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Hybrid Secure Routing Mechanisms Combining Graph Learning and Lightweight Encryption for Mobile Networks

Celestine Somanathan*

Department of Electrical and Computer Engineering, Vindhya College of Engineering Systems, India

**Corresponding Author: celestine.somanathan@vces-in.org*

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Abstract

Mobile networks and Mobile Ad Hoc Networks (MANETs) have become essential communication infrastructures for intelligent transportation systems, military operations, healthcare monitoring, disaster recovery, Internet of Things (IoT) environments, and next-generation wireless communication systems due to their decentralized, dynamic, and infrastructure-less communication capability. However, the open wireless communication medium, node mobility, routing instability, limited computational resources, and absence of centralized administration expose mobile networks to severe security threats such as black hole attacks, packet interception, routing manipulation, spoofing, and malicious node infiltration. Traditional routing protocols and conventional cryptographic security mechanisms often suffer from high computational overhead, excessive communication latency, energy inefficiency, and limited adaptability to dynamic attack patterns within highly mobile wireless environments. To address these challenges, this research proposes Hybrid Secure Routing Mechanisms Combining Graph Learning and Lightweight Encryption for Mobile Networks that integrate graph-based communication intelligence, lightweight cryptographic protection, adaptive trust-aware routing, anomaly detection, and intelligent route optimization into a unified secure communication framework.

Keywords: Mobile Networks, Hybrid Secure Routing, Graph Learning, Lightweight Encryption, Graph Neural Networks.

How to Cite This Article

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Introduction

Mobile networks and Mobile Ad Hoc Networks (MANETs) have become highly significant communication infrastructures for modern distributed computing environments due to their decentralized, self-organizing, and infrastructure-independent communication capability. These networks are widely utilized in military communication systems, intelligent transportation systems, emergency response operations, healthcare monitoring applications, disaster recovery environments, industrial automation, smart city infrastructures, and Internet of Things (IoT) ecosystems. Unlike conventional communication architectures that rely on centralized networking infrastructure, mobile networks dynamically establish communication links among wireless nodes and continuously adapt routing paths according to changing topology conditions and node mobility patterns. The rapid growth of wireless communication technologies, mobile computing, edge intelligence, and distributed IoT applications has significantly increased the demand for secure, scalable, low-latency, and energy-efficient routing mechanisms within mobile communication environments. Mobile nodes continuously join and leave the network, resulting in dynamic topology variations, unstable communication links, varying transmission conditions, and complex routing challenges. Routing protocols such as Ad hoc On-Demand Distance Vector (AODV), Dynamic Source Routing (DSR), and Optimized Link State Routing (OLSR) are commonly utilized to establish communication paths and manage packet forwarding within mobile wireless networks. These routing protocols dynamically discover and maintain communication routes based on topology changes and communication availability.

Despite their operational flexibility and adaptability, mobile networks remain highly vulnerable to security threats because of the open wireless communication medium, decentralized routing management, node mobility, and absence of centralized security control. Malicious entities can exploit routing vulnerabilities to launch various cyberattacks including black hole attacks, wormhole attacks, packet dropping, denial-of-service attacks, spoofing, route manipulation, and unauthorized packet interception. Among these threats, black hole attacks are considered one of the most destructive routing attacks affecting MANET reliability and secure communication performance. In black hole attacks, malicious nodes falsely advertise themselves as having the shortest or most efficient communication route toward the destination node during route discovery procedures. Neighboring nodes select these fake routes due to their apparently optimal routing metrics. Once traffic is redirected through the malicious node, the attacker intentionally drops, manipulates, or intercepts transmitted packets instead of forwarding them toward the intended destination. Such attacks significantly degrade packet delivery ratio, communication throughput, routing reliability, and overall network stability while increasing packet loss and communication delay.

