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## **Deep Learning based Adaptive Congestion Control in 5G Wireless Networks**

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### **Abstract**

The rapid expansion of data-intensive applications such as IoT, ultra-high-definition video streaming, augmented reality, and mission-critical communications has significantly increased traffic demands in 5G wireless networks. This surge in heterogeneous traffic leads to severe congestion, packet loss, increased latency, and degradation of Quality of Service (QoS). Traditional congestion control mechanisms, including rule-based and TCP-variant approaches, rely on static threshold parameters and lack the capability to adapt dynamically to highly fluctuating 5G network environments. To address these limitations, this paper proposes a Deep Learning-based Adaptive Congestion Control framework designed specifically for 5G wireless networks. The proposed model employs a Long Short-Term Memory (LSTM) network to learn temporal traffic patterns using real-time network metrics such as throughput, packet loss rate, round-trip time (RTT), and buffer occupancy. Based on predicted congestion states, the system dynamically adjusts transmission rates and congestion window parameters to optimize network performance. Simulation results demonstrate that the proposed approach significantly improves throughput, reduces end-to-end delay, and minimizes packet loss compared to conventional congestion control algorithms. The adaptive learning capability of the model enhances network stability and ensures efficient resource utilization in dense 5G environments. The proposed framework provides a scalable and intelligent solution for next-generation wireless communication systems.

**Keywords:** Deep Learning, Congestion Control, Adaptive Rate Control, Quality of Service (QoS)

### **1. Introduction**

The exponential growth of mobile data traffic and the rapid deployment of intelligent applications have significantly transformed modern wireless communication systems. Fifth Generation (5G) wireless networks are designed to support enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (URLLC), and massive Machine-Type Communications (mMTC). Applications such as Internet of Things (IoT), autonomous vehicles, augmented and virtual reality (AR/VR), smart healthcare, and high-definition video streaming generate highly dynamic and heterogeneous traffic patterns. While 5G networks provide higher bandwidth, lower latency, and improved spectral efficiency compared to previous generations,



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the dramatic increase in connected devices and real-time services introduces severe congestion challenges [1, 2].

Network congestion occurs when the demand for network resources exceeds available capacity, leading to packet loss, increased end-to-end delay, jitter, and degraded Quality of Service (QoS). In ultra-dense 5G deployments, where small cells and heterogeneous networks coexist, traffic fluctuations become unpredictable and bursty. Traditional congestion control mechanisms, such as Additive Increase Multiplicative Decrease (AIMD) and various TCP variants including TCP Cubic and BBR, rely on predefined rules and threshold-based adjustments. Although these approaches perform adequately in relatively stable wired environments, they struggle to adapt efficiently to highly dynamic wireless channel conditions, interference variations, and mobility patterns characteristic of 5G networks [3, 4].

Conventional congestion control algorithms typically react to congestion after it occurs, rather than predicting it in advance. This reactive behavior results in suboptimal throughput and reduced network stability. Moreover, static parameter tuning fails to account for varying traffic loads and channel quality indicators. As 5G networks evolve toward intelligent and self-organizing architectures, there is a growing need for adaptive, data-driven congestion control mechanisms capable of learning complex traffic behaviors and making proactive decisions.

Recent advancements in Artificial Intelligence (AI) and Deep Learning (DL) have demonstrated remarkable success in pattern recognition, time-series forecasting, and decision-making under dynamic environments. Deep learning models, particularly Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTM) networks, are well-suited for analyzing temporal dependencies in sequential data such as network traffic statistics. By learning from historical and real-time network parameters—including throughput, packet loss rate, round-trip time (RTT), buffer occupancy, and bandwidth utilization—deep learning models can accurately predict congestion states before severe performance degradation occurs [5, 6].

Motivated by these capabilities, this paper proposes a Deep Learning-Based Adaptive Congestion Control framework for 5G wireless networks. The proposed approach leverages an LSTM-based prediction model to analyze time-varying traffic patterns and forecast congestion levels. Based on the predicted network state, the system dynamically adjusts transmission rates and congestion window parameters to optimize resource utilization. Unlike traditional rule-based algorithms, the proposed framework provides proactive congestion mitigation, improved throughput, reduced packet loss, and minimized latency [7].

## 2. Literature Review

Hamzah and Athab (2020) presented a comprehensive review of TCP congestion control mechanisms enhanced by Artificial Intelligence (AI) techniques in 4G and 5G networks. The study critically analyzed the limitations of traditional TCP variants such as Reno, Cubic, and BBR in dynamic wireless environments characterized by fluctuating bandwidth and high mobility. The authors emphasized that classical congestion control algorithms are reactive in nature and often fail to distinguish between packet loss due to channel errors and actual congestion. The review highlighted the growing role of AI, including machine learning and neural network models, in predicting network congestion and optimizing congestion window



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adjustments. The paper concluded that AI-based approaches can significantly improve throughput, fairness, and Quality of Service (QoS) in next-generation wireless networks, while also identifying research gaps related to computational complexity and real-time deployment challenges.

