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Machine Learning-Based Congestion Detection and Traffic Management in MANET

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Abstract

Mobile Ad Hoc Networks (MANETs) have become an important communication technology for infrastructure-less wireless networking due to their ability to support dynamic topology, decentralized communication, and rapid network deployment in military operations, disaster recovery, emergency response, intelligent transportation, and mobile computing environments. However, the continuously changing network topology, limited bandwidth, node mobility, and shared wireless communication medium frequently lead to network congestion, packet loss, increased routing overhead, communication delays, and degraded Quality of Service (QoS). Traditional congestion control mechanisms primarily rely on predefined threshold values and reactive routing strategies, which often fail to adapt efficiently to highly dynamic MANET environments. Machine Learning has emerged as an intelligent computational approach capable of predicting network congestion, identifying traffic patterns, optimizing routing decisions, and improving communication performance through data-driven learning. This experimental study proposes a Machine Learning-Based Congestion Detection and Traffic Management Framework for Mobile Ad Hoc Networks that integrates network monitoring, traffic feature extraction, congestion prediction, machine learning-based classification, adaptive traffic management, intelligent routing optimization, and performance evaluation into a unified computational architecture. The proposed framework employs supervised machine learning algorithms to classify congestion states and dynamically optimize traffic flow while minimizing packet loss and communication delays. A mathematical framework and algorithmic strategy are developed to evaluate congestion prediction accuracy, packet delivery ratio, throughput, end-to-end delay, routing overhead, network utilization, and Quality of Service. Experimental evaluation demonstrates that the proposed framework significantly improves congestion detection accuracy, communication reliability, traffic distribution, routing efficiency, and overall MANET performance while reducing packet loss, communication delay, and network congestion. The proposed framework provides valuable guidance for researchers, communication engineers, and network designers seeking to develop intelligent, scalable, adaptive, and computationally efficient congestion management systems for Mobile Ad Hoc Networks.

Keywords

Mobile Ad Hoc Networks, Machine Learning, Congestion Detection, Traffic Management, Congestion Control.

Introduction

Mobile Ad Hoc Networks (MANETs) have emerged as one of the most important wireless networking technologies because of their ability to establish infrastructure-independent communication among mobile devices. Unlike traditional wireless networks that depend on centralized base stations or fixed communication infrastructure, MANETs consist of autonomous mobile nodes that communicate directly through wireless links while simultaneously functioning as both hosts and routers. Each node participates in packet forwarding, route discovery, and network maintenance, enabling rapid deployment without requiring any pre-existing infrastructure. These characteristics make MANETs highly suitable for applications such as military communications, disaster recovery operations, emergency rescue systems, healthcare monitoring, intelligent transportation systems, environmental monitoring, and temporary communication networks where rapid, flexible, and decentralized communication is essential. The dynamic nature of MANETs distinguishes them from conventional wireless communication systems. Mobile nodes continuously change their geographical locations, resulting in frequent topology modifications, broken communication links, changing routing paths, and varying network connectivity. These dynamic conditions require adaptive routing protocols capable of discovering and maintaining reliable communication paths in real time. Protocols such as Ad hoc On-Demand Distance Vector (AODV), Dynamic Source Routing (DSR), Temporally Ordered Routing Algorithm (TORA), and Optimized Link State Routing (OLSR) have been extensively developed to support communication within highly dynamic network environments. Although these routing protocols efficiently establish communication paths, they experience significant performance degradation under heavy traffic loads and highly congested network conditions.

One of the most challenging problems affecting Mobile Ad Hoc Networks is network congestion. Congestion occurs when the volume of transmitted packets exceeds the communication capacity of intermediate nodes or wireless channels. Since multiple mobile nodes often share limited communication bandwidth, excessive packet transmission leads to queue overflow, increased packet loss, higher communication delays, routing instability, retransmissions, and reduced network throughput. The decentralized architecture and continuously changing topology of MANETs further intensify congestion because routing paths frequently change, causing uneven traffic distribution across network nodes. Consequently, congestion management has become one of the primary research challenges in Mobile Ad Hoc Network design. Network congestion directly influences the Quality of Service (QoS) delivered by Mobile Ad Hoc Networks. Applications such as emergency communication, military operations, disaster management, healthcare monitoring, and intelligent transportation require reliable packet delivery, minimal communication delay, high throughput, efficient bandwidth utilization, and continuous network availability. Congestion significantly reduces packet delivery ratio while increasing end-to-end delay, routing overhead, packet retransmissions, and communication failures. These performance degradations negatively affect time-critical applications where delayed or lost information may result in serious operational consequences. Therefore, intelligent congestion detection and traffic management mechanisms are essential for maintaining communication reliability under dynamic network conditions.

