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Research Article

Intelligent Routing in MANETs: Bridging AI and Protocol Design for Next-Gen Networks

Amit Sharma[1], Pritibha Sukhroop[2], Shilpi Gupta[3], Akshita Chaudhary[4], Anshu Shukla[5], Sachin Agrawal[6], Gaurav Tyagi[7],

Assistant Professor Deptt. of CSE, SCRIET C.C.S.University[1-7],
Assistant Professor Deptt. of EE, ABSS Institute of Technology[2],
Assistant Professor Deptt.of CSE, Meerut Institute of Tech. Meerut[3]
Assistant Professor Deptt.of M.C.A. SRM Institute of Science & Technology NCR Campus[4]
Assistant Professor Deptt.of C.A. Hi-Tech Institute of Engg. & Technology, C.C.S.University[5],
Assistant Professor Deptt. of CSE, IIMT University, Meerut[6].
Corresponding Author- pritibhadhadli@gmail.com

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ABSTRACT

Decentralized wireless networks with self-configuring nodes that can interact without the need for fixed infrastructure are known as mobile ad hoc networks, or MANETs. Reliable and effective communication is a difficulty for traditional routing methods because of node mobility, bandwidth limitations, and energy limits. A potential remedy for these issues is the use of machine learning (ML) and artificial intelligence (AI) into the design of routing protocols. MANETs can optimize routing choices, adjust flexibly to shifting network conditions, and enhance overall network performance in real-time thanks to AI-driven techniques.

In order to improve routing efficiency, scalability, and energy consumption, this study investigates the use of AI techniques in MANETs, including deep learning, reinforcement learning, and clustering algorithms. By enabling adaptive resource allocation, predictive traffic management, and intelligent path selection, AI-based protocols can greatly boost network resilience, lower latency, and increase throughput. In order to handle the intricate dynamics of MANETs, the study also looks at hybrid AI techniques that incorporate several learning philosophies.

The study also addresses the difficulties in putting AI-driven routing into practice, such as security issues, computing cost, and handling extremely dynamic network conditions. It also emphasizes how AI might be integrated with cutting-edge technologies like edge computing, 5G, and the Internet of Things to facilitate the creation of next-generation MANETs. In order to overcome the current constraints and spur innovation in AI-based routing protocols for MANETs, the study concludes by outlining future research topics.

The goal of this research is to help develop more intelligent, effective, and self-optimizing MANETs for next-generation communication networks by bridging the gap between AI and routing protocols.

Keywords: Mobile Ad-Hoc Networks (MANETs), Intelligent Routing, Artificial Intelligence (AI), Machine Learning (ML), Routing Protocols.

1. Introduction

1.1 Overview of MANETs

Mobile Ad-Hoc Networks (MANETs) are dynamic, self-organizing, and decentralized wireless networks in which nodes—such as laptops, mobile devices, or sensors—communicate directly with one another without the need for central management or established infrastructure. In contrast to traditional networks, which use centralized servers and routers to ease data transfer, MANETs allow nodes to communicate with one another and create communication channels on the fly. These networks are especially useful in situations where fixed infrastructure is neither feasible or accessible, like in rural locations, military operations, disaster recovery scenarios, and automobile networks.

The mobility of MANETs is one of their key features. The network topology frequently changes as a result of each node's unrestricted mobility. Dynamic routing is necessary because nodes can join or exit the network at any time. Because of this mobility, MANET routing protocols need to be extremely adaptive in order to react rapidly to changes in topology.Other essential features of MANETs include:

1. **Decentralized Nature**: Since the network is not governed by a single entity, each node is in charge of forwarding and routing its own data.

2**. Dynamic Topology**: The network's topology is always shifting as a result of node mobility. Routing protocols must therefore be able to swiftly adjust to these modifications.

3. **Limited Resources**: A large number of MANET nodes are usually mobile devices with constrained bandwidth, computing power, and battery life. One of the biggest challenges is making efficient use of resources.

4**. Scalability:** MANETs ought to be able to accommodate a lot of nodes, but as the network expands, problems like congestion and overhead could appear.

These features make routing in MANETs a crucial problem because nodes may need to rely on one another for data transfer and the network architecture can change quickly. Establishing effective communication channels between nodes while reducing the overhead of routing decisions, controlling resource constraints, and handling network dynamics such node mobility are the primary goals of routing protocols in MANETs.

