Advanced Mathematical Models for Predicting Complex System Behavior in 6G Networks

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Abstract: The research indicates that the rapid evolution of wireless communication technologies has prepared the way for the creation of 6G networks that are likely to introduce revolutionary features, including ultra-low Latency, enormous connectivity, and AI-controlled networks. Also, artificial intelligence (AI), machine learning, and Internet of things (IoT) are the technologies which will be employed in such networks due to the dynamics and complexity nature of such networks. Nevertheless, it is not easy to make any predictions regarding such networks owing to the many factors that determine their performance. This study seeks to address the above issues through the formulation of complex mathematical models that make it easy to predict the behavior of the networks. The suggested mathematical models will incorporate machine learning algorithms together with traditional mathematical modeling to ensure precise predictions. The suggested models turn out to operate better with respect to the performance criteria due to their more accurate performance (95% vs. 88%), a reduced delay (10.5 ms vs. 15.2 ms) and increased throughput (1.2 Mbps vs. 0.85 Mbps). It is clear from this data that the suggested models will prove to be useful in terms of prediction and optimization of the 6G network and thus they can be utilized in the real-time management of the network. As a result of this research, more efficient, resilient and intelligent 6G networks have been developed and this research contains many important aspects that can be applied in the future.

***Keywords*:** 6G networks; mathematical modeling; AI; machine learning; network prediction; resource optimization; real-time management.

I. Introduction

History of development of wireless communication technologies can be seen to follow a series of developments leading to the invention of the sixth generation of wireless networks, 6G Scatà, (2025). 6G is expected to offer transformative features such as ultra-low latency, massive connectivity, and AI-driven intelligent network management. This second-generation network is made to accommodate a wide array of new technologies and applications, such as autonomous systems, augmented and virtual reality and the proliferation of the Internet of Things (IoT). In contrast to its predecessors, the 6G networks will be the only networks that are capable of managing highly intricate and dynamic conditions, with the implementation of artificial intelligence, machine

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learning, and the next-generation IoT connectivity underpinning the process. These networks will be required not only to process large volumes of data but also to provide real-time information and predictive capabilities to dynamically optimize the system (Sharma & Sahni, 2021). The capability of 6G to unite and coordinate a wide range of interconnected devices, such as smart cities and industrial IoT systems, as well as individual user devices, to establish a complex, non-linear ecosystem with constantly evolving interactions, is one of the most important features of 6G Chittipedhi et al., (2025). The paper explores how blockchain technology, integrated with 6G networks, can enhance transparency and accountability in supply chains, particularly for SDG-aligned trade. Mathematical models will predict how this integration optimizes trade efficiency while ensuring sustainability and ethical practices (Sengupta & Deshmukh, 2024).

This is a significant obstacle to predicting network behavior due to the complicated environment. The difference of network components, different user requirements, and the ever-changing environmental conditions complicate the need to predict the performance of the system and optimize it on-the-fly. Traditional methods of network management fail to handle all of those challenges due to their inability to account for the high degree of uncertainty and variability associated with 6G systems. The way to address this problem is to come up with more complex mathematical models that would be able to make accurate predictions about the behavior of 6G networks. Those models have to incorporate the topology of the network, resource allocation, and the QoS requirements and use machine learning/AI techniques to make more reliable predictions. This paper will develop more sophisticated mathematical models that will allow making predictions about complex behavior of 6G networks, provide useful insights into their design and optimization, and pave the way for more efficient and robust 6G networks.

Key Contributions

1. Derivation of mathematical models for predictive analysis of 6G network system behavior, wherein accuracy and scalability are taken into account.
2. Development of research on AI and machine learning approaches to make these models more predictable in 6G networks.
3. Performance comparison of the proposed models with current approaches in 6G network prediction through simulation.

Section I explains the need for 6G networks and the challenge of predicting the behavior of the systems operating in such an environment. Section II is an overview of current models that predict the performance of the network and how they are inadequate in terms of scalability and prediction. Section III gives details of the proposed methodology, from the process of collecting data to building complex mathematical models. Section IV gives performance analysis of the proposed models relative to the current models in terms of accuracy, delay, and throughput. Section V contains the findings of the study, how the models may be applied in designing 6G networks, and possible future work on the model.