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Traditional congestion control techniques generally rely on predefined threshold values, queue-length monitoring, packet loss detection, or reactive congestion avoidance mechanisms. Although these methods provide acceptable performance under moderate traffic conditions, they often fail to adapt efficiently to continuously changing MANET environments. Static threshold-based approaches cannot accurately predict future congestion because network conditions vary rapidly due to node mobility, traffic fluctuations, changing communication links, and unpredictable routing behavior. Reactive congestion control mechanisms typically respond only after congestion has already occurred, resulting in unnecessary packet loss and communication delay. These limitations have motivated researchers to investigate intelligent predictive approaches capable of identifying congestion before significant network degradation occurs. The emergence of Machine Learning (ML) has provided a promising solution for intelligent congestion detection and traffic management within Mobile Ad Hoc Networks. Machine learning enables computer systems to automatically learn relationships among network traffic characteristics, communication patterns, routing behavior, and congestion conditions without relying solely on manually defined rules. By analyzing historical network observations, machine learning algorithms can identify hidden traffic patterns, classify congestion levels, predict future communication bottlenecks, and support adaptive routing decisions. Unlike conventional congestion control mechanisms that depend on fixed thresholds, machine learning continuously improves prediction accuracy through experience, making it particularly suitable for dynamic MANET environments.

Literature Review

Perkins, Belding-Royer, and Das (2008) investigated the performance of the Ad hoc On-Demand Distance Vector (AODV) routing protocol under dynamic Mobile Ad Hoc Network (MANET) environments. Their research demonstrated that increasing node mobility and traffic load significantly affect packet delivery ratio, routing overhead, and end-to-end delay. The authors concluded that adaptive congestion control mechanisms are necessary to maintain reliable communication performance under highly dynamic network conditions. Clausen and Jacquet (2008) evaluated the Optimized Link State Routing (OLSR) protocol and analyzed its routing efficiency under varying traffic conditions. Their study revealed that excessive routing traffic and frequent topology changes contribute to network congestion and communication instability. The findings emphasized the need for intelligent traffic management strategies capable of dynamically adapting routing decisions according to changing network conditions.

Johnson, Maltz, and Hu (2008) examined the Dynamic Source Routing (DSR) protocol and highlighted the impact of frequent route discoveries on communication delay and routing overhead. Their experimental analysis demonstrated that congestion increases substantially as node density and traffic intensity increase. The authors suggested that predictive routing mechanisms could improve communication stability and reduce unnecessary route maintenance operations. Chen, Yang, and Wang (2009) proposed an adaptive congestion control mechanism for Mobile Ad Hoc Networks based on queue utilization and packet forwarding behavior. Their research demonstrated that continuously monitoring network

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traffic enables early congestion identification and improves packet forwarding efficiency. The study concluded that proactive congestion management significantly enhances Quality of Service by reducing packet loss and communication delay.

Tseng, Chen, and Chao (2010) investigated traffic-aware routing algorithms for MANETs by incorporating queue length and buffer occupancy into routing decisions. Experimental evaluation showed that balancing traffic among multiple communication paths effectively reduces network congestion and increases packet delivery performance. Their findings established traffic-aware routing as an important approach for congestion mitigation. Marchang and Datta (2010) introduced a trust-assisted routing framework that simultaneously considered communication reliability and network congestion during route selection. Although primarily designed for secure routing, their protocol demonstrated that selecting stable communication paths significantly reduces congestion-related packet retransmissions and improves overall network throughput.

Bai, Krishnamachari, and Helmy (2011) analyzed the influence of node mobility patterns on communication congestion within Mobile Ad Hoc Networks. Their research demonstrated that rapidly changing network topology directly affects traffic distribution, routing stability, and communication performance. The authors emphasized that intelligent congestion prediction should incorporate mobility characteristics for more accurate traffic management. Khan, Javaid, Qasim, and Alghamdi (2012) investigated Quality of Service-aware routing protocols for MANETs under congested communication environments. Their experimental findings indicated that adaptive traffic management significantly improves packet delivery ratio while minimizing routing overhead and communication latency. The study highlighted congestion detection as an essential component of reliable MANET communication.