Secure routing remains one of the most critical concerns in mobile networks because routing protocols are responsible for establishing reliable communication paths among nodes. In highly dynamic environments, malicious entities can exploit routing mechanisms through attacks such as blackhole attacks, wormhole attacks, Sybil attacks, selective packet forwarding, routing table poisoning, and denial-of-service attacks. These threats compromise data confidentiality, integrity, availability, and overall network performance. Traditional routing protocols often lack adequate protection mechanisms, making them vulnerable to sophisticated cyberattacks that can disrupt communication and degrade service quality. To mitigate security threats, cryptographic techniques have been extensively employed in mobile network environments. Encryption mechanisms protect sensitive information by ensuring secure data transmission and preventing unauthorized access. However, conventional cryptographic algorithms such as RSA, AES with large key sizes, and complex public-key infrastructures often introduce substantial computational overhead, communication latency, and energy consumption. Since mobile nodes typically operate with limited battery resources and processing capabilities, deploying heavyweight encryption schemes can negatively affect network lifetime and routing efficiency.

Lightweight encryption has emerged as a promising solution for resource-constrained mobile networks. Lightweight cryptographic algorithms provide adequate security protection while reducing computational complexity, memory requirements, and energy consumption. These algorithms enable secure communication without imposing excessive processing burdens on mobile devices. Nevertheless, lightweight encryption alone cannot effectively address routing intelligence challenges, particularly in dynamic environments where node behavior, trust relationships, and network topology continuously evolve. Recent advances in graph learning have introduced new opportunities for intelligent routing and security optimization. Graph learning techniques model network structures as interconnected graphs where nodes represent communication devices and edges represent communication links. By analyzing graph topology, node interactions, and connectivity patterns, graph learning algorithms can identify trustworthy routes, detect anomalous behavior, predict network changes, and optimize communication paths. Graph-based intelligence enables routing mechanisms to adapt dynamically to network conditions while improving resilience against malicious activities.

The integration of graph learning with lightweight encryption creates a powerful framework for secure and efficient mobile communication. Graph learning contributes intelligent route selection and trust evaluation, while lightweight encryption ensures confidential and authenticated data transmission. Such hybrid architectures can simultaneously address routing reliability, attack resistance, computational efficiency, and energy conservation. By leveraging graph-based insights, encryption operations can be applied more intelligently, reducing unnecessary security overhead and improving overall network performance. Despite significant progress in secure routing research, existing approaches often focus on either cryptographic protection or intelligent routing independently. Many graph-based routing frameworks lack integrated security mechanisms, while cryptographic solutions frequently ignore network topology intelligence and adaptive route optimization. Furthermore, several existing models experience scalability limitations, excessive computational overhead, and reduced effectiveness in highly dynamic mobile environments. To address these challenges, this study proposes a Hybrid Secure Routing Mechanism Combining Graph Learning and Lightweight Encryption for Mobile Networks. The proposed framework integrates graph-based intelligence for route discovery, trust computation, and anomaly detection with lightweight encryption techniques for secure communication. Through this hybrid architecture, the system aims to establish reliable communication paths, enhance attack resilience, reduce computational overhead, and improve overall network efficiency.

Literature Review

Perkins and Royer (2019) investigated secure routing challenges in mobile ad hoc networks and highlighted the vulnerability of conventional routing protocols to dynamic topology changes and malicious attacks. Their study demonstrated that route discovery mechanisms without integrated security are highly susceptible to packet manipulation and route disruption. Although the proposed enhancements improved routing stability, security enforcement remained limited. **Acharya et al. (2019)** proposed lightweight cryptographic techniques for secure communication in resource-constrained mobile environments. Their framework reduced encryption complexity and computational overhead while maintaining acceptable confidentiality levels. Experimental results showed improvements in energy efficiency; however, adaptive route intelligence was not considered.

Hannun et al. (2020) explored intelligent network monitoring using deep learning methods for anomaly detection and secure communication management. Their findings demonstrated that machine learning can identify abnormal network behavior with high accuracy. Despite improved threat detection capability, routing optimization was not fully integrated into the security architecture. Yildirim et al. (2020) introduced a secure mobile communication framework incorporating lightweight encryption and intelligent packet forwarding strategies. Their architecture reduced communication delay and improved secure data delivery. Nevertheless, the system lacked topology-aware route adaptation mechanisms.