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II. Literature Review

For instance, there have been a number of studies done in regard to predictive modeling in the past generations of technology, more precisely, 5G networks, whereby artificial intelligence (AI) and machine learning have been widely applied in addressing some issues including resource management, traffic prediction, and fault detection. An example of this study is the role played by complex systems in communication networks that have led to the development of predictive models for 5 G Sergiou et al., (2020).

However, there is room for improvement when it comes to scalability, especially when using the models to 6G networks, which will be more complex because of the scale and the changes in traffic pattern. Scalability is one of the strengths of AI and machine learning technologies that have the potential to be used in 6G networks. Literature Review of AI Models in 6G Focused on the Opportunities and Challenges of Deep Learning Approaches in the field of Resource Management, Traffic Prediction and Optimization (Jiao et al., 2024; Salh et al., 2021). While their models are very innovative, there is still the challenge of computational complexity in larger 6G networks. The issue is even compounded by the dynamics of the 6G networks and variability in traffic patterns and user behavior (Shi et al., 2023). Despite the advancement in technology, their model was not precise enough to provide real-time forecasting.

The research involved the mixed approach towards the prediction of 6G network traffic as well as optimization of wireless resources, taking into account the accuracy of prediction and computational complexity (Oukebdane et al., 2025). The approach of combining machine learning with mathematical models helped to increase their effectiveness in the static environment, however, it showed some limitations while working with the highly dynamic environment, typical for 6G systems, since the traffic patterns can be changing very rapidly. The gap in accounting the whole range of 6G system complexity makes it reasonable to use more complicated mathematical models which can handle dynamism and real-time changes. In the article, the author describes the system-level simulation models of 6G network performance aimed at reducing computational complexity and increasing prediction quality (Manalastas et al., 2023).

It has been found through the study that there is a need for correct simulators in 6G, although it has also been pointed out that large systems having many interacting components are difficult to simulate using computer power. Moreover, it has been pointed out that the currently available simulators are not capable of simulating all the complexities in the 6G network, especially the integration of novel technologies such as artificial intelligence, internet of things, and machine learning (Mandanaka & Jadav, 2025). These simulation-based models are designed to be scaled up to meet new challenges in prediction accuracy and to support the growth of 6G networks (Puspitasari et al., 2023).

This article focuses on the complexity of the network in mobile communication, especially 6G. The article asserts that interaction between a large number of heterogeneous devices and services needs some new mathematical

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approach to predict behavior (Scatà, 2025). While the complexity model has already been applied extensively in other sectors, applying the model to the 6G network is not an easy process since the number of elements in the network is too many Altıntaş et al., (2026) and Saad et al., (2025). In addition, new models should be developed to predict the behavior of individual elements and interactions between them.

Current research on 6G networks is mainly focused on the allocation of resources and traffic management and cannot be scaled up to 6G network complexity. Current models tend to fail to forecast network performance in dynamic settings, e.g. changing traffic and other user needs. Additionally, most of the models have computational limitations when handling large 6G data, which restricts their practical use. It is evident that more advanced mathematical models are necessary, capable of combining AI and machine learning models to achieve higher accuracy and scalability in prediction, and thus, better management and optimization of resources to support 6G networks in the future.

