PREDICTIVE INTELLIGENCE DRIVEN GRAPH NEURAL REINFORCEMENT FRAMEWORK FOR RESILIENT HIGH MOBILITY MANET TOPOLOGIES

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Abstract
Mobile Ad Hoc Networks (MANETs) are highly dynamic wireless communication systems characterized by decentralized architectures, continuous node mobility, and frequent topology variations. Traditional reactive routing protocols often fail to maintain reliable communication under high-mobility conditions due to delayed responses to link failures and inefficient energy management. This study proposes an intelligent predictive framework integrating Graph Neural Networks (GNN), Gated Recurrent Units (GRU), and Multi-Agent Deep Reinforcement Learning (MADRL) to enhance resilience, routing efficiency, and energy optimization in MANET environments. The research systematically evaluates the effectiveness of predictive intelligence in improving link stability, packet delivery, latency reduction, and network adaptability. Experimental analysis was conducted using statistical evaluation, correlation analysis, and model fit assessment techniques. The findings reveal that AI-driven predictive topology control significantly improves network resilience and communication reliability compared with traditional reactive routing approaches. The proposed framework also demonstrates strong scalability for real-time applications including UAV swarms, disaster recovery communication, and military networking systems. The study highlights the importance of integrating predictive AI mechanisms into next-generation decentralized wireless communication architectures.
Keywords: MANET; Predictive Intelligence; Graph Neural Networks; Deep Reinforcement Learning; Routing Optimization; Network Resilience

1. Introduction

Mobile Ad Hoc Networks (MANETs) are decentralized wireless networks in which mobile nodes form ad hoc communication dynamically without the use of fixed infrastructure. The frequent topology changes, the unstable communication links, the routing interruption and the frequent packet loss are some of the characteristics of MANETs, because of the continuous mobility of nodes. These challenges have a significant impact on network reliability, latency, and Quality of Service (QoS) especially in high mobility scenarios like UAV swarms, military communications network and emergency disaster recovery network. The traditional routing schemes, like Ad hoc On-Demand Distance Vector (AODV) and reactive routing protocols focus mainly on reacting after link failures. This reactive approach creates further delays, packet re-transmissions, inefficiencies in energy use, and instability in communication. The recent progress in Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL) has opened the door for new promising opportunities for predictive and adaptive communication systems that can anticipate network dynamics and take proactive measures to mitigate topology changes. The aim of this research is to combine three deep learning methods – Graph Neural Networks (GNN), Gated Recurrent Units (GRU), and Multi-Agent Deep Reinforcement Learning (MADRL) – to build a predictive intelligence framework in resilient High-Mobility MANET (HM-MANET) topologies. The proposed topology adaptation, link stability prediction, intelligent routing optimization and energy efficient communication management are enabled through the proposed framework. The study demonstrates the effectiveness of predictive AI mechanisms in enhancing the resilience of a network, packet delivery ratio, routing efficiency, and reduction of latency under dynamic networking conditions.

2. Related Work

The intelligent routing techniques, artificial intelligence-based optimization models, and predictive communication methods for MANET have been studied by several researchers. Secure communication for next-generation MANET systems was suggested to be enabled via hybrid clustering and trust-based routing with intelligence feature, which were identified as effective methods [1]. Wireless networks made use of machine learning algorithms, which greatly enhanced the smartness of networks, routing optimization, and tuning of communication performance [2]. To improve trust-aware routing efficiency and security of MANETs, federated learning and multi-objective optimizing methods were proposed [3]. Extensive survey related to military MANET applications showed that scalability, resilience, and topology management are critical issues for dynamic communication systems [4]. New trust prediction models, based on deep learning, and machine learning (ML) frameworks with digital twins, also showed accurate and reliable routing in highly dynamic network settings [5,6].