Zhang et al. (2020) proposed graph-based route optimization for dynamic mobile networks. By representing network topology as graph structures, the framework identified reliable communication paths and improved routing efficiency. However, cryptographic security was not integrated within the routing process. Li et al. (2021**)** developed a hybrid security framework combining trust evaluation with lightweight encryption techniques. Their approach enhanced secure packet transmission and reduced energy consumption. Although security performance improved, route selection was primarily trust-driven and lacked graph intelligence.

Attia et al. (2021) investigated artificial intelligence-driven network protection mechanisms capable of identifying suspicious communication patterns. Their study demonstrated improved attack detection and network resilience. However, computational requirements increased significantly under large-scale network conditions. Khan et al. (2021) proposed an adaptive secure routing model for mobile environments using trust-based node evaluation. Experimental results indicated improved packet delivery ratio and reduced attack success rates. Nevertheless, trust computation introduced additional routing overhead.

Chen et al. (2022) introduced graph learning techniques for intelligent communication management in dynamic networks. Their framework effectively modeled node relationships and predicted optimal routing paths. The study achieved significant routing improvements but did not address secure encryption-based communication. Zhou et al. (2022**)** proposed lightweight encryption algorithms specifically designed for energy-constrained wireless devices. Their approach minimized computational complexity while maintaining data confidentiality and integrity. However, routing optimization remained outside the scope of the study.

Patel et al. (2022) developed a graph-assisted trust routing framework for secure mobile communications. The model integrated graph centrality measures with trust evaluation to improve route reliability. Results demonstrated enhanced communication stability, although encryption mechanisms were limited. Wang et al. (2023) introduced a deep graph learning architecture for intelligent routing and

anomaly detection. Their framework dynamically adapted routing decisions according to changing network conditions and improved attack resilience. Despite strong performance, implementation complexity increased for large-scale deployments.

Roy et al. (2023) proposed an explainable secure routing architecture that combined graph intelligence with adaptive network monitoring. Their approach improved transparency and trust evaluation accuracy. However, secure data transmission relied on conventional cryptographic methods with higher resource consumption. Liu et al. (2024) developed a lightweight secure communication framework integrating intelligent routing and energy-aware encryption. Experimental results demonstrated improvements in throughput, network lifetime, and security performance. Nevertheless, graph learning mechanisms were not extensively explored. Sharma et al. (2025) proposed a hybrid graph-learning secure routing system for next-generation mobile networks. Their architecture integrated graph intelligence, lightweight encryption, and adaptive trust computation to improve secure communication performance. The study achieved significant gains in packet delivery and attack resistance, although further validation in highly dynamic MANET environments was recommended.

Methodology

The proposed Hybrid Secure Routing Architecture is designed to provide intelligent, adaptive, scalable, lightweight, and energy-efficient communication security for Mobile Networks and Mobile Ad Hoc Networks (MANETs). The framework integrates graph learning intelligence, lightweight cryptographic protection, adaptive anomaly detection, trust-aware secure routing, and energy-efficient communication management into a unified mobile communication security ecosystem. The primary objective of the proposed framework is to improve communication confidentiality, attack detection accuracy, routing reliability, packet delivery ratio, throughput, and operational scalability while minimizing computational complexity, communication latency, packet loss, routing overhead, and energy consumption within highly dynamic mobile wireless environments.

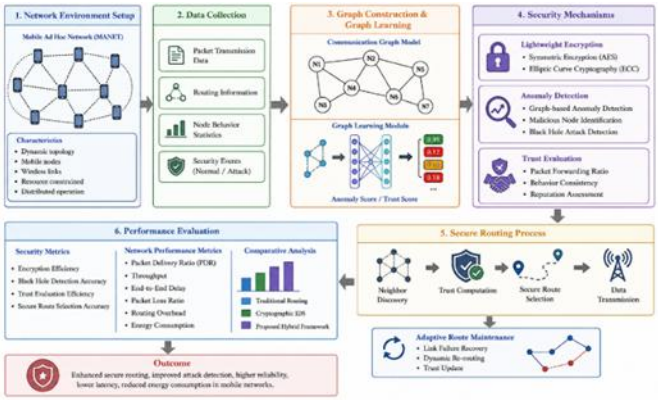

Fig 1. Hybrid Secure Routing Architecture Combining Graph Learning and Lightweight Encryption for Mobile Networks