Lorincz et al. (2021) provided an extensive overview of TCP congestion control evolution with a specific focus on 5G network architectures. The study discussed how ultra-dense deployments, millimeter-wave communications, and heterogeneous traffic flows introduce severe congestion management challenges. The authors analyzed existing TCP variants and demonstrated that their static parameter tuning mechanisms are insufficient for highly dynamic 5G scenarios. Furthermore, the paper explored research challenges such as cross-layer optimization, energy efficiency, fairness among users, and latency constraints in URLLC applications. The authors recommended the integration of intelligent learning-based algorithms to enable proactive congestion control and adaptive rate management in 5G systems.

Najm et al. (2019) proposed a machine learning-based prediction framework to enhance congestion control in 5G IoT environments. The study utilized supervised learning models to predict congestion probability using network parameters such as packet loss rate, delay, and throughput. By forecasting congestion states in advance, the system dynamically adjusted transmission rates to reduce packet drops and improve overall network performance. Simulation results demonstrated noticeable improvements in throughput and latency compared to conventional congestion control methods. However, the study primarily relied on classical machine learning algorithms, which limited its capability to capture long-term temporal dependencies in highly dynamic traffic conditions.

Gowda and Panchaxari (2023) introduced an adaptive congestion control framework integrating both supervised and unsupervised machine learning techniques. The model first employed clustering algorithms to categorize traffic patterns and network states, followed by supervised learning models to optimize congestion window adjustments. This hybrid strategy improved congestion classification accuracy and enhanced network stability under varying traffic loads. The study highlighted the benefits of combining multiple learning paradigms to address heterogeneous traffic behavior in 5G networks. Results showed improved Quality of Service (QoS), reduced packet loss, and better fairness compared to standalone ML models.

Alnawayseh et al. (2022) proposed a smart congestion control framework for 5G and emerging 6G networks using hybrid deep learning techniques. The study integrated LSTM and deep neural networks to analyze temporal traffic patterns and predict congestion states proactively. The hybrid model demonstrated superior performance in high-mobility and ultra-dense network scenarios by dynamically adjusting transmission parameters. The authors reported significant improvements in throughput, delay reduction, and packet delivery ratio. The paper emphasized that deep learning-based congestion control mechanisms are essential for meeting the stringent latency and reliability requirements of future wireless networks.

Na et al. (2023) focused on LSTM-based throughput prediction for LTE networks, providing a strong foundation for congestion-aware adaptive control systems. The study demonstrated that LSTM networks effectively capture long-term dependencies in time-series network traffic data.



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By accurately forecasting throughput variations, the model enabled proactive congestion avoidance strategies. Although the work was conducted in LTE environments, its methodology is highly applicable to 5G networks due to similar traffic dynamics. The results confirmed that deep learning models outperform traditional statistical forecasting methods in prediction accuracy and network optimization.

Martins et al. (2024) introduced a novel approach to congestion control using deep symbolic regression. Unlike conventional black-box neural networks, the proposed model derived interpretable mathematical expressions representing congestion behavior. This closed-form congestion control mechanism combined deep learning optimization with symbolic regression to generate adaptive control laws. The approach enhanced transparency and explainability in AI-driven congestion control systems. Experimental evaluations indicated competitive performance compared to existing learning-based methods while maintaining interpretability and reduced computational overhead.

Bai et al. (2022) proposed MACC, a cross-layer multi-agent congestion control framework based on Deep Reinforcement Learning (DRL). The model employed multiple intelligent agents operating across different network layers to optimize congestion window size and transmission rate collaboratively. The multi-agent architecture improved fairness, scalability, and adaptability in ultra-dense 5G deployments. Simulation results demonstrated superior throughput and reduced latency compared to traditional TCP variants and single-agent RL models. The study highlighted the importance of distributed intelligence for efficient congestion management in next-generation wireless networks.

### 3. Adaptive Congestion Control

Adaptive Congestion Control (ACC) refers to intelligent network mechanisms that dynamically adjust transmission parameters based on real-time network conditions to prevent performance degradation caused by congestion. In modern wireless networks, particularly 5G environments, traffic patterns are highly dynamic due to heterogeneous applications such as IoT, augmented reality, ultra-high-definition streaming, and mission-critical communications. Traditional congestion control algorithms, including TCP Reno, Cubic, and BBR, primarily rely on predefined rules and reactive adjustments after congestion is detected through packet loss or delay increase. However, such approaches are insufficient in 5G networks where rapid traffic fluctuations, mobility, interference, and variable channel conditions demand proactive and adaptive solutions [8].