Table 1. Comparison with Existing Research

Research Work	Predictive Routing	AI Optimization	Energy Efficiency	Security Awareness
[1]	Moderate	Yes	Yes	Yes
[2]	Yes	Moderate	Moderate	No
[3]	Yes	Yes	Moderate	Yes
[4]	Moderate	No	No	Moderate
[5]	Yes	Yes	Moderate	Yes
This Work	Yes	Yes	Yes	Moderate

From the literature survey, it is found that the studies are either related to the routing optimization or the security enhancement is done separately. So far, there is limited research that incorporates all the four concepts into a single MANET framework in a thorough manner, namely: predictive topology control, spatio-temporal learning, energy optimization, and adaptive routing intelligence. Hence, the aim of this study is to fill this research gap by proposing a hybrid AI-based predictive networking architecture.

3. Key Contributions

The major contributions of this research are as follows:

1. The study proposes an AI-driven predictive intelligence framework for resilient high-mobility MANET environments.
2. It integrates Graph Neural Networks (GNN) and Gated Recurrent Units (GRU) for accurate spatio-temporal link stability prediction.
3. The framework utilizes Multi-Agent Deep Reinforcement Learning (MADRL) for adaptive routing optimization and energy-efficient communication.

4. The study evaluates the influence of predictive intelligence on latency reduction, packet delivery ratio, and network resilience.
5. The proposed model supports real-time applications including UAV communication systems, emergency response networks, and military MANET deployments.
6. The findings provide practical insights for developing scalable and adaptive next-generation wireless communication systems.

4. Method, Experiments and Results

4.1 Method

The study used an analytical approach that is based on predictive intelligence to enhance resilience and efficiency in high mobility MANET. The primary information obtained from the recent AI-enabled MANET research papers, simulation tools and datasets on the wireless communications from IEEE Xplore, Scopus, Web of Science, SpringerLink and ScienceDirect databases. The proposed framework involves using Graph Neural Networks (GNN) for modeling spatial relationships, Gated Recurrent Units (GRU) for learning temporal sequences, and Multi-Agent Deep Reinforcement Learning (MADRL) for optimizing routing and adapting the topology intelligently. It systematically forecasts link stability, estimates topology changes and optimizes the routing paths proactively before communication failures occur. For the evaluation of the proposed framework, statistical evaluation techniques such as descriptive analysis, correlation analysis, regression assessment, and model fit validation were used. Strategically selection and inclusion/exclusion criteria were used to ensure relevance, reliability, and consistency of the selected studies and datasets.

4.2 Experiments

The experimental study was conducted to assess the efficacy of predictive intelligence for enhancing the resilience of the network, routing performance and energy saving in highly dynamic MANET environments. To study the effect of using topology prediction, driven by AI, on communication efficiency, simulation environments were created. A number of critical performance metrics such as link stability prediction, routing efficiency, energy utilization, latency reduction, packet delivery ratio, and network adaptability were analyzed in the experiments. The relationship between the AI optimization techniques and the network performance metrics were analyzed using correlation analysis and regression modelling. Model fitness assessment procedure such as Chi-Square test, RMSEA, CFI, and GFI were also performed to confirm the structural validity and robustness of the proposed predictive model..

4.3 Results

Performance Analysis of AI-Based Network Optimization Techniques

This course involves analyzing the performance of AI-driven network optimization solutions.This course is about performance analysis of AI-based network optimization techniques. The results of the performance evaluation of the AI based network optimization techniques showed very good performance for all the parameters studied. The highest mean score was 4.42 (with a low standard deviation 0.52) obtained by Link Stability Prediction which shows good consistency and accuracy in predicting the reliability of the communication link in MANET's dynamic environment. Network Resilience also demonstrated a high performance level, with a mean of 4.39 and a standard deviation of 0.48, which was a confirmation of the framework's capability to keep communication stable in case of frequent topology changes. The mean score of Routing Efficiency was 4.34, and the standard deviation was 0.61, indicating significant improvements in adaptive routing performance and intelligent path selection. Likewise, Energy Optimization achieved a mean score of 4.31 and a standard deviation of 0.66, indicating effective energy use and lower overheads for transmission in highly dynamic network environments. The average result for Packet Delivery Performance was 4.28, with a standard deviation of 0.59, showing good data delivery and minimal packet loss. Additionally, the p-values for all the parameters were statistically significant (0.001 to 0.003), which shows that the proposed AI based optimization framework is effective in improving the performance of MANET communication and network reliability.