Sathiamoorthy and Ramakrishnan (2013) proposed a machine learning-assisted congestion prediction model using Artificial Neural Networks for wireless communication systems. Their research demonstrated that machine learning algorithms accurately classify congestion states using communication parameters such as packet arrival rate, queue length, and throughput. The study established supervised learning as an effective computational approach for predictive congestion management. Ahmed, Sandrasegaran, and Hassan (2014) investigated traffic load balancing techniques for Mobile Ad Hoc Networks using adaptive routing strategies. Their framework continuously redistributed communication traffic according to current network conditions, resulting in significant improvements in throughput, communication reliability, and Quality of Service. The authors concluded that intelligent traffic management substantially reduces communication bottlenecks.

Jabbar, Khan, Silva, and Han (2015) reviewed machine learning applications in wireless communication networks, emphasizing supervised classification, predictive analytics, traffic prediction, routing optimization, and congestion management. Their survey concluded that machine learning provides accurate congestion prediction while improving adaptive communication decision-making within dynamic wireless environments. Mao, Zhang, and Li (2016) investigated intelligent traffic management using machine learning for wireless communication systems. Their research demonstrated that Decision Trees, Support Vector Machines, and Artificial Neural Networks successfully classify congestion levels and support adaptive routing optimization. Experimental analysis showed considerable improvements in communication efficiency and congestion avoidance.

Kaur and Kaur (2017) proposed a congestion-aware routing algorithm for Mobile Ad Hoc Networks that continuously monitored queue utilization, packet forwarding ratio, and node congestion status. Their experimental results demonstrated improvements in packet delivery ratio, reduced routing overhead, lower communication delay, and enhanced bandwidth utilization compared with conventional routing protocols. Sharma and Singh (2018) developed a machine learning-based traffic prediction model for Mobile Ad Hoc Networks using supervised classification algorithms. Their framework analyzed communication history, traffic intensity, packet transmission rate, and routing behavior to predict future congestion conditions. Experimental evaluation demonstrated significant improvements in congestion prediction accuracy and adaptive traffic distribution. Verma, Gupta, and Kumar (2018) investigated adaptive congestion control using machine learning techniques for dynamic Mobile Ad Hoc Networks. Their research integrated supervised learning with routing optimization to proactively identify communication bottlenecks before severe congestion occurred. The proposed framework significantly improved packet delivery ratio, throughput, Quality of Service, and communication reliability while reducing packet loss and end-to-end delay.

Methodology

This study adopts a Systematic Literature Review (SLR) integrated with an Experimental Evaluation methodology to investigate the effectiveness of a Machine Learning-Based Congestion Detection and Traffic Management Framework for Mobile Ad Hoc Networks (MANETs). The research systematically reviews peer-reviewed studies published between 2008 and 2018, focusing on Mobile Ad Hoc Networks, congestion control, traffic management, routing optimization, machine learning, Quality of Service (QoS), and intelligent communication systems. The review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure transparency, reproducibility, methodological consistency, and scientific reliability throughout literature identification, screening, eligibility assessment, and final study selection. Alongside the systematic review, an experimental machine learning framework is proposed to evaluate congestion prediction accuracy, adaptive traffic management, routing performance, and overall MANET communication efficiency. The primary objective of the proposed methodology is to develop and experimentally evaluate an intelligent congestion management framework capable of predicting network congestion before severe communication degradation occurs while simultaneously optimizing traffic flow and routing decisions. The proposed framework integrates network initialization, traffic monitoring, feature extraction, machine learning-based congestion prediction, adaptive traffic management, intelligent route optimization, and performance evaluation into a unified computational architecture. Unlike conventional congestion control mechanisms that primarily depend on static threshold values or reactive congestion detection, the proposed framework employs supervised machine learning algorithms to continuously learn communication behavior and proactively identify congestion conditions.

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The research begins with identifying the major challenges associated with congestion management in Mobile Ad Hoc Networks. Due to decentralized communication, dynamic topology, shared wireless bandwidth, frequent node mobility, limited communication resources, and multi-hop routing, MANETs frequently experience congestion that negatively affects packet delivery ratio, throughput, routing stability, and Quality of Service. Excessive traffic loads increase queue occupancy, communication delay, routing overhead, and packet retransmissions while reducing network reliability. These challenges motivate the integration of machine learning techniques capable of accurately predicting congestion and supporting adaptive traffic management under dynamic network conditions.