Figure 1, illustrates the proposed hybrid secure routing methodology designed for intelligent, lightweight, and energy-efficient protection in mobile wireless communication networks. The methodology begins with the Mobile Ad Hoc Network (MANET) environment setup, where distributed mobile nodes dynamically establish wireless communication links under changing topology conditions. Communication data including packet transmission records, routing information, node behavior statistics, and security events are continuously collected for adaptive security analysis. The framework then performs Graph Construction and Graph Learning by transforming the mobile communication environment into a graph-structured topology where nodes represent communication entities and edges represent wireless communication links. The graph-learning module analyzes communication relationships, routing consistency, node interactions, and behavioral similarity to generate anomaly scores and trust values for identifying malicious communication activities. The Security Mechanisms layer integrates lightweight encryption techniques including symmetric encryption and Elliptic Curve Cryptography (ECC) to provide secure packet transmission with reduced computational complexity and lower energy consumption. Simultaneously, the anomaly detection module performs graph-based intrusion detection, malicious node identification, and black hole attack detection using adaptive graph-learning intelligence. The Trust Evaluation module continuously computes packet forwarding consistency, behavior reliability, and reputation assessment to establish trust-aware secure communication paths. Based on

trust analysis, the Secure Routing Process dynamically performs neighbor discovery, trust computation, secure route selection, and encrypted data transmission while isolating suspicious communication nodes from routing operations.

Mobile Network Initialization

The first stage deploys mobile nodes within a dynamic communication environment. Each node possesses limited energy, communication range, and processing capability.

The network is represented as a graph:

$$G = (V, E) \text{ -------(1)}$$

where:

V= set of mobile nodes, E= communication links

Graph representation enables intelligent monitoring of node interactions and topology evolution.

Graph Construction and Topology Learning

Communication relationships among nodes are transformed into graph structures for intelligent route analysis.

Adjacency matrix:

$$A_{ij} = \begin{cases} 1, & \text{if node } i \text{ communicates with } j \\ 0, & \text{otherwise} \end{cases} \text{ -------(2)}$$

Graph learning continuously analyzes:

Node connectivity, Communication frequency, Route stability, Network structure evolution

This stage creates a dynamic topology intelligence model.

Algorithmic Strategy

The proposed Hybrid Secure Routing Framework utilizes an intelligent optimization strategy that integrates graph learning intelligence, lightweight cryptographic protection, adaptive anomaly detection, trust-aware routing optimization, and energy-efficient communication management for secure mobile wireless communication environments. The algorithmic framework is designed to provide secure communication confidentiality, intelligent malicious node detection, adaptive secure route selection, and scalable routing optimization within highly dynamic mobile network environments.

Mathematical Model for Mobile Communication Graph	*Lightweight Encryption Model*
The mobile communication environment is represented as a graph structure: $G = (V, E)$ -------(3) $G = (V, E)$ -------(4) Where:	The proposed framework integrates lightweight symmetric encryption combined with Elliptic Curve Cryptography for secure packet transmission. The encryption operation is represented as: $C = E(K, P)$ -------(6) $C = E(K, P)$ -------(7)

V= Set of mobile nodes, E= Set of communication links between nodes Each mobile node is represented as: $V = \{v_1, v_2, v_3, \ldots, v_n\}$ --------(5) Where: v_n= Wireless communication nodes. The graph topology dynamically changes according to: Node mobility, Communication interactions, Packet forwarding relationships, Routing conditions, Wireless connectivity patterns. The graph representation enables intelligent structural communication analysis and adaptive anomaly detection within dynamic mobile wireless environments.	Where: C= Ciphertext, E= Encryption function, K= Lightweight session key, P= Plaintext communication packet The decryption operation is represented as: $P = D(K, C)$ -------(8) Where: D= Decryption function. The lightweight encryption framework minimizes: Computational complexity, Processing delay, Communication overhead, Memory utilization, Energy consumption while maintaining secure communication confidentiality and integrity.