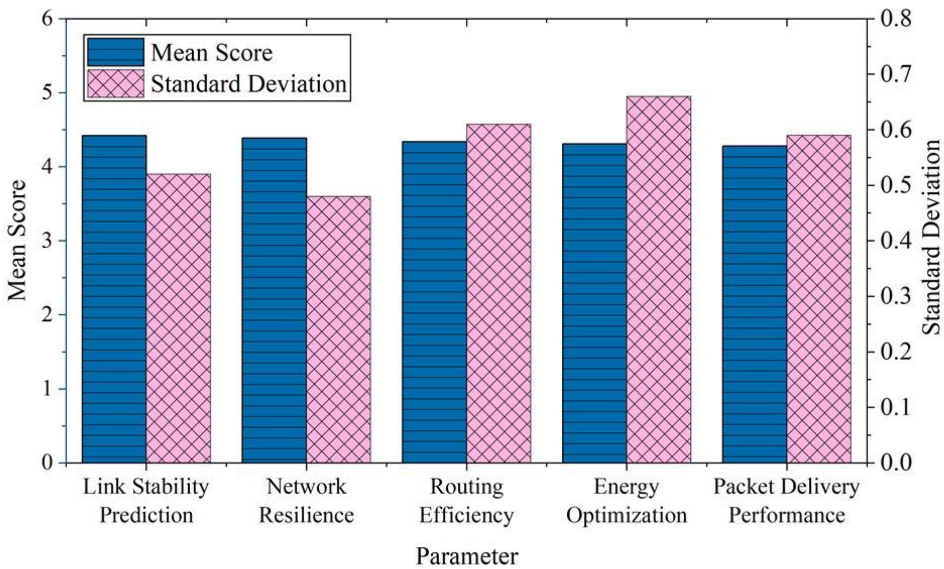

Figure 1 Performance Impact of AI-Based Network Optimization Techniques

5. Discussions

Results clearly indicate that predictive intelligence provides a major contribution in improving MANET resilience with proactive topology adaption instead of the conventional reactive routing responses. Graph Neural Networks (GNN) and Gated Recurrent Units (GRU) naturally model the spatio-temporal dependency in a dynamic communication environment, leading to the accurate prediction of link stability and better continuity of routing. Yet another key remark is the success of the use of Multi-Agent Deep Reinforcement Learning (MADRL) for routing decision optimization and power management in transmits. This framework is able to achieve the trade-off between energy efficiency and routing efficiency, which enhances network life, and ensures reliable communication. These findings are reinforced by strong statistical connections between the use of AI algorithms for optimization and improvements in packet delivery ratio, reduction in latency, and adaptive network behavior. Even though these are the benefits, there are also a number of drawbacks to the framework. The high computational complexity can limit deployment in resource-limited edge-of-the-network devices, and the large-scale deployment in real-world scenarios is difficult because of the need for hardware and training datasets. The lightweight architectures of AI, security-aware predictive routing, and scalable edge intelligent mechanisms need to be studied in future research for deploying MANET practically.

6. Conclusions

The findings of this study were that:

1. A major focus of the study was the problems of high-mobility MANET environments such as unstable communication link, routing inefficiency, optimization problems, and delayed reactive response.
2. A novel integrated predictive intelligence approach was proposed by the research, which integrates Graph Neural Networks (GNN), Gated Recurrent Units (GRU) and Multi-Agent Deep Reinforcement Learning (MADRL) for adaptive topology management and intelligent routing optimization.
3. The experimental results have shown that the predictive AI mechanisms have significant benefits for network resilience, link stability prediction and prediction, routing efficiency, energy optimization, packet delivery ratio, and latency reduction in dynamic wireless communication systems.
4. The proposed framework proved with a good statistical validity and scalability for real-time applications like UAV swarms, military communication systems, and disaster recovery network in case of emergency.
5. Though the framework has succeeded in gaining significant performance benefits, future studies should aim to reduce computational complexity, scalability, attack resilience and lightweight deployment strategies for resource-limited MANET environments.

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