1.2 The Role of Routing Protocols' in MANETs

In MANETs, routing protocols are in charge of figuring out the best routes for data transfer throughout the network. These networks are dynamic and decentralized, therefore routing protocols need to be reliable, flexible, and effective. The MANET's performance in terms of throughput, delay, energy consumption, and overall network scalability is directly impacted by the routing protocol used.

Types of routing protocols in MANETs:

1. **Proactive Protocols (Table-driven)**:

- To keep an updated routing table, every node in proactive protocols continuously exchanges routing information. When needed, these protocols guarantee that routes are constantly accessible.
- For instance, Optimized Link State Routing (OLSR) and Destination-Sequenced Distance Vector (DSDV).
- **Benefits:** Immediate route availability minimizes latency.
- **Drawbacks:** High overhead brought on by constant updates, which makes highly dynamic networks inefficient.

2. **Reactive Protocols (On-Demand):**

- Also referred to as on-demand protocols, reactive protocols only generate routes when required. By avoiding frequent updates and starting route discovery only when a node wishes to communicate data to another node, they lower overhead.
- Ad-hoc On-demand Distance Vector (AODV) and Dynamic Source Routing (DSR) are two examples.
- **Benefits:** Minimal bandwidth usage and control overhead.
- **Drawbacks:** Inefficient in highly mobile environments and increased latency during route discovery.

3. Hybrid Protocols:

- These protocols integrate the advantages of reactive and proactive approaches. Reactive protocols are used for larger distances, whereas proactive routing is maintained within a small area.
- Zone Routing Protocol (ZRP) and Hybrid Ad-Hoc Routing Protocol (HARP) are two examples.
- **Benefits:** More scalable and flexible in response to changing network circumstances.
- **Drawbacks:** Potential inefficiency in highly dynamic networks and increased design complexity.

Traditional Routing Protocols' Drawbacks

In MANETs, traditional routing protocols encounter a number of difficulties:

- **Scalability:** Network congestion and decreased efficiency result from the overhead needed to maintain and update routing tables or start route discoveries as the number of nodes rises.
- **Energy Efficiency:** A large number of MANET nodes run on batteries. Conventional methods might not maximize energy use, which could result in node failures and early battery depletion.
- **Adaptability to Mobility:** Traditional protocols may find it difficult to maintain stable routes due to the nodes' continuous movement, which could lead to more frequent route reconfigurations and longer communication delays.
- **Security:** Eavesdropping, node compromise, and routing assaults are just a few of the security risks that MANETs are susceptible to. Strong security measures to counter these threats in dynamic contexts are sometimes absent from traditional protocols.

These drawbacks demonstrate that, particularly in next-generation network environments, conventional routing methods by themselves are unable to manage the complexity of contemporary MANETs.

1.3 Integration of Artificial Intelligence (AI)

Overview of Artificial Intelligence and Machine Learning (ML)

The term artificial intelligence (AI) describes how machines may mimic human intelligence functions, especially learning, reasoning, and problem-solving. A subset of artificial intelligence called machine learning (ML) entails teaching algorithms to recognize patterns in data and generate predictions or judgments without the need for explicit programming.

Because AI and ML allow nodes to learn from past experiences and adjust to network conditions in real-time, they have the potential to optimize routing in MANETs. Intelligent decision-making is made possible by these AI techniques, which are not possible with conventional protocols.

The Potential Use of AI to Improve Routing Protocols . AI can enhance MANET routing protocols in a number of ways.

1. **Dynamic Route Selection:** AI can forecast the best routing routes by examining variables such node mobility, congestion, and link quality through the use of reinforcement learning (RL) and deep learning (DL).

2. **Energy Efficiency:** By anticipating patterns of energy use and making sure that data is transmitted over energy-efficient channels, AI algorithms can improve energy consumption.
3. **Load balancing and traffic prediction**: AI can anticipate network congestion and modify routing routes appropriately, preventing bottlenecks and increasing network throughput overall.
4. **Fault Detection and Self-Healing**: Without human assistance, AI can identify network faults like broken links or node crashes and automatically identify alternate pathways.

5. **Security Enhancement:** By using adaptive routing techniques, AI can reduce risks and identify unusual activity or harmful activity in the network, such as routing assaults or unauthorized access attempts.

