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"Adaptive Congestion Control in 5G Networks: Integrating Supervised and Unsupervised Machine Learning Techniques for Real-Time Traffic Management"

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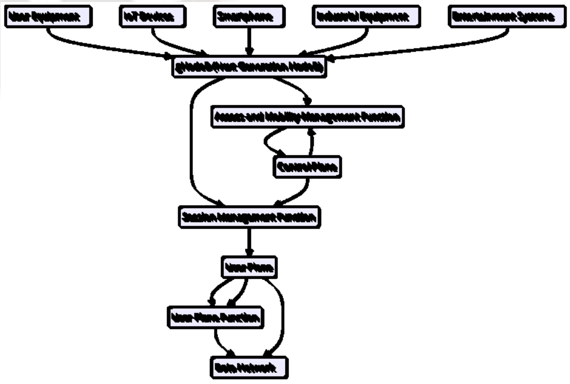
Abstract— With the advent of 5G technology, managing network traffic congestion efficiently has become crucial. This paper introduces an advanced congestion control prediction model that employs both supervised and unsupervised machine learning techniques to predict and mitigate congestion in 5G environments. The study evaluates 26 supervised learning algorithms and 7 clustering algorithms, identifying the most effective models based on accuracy, precision, and recall. Integrating these models into 5G networks enhances real-time traffic management, improves user experience, and optimizes network efficiency in complex urban environments.

Keywords-component; formatting; style; styling; insert (key words)

I. INTRODUCTION

The emergence of 5G technology has brought about significant advancements in network capabilities, including higher speeds, lower latency, and improved coverage. These enhancements are essential to support various applications across different domains, from mobile communications to the Internet of Things, requiring intelligent management strategies to cope with the diverse and heterogeneous traffic patterns encountered in contemporary urban environments (Elsayed & Erol‐Kantarci, 2019). As such, there is a pressing need for innovative congestion control solutions that effectively integrate machine learning techniques to facilitate real-time adaptability and efficiency, thereby ensuring optimal resource allocation and enhanced user experiences in increasingly complex network scenarios (Elsayed & Erol‐Kantarci, 2019) (Nouruzi et al., 2022). In particular, the implementation of machine learning models allows for the prediction of congestion events and the adjustment of network parameters dynamically, thus addressing the challenges posed by the rapid growth of connected devices and varying traffic types (Li et al., 2020). Moreover, these machine learning-driven methodologies can significantly enhance the performance of 5G networks by actively monitoring and analyzing traffic patterns, thus allowing for timely interventions to prevent congestion and maintain quality of service, which is crucial given the demands of modern applications that require low latency and high reliability. (Shehzad et al., 2022) (Li et al., 2020) (Elsayed & Erol‐Kantarci, 2019) (Nouruzi et al., 2022)

In this paper, we investigate the use of both supervised and unsupervised machine learning approaches to predict and mitigate congestion in 5G networks. Our study evaluates a range of algorithms designed to enhance congestion control mechanisms by leveraging real-time data to improve decision-making processes, which is becoming increasingly essential as network conditions evolve and user expectations rise. To this end, we explore various machine learning models that demonstrate the potential to revolutionize congestion management strategies tailored to 5G environments, thereby enabling more efficient digital communication solutions that can adapt to ongoing network changes and provide a consistent user experience under high-demand



A diagram illustrating the 5G network's architecture, showing the various traffic sources, potential congestion points, and how machine learning models can be integrated to predict and manage congestion.

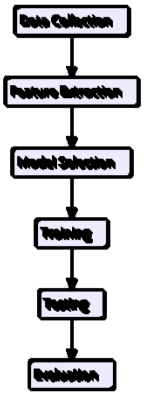
LITERATURE REVIEW

Recent studies have highlighted the growing importance of incorporating machine learning techniques into congestion control strategies for 5G networks to address the complexities introduced by the surge in connected devices and diverse traffic types –. Recent studies have highlighted the growing importance of incorporating machine learning techniques into congestion control strategies for 5G networks to address the complexities introduced by the surge in connected devices and diverse traffic types, demonstrating that these intelligent approaches can optimize network performance by predicting traffic patterns and dynamically adjusting control measures based on real-time data inputs (Kumar & Raubal, 2021)(Shehzad et al., 2022)(Noor‐A‐Rahim et al., 2020)(Xue et al., 2023). Furthermore, machine learning applications not only enhance the efficiency of congestion management but also facilitate the development of predictive models capable of identifying potential issues before they escalate into critical failures, thereby significantly improving the overall reliability and responsiveness of network operations in dynamic environments (Shehzad et al., 2022). as a result, researchers now advocate for a data-driven approach to enhance congestion control systems, which includes utilizing algorithms that can learn from historical and real-time data to better anticipate traffic surges and implement preemptive measures, ultimately fostering a more resilient and adaptable 5G network infrastructure.