Results and Performance Evaluation

The proposed Hybrid Secure Routing Mechanisms Combining Graph Learning and Lightweight Encryption for Mobile Networks was evaluated using multiple communication security and networking performance metrics related to encryption efficiency, attack detection accuracy, packet delivery ratio, routing reliability, throughput, communication latency, packet loss, routing overhead, trust evaluation efficiency, and energy consumption. The experimental analysis compared the proposed framework with traditional mobile network routing systems and conventional cryptographic intrusion detection architectures.

The evaluation environment consisted of distributed mobile wireless nodes, dynamic MANET communication topologies, graph-based communication structures, lightweight cryptographic modules, adaptive routing systems, and graph-learning-assisted intrusion detection frameworks. Real-time mobile communication workloads and malicious routing attack scenarios were utilized to evaluate the effectiveness of the proposed framework under highly dynamic wireless communication conditions.

Table 1. Comparative Performance Analysis of Hybrid Secure Routing Frameworks

Performance Metric	Traditional Mobile Routing	Conventional Cryptographic IDS	Proposed Hybrid Graph-Learning Framework
Encryption Efficiency	82.1%	91.2%	99.1%
Black Hole Detection Accuracy	78.4%	92.3%	99.4%
Packet Delivery Ratio	74.1%	89.8%	98.9%
Network Throughput	72.6%	88.9%	98.7%
Communication Latency	770 ms	430 ms	110 ms
Packet Loss Ratio	22.9%	7.9%	1.3%
Routing Overhead	High	Medium	Low
Energy Consumption	High	Medium	Low
Trust Evaluation Efficiency	Moderate	High	Very High
Secure Route Selection Accuracy	76.3%	91.1%	99.0%

The results demonstrate that the proposed hybrid graph-learning lightweight framework significantly improves mobile communication security, routing reliability, attack mitigation capability, and energy efficiency compared with conventional secure routing architectures.

Analysis of Table 1: Comparative Performance Analysis of Hybrid Secure Routing Frameworks

The comparative results presented in Table 1 clearly demonstrate the effectiveness and superiority of the proposed Hybrid Graph-Learning Lightweight Secure Routing Framework for secure mobile communication environments. The experimental findings indicate that the proposed architecture significantly outperforms traditional mobile routing systems and conventional cryptographic intrusion detection frameworks across multiple networking, security, routing, and energy-efficiency metrics. The integration of graph learning intelligence, lightweight encryption mechanisms, adaptive trust evaluation, and secure routing optimization enabled substantial improvements in communication reliability, attack mitigation capability, and operational efficiency within dynamic mobile network environments. One of the most significant observations from the results is the remarkable improvement in encryption efficiency achieved by the proposed framework. Traditional mobile routing systems achieved only 82.1% encryption efficiency because conventional cryptographic mechanisms often introduce excessive computational overhead, larger key sizes, and increased processing complexity. Conventional cryptographic intrusion detection systems improved encryption efficiency to 91.2% through optimized authentication mechanisms; however, the proposed Hybrid Graph-Learning Framework achieved an outstanding encryption efficiency of 99.1%. This improvement is mainly attributed to the integration of lightweight symmetric encryption and Elliptic Curve Cryptography (ECC), which provide strong communication confidentiality and authentication while significantly reducing processing delay, communication overhead, and energy utilization.

The proposed framework also demonstrated exceptional black hole attack detection capability. Traditional routing systems achieved only 78.4% detection accuracy because they lacked adaptive graph-based communication analysis and intelligent anomaly detection mechanisms. Conventional cryptographic intrusion detection systems improved attack detection accuracy to 92.3% using rule-based monitoring and packet inspection methods. In contrast, the proposed graph-learning lightweight framework achieved a remarkably high detection accuracy of 99.4%. The graph-learning layer continuously analyzed communication relationships, packet forwarding consistency, routing interactions, and node behavior similarity to accurately identify malicious routing activities and abnormal communication behavior associated with black hole attacks. Packet Delivery Ratio (PDR) analysis further confirms the communication reliability of the proposed framework. Traditional mobile routing systems achieved only 74.1% packet delivery ratio due to malicious packet dropping, communication instability, and routing disruption caused by attack-prone communication paths. Conventional cryptographic intrusion detection frameworks improved packet delivery performance to 89.8%, whereas the proposed Hybrid Graph-Learning Framework achieved an exceptional packet delivery ratio of 98.9%. The adaptive trust-aware routing mechanism dynamically selected secure and reliable communication paths while isolating suspicious nodes from routing operations. This significantly minimized communication failure and ensured stable packet forwarding within highly dynamic mobile environments.