1.4 **Paper Objective**

The purpose of this work is to investigate how AI and machine learning approaches might be incorporated into the planning and enhancement of routing protocols for mobile ad hoc networks (MANETs). The following are the paper's objectives

1. Examine AI-Driven Routing Protocols: Look into how AI and ML methods, such clustering, deep learning, and reinforcement learning, might enhance routing choices in MANETs, improving network performance in terms of latency, throughput, and energy efficiency.
2.Examine the advantages and difficulties: Examine the benefits of AI-powered routing, such as improved flexibility, decreased overhead, fault tolerance, and energy management. Examine the difficulties of integrating AI into MANET routing as well, including the requirement for big datasets for AI model training, security issues, and computational complexity.

3.Connect AI with Conventional Routing Design: Determine how AI may assist next-generation applications by supplementing or replacing conventional routing protocols in MANETs, especially when it comes to managing mobility, network congestion, and energy restrictions.
4.Determine Future Lines of Research: Make suggestions for future research directions to improve AI-driven routing, especially in light of cutting-edge technologies like edge computing, 5G, and the Internet of Things. Research avenues could involve creating more scalable, secure, and energy-efficient routing systems as well as integrating AI with hybrid protocols.

2. Background

2.1 The Features of Mobile Ad-Hoc Networks (MANETs)

Decentralized wireless networks called Mobile Ad-Hoc Networks (MANETs) allow mobile devices, or nodes, to speak with one another directly without the need for centralized control or a fixed infrastructure. A MANET is a dynamic and extremely adaptable network since each node can function as both a host and a router, passing data packets to other nodes. These networks are especially helpful in situations like disaster recovery efforts, military applications, and automobile networks where fixed infrastructure is neither feasible or accessible.

The attributes of MANETs

1. **Decentralized Nature:**MANETs' decentralized operation is one of their distinguishing features. Every node takes part in the routing process and helps to maintain the network; there is no central controller or server in charge of it.

2. Dynamic Topology: Because nodes in MANETs are free to move around, the network topology frequently changes as a result of their movements. Routing methods must swiftly adjust to this changing topology in order to maintain dependable and continuous communication.

3. Limited Resources: Mobile devices such as smartphones, tablets, and sensors, as well as nodes in MANETs, have limited resources. These consist of low battery life,bandwidth and processing power. Making effective use of these resources is essential to preserving network performance and extending network lifespan.

4. Scalability: MANETs can function in highly scalable contexts, but as the number of nodes rises, routing protocol efficiency frequently declines, particularly when infrastructure or central management are lacking.

5. Mobility: A MANET's nodes are movable, which allows them to shift positions and locations. Routing becomes more intricate and dynamic as a result of variations in signal intensity, connection, and route pathways between nodes.

Because of these special features, routing in MANETs poses a number of difficulties, such as network instability, high overhead, energy consumption, and the requirement for effective path maintenance and discovery.

2.2 Conventional MANET Routing Protocols

Three general categories can be used to group routing protocols in MANETs: proactive, reactive, and hybrid.

2.2.1. Table-Driven Proactive Protocols

Routing tables are always kept current by proactive routing protocols, sometimes referred to as table-driven protocols. To make sure that routes are always available when needed and that routing information is up to date, these protocols exchange control messages on a regular basis. Typical instances consist of:

• **Destination-Sequenced Distance Vector (DSDV):** This protocol maintains routing tables using a distance-vector methodology. To avoid routing loops, each node updates its routing information based on sequence numbers and broadcasts its routing table to its neighbors on a regular basis.
• **Optimized Link State Routing (OLSR):** OLSR minimizes the number of nodes required to take part in the periodic updates of the routing information by employing a technology known as MultiPoint Relays (MPRs) to lower the control overhead.
Benefits: include minimum route search latency and instant route availability when required.
Cons: High overhead from frequent updates, which makes it inefficient in contexts with a lot of topological changes.

2.2.2. On-Demand Reactive Protocols

On-demand protocols, sometimes referred to as reactive protocols, create routes only when necessary. When a node wishes to transfer data to a destination node for which it does not yet have a route, they start the route discovery process. Typical instances consist of:
• **Ad-hoc On-demand Distance Vector (AODV):** AODV employs a route management mechanism to guarantee route validity and a route discovery procedure to find a path as needed.
• **Dynamic Source Routing (DSR):** DSR eliminates the need for nodes to constantly maintain routes by enabling them to dynamically find a source route over a number of hops to the destination.

