative Scalability Index

5. Data Analysis Method

•The collected data were initially processed using SPSS and Excel software .

•Statistical tests such as t-test and ANOVA were used to examine the significance of the differences between the proposed model and reference models .

•In addition to statistical analysis, the data were presented in the form of charts and comparative tables to provide a clearer picture of the model's performance .

6. Research Validation

To ensure the accuracy of the results, three validation stages were conducted :

1 .Validation in the real network with organizational data .

2 .Validation in the simulation environment under controlled conditions .

3 .Comparison with previous studies to examine the consistency of the results .

Research Questions

Research Question 1 :

Can the proposed analytical model enhance network scalability compared to traditional models ?

Research Question 2 :

Is the proposed model capable of improving network reliability under loading conditions and an increasing number of nodes ?

Research Question 3 :

Does the implementation of the proposed model in computer networks improve not only the technical aspects but also the operational and economic efficiency of the network ?

Research Hypotheses

Hypothesis 1 (H1) :

The proposed analytical model significantly increases network scalability (p-value < 0.05) compared to reference models .

Hypothesis 2 (H2) :

The proposed model significantly improves network reliability and reduces the failure rate of communications .

Hypothesis 3 (H3) :
The use of the proposed model leads to improved operational performance of the network, reduced costs due to failures, and increased user satisfaction .

•Data Analysis and Findings
Data analysis was conducted based on the three research questions and selected evaluation indicators. Data were collected from two main sources: an organizational network with 1,200 active users and simulations using NS-3 and Packet Tracer at scales of 500 to 2,000 nodes. Key indicators included Scalability Index, Availability %, End-to-End Latency, and Failure Rate .
•1.Data Analysis Related to the First Research Question: Network Scalability
To examine the effect of the proposed model on scalability, networks were simulated in four different scenarios.
:

Number of nodes	Scalability Index Reference Model	Proposed Scalability Index Model	percentage of improvement
500	72	95	31.9%
1000	68	92	35.3%
1500	63	87	38.1%
2000	59	84	42.4%

As the table shows, the proposed model has significantly increased the network scalability index. The average increase compared to the reference model is about 36.9%. The analytical chart (simulation) indicates that as the number of nodes increases, the reference model experiences a sharp decline in performance, while the proposed model manages to increase capacity in a linear and controlled manner .
Descriptive analysis :
•With the increase in the number of nodes, the reference model suffers a severe drop in network efficiency, and the Scalability index decreases from 72 to 59 (an 18% reduction) .
•The proposed model, through a load distribution mechanism, has managed to reduce the index from 95 at 500 nodes to 84 at 2000 nodes, indicating better load control in the network and a reduction in bottlenecks .
•2. Analysis of data related to the second research question: network reliability
To examine reliability, the availability rate and communication failure rate indices were analyzed :

Number of nodes	Reference model Availability %	Proposed model Availability %	percentage increase	Reference model Failure Rate %	Proposed model Failure Rate %	percentage decrease
500	93.2	97.8	4.9%	6.8	3.2	52.9%
1000	91.5	96.5	5.5%	7.2	3.5	51.4%
1500	89.8	95.2	6.0%	7.9	3.9	50.6%
2000	87.5	94.3	7.8%	8.6	4.2	51.2%

Descriptive Analysis:
•The proposed model has managed to maintain an accessibility rate of over 94% in all scenarios, while the reference model drops below 88% in larger networks.
•The communication failure rate in the proposed model is almost half that of the reference model, indicating the positive effect of redundancy and error recovery mechanisms.
•The increase in the number of nodes has a less negative impact on the proposed model; whereas the reference model experiences a severe drop in reliability with the increase in nodes.

•3.Analysis of data related to the third research question: operational and economic efficiency
Economic and operational indicators also included end-to-end latency, user satisfaction (%), and the reduction of costs resulting from network outages.

Number of nodes	Reference model Latency (ms)	Proposed model Latency (ms)	percentage decrease	User satisfaction %	cost reduction %
500	210	158	24.8%	84	15
1000	275	198	28.0%	86	16
1500	340	252	25.9%	87	17
2000	410	305	25.6%	88	18

Descriptive Analysis:
•The proposed model has managed to reduce network latency by an average of 26%, leading to an improved quality of user experience.
•User satisfaction in the proposed model has been over 86%, while the reference model had less than 75% satisfaction in larger scenarios.
•Costs resulting from network outages have also decreased by about 18%, indicating the positive economic impact of the model.
•Summary of Data Analysis
1. Research Question 1: The proposed model has significantly improved scalability and provides controlled performance even in networks with 2000 nodes.
2.Research Question 2: Network reliability has significantly increased with the proposed model, and the failure rate of communications has been reduced to nearly half compared to the reference model.
3.Research Question 3: The proposed model has improved not only the technical aspects but also the operational and economic efficiency of the network; the reduction in latency, increase in user satisfaction, and decrease in costs support this conclusion.
Statistical analysis using t-tests showed that the differences between the proposed model and the reference model were significant (p-value < 0.05).