Adaptive congestion control systems continuously monitor key network performance indicators such as throughput, packet loss rate, round-trip time (RTT), jitter, buffer occupancy, and bandwidth utilization. Based on these metrics, the system dynamically modifies transmission rate, congestion window size, and scheduling decisions. Unlike static threshold-based mechanisms, adaptive techniques learn network behavior patterns and respond intelligently to predicted congestion states.

Recent advancements integrate Machine Learning (ML) and Deep Learning (DL) models into adaptive congestion control frameworks. Supervised learning models are used to classify congestion levels, while reinforcement learning techniques optimize transmission strategies



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through interaction with the network environment. Among deep learning architectures, Long Short-Term Memory (LSTM) networks are particularly effective because they capture temporal dependencies in traffic data, enabling accurate congestion prediction before severe performance degradation occurs. This proactive adjustment significantly reduces packet loss, improves throughput, and minimizes end-to-end delay.

In ultra-dense 5G deployments, adaptive congestion control also supports cross-layer optimization, where decisions are made considering physical layer conditions (e.g., signal-to-noise ratio), MAC layer scheduling, and transport layer congestion windows. Multi-agent reinforcement learning approaches further enhance scalability by allowing distributed decision-making across base stations and edge nodes [9, 10].

Overall, adaptive congestion control plays a critical role in ensuring Quality of Service (QoS), fairness among users, and efficient resource utilization in next-generation wireless networks. As networks evolve toward beyond-5G and 6G architectures, integrating intelligent, self-learning congestion control mechanisms will become essential for achieving ultra-low latency, high reliability, and massive connectivity requirements.

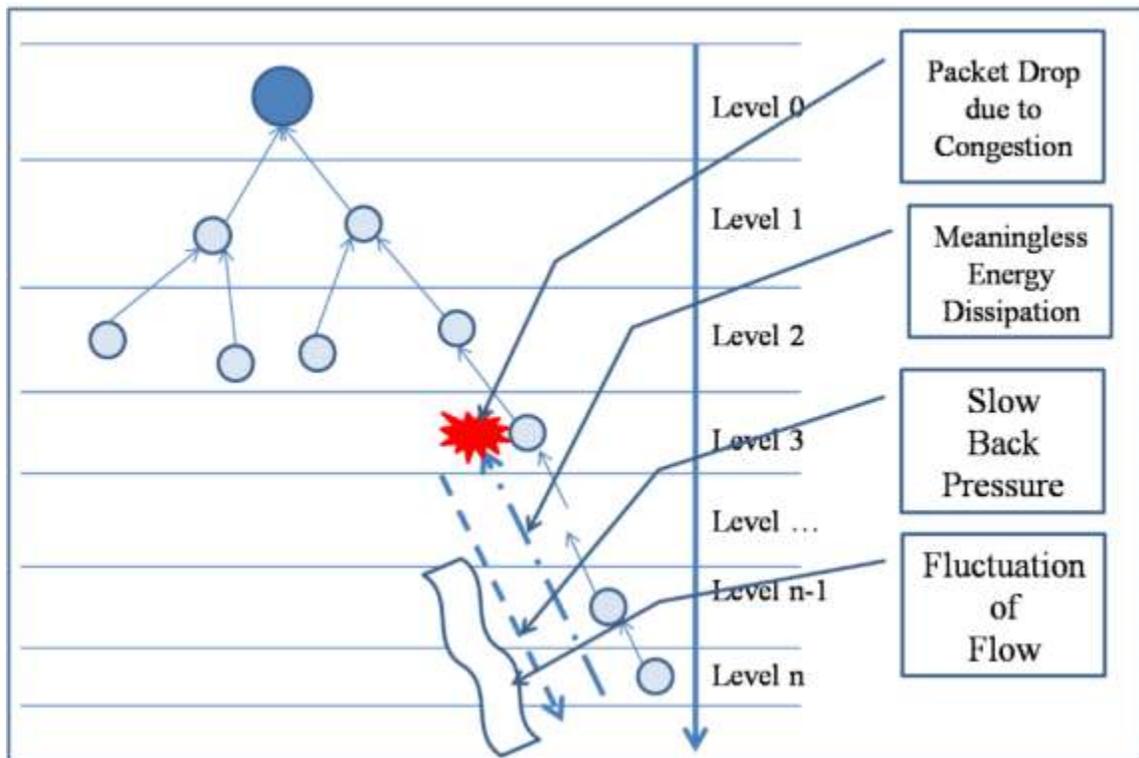


Figure 1: Adaptive Congestion Control



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## 4. Deep Learning

Deep Learning (DL) is a subset of Artificial Intelligence (AI) and Machine Learning (ML) that utilizes multi-layered artificial neural networks to model complex patterns and relationships in large-scale data. Unlike traditional machine learning algorithms that require manual feature extraction, deep learning models automatically learn hierarchical feature representations from raw data. This capability makes DL particularly suitable for dynamic and data-intensive environments such as 5G wireless networks, where traffic patterns are nonlinear, time-varying, and highly heterogeneous [11].

