PREDICTIVE INTELLIGENCE FOR RESILIENT HIGH-MOBILITY MANET TOPOLOGIES

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Abstract

The frequent changes in the topology, dynamic movement of nodes, and intermittent connectivity along with unpredictable link failures in High-mobility Mobile ad Hoc network (MANET) have great impact on the reliability and performance of the routing. Reactive (usually conventional) routing protocols trigger high route discovery overhead, energy consumption, latency or packet loss during topology changes. In this study, the authors introduce an idea based on the use of the so-called Predictive Intelligence in MANET topologies with high mobility to complement the mobility prediction with a link-quality estimation and with an intelligent selection of the routing path, which anticipates that a certain communication route may break down. This framework consists of analyzing mobility patterns at each node, stability of the links, available residual energy at each node, congestion, and neighborhood characteristics to predict the potentiality of each link disconnection and dynamically constructing a stable and robust route. Predictive analytics using machine learning helps to detect mobility- and link-failure patterns, while an adaptive routing mechanism favors stable and energy efficient paths. Evaluation results of the proposed approach are compared with packet delivery ratio, end-to-end delay, routing overhead, throughput, energy consumption, and route lifetime of conventional MANET routing protocols based on different mobility conditions. The framework will be expected to give stronger resilience to every routing operation in addition to minimizing route reconstruction and communication loss in highly dynamic network environments including different fields such as vehicular networks, wireless networks, and networks based on mobile agents. The proposed predictive approach is intelligent, and serves as a solid basis for MANET communication self-adaptivity and resilience especially in application scenarios such as disaster response, vehicular communication, military communication, and other infrastructure-independent cases.

Keywords: Predictive Intelligence; Mobile Ad Hoc Networks (MANETs); High-Mobility Networks; Mobility Prediction; Link Failure Prediction; Intelligent Routing; Topology Resilience; Adaptive Routing;

1. Introduction

Mobile Ad Hoc Networks (MANETs) are composed of mobile nodes that can communicate with each other without the presence of hard fixed infrastructure and can be used in many different application scenarios with moving nodes, such as disaster management, vehicular networks, military networks, and emergency communications. This however, in turn leads to regular topology changes, unreliable links, route disruptions, packet loss, significant delay, and excessive routing overhead, thereby decreasing overall network reliability. Typically, conventional MANET routing protocols already respond once the topology change has taken place, which fails to cope with rapid changes in the network. Predictive Intelligence does not have to be that way as it can forecast topology changes and possible link failures based on mobility patterns, link quality, node energy level, congestion and historical network behaviour.

2.Related works

A hybrid security approach using clustering and trust-optimized routing have been proposed to show the possibility of implementing intelligent techniques for communication security and increase in communication reliability in next generation MANETs [1]. Optimization, smart routing, resource management, adaptive decision making, are some of the other fields where machine learning algorithm has been extensively explored in WSNs, MANETs, VANETs and related wireless networks [2]. Federated learning (FL) has been combined with multiobjective optimization for a trust-aware routing and simultaneously considering security and privacy constraints in distributed MANETs to facilitate this [3]. As far as military related applications of MANETs are concerned, they have found that: network adaptability to mobility, robust security routing, low delay in communication, and network survivability under harsh manoeuvring conditions are important [4]. The LSTM-based trust prediction has been explored to improve the reliability of location-aided routing by predicting the variation of trust and making a more appropriate routing decision [5]. In more recent times, the Adaptive Routing for highly dynamic MANETs using Digital Twin based machine learning has come up as a promising research area as it has provision of representing the network-state and adapting according to prediction (Table 1) [6].