Benefits: Less control overhead because routes are generated as needed, making them better suited for highly mobile networks.

The inefficiency in networks where routes are regularly required and the high latency during route identification are the **drawbacks.**

2.2.3. Hybrid Protocol

The advantages of reactive and proactive routing are combined in hybrid protocols. They use reactive routing for nodes outside of their local region and proactive routing for nodes inside it. Here's an example:

• **Zone Routing Protocol (ZRP**): ZRP integrates the advantages of reactive routing for nodes outside of a zone and proactive routing within a predetermined zone.
Benefits include scalability in bigger networks and increased efficiency in managing networks with both mobile and static nodes. Increased complexity and possible inefficiency in extremely dynamic contexts are drawbacks.

2.3 Machine Learning and Artificial Intelligence overview

The creation of systems that are able to carry out operations like pattern recognition, problem solving, and decision making that often call for human intelligence is known as artificial intelligence (AI). By offering systems that can learn from experience and adjust to changing conditions, artificial intelligence (AI) can assist in addressing the difficulties associated with network management and routing in the context of MANETs.
In the context of MANETs, machine learning (ML), a branch of artificial intelligence, is especially pertinent. The development of algorithms that enable systems to learn from and make predictions or judgments based on data is known as machine learning (ML). Three primary forms of machine learning can be distinguished:

1. **Supervised Learning**: The algorithm learns to anticipate the output based on the input data after being trained on labeled data.
2. **Unsupervised Learning**: This technique finds hidden structures in data by recognizing patterns in data without the need for prior classifications.
3. **Reinforcement Learning (RL):** To maximize long-term choices, the algorithm learns by interacting with the environment and getting feedback in the form of rewards or penalties.
   By allowing nodes to independently learn the best routes, forecast future network conditions, and make judgments based on prior experiences, AI and ML offer major benefits for routing in MANETs.

2.4 Key Benefits of Integrating AI into MANET Routing

There are numerous important advantages to using AI and ML into MANET routing systems.

1. Adaptive Routing: AI algorithms can assist routing protocols in instantly adjusting to the unpredictable and dynamic characteristics of MANETs. AI can optimize routing channels to prevent congestion, reduce latency, and increase throughput by learning from network activity.
2. Energy Efficiency: Energy efficiency is a critical issue in a MANET because of the resource limitations of its nodes. AI-based routing protocols are able to identify trends in energy usage and improve route choices to increase nodes' battery life.

3. Enhanced Scalability: Conventional routing systems have scalability challenges when MANETs expand in size. Large-scale networks can be managed using AI-based techniques like reinforcement learning, which reduce overhead and make better routing decisions.
4. Fault Tolerance and Self-Healing: By identifying network faults, such as link or node failures, and

automatically rearranging the routing patterns, AI can improve the resilience of MANETs. Even in the event of malfunctions, the network will continue to function because to its self-healing potential.
5. Traffic Prediction and Load Balancing: AI can forecast times of heavy traffic or congestion and modify routing choices appropriately by examining traffic trends. AI-based protocols can better control traffic and distribute the load throughout the network thanks to this predictive capability.

6. Security Improvement: AI can also be used to identify network intrusions or harmful activity. Artificial intelligence (AI) systems can detect abnormalities that might indicate security breaches, including routing assaults or node compromise, by examining patterns of behavior. They can then take proactive steps to mitigate these threats.

3. MANET Intelligent Routing Techniques

3.1 Routing Methods Based on Machine Learning

Traditional protocols frequently fail to manage changing topologies, resource constraints, and mobility in Mobile Ad-Hoc Networks (MANETs), where Machine Learning (ML) has emerged as a viable approach for routing optimization. By using machine learning (ML) techniques, nodes can learn from their experiences, adjust to shifting network conditions, and make wise routing choices that maximize performance across a range of parameters, including latency, throughput, and energy usage.

3.1.1 Routing via Supervised Learning

By training models using labeled data, supervised learning algorithms—like decision trees, support vector machines, and neural networks—can be used to make routing decisions in MANETs. Based on input characteristics including link quality, node density, and energy levels, these models are able to forecast the best routing routes. In order for the network to choose the optimal routes for upcoming transmissions, the model is trained on historical data to identify trends that lead to effective routing.

For instance, supervised learning can improve routing decisions by predicting, based on past network conditions, the chance of successful data transmission along a specific route.