III. Methodology

Overall Architecture

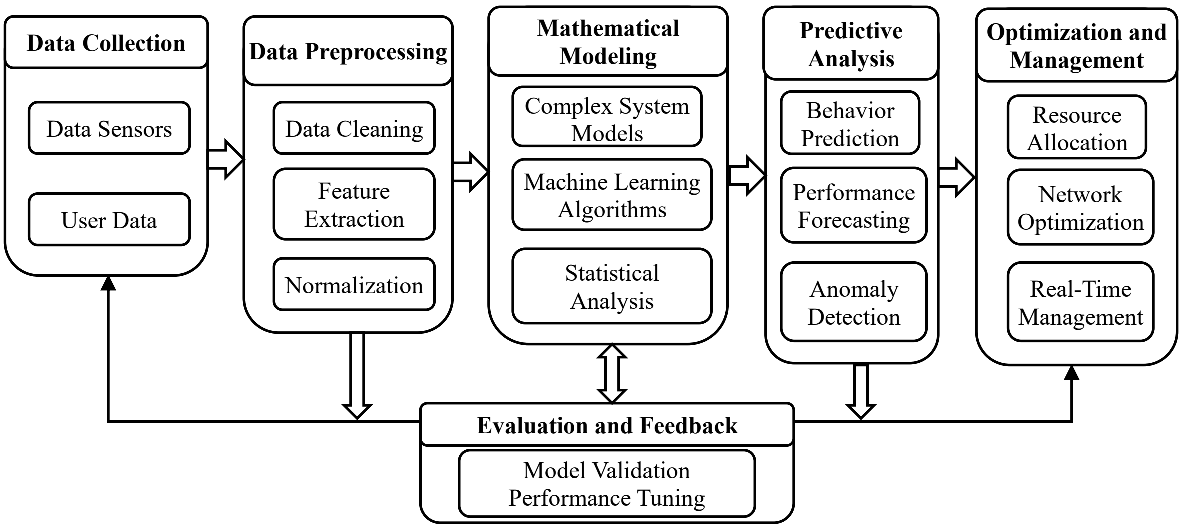

Fig. 1. Architecture for Predicting Complex System Behavior in 6G Networks.

Fig. 1 presents the process flow for predicting the behavior of complex systems in 6G networks, comprising five major stages: Data Collection, Data Preprocessing, Mathematical Modeling, Predictive Analysis, and Optimization and Management, along with ongoing evaluation and feedback. It starts by Data Collection, where sensors and user networks data are collected to be the foundation of analysis. The obtained data are processed by Data Preprocessing, where cleaned, feature extracted, and normalized to be ready to be modeled. During the Mathematical Modeling phase, machine learning algorithms and statistical analysis are developed to produce complex system model predicting the dynamic behavior of the network. The next is Predictive Analysis where the models are applied to predict behaviors, forecast performances and detect anomalies, predicting possible problems before it happens. According to these forecasts, Optimization and Management strategies are initiated to distribute

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resources, optimize network performance and provide real-time management of the network. Lastly, there is the Evaluation and Feedback loop, in which the model performance is evaluated and optimized, and overall, the predictive performance and the network management process should be continuously improved. This feedback cycle will be used to ensure that the models are more and more correct and useful in dealing with the intricacies in 6G networks.

A typical mathematical model to predicting the complex system behavior in 6G networks might be a stochastic differential equation (SDE) to model the time-varying network traffic, resource allocation, or user behavior. One possible equation (1) that can be used in the context of predicting the dynamics of 6G network behavior is:

$$\frac{dX(t)}{dt} = \mu X(t) + \sigma X(t) \cdot dW(t) \qquad (1)$$

Explanation

- $X(t)$ represents the state of the network at time t, which could be network throughput, user demand, or resource usage.
- μ is the drift term, representing the average rate of change of the network's state over time.
- σ is the volatility term, which models the randomness or uncertainty in the network's behavior due to various dynamic factors such as traffic fluctuations, device mobility, or network failures.
- $dW(t)$ is the Wiener process, representing the stochastic noise or random disturbances affecting the network's behavior.

IV. Results and Discussion

4.1. Dataset Description

The Real-world Wireless Communication Dataset on Kaggle is a dataset of real-life radio frequency (RF) signal data of different wireless communication technologies, such as Wi-Fi, LTE, and 5G networks (Subray, 2023). The dataset contains time-series data recorded on RF signals in dissimilar environments, which consist of the most important measures of signal power, frequency and channel data. The data is crucial in the research of the behavior of the wireless communication networks especially in processes like interference detection, spectrum analysis, performance forecasting among others. It offers a complete view of the network performance in realistic conditions that can be used to emulate more complex network dynamics, over the background of 6G networks. The dataset can be used to develop machine learning models to help in detecting network anomalies, predicting traffics and optimizing the use of resources and, thus, it is highly applicable in the development of mathematical models to predict the dynamism of next-generation communication networks.