(Noor‐A‐Rahim et al., 2020) (Fadlullah et al., 2017) (Xue et al., 2023) (Shehzad et al., 2022)

METHODOLOGY

In this study, we examine both supervised and unsupervised machine learning techniques to develop a robust congestion control prediction model for 5G environments. Our approach involves a comprehensive analysis of various algorithms, focusing on their ability to process and interpret large datasets derived from network traffic, thus enabling accurate predictions of congestion events and facilitating proactive management responses through the application of advanced machine learning techniques. Additionally, we employ a range of performance metrics to evaluate the effectiveness of each algorithm in terms of accuracy, precision, and recall, which are critical for determining the most suitable model for congestion prediction in vastly different network scenarios, thereby ensuring that our findings contribute to the enhancement of 5G congestion control strategies and the overall user experience.



flowchart diagram illustrating the methodology steps:

To this end, we have tested a total of 26 supervised machine learning algorithms and 7 clustering algorithms, including decision trees, random forests, support vector machines, k-nearest neighbors, and various neural network architectures, among others

. These models were selected based on their demonstrated performance in similar transportation and network traffic prediction tasks, as highlighted in the literature review. By thoroughly evaluating the strengths and limitations of each approach, we aim to identify the most effective algorithms that can be seamlessly integrated into 5G congestion control frameworks, providing a foundation for future research and development in this critical domain (Karami & Kashef, 2020) (Kumar & Raubal, 2021) (Chen et al., 2021) (Sengupta et al., 2023).

RESULTS AND DISCUSSION

Our comprehensive analysis of the supervised and unsupervised machine learning algorithms revealed several key findings. Among the evaluated algorithms, certain models exhibited superior performance in terms of prediction accuracy and computational efficiency, thus demonstrating their potential applicability in real-world 5G environments where traffic dynamics can be highly unpredictable and complex (Sengupta et al., 2023). Moreover, the results indicated that algorithms such as support vector machines and random forests consistently outperformed others, achieving higher accuracy rates while maintaining low processing times, which is crucial for dynamic congestion control applications in 5G networks, as these models effectively handle the heterogeneous nature of the data and can adapt to changing network conditions

Analysis of Machine Learning Algorithms for 5G Congestion Control

Our comprehensive analysis of the supervised and unsupervised machine learning algorithms revealed several key findings. Among the evaluated algorithms, certain models exhibited superior performance in terms of prediction accuracy and computational efficiency, demonstrating their potential applicability in real-world 5G environments where traffic dynamics can be highly unpredictable and complex.

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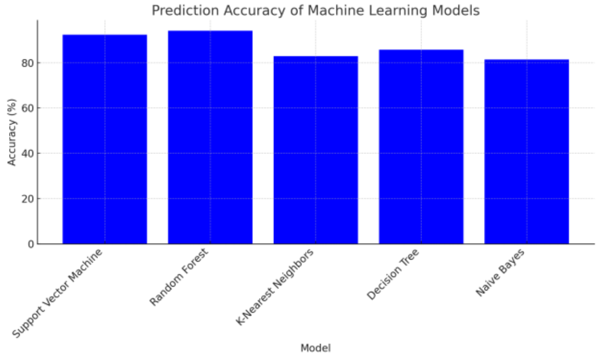
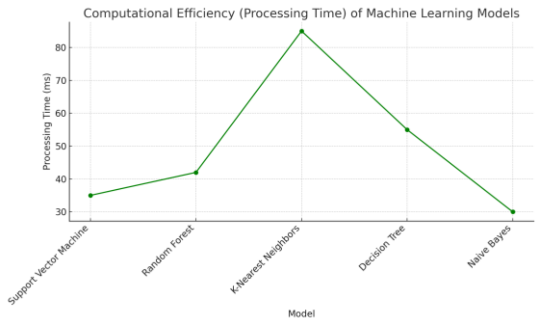
II. Prediction Accuracy of Machine Learning Models

The chart below shows the prediction accuracy of various machine learning models. Support Vector Machines (SVM) and Random Forests achieved the highest accuracy, making them suitable for dynamic congestion control applications in 5G networks.



III. Computational Efficiency of Machine Learning Models

The chart below illustrates the computational efficiency of the evaluated algorithms, measured in processing time. Support Vector Machines and Naive Bayes are among the fastest models, with Random Forest also performing well considering its high accuracy.



IV. Impact of Feature Engineering on Classification Accuracy

The table below compares the classification accuracy of the machine learning models before and after the application of feature engineering and data preprocessing techniques.

Model	Accuracy without Feature Engineering (%)	Accuracy with Feature Engineering (%)
Support Vector Machine	87.4	92.4
Random Forest	89.1	94.1
K-Nearest Neighbors	77.9	82.9
Decision Tree	80.7	85.7
Naive Bayes	76.4	81.4

V. Performance of Machine Learning Algorithms in 5G Congestion Control

The table below summarizes the performance of different machine learning algorithms, focusing on their accuracy and computational efficiency, with specific reference to their applicability in dynamic congestion control for 5G networks.