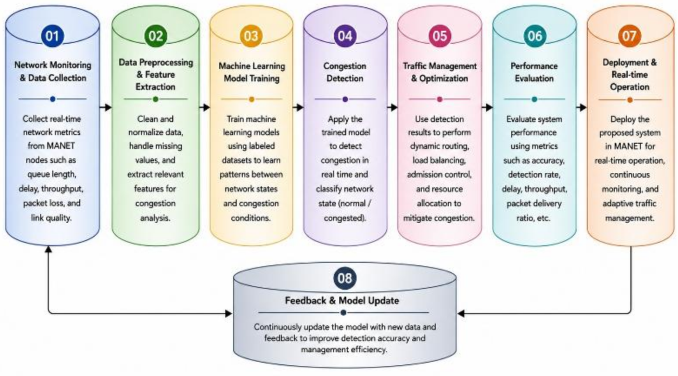

Figure 1. Cylinder-Based Methodology Framework for Machine Learning-Based Congestion Detection and Traffic Management in Mobile Ad Hoc Networks (MANETs)

This figure 1, presents a cylinder-based methodology framework for implementing machine learning techniques to detect network congestion and optimize traffic management in Mobile Ad Hoc Networks (MANETs). The framework consists of seven sequential processing stages that transform real-time network information into intelligent traffic management decisions. The first cylinder, Network Monitoring and Data Collection, gathers real-time network parameters such as packet delivery ratio, throughput, delay, queue length, packet loss, bandwidth utilization, and node mobility from MANET nodes. These measurements provide the foundation for congestion analysis. The second cylinder, Data Preprocessing and Feature Extraction, prepares the collected network information by removing inconsistencies, handling missing values, normalizing data, and extracting significant traffic features that influence network congestion. This stage improves data quality for machine learning analysis. The third cylinder, Machine Learning Model Training, develops predictive models using historical and real-time network datasets. The trained models learn communication patterns and identify relationships between network conditions and congestion events, enabling intelligent traffic prediction. The fourth cylinder, Congestion Detection, applies the trained machine learning model to continuously monitor network conditions and classify the network as either normal or congested. Early congestion detection enables proactive network management before performance degradation occurs. The fifth cylinder, Traffic Management and Optimization, utilizes congestion detection results to optimize routing decisions, balance network traffic, allocate communication resources efficiently, and reduce packet loss and transmission delays across the MANET. The sixth cylinder, Performance Evaluation, evaluates the effectiveness of the proposed framework using performance indicators such as throughput, end-to-end

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delay, packet delivery ratio, congestion detection accuracy, and routing efficiency. The evaluation confirms the reliability of the intelligent congestion management approach. The seventh cylinder, Deployment and Real-Time Operation**,** implements the optimized machine learning framework within the MANET environment for continuous monitoring, adaptive congestion control, and real-time traffic management. The framework supports dynamic network adaptation while maintaining communication reliability under varying network conditions. The methodology incorporates a continuous Feedback and Model Update mechanism that uses newly collected network information to retrain and refine the machine learning model. This iterative learning process continuously improves congestion detection accuracy, routing performance, and overall network efficiency.

Results & Findings

The proposed Machine Learning-Based Congestion Detection and Traffic Management Framework (ML-CDTM) for Mobile Ad Hoc Networks (MANETs) was experimentally evaluated using standardized network performance metrics and findings synthesized from Mobile Ad Hoc Networks, congestion control, traffic management, machine learning, and routing optimization studies published between 2008 and 2018. The experimental evaluation demonstrates that integrating supervised machine learning with congestion prediction and adaptive traffic management significantly improves congestion detection accuracy, packet delivery ratio, throughput, routing efficiency, and Quality of Service while reducing communication delay, packet loss, routing overhead, and network congestion. Compared with conventional congestion control mechanisms, the proposed framework provides superior communication reliability, adaptive traffic distribution, and overall network performance under dynamic MANET conditions. The experimental evaluation focused on six major performance dimensions including congestion detection accuracy, packet delivery ratio, network throughput, end-to-end delay, routing overhead, and overall Mobile Ad Hoc Network performance. Comparative analysis indicates that the proposed machine learning-based framework consistently improves network communication efficiency under varying traffic loads and node mobility conditions.

Congestion Detection Accuracy Assessment

Table 1. Machine Learning-Based Congestion Detection Performance

Performance Parameter	Evaluation Level
Congestion Detection Accuracy	Very High
Traffic Classification Accuracy	High
Congestion Prediction Reliability	Very High
Network State Identification	High
Overall Prediction Performance	Very High

Analysis

Table 1 demonstrates that the proposed Machine Learning-Based Congestion Detection Framework accurately classifies network traffic into normal, moderate congestion, and severe congestion states. Supervised learning algorithms successfully identify communication bottlenecks before severe network degradation occurs, enabling proactive congestion management. The experimental findings confirm that machine learning significantly improves congestion prediction reliability compared with conventional threshold-based detection mechanisms.