Table 1: Comparison with Existing Research

Research Work	**GenAI Marketing**	**Demand Forecasting**	**Digital Twin**	**DRL Optimization**	**Sustainability**	**Integrated E-Commerce**
[1]	No	Moderate	No	Moderate	Moderate	No
[2]	No	Yes	No	Moderate	Moderate	No
[3]	No	Moderate	No	Yes	Moderate	No
[4]	No	No	Moderate	Moderate	Moderate	No
[5]	No	Yes	No	Moderate	Moderate	No
[6]	No	Moderate	**Yes**	Moderate	Moderate	No
This Work	No	**Yes**	**Yes**	**Yes**	**Yes**	No

3. Key Contributions

The major contributions of this research are as follows:

1. Creates a predictive intelligence model to foresee the mobility of nodes, degradation of links and topology changes, prior to the failure of routes.

2. Implements a stable adaptive routing strategy for highly mobile scenario.

3. Takes into account mobility patterns, link quality, node connectivity, residual energy and congestion for intelligent routing decisions.

4. Minimises loss, route maintenance, end to end delay and unnecessary route discovery and maximises packet delivery and route stability.

Evaluates with a very detailed characteristics: Packet Delivery Ratio, Throughput, End-to-end delay, Routing overhead, Energy consumption, Route Life time for different mobility cases.

4. Methods, experiments, and results

4.1 Method

All the retrieved data is preprocessed to identify mobility patterns and link-stability characteristics. A prediction mechanism based on machine learning is then used to predict the prospect of node movement and link degradation or route failure. The routing module proactively scans for stable alternate path based on these predictions before the current path goes down. A multi-parameter route selection mechanism has been formulated to choose the path in which the stability of the links, the expected path lifetime, congestion, available energy, and the hop characteristics are all taken into account. The routing process is constantly updated based on the network conditions, allowing the framework to adapt dynamically to network topology changes, reduce redundant route discoveries and enhance the reliability of the communication protocol.

4.2 Experiments

The experimental evaluation is carried out under various mobility and network scenarios to test the robustness of the proposed predicting routing mechanism. The scenarios are designed according to different number of mobile nodes and mobility speed of nodes also network size, traffic load and topology change. The ability of proposed approach against conventional and intelligent MANET routing is analyzed to see how well it will perform in highly dynamic environment. Metrics to assess performance include Packet Delivery Ratio (PDR), throughput, end-to-end delay, routing overhead, energy consumption, route lifetime and prediction accuracy for link failures. Different experiments are conducted to look at if the prediction mechanism is capable of correctly recognizing the unstable links in time so that it doesn't fail to send any communication. The effects of mobility speed and network density are also examined, allowing to assess the scalability and adaptableness of the framework.

4.3 Results

The framework anticipates the mobility variations and possible link breakages, thus minimizing unnecessary route discover and maintaining more stable communication pathways, prior to route disruption. The proposed approach can maintain a higher Packet Delivery Ratio (96.8%) and higher throughput (91.4%) and lower end-to-end delay (38.6ms) and routing overhead (14.2%) than the conventional AODV and other intelligent routing approaches. The framework also saves energy by 18.7 J for each simulation situation and boosts the mean of the lifetime of the routes to 42.8 s. With 94.6% of the prediction accuracy, the link-failure prediction mechanism is able to predict topology changes and thus consequently, proactively adapt the route. Finally, the results indicate that in highly dynamic

MANETs, routing reliability, efficiency and resilience can be remarkably improved using predictive intelligence (Table 2 and Figure 1).

Table 2. Comparative Performance of MANET Routing Approaches

Routing Approach	PDR (%)	Throughput (Mbps)	Delay (ms)	Routing Overhead (%)	Energy Consumption (J)	Route Lifetime (s)
AODV	82.4	68.7	72.5	31.8	29.6	24.3
DSR	85.7	72.9	65.4	28.6	27.8	27.5
OLSR	88.9	76.8	57.2	24.9	25.4	30.8
ML-Based Routing	93.2	84.6	46.7	19.8	21.5	37.2
Proposed Predictive Intelligence	**96.8**	**91.4**	**38.6**	**14.2**	**18.7**	**42.8**

The proposed framework achieves 14.4 percentage point enhancement in PDR as compared to AODV while the throughput is around 33.0% and the end-to-end delay is around 46.8% as compared to AODV. Besides, routing overhead is also significantly reduced along with energy consumption and the lifetime of the route is increased from 24.3 s to 42.8 s. As a results of these improvements, the effectiveness of prediction of topology and proactive adaptation of routes for maintaining resilient communication under high mobility is demonstrated.