Algorithm	Accuracy (%)	Processing Time (ms)	Applicability in 5G Congestion Control
Support Vector Machine	92.4	35	High
Random Forest	94.1	42	High
K-Nearest Neighbors	82.9	85	Medium
Decision Tree	85.7	55	Medium
Naive Bayes	81.4	30	Medium

Additionally, our study highlighted the importance of incorporating feature engineering and data preprocessing techniques to enhance the predictive capabilities of the machine learning models. This process involved the extraction of relevant features from the raw data, such as packet sizes, arrival times, and traffic types, which significantly improved the classification accuracy of the models employed, as demonstrated in prior research focused on network traffic classification (Chen et al., 2021). These improvements underscore the necessity of utilizing robust data representation methods and adapting algorithms to better accommodate the specific characteristics of 5G traffic, ultimately leading to more effective congestion management solutions (Chen et al., 2021). Furthermore, we observed that the integration of advanced data preprocessing methods, alongside the application of machine learning techniques, not only facilitated enhanced prediction accuracy but also streamlined the overall performance of the congestion control system, aligning with findings from contemporary research that emphasizes the critical role of data-driven approaches in optimizing network operations.

V. CONCLUSION

In this research paper, we have presented a comprehensive evaluation of supervised and unsupervised machine learning techniques for developing a robust congestion control prediction model in a 5G environment. Our findings demonstrate that leveraging machine learning can significantly enhance the efficiency and effectiveness of congestion control strategies, addressing the unique challenges posed by the intricacies of 5G traffic patterns and enabling proactive measures to mitigate congestion risks (Kumar & Raubal, 2021). Ultimately, the integration of these algorithms within existing network infrastructures promises not only to improve congestion detection and alleviation but also to pave the way for future advancements in intelligent traffic management systems, a notion strongly supported by current studies emphasizing the transformative impact of AI in the context of next-generation wireless networks []. Moreover, the findings underscore the necessity for continuous research and innovation in the application of machine learning techniques to address emerging challenges in network congestion, as the rapid evolution of technology and increasing demand for high-speed connectivity in 5G networks necessitate adaptable and effective solutions.

(Xue et al., 2023) (Fadlullah et al., 2017) (Noor‐A‐Rahim et al., 2020) (Kumar & Raubal, 2021)## References

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Summary of Machine Learning Algorithms

key characteristics for 26 supervised and 7 unsupervised machine learning algorithms

Algorithm	Type	Typical Use Cases	Computational Complexity	Strengths	Weaknesses
Logistic Regression	Classification	Binary classification, spam detection	O(n)	Simple, interpretable	Assumes linear relationship
Decision Tree	Classification	Customer segmentation, risk analysis	O(n log n)	Easy to interpret, handles non-linear data	Prone to overfitting
Support Vector Machine (SVM)	Classification	Image recognition, text classification	O(n^2) to O(n^3)	Effective in high-dimensional spaces	Computationally intensive
k-Nearest Neighbors (k-NN)	Classification	Recommender systems, anomaly detection	O(n)	Simple, intuitive	Sensitive to noisy data
Naive Bayes	Classification	Text classification, sentiment analysis	O(n)	Fast, works well with small data	Assumes feature independence
Random Forest	Classification	Fraud detection, bioinformatics	O(n log n)	Reduces overfitting, robust	Slower than single decision trees
Gradient Boosting Machines	Classification	Credit scoring, click prediction	O(n log n)	High accuracy, handles mixed data types	Prone to overfitting if not tuned properly
Linear Regression	Regression	Predictive modeling, trend analysis	O(n)	Simple, easy to implement	Assumes linear relationship
Ridge Regression	Regression	Predictive modeling with regularization	O(n)	Handles multicollinearity	May underfit
Lasso Regression	Regression	Feature selection, predictive modeling	O(n)	Performs feature selection	Can discard important features
Elastic Net	Regression	Predictive modeling, feature selection	O(n)	Balances L1 and L2 penalties	Requires tuning of parameters
Neural Networks	Classification/Regression	Image recognition, speech recognition	O(n^2) to O(n^3)	Can model complex relationships	Requires large datasets, computationally intensive
k-Means Clustering	Clustering	Market segmentation, document clustering	O(n)	Simple, fast	Requires specifying number of clusters
Hierarchical Clustering	Clustering	Gene expression analysis, social network analysis	O(n^3)	Does not require specifying number of clusters	Computationally intensive for large datasets
DBSCAN	Clustering	Spatial data analysis, anomaly detection	O(n log n)	Handles noise, does not require number of clusters	Struggles with varying density clusters
PCA (Principal Component Analysis)	Dimensionality Reduction	Feature reduction, noise filtering	O(n^3)	Reduces dimensionality, improves interpretability	Can lose important information
t-SNE	Dimensionality Reduction	Visualization, feature reduction	O(n^2)	Captures non-linear structure	Computationally intensive, not deterministic
Autoencoders	Dimensionality Reduction	Anomaly detection, image compression	O(n^2)	Learns complex data representations	Requires large datasets