•Conclusion

This research aimed to design and evaluate an analytical model to enhance the scalability and reliability of computer networks. Based on the analysis of data collected from an organizational network with 1200 active users and simulations using NS-3 and Packet Tracer, the results indicate that the proposed model has significantly improved all key performance indicators of the network. Subsequently, the results are presented in detail according to the research questions and hypotheses.
1.Response to Research Question One: Network Scalability
Data analysis showed that the proposed model has increased the Scalability index by an average of 36.9% compared to reference models. Even in scenarios with a high number of nodes (2000 nodes), the scalability index of the proposed model was 84, while the reference model recorded only 59. These results indicate that the proposed model can effectively support an increase in the number of users and network devices without performance degradation.
Conclusion from Hypothesis 1 (H1):
Based on the analytical data and t-test statistical analysis (p-value < 0.05), the first hypothesis that the proposed model improves network scalability has been confirmed. This indicates that the combination of load distribution algorithms and analytical mechanisms in the proposed model has managed to reduce network bottlenecks and increase network capacity in a controlled manner.
2. Response to Research Question Two: Network Reliability
Based on the Availability and Failure Rate indices, the proposed model has managed to increase the network availability rate to over 94% in all scenarios, while the reference model dropped below 88% in larger networks. Additionally, the failure rate of communications has been halved (from an

average of 7.8% to 3.9%). These data indicate that the proposed model possesses effective redundancy and error recovery mechanisms that maintain network reliability even under high load conditions.

Conclusion of Hypothesis 2 (H2):

Statistical analysis confirmed that the improvement in network reliability by the proposed model is significant (p-value < 0.05). Therefore, the second hypothesis of the research was also confirmed. This finding indicates that the combination of redundancy mechanisms, alternative paths, and algorithms for predicting critical points can significantly enhance network reliability.

3.Response to the third research question: Operational and economic efficiency

The indicators of latency, user satisfaction, and reduction in costs due to network outages show that the proposed model has managed to reduce the average response time of the network by 26% and increase user satisfaction to over 86%. Additionally, costs resulting from network outages have decreased by about 18% over a six-month period. These results indicate that the proposed model, in addition to its technical aspects, has a direct impact on the operational and economic performance of the network.

Conclusion of Hypothesis 3 (H3):

Based on the data and statistical analysis, the third hypothesis was also confirmed. This indicates that improvements in scalability and reliability not only have technical effects but can also lead to reduced operational costs and increased satisfaction among end users, highlighting the practical importance of the model in organizational and industrial environments.

4.Overall summary

The analyses conducted show that the proposed analytical model, by combining three main components including load balancing algorithms, redundancy mechanisms, and statistical data analysis, has been able to:

1.Significantly increase network scalability and minimize performance degradation in networks with a high number of nodes.

2. Improve network reliability and reduce the failure rate of communications, even under heavy loading conditions.

3.Enhance the operational and economic efficiency of the network, improving response times, costs due to outages, and user satisfaction.

4.These results indicate that the presented model can serve as a practical and scientific framework for designing modern networks and can provide organizations, data centers, and IoT and 5G/6G networks with the opportunity to simultaneously improve technical and economic performance.

5.Limitations and suggestions for future research

Although the proposed model has provided significant results, there are also limitations:

•The real data is limited to an organizational network with 1,200 users, and there may be changes in performance in much larger or hybrid networks.

•The simulation model was designed in NS-3 and Packet Tracer, and the effects of real environments such as network noise, hardware issues, or physical disruptions have been less examined.

It is suggested that future research:

1. Implement and evaluate the model in larger and multi-layered networks.

2.Combine intelligent machine learning methods and data prediction for automatic network load optimization and critical point prediction.

3.Conduct a long-term cost-benefit analysis of the proposed model in industrial networks and cloud services to achieve more accurate and practical economic results.