3.1.2 Strengthening Learning to Optimize Routing

In MANETs, Reinforcement Learning (RL) is essential to routing. In reinforcement learning (RL), agents (nodes) engage with their surroundings (the network) and learn how to make decisions on how to proceed in order to maximize cumulative rewards over time. The observed reward—such as a successful packet delivery, little delay, or low energy consumption—is used to continuously update the value of the selected action in order to train the RL model. In MANETs, methods like as Q-learning and Deep Q-learning are frequently used to enhance routing performance through experience-based learning.

One of RL's main advantages is its ability to constantly adjust to the shifting network environment. Based on observed performance, it chooses energy-efficient routes and learns to avoid crowded or unreliable paths. Furthermore, the trade-off between exploitation (using the most well-known route) and exploration (trying novel routes) can be balanced via RL-based routing protocols.

3.1.3 Routing Discovery using Unsupervised Learning

Unsupervised learning can be used to identify patterns in routing behavior without preexisting labels, unlike supervised learning, which depends on labeled data. Clustering techniques like hierarchical clustering and k-means are frequently used to group nodes according to comparable attributes (e.g., energy levels or geographic location). This method makes it possible to identify possible routing regions and aids in the discovery of effective routes that reduce overall network congestion and energy usage.

3.2 AI-Powered Protocols

The goal of AI-driven protocols in MANETs is to use AI methods to improve network performance through more intelligent, efficient, and adaptable routing. By integrating AI-driven decision-making processes that optimize routing decisions dynamically and autonomously, these protocols go beyond conventional methods.

3.2.1 Making Decisions Using AI

Because they rely on preset rules or algorithms, traditional MANET routing protocols are unable to quickly adjust to changes in the network topology. AI-driven protocols, on the other hand, employ AI models to assess network circumstances in real time and choose the best routing route. These protocols use methods like neural networks, fuzzy logic, genetic algorithms, and reinforcement learning to assess network conditions (such congestion, energy levels, or packet loss) and choose the most effective path in light of them. A fuzzy inference system (FIS), for example, might be used by an AI-based routing protocol to evaluate the network environment and dynamically modify routing tactics based on variables such as link quality, packet arrival rates, and battery utilization.

3.2.2 Self-Learning and Autonomous Routing

The autonomous and self-learning nature of AI-driven protocols is part of their architecture. Since the network itself learns and adjusts to the current environment, they do not require central coordination or static routing tables. More robust and scalable networks are made possible by this capacity for self-learning. Reinforcement learning-based routing algorithms, for example, allow nodes to gradually improve performance without explicit programming by learning the best routing strategies through trial and error.

Furthermore, by automatically rearranging the routing paths in the event of network faults (such as node or link failures), AI-driven protocols can guarantee uninterrupted network operation. Network reliability can be increased over time by these protocols' ability to "learn" from past mistakes and prevent them from happening again.

3.3 Self-Organizing and Self-Optimizing Networks

The frequent changes in network architecture brought on by node mobility, which can lead to broken links and erratic routing, are one of the main problems with MANETs. Self-organizing and self-optimizing networks that can autonomously configure and optimize themselves in response to

these dynamic changes are made possible by AI-based techniques.

3.3.1Self Organizing Network

A centralized authority is not necessary for the management of self-organizing networks. Rather, every network node works together with its neighbors to create routes and oversee network functions. Because nodes can move independently and dynamically alter the network architecture, this feature is essential in MANETs. Swarm intelligence and other AI-based methods assist nodes in finding and maintaining routing routes on their own.

For instance, by using decentralized cooperation among nodes, the Ant Colony Optimization (ACO) algorithm—which draws inspiration from ant behavior—can be used to determine the best routes. Nodes in a self-organizing network assess possible routes according to a number of criteria (such energy usage and link quality) and work together to preserve the optimal pathways. Self-organizing protocols lower the total control overhead by enabling effective routing without requiring global coordination.

3.3.2 Self-Optimizing Networks

In order to enhance performance, a self-optimizing network uses AI algorithms to modify its routing plans and settings in real time. By adapting to changes in node density, network traffic, or mobility, these networks are able to optimize routing decisions in real time. Network performance can be optimized using methods like Reinforcement Learning (RL) and Genetic Algorithms (GAs) based on real-time feedback.