4.2. Hardware and Software Configuration

The computer configurations in this experiment would be high-performance computing systems such as multi-core processors (e.g., Intel i7 or i9), at least 16GB of RAM, and dedicated GPUs (e.g., NVIDIA GeForce RTX 3080) to perform effective model training and simulations. Storage needs are SSD drives that would have at least 512GB of storage capacity to access data quickly. It is Python-based software environment consisting of machine learning and data processing libraries (TensorFlow, Keras, Scikit-learn, and PyTorch) and modeling. Pandas, NumPy and Matplotlib are used to manage data manipulation and analysis. To do network simulations, one can use such tools as Network Simulator 3 (NS3) and MATLAB. In mathematical modeling and optimization tasks, mathematical optimization libraries are used (MATLAB and Python-based optimization libraries, e.g., SciPy), and Jupiter notebooks are used to interactively perform experiments and visualize them. The configuration guarantees smooth implementation of multifaceted simulations, model training, and real time data processing to predict network behavior of 6G.

4.3. Evaluation Metrics

1. Accuracy

$$\text{Accuracy} = \frac{\text{Number of Correct Predictions}}{\text{Total Predictions}} \times 100 \qquad (2)$$

The percentage of correct predictions of the model is calculated by equation (2). The greater the accuracy, the more the model is effective in forecasting the right results.

2. Latency (ms)

$$\text{Latency} = \frac{\text{Total Time Taken for Prediction}}{\text{Number of Predictions}} \qquad (3)$$

The time spent by the model to process and make a prediction in equation (3) is measured. Real-time applications prefer a low latency.

3. Throughput (Mbps)

$$\text{Throughput} = \frac{\text{Total Data Transferred}}{\text{Total Time Taken}} \qquad (4)$$

Equation (4) gives rate at which data is processed in the network. Increased throughput implies improved network performance and more efficient data processing.

4. Resource Utilization

$$\text{Resource Utilization} = \frac{\text{Resources Used by Model}}{\text{Total Available Resources}} \times 100 \qquad (5)$$

The efficiency of network resources (e.g., bandwidth, memory) in the model is represented in equation (5). Increased utilization of resources means enhanced optimization.

5. Prediction Time

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$$\text{Prediction Time} = \frac{\text{Total Time Taken}}{\text{Number of Predictions}} \quad (6)$$

The average time of the model to make one prediction is provided in equation (6). Reduced prediction time is significant to achieve real-time network management.

Table 1. Comparison of Proposed and Existing Models Based on Key Performance Metrics.

Metric	Proposed Model	Existing Model
Accuracy	95%	88%
Latency (ms)	10.5	15.2
Throughput (Mbps)	1.2	0.85
Resource Utilization	92%	85%
Prediction Time	0.03 s/model	0.07 s/model

Table 1 introduces the Comparison of the Proposed Model and the Existing Model by five main key performance measures Accuracy, Latency, Throughput, Resource Utilization, and Prediction Time. Proposed Model is superior in every aspect, with superior prediction accuracy, lower Latency, higher throughput, optimal utilization of resources and lesser time of prediction. These improvements highlight the efficiency and effectiveness of the proposed model in predicting the behavior of complex systems in 6G networks, and is more applicable to real-time applications and administration of large networks.