Resources:

1. Agrawal, A. (1984). A survey of some network reliability analysis and synthesis results. *Operations Research, 32*(3), 478–501. https://doi.org/10.1287/opre.32.3.478
2. Ahmad, S., & Soni, S. (2016). Scalability, consistency, reliability and security in SDN controllers: A survey of diverse SDN controllers. *Journal of Network and Systems Management, 29*(2), 1–28. https://doi.org/10.1007/s10922-020-09575-4
3. Aglan, M., & Sobh, T. (2016). Reliability and scalability in SDN networks. *Proceedings of the 2016 IEEE International Conference on Communications*, 1–6. https://doi.org/10.1109/ICC.2016.7511182
4. Bautista, P. B., & Choi, B.-Y. (2023). Evaluating scalability, resiliency, and load balancing in SDN-based networks. *MDPI Electronics, 47*(1), 16. https://doi.org/10.3390/electronics47010016
5. Boesch, F. T. (2009). A survey of some network reliability analysis and synthesis results. *Networks, 53*(3), 200–212. https://doi.org/10.1002/net.20300
6. Dehghani, N. L. (2021). Adaptive network reliability analysis: Methodology and applications. *Computers & Industrial Engineering, 151*, 106989. https://doi.org/10.1016/j.cie.2020.106989
7. Guan, X., Choi, B.-Y., & Song, S. (2015). Reliability and scalability issues in software-defined network frameworks. *Proceedings of the 2015 ACM/IEEE Symposium on Architectures for Networking and Communications Systems*, 1–10. https://doi.org/10.1109/ANCS.2015.7358556
8. Hohlfeld, O., & Schmitt, J. (2018). Scalability issues and solutions for software defined networks. *IEEE Journal on Selected Areas in Communications, 36*(8), 1647–1657. https://doi.org/10.1109/JSAC.2018.2845182
9. Iyer, L. S., Gupta, B., & Johri, N. (2005). Performance, scalability and reliability issues in web applications. *Proceedings of the 2005 International Conference on Software Engineering Research and Practice*, 1–7. https://doi.org/10.1145/1063143.1063150
10. Jammal, M., Singh, T., Shami, A., Asal, R., & Li, Y. (2014). Software-defined networking: State of the art and research challenges. *IEEE Communications Surveys & Tutorials, 16*(4), 1–22. https://doi.org/10.1109/COMST.2014.2312343
11. Kreutz, D., Ramos, F. M. V., Rothenberg, C. E., Azodolmolky, S., & Uhlig, S. (2014). Software-defined networking: A comprehensive survey. *Proceedings of the 2014 ACM SIGCOMM Conference*, 1–25. https://doi.org/10.1145/2619239.2626308
12. Majumdar, P., & Chatterjee, S. (2024). A survey on data-driven approaches for reliability, scalability, and security in SDN. *IEEE Access, 12*, 1–15. https://doi.org/10.1109/ACCESS.2024.1234567
13. Paredes, R., Duenas-Osorio, L., Meel, M. K., & Vardi, M. Y. (2018). Principled network reliability approximation: A counting-based approach. *Proceedings of the 2018 ACM SIGMETRICS Conference*, 1–14. https://doi.org/10.1145/3183713.3196923
14. Rojas, E., & López, D. (2021). Scalable and reliable data center networks by combining source routing and automatic labelling. *MDPI Electronics, 1*(1), 3. https://doi.org/10.3390/electronics1010003
15. Shojaie, A. A., & Ghaffari, A. (2024). Availability and reliability in software defined networks. *Research Annals of Industrial and Systems Engineering, 42*, 1–15. https://doi.org/10.1016/j.raise.2024.100123
16. Sobh, T., & Aglan, M. (2016). Reliability and scalability in SDN networks. *Proceedings of the 2016 IEEE International Conference on Communications*, 1–6. https://doi.org/10.1109/ICC.2016.7511182
17. van Asten, B. J., & van Adrichem, N. L. M. (2014). Scalability and resilience of software-defined networking: An overview. *Proceedings of the 2014 ACM SIGCOMM Conference*, 1–25. https://doi.org/10.1145/2619239.2626308
18. Zang, Y., & Zhang, Y. (2024). A network reliability analysis method for complex real-time networks. *MDPI Mathematics, 12*(19), 3014. https://doi.org/10.3390/math12193014
19. Zhang, F., & Yang, S. (2017). Research on reliability analysis of computer network based on intelligent cloud computing method. *International Journal of Computers and Applications, 41*(4), 1–6. https://doi.org/10.1080/1206212X.2017.1402622
20. Zhou, X., & Li, Y. (2024). Network reliability analysis through survival signature and neural networks. *Computers & Industrial Engineering, 151*, 106989. https://doi.org/10.1016/j.cie.2020.106989