In a self-optimizing MANET, for instance, the system can automatically modify the routing protocol to locate alternative, less crowded paths if a node detects high congestion on a certain route. Similarly, the network can reroute traffic through more energy-efficient channels if a node's energy usage is higher than anticipated.

Due to their great degree of adaptability and scalability, self-optimizing networks are appropriate for large-scale networks with a dynamic set of circumstances. Because they can adapt to maintain network performance without manual intervention, they are also more resilient to outages or attacks.

3.4 AI-Powered Energy-Saving Routing

Because mobile devices have a limited battery life, energy efficiency is one of the main issues in MANETs. Energy consumption is frequently ignored by traditional routing protocols as a key indicator for route selection, which can result in rapid node battery depletion and decreased network performance. On the other hand, AI-based methods can be used to maximize energy use and extend network node lifespan.

3.4.1 Routing with Energy Awareness

Energy-aware routing systems powered by AI seek to reduce energy usage without sacrificing timely packet delivery. The network's energy consumption patterns can be learned and predicted using methods like Reinforcement Learning (RL). RL may choose routes that use the least amount of energy by analyzing energy levels and link quality. This includes lowering the number of hops, choosing shorter paths, or routing through nodes with higher battery levels.

3.4.2 Swarm Intelligence-Based Energy-Efficient Routing

The collective behavior of ants, bees, and other organisms serves as an inspiration for swarm intelligence, which can also be used to maximize energy use in MANETs. For instance, Ant Colony Optimization (ACO) can be expanded to take energy efficiency into consideration by calculating the energy cost of each route and choosing the ones that use the least amount of energy. Nodes in a MANET can "mark" routes based on energy consumption, encouraging the gradual adoption of more energy-efficient paths, much like ants in nature mark successful routes with pheromones.

3.4.3 Adaptive Power Control

Adaptive power regulation in MANETs is another application of AI. Artificial intelligence (AI) algorithms can modify each node's transmission power to reduce energy consumption while preserving dependable communication by examining variables including network traffic, signal quality, and node distance. Based on current network conditions, transmission power can be dynamically optimized using fuzzy logic and reinforcement learning techniques.

3.4.4 Hybrid Artificial Intelligence Methods for Energy Efficiency

To further optimize energy consumption in MANETs, hybrid AI approaches that combine several AI techniques, including fuzzy logic, evolutionary algorithms, and reinforcement learning, can be applied. For instance, hybrid algorithms can control transmission power levels (using reinforcement learning or fuzzy logic) and optimize routing patterns (using RL or GA) at the same time. These methods make it possible to use resources more effectively, increasing network lifetime without sacrificing performance.

4. Challenges and Future Directions

- **Scalability:**
  - Scalability issues arise as the number of mobile nodes rises. How can AI assist in resolving large-scale MANET scalability issues?
- **Security and privacy:**
  o To stop assaults like hostile nodes mimicking others or jamming attacks, secure AI-based routing protocols are required.
  o Methods for guaranteeing data integrity and secrecy in a routing environment augmented by AI.
- **Energy Efficiency:**
  o Even if AI has the capacity to optimize energy, how can we strike a balance between computational efficiency and precision to reduce overhead in nodes with limited resources?
- **Network Mobility and Dynamics:**
  o Handling extremely dynamic situations with shifting node mobility and network topologies.
  - How real-time AI-based optimization and reinforcement learning might help address

  these shifts.

- **Ethical Considerations:**

o Problems with AI systems' routing decision-making process. How can we guarantee justice, accountability, and transparency?

  - Juggling human supervision with autonomous decision-making.

- **Future Research Directions:**
  o Examining how to advance MANET routing protocols by incorporating cutting-edge technologies like 5G, Edge Computing, and AI.
  o Federated learning's promise to enable decentralized training of AI models across dispersed MANET nodes.
  - Investigations explore hybrid AI methods that combine multiple models to provide more resilient and flexible routing.

5. Conclusion

• **Key Findings Summary:**

o AI approaches offer the potential to greatly improve MANET routing protocol performance by addressing problems including fault tolerance, scalability, and energy efficiency.

• **Effect on Future Networks:**

o AI integration is probably going to be crucial to the development of next-generation networks since it will allow for highly adaptive, self-optimizing, and autonomous systems.

• **Final Thoughts:**

o To fully utilize AI-based routing solutions in a variety of real-world contexts, more study and testing are required.

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