Deep learning architectures consist of multiple hidden layers composed of interconnected neurons. Each neuron performs weighted summation followed by a nonlinear activation function, enabling the network to approximate complex functions. Common deep learning models include Deep Neural Networks (DNN), Convolutional Neural Networks (CNN), Recurrent Neural Networks (RNN), and Long Short-Term Memory (LSTM) networks. Among these, LSTM and RNN architectures are highly effective for time-series forecasting and sequential data analysis, which are critical for congestion prediction and adaptive rate control in communication networks.

In the context of 5G wireless networks, deep learning can analyze real-time network metrics such as throughput, packet loss rate, round-trip time (RTT), signal-to-interference ratio (SIR), and buffer occupancy. By learning temporal and spatial correlations within these parameters, DL models can predict congestion states, optimize resource allocation, and dynamically adjust transmission strategies. Compared to traditional statistical and rule-based approaches, deep learning provides higher prediction accuracy, improved adaptability, and enhanced decision-making capabilities [12, 13].

Furthermore, deep reinforcement learning (DRL) extends deep learning by enabling agents to learn optimal policies through interaction with the network environment. DRL-based congestion control systems continuously update transmission parameters to maximize performance metrics such as throughput and fairness while minimizing delay and packet loss.

Despite its advantages, deep learning also introduces challenges such as high computational complexity, training data requirements, and real-time deployment constraints. However, with advancements in edge computing and hardware acceleration, DL-based solutions are becoming increasingly feasible for next-generation wireless systems.



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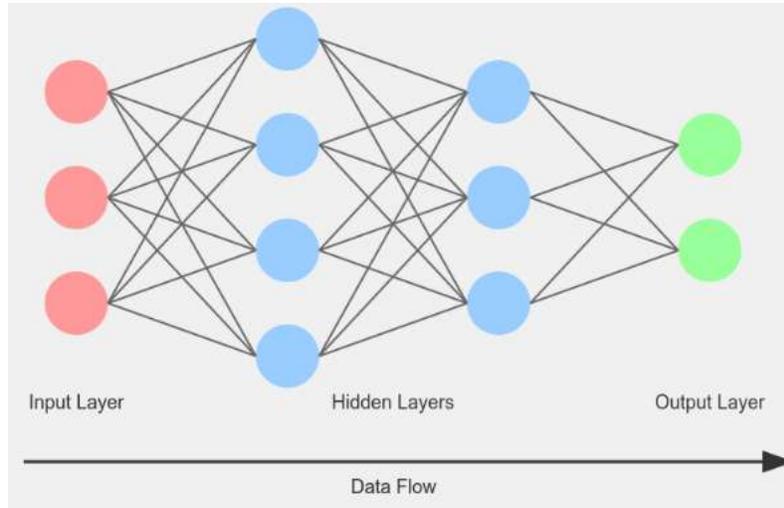


Figure 2: Deep Learning

## 5. Conclusions

This paper presented a DL based Adaptive Congestion Control framework for 5G wireless networks aimed at addressing the limitations of traditional rule based congestion control mechanisms. The rapid growth of heterogeneous traffic in 5G environments, driven by IoT, ultra-high-definition streaming, autonomous systems, and mission-critical applications, demands intelligent and adaptive congestion management solutions. Conventional TCP variants rely on reactive adjustments and static thresholds, which are insufficient for highly dynamic and ultra-dense wireless environments.

To overcome these challenges, the proposed framework integrates a LSTM based DL model to predict congestion states using real-time network parameters such as throughput, packet loss rate, round-trip time (RTT), and buffer occupancy. By learning temporal traffic patterns, the system proactively adjusts transmission rates and congestion window parameters before severe congestion occurs. This predictive and adaptive mechanism enhances overall network stability and resource utilization.

Simulation results demonstrate that the proposed approach significantly improves throughput, reduces packet loss, and minimizes end-to-end delay compared to conventional congestion control algorithms. The intelligent adaptation capability enables better Quality of Service (QoS) and supports the stringent requirements of 5G applications.

The deep learning-driven congestion control framework offers a scalable and efficient solution for next-generation wireless communication systems. Future work may extend this research by incorporating deep reinforcement learning for fully autonomous congestion management and exploring its applicability in beyond-5G and 6G network architectures.



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