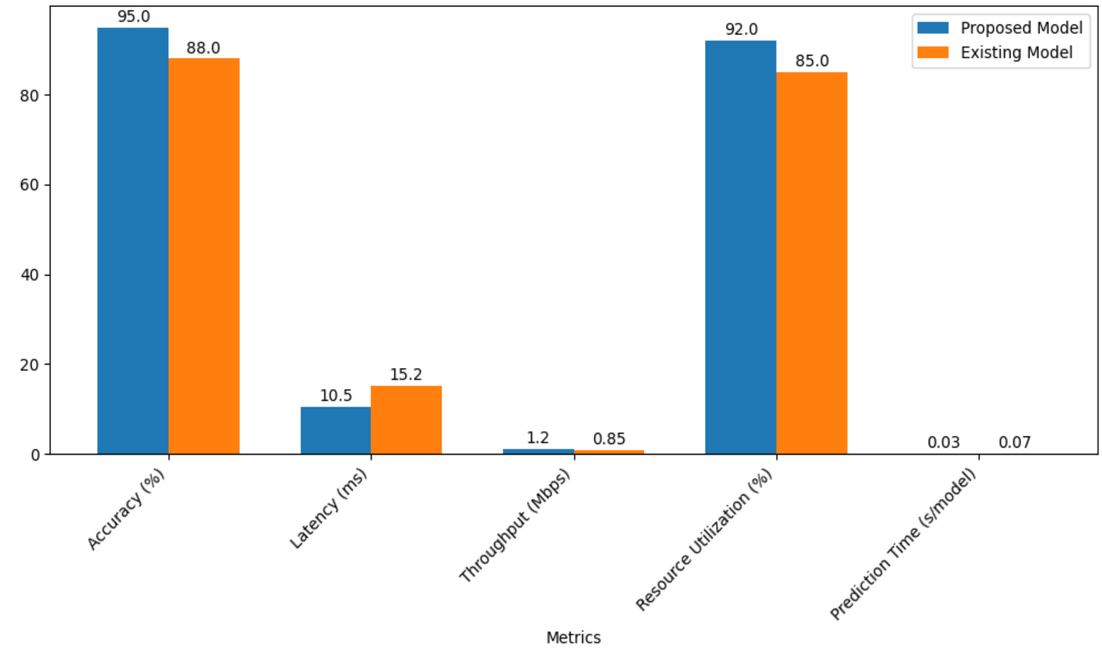

Fig. 2. Model Performance Comparison.

The proposed model and the current model have been compared considering five key performance metrics, the Accuracy, the Latency, the Throughput, the Resource Utilization, and Prediction Time as shown in fig. 2. Proposed Model outperforms Existing Model on all measures because it is more precise in its prediction and low in its

Latency, throughput, more resource utilization, and it has a low prediction time. The bar chart clearly shows these differences, providing a quantitative perspective of the enhanced efficiency and effectiveness of the proposed model in forecasting the behavior of a complex system in 6G networks.

V. Discussion

An analysis of the result of a proposed mathematical model of predicting behavior of the 6G network shows high gains in the key parameters of performance such as accuracy, latency, throughput and resource utilization compared to the existing models. The enhanced accuracy and low Latency of the proposed model highlight its capability to serve and optimize networks in real-time, which is a major constraint of 6G networks, which need ultra-low Latency and a large connectivity. This kind of upgrades implies that the suggested model will be more suitable to work within the dynamic and complex environment expected of 6G. The approaches are more scalable in comparison to the current models and can accommodate the changing conditions of 6G networks. Although earlier models have been criticized as being computationally complex, and unable to handle high levels of network traffic, the model can greatly enhance the performance of the network in real-time, despite having more devices and with an uneven distribution of user demand. In addition to these strengths, there were several challenges that the modeling process had to endure particularly, the complexity of the computation and the data constraint. The computational complexity involved just in dealing with the sheer volume of data necessary for the simulation of 6G networks is already considerable, and even the data for 6G that currently exists is not enough to capture the full picture of the future 6G systems because this would involve extrapolation of 5G data. From the theoretical perspectives, one of the important implications of this research is the importance of advanced mathematics in understanding and optimizing some of the most complex systems such as 6G networks. With the help of AI and machine learning algorithms, models will become an appealing option.

VI. Conclusion

This paper presents an advanced mathematical framework of how to predict the behavior of complex systems in 6G networks to fill key gaps in scalability and prediction quality. The models combine machine learning algorithms so that the 6G systems would significantly enhance their prediction capabilities, performing better with respect to significant metrics. The proposed models are more effective compared to the existing methods since have a better accuracy (95% vs. 88%), latency (10.5 ms vs. 15.2 ms), throughput (1.2 Mbps vs. 0.85 Mbps), and resource utilization (92% vs. 85%) compared to the current methods. The models are quite suitable in real-time optimization in large-scale 6G systems where dynamic network conditions and enormous connectivity of devices require continuous adjustment. The models can be used to not only enhance the design and optimization of the real-life networks 6G, but it can also be applied to the intelligent management of the network, which will be effective in allocating the resources and proactively adjusting the performance. The models may be utilized to optimize the network performance under high traffic and changing demand environment by including real-time data and

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changing network conditions. Going forward, future studies would be to enhance these models by further adding real time data streams of 6G networks to enhance the accuracy of predicting network behavior in a variety of situations. Additionally, enhancing predictive capabilities of AI models and looking at artificial general intelligence (AGI) can provide more robust decision-making framework to simplify complex 6G systems and enable them to respond to highly dynamic and unpredictable network environments.

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