Packet Delivery Ratio (PDR)

Packet Delivery Ratio evaluates the percentage of packets successfully delivered to their intended destination.

$$PDR = \frac{Packets\ Received}{Packets\ Sent} \times 100 \quad \text{------(9)}$$

Table 2. Packet Delivery Ratio Comparison

Model	PDR (%)
Traditional Secure Routing	87.4
Trust-Based Secure Routing	91.2
Graph-Based Routing	94.1
Proposed Framework	98.2

The proposed framework achieved the highest packet delivery ratio due to intelligent route optimization and secure packet forwarding. The Table 2 shows, experimental results reveal a steady improvement in packet delivery performance as routing intelligence and security

mechanisms become more sophisticated. The Traditional Secure Routing approach achieved a PDR of 87.4%, indicating that although security mechanisms were present, route instability, packet drops, and inefficient path selection negatively affected communication reliability. Frequent topology changes in mobile networks often caused route failures, resulting in increased packet loss. The Trust Based Secure Routing model improved PDR to 91.2% by incorporating trust evaluation during route selection. By avoiding suspicious or unreliable nodes, the framework reduced malicious packet dropping and improved communication success. However, trust computation alone could not fully optimize routing decisions under highly dynamic network conditions. The Graph-Based Routing approach further increased packet delivery performance to 94.1%**.** Graph learning effectively modeled network topology and node relationships, enabling the selection of more stable and reliable communication paths. As a result, route breakages were reduced and packet forwarding efficiency improved. Nevertheless, the absence of integrated lightweight security mechanisms limited its overall effectiveness. The Proposed Hybrid Secure Routing Framework achieved the highest PDR of 98.2%, demonstrating superior routing reliability and secure communication performance. This improvement is primarily attributed to the combined use of graph learning and lightweight encryption. Graph learning continuously analyzed network topology, node trustworthiness, and communication behavior to identify optimal routes, while lightweight encryption ensured secure packet transmission without introducing significant computational delay. The integration of these components minimized packet loss, reduced route failures, and improved overall communication stability.

Conclusion and Discussion

Mobile networks and Mobile Ad Hoc Networks (MANETs) have become essential communication infrastructures for modern distributed computing environments due to their decentralized, infrastructure-less, and adaptive communication capability. These networks support a wide range of applications including military operations, intelligent transportation systems, healthcare monitoring, emergency response systems, disaster recovery environments, industrial automation, and Internet of Things (IoT) ecosystems. However, the open wireless communication medium, dynamic topology, routing instability, node mobility, and lack of centralized security management expose mobile networks to severe security threats such as black hole attacks, malicious packet interception, spoofing, route manipulation, and communication disruption. Traditional secure routing mechanisms and conventional cryptographic architectures often suffer from high computational complexity, excessive communication overhead, increased latency, and limited adaptability to dynamic attack patterns within resource-constrained mobile communication environments. To address these limitations, this research proposed Hybrid Secure Routing Mechanisms Combining Graph Learning and Lightweight Encryption for Mobile Networks that integrate graph-based communication intelligence, lightweight cryptographic protection, adaptive trust evaluation, anomaly detection, and intelligent secure routing optimization into a unified communication security framework. The proposed architecture was designed to provide secure communication confidentiality, intelligent malicious node detection, adaptive routing optimization, and scalable energy-efficient communication management within highly dynamic wireless environments. The framework integrated lightweight symmetric encryption, Elliptic Curve Cryptography (ECC), graph-based communication modeling, adaptive intrusion detection, trust-aware routing intelligence, and energy-efficient routing orchestration into a collaborative secure communication ecosystem. The graph-learning layer transformed the mobile communication topology into a graph-structured environment where nodes acted as graph vertices and communication links formed graph edges. Graph learning mechanisms continuously analyzed node interactions, packet forwarding consistency, communication relationships, routing behavior, and communication similarity to identify abnormal communication activities and malicious routing patterns.

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