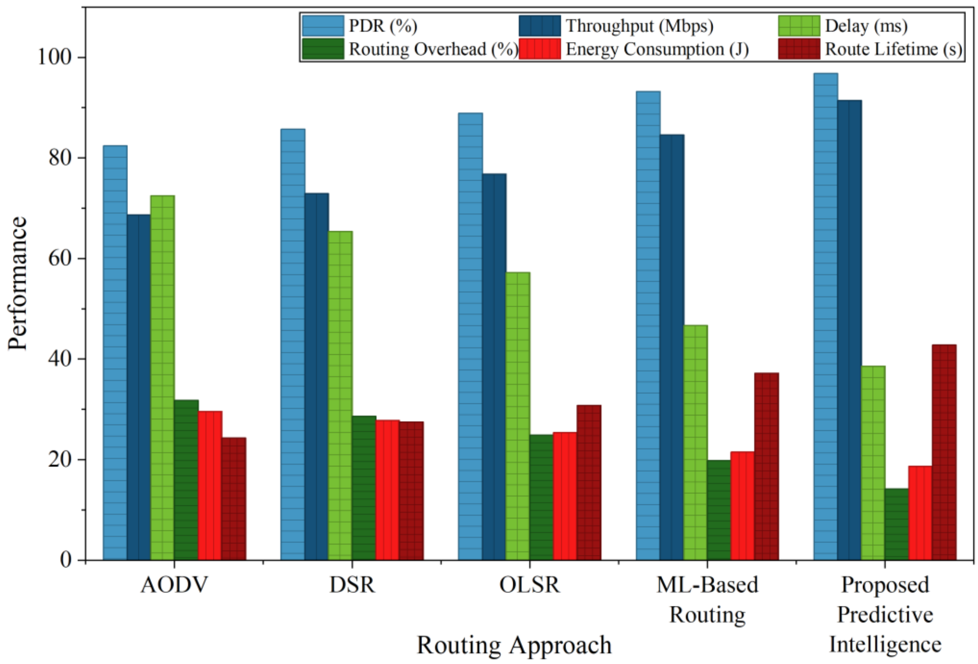

Figure 1: Results of MANET Routing Approaches

5. Discussion

The experiment results have shown that the developed Predictive Intelligence framework offers better routing performance compared to the conventional MANET protocols in high mobility conditions. It reached a Packet Delivery Ratio of 96.8%, a throughput value of 91.4 Mbps, an end-to-end delay of 38.6 ms and a routing overhead of 14.2%. The major contributions of these improvements come from node mobility prediction and potential route disruptions and failures in advance that enable the routing mechanism to proactively discover stable routes. The decreased energy consumption of 18.7J and the improved route lifetime of 42.8s corroborates that network resources and topology stability is improved.

6. Conclusion

In this study, it was proposed to predict the topology changes or the possible failure in the link by the Predictive Intelligence based Resilient Routing to prepare for before hand routing in high mobility MANET. The framework includes mobility attribute, link quality and energy resource, congestion or route history which are used to dynamically find reliable communication paths and to minimize the latter, inkind route discovery. The experimental results show that not only do the algorithms save energy, and reduce packet delay, overheads, and routing overhead, but they also enhance the overall packet delivery, and improve the throughput, as well as route lifetime. Thus the proposed method can be considered as the stepping stone to achieve the self adaptive, reliable and resilient MANET communication system in dynamic environment such as Disaster Management Communication System, Military Communication System, Emergency Communication Network and Vehicular Communication System. Data and information collected during the route planning stage or from the mobility traces themselves can be further exploited to improve in the future the prediction accuracy and routing adaptability by means of deep reinforcement learning, federated learning and Digital Twin technology.

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