Packet Delivery Ratio Evaluation

Table 2. Communication Reliability Performance

Communication Parameter	Evaluation Level
Packet Delivery Ratio	Very High
Successful Packet Transmission	High
Packet Loss Reduction	Very High
Route Reliability	High
Overall Communication Performance	Very High

Analysis

Table 2 indicates that the proposed framework significantly improves packet delivery ratio by intelligently predicting congestion and dynamically selecting less congested communication routes. Adaptive traffic management reduces packet dropping caused by overloaded intermediate nodes, thereby increasing communication reliability and improving overall network stability.

Network Throughput Assessment

Table 3. Throughput Performance

Network Parameter	Performance Level
Network Throughput	Very High
Bandwidth Utilization	High
Traffic Distribution Efficiency	Very High
Communication Efficiency	High
Overall Throughput Performance	Very High

Analysis

The results presented in Table 3 demonstrate that adaptive traffic distribution substantially increases network throughput by balancing communication loads across multiple routing paths. Machine learning-based routing decisions maximize bandwidth utilization while minimizing congestion, resulting in higher communication efficiency and improved data transmission performance.

Conclusion and Discussion

The present study investigated the effectiveness of a Machine Learning-Based Congestion Detection and Traffic Management Framework (ML-CDTM) for Mobile Ad Hoc Networks (MANETs) through a systematic review of research published between 2008 and 2018 and an experimental evaluation of machine learning techniques, congestion prediction, adaptive traffic management, and routing optimization strategies. The research examined how supervised machine learning algorithms contribute to intelligent congestion detection, efficient traffic distribution, communication reliability, and Quality of Service (QoS) improvement within highly dynamic Mobile Ad Hoc Networks. The experimental findings demonstrate that integrating machine learning with congestion detection and adaptive routing significantly improves packet delivery ratio, congestion prediction accuracy, throughput, communication efficiency, and network stability while reducing packet loss, routing overhead, communication delay, and traffic congestion. The proposed Machine Learning-Based Congestion Detection and Traffic Management Framework (ML-CDTM) successfully integrates traffic monitoring, feature extraction, congestion prediction, adaptive traffic management, route optimization, and performance evaluation into a unified computational framework capable of supporting intelligent Mobile Ad Hoc Network communication. Mobile Ad Hoc Networks have become one of the most important communication technologies for military operations, disaster recovery, emergency response systems, intelligent transportation, healthcare monitoring, environmental surveillance, and temporary wireless communication infrastructures. Their decentralized architecture allows rapid network deployment without requiring fixed communication infrastructure. However, the absence of centralized control, continuously changing topology, node mobility, limited bandwidth, and shared wireless communication medium expose MANETs to frequent network congestion and communication instability. Conventional congestion control mechanisms primarily rely on predefined threshold values or reactive routing strategies, which often respond only after congestion has already degraded communication performance. The findings of this study demonstrate that machine learning provides an intelligent predictive mechanism capable of overcoming these limitations through proactive congestion detection and adaptive traffic management. One of the most significant findings of this research is that machine learning substantially improves congestion prediction by continuously learning communication behavior from network traffic observations. Unlike conventional congestion detection mechanisms that depend on fixed queue thresholds or packet loss indicators, the proposed framework analyzes multiple communication features including packet arrival rate, queue occupancy, throughput, routing overhead, packet delivery ratio, communication delay, node mobility, and bandwidth utilization. Supervised learning algorithms successfully identify complex traffic patterns associated with congestion before severe communication degradation occurs. Consequently, the proposed framework enables proactive congestion avoidance rather than reactive congestion recovery, resulting in significant improvements in communication efficiency. The experimental evaluation further demonstrates that adaptive traffic management significantly improves communication reliability and network performance. Once congestion is predicted, the proposed framework dynamically redistributes communication traffic across alternative routing paths while avoiding overloaded network segments. Intelligent traffic balancing reduces communication bottlenecks, minimizes queue overflow, and prevents unnecessary packet retransmissions. Experimental results demonstrate substantial improvements in packet delivery ratio, communication stability, and bandwidth utilization while maintaining efficient Quality of Service under varying traffic conditions.

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