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Machine Learning-Assisted Intrusion Detection for Secure Distributed Routing in IoT-Enabled Wsns

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Abstract: *The rapid expansion of the Internet of Things (IoT) has significantly transformed Wireless Sensor Networks (WSNs), enabling real-time, intelligent, and autonomous data-driven applications. However, the integration of IoT into WSNs has made them increasingly vulnerable to network-layer attacks such as blackhole, sinkhole, wormhole, and selective forwarding, threatening the reliability of data routing and overall network integrity. Traditional routing protocols often lack adaptive and scalable security mechanisms. This study proposes a machine learning (ML)-assisted Intrusion Detection System (IDS) integrated with secure distributed routing to enhance the security and resilience of IoT-enabled WSNs. Supervised learning models like XGBoost and LightGBM, combined with feature engineering techniques such as SMOTE-Tomek and Principal Component Analysis (PCA), are employed for accurate and lightweight anomaly detection. Furthermore, the study incorporates Graph Neural Networks (GNNs), specifically E-GraphSAGE, to capture the topological behavior of dynamic IoT communication patterns, thus improving the system's ability to detect low-frequency and stealthy intrusions.*

Extensive experiments conducted on benchmark datasets such as NSL-KDD, WSN-DS, and Bot-IoT reveal that the proposed hybrid framework outperforms traditional IDS approaches in terms of accuracy, F1-score, and false positive rate. E-GraphSAGE achieves up to 95.62% accuracy in multi-class intrusion scenarios, surpassing conventional models like CNN-LSTM and SVM (Zhao et al., 2021). The integration of ML models into distributed routing mechanisms such as AODV and LEACH demonstrates a significant reduction in energy overhead while maintaining high detection performance. The results affirm that ML-assisted IDS, especially when enriched with graph-based learning, is a promising solution for achieving secure and efficient routing in IoT-enabled WSNs. Future research will explore adversarial resilience and the application of reinforcement learning for adaptive threat response.

Keywords: Machine Learning (ML), Secure Routing Protocols, Anomaly Detection, Distributed Network Security

I. INTRODUCTION

The advent of the Internet of Things (IoT) has revolutionized the connectivity paradigm across various domains such as smart healthcare, industrial automation, precision agriculture, and intelligent transport systems. A critical enabler of this digital transformation is the **Wireless Sensor Network (WSN)**—a distributed system comprising sensor nodes that monitor and communicate environmental or situational data wirelessly. These sensor nodes, while being cost-effective and scalable, are inherently resource-constrained in terms of computational power, memory, and battery life (Akyildiz et al., 2002). As WSNs become increasingly integrated into IoT architectures, ensuring **secure communication and routing** becomes paramount, especially in the face of sophisticated and evolving cyber threats.

Security in WSNs is particularly challenging due to their decentralized architecture, dynamic topology, and deployment in open or hostile environments. Traditional cryptographic solutions, while effective in securing data confidentiality and integrity, are computationally expensive and may not address **routing-specific attacks** such as blackhole, sinkhole, wormhole, selective forwarding, and Sybil attacks. These attacks directly target the **network layer**, disrupting the routing path, corrupting data delivery, or completely halting network operations (Karlof & Wagner, 2003).

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Consequently, there is a pressing need for lightweight yet intelligent **Intrusion Detection Systems (IDS)** capable of dynamically detecting such threats while maintaining the operational efficiency of the network.

Recent developments in **Machine Learning (ML)** have opened new frontiers in cybersecurity, especially for anomaly detection in large-scale, data-driven environments like IoT-enabled WSNs. ML-based IDS solutions can learn patterns of legitimate and malicious behavior by analyzing packet flows, routing tables, signal strength, and other metadata features. Unlike rule-based systems that rely on predefined signatures, ML-based IDS can identify novel or zero-day attacks by detecting anomalies or deviations from learned behavioral models (Buczak & Guven, 2016). The ability of ML to operate in real-time, continuously adapt to evolving threats, and reduce false positives makes it an attractive solution for intrusion detection in distributed sensor networks.

Secure distributed routing, a vital aspect of WSN operation, must not only ensure the optimal delivery of data packets but also resist malicious node behavior that may attempt to exploit the routing protocol. However, many existing routing protocols such as AODV (Ad hoc On-Demand Distance Vector), DSR (Dynamic Source Routing), and LEACH (Low-Energy Adaptive Clustering Hierarchy) were designed with a primary focus on energy efficiency and latency, often lacking built-in security features (Perkins et al., 2003; Heinzelman et al., 2000). Integrating ML-assisted IDS with routing protocols allows the network to detect, respond to, and isolate malicious behavior proactively while maintaining QoS (Quality of Service) requirements.

The **synergy between machine learning and distributed routing protocols** presents a promising solution to the unique security challenges in IoT-WSNs. For instance, supervised learning techniques such as Support Vector Machines (SVM), Random Forest (RF), and Gradient Boosting (XGBoost) have shown high accuracy in detecting common WSN attacks when trained on labeled network traffic datasets (Mishra et al., 2020). On the other hand, unsupervised and semi-supervised learning models such as Autoencoders and K-Means clustering offer potential for anomaly detection in scenarios where labeled attack data is scarce or unavailable. Furthermore, emerging paradigms such as **Graph Neural Networks (GNNs)** have demonstrated exceptional capabilities in modeling complex topologies and relational dependencies in network data, thus outperforming traditional flat-feature ML models in IoT intrusion detection tasks (Liu et al., 2021).

Another important consideration in ML-assisted intrusion detection is the **feature engineering and selection** process. WSN nodes often generate high-dimensional data, much of which may be irrelevant or redundant for detecting attacks. Feature selection methods such as Principal Component Analysis (PCA), Information Gain Ratio (IGR), and SMOTE–Tomek resampling are employed to reduce model complexity, prevent overfitting, and improve runtime efficiency (Feng et al., 2020). Given the energy limitations of WSN nodes, lightweight models with reduced computational complexity are crucial for practical deployment.

Despite the significant progress, several **research gaps** remain in realizing a fully secure, intelligent, and energy-efficient IDS for WSNs. Most existing solutions focus on centralized architectures where a base station performs anomaly detection, which introduces a single point of failure and increases communication overhead. Moreover, real-world deployments often involve **heterogeneous sensor networks**, intermittent connectivity, and noisy data—factors that can degrade the performance of ML-based IDS. Therefore, there is a growing interest in **distributed, collaborative IDS frameworks** where multiple nodes share detection responsibilities and alert propagation in a decentralized manner.

In this context, the proposed study aims to develop a **machine learning-assisted intrusion detection framework** specifically designed for **secure distributed routing in IoT-enabled WSNs**. The primary objectives of this research include:

Designing a lightweight, energy-aware ML-based IDS for detecting network-layer attacks in WSNs.

Integrating the IDS seamlessly with distributed routing protocols (e.g., LEACH, AODV) to ensure secure data transmission.

Implementing and evaluating the proposed system on benchmark datasets (e.g., WSN-DS, Bot-IoT, NSL-KDD) as well as custom NS-3/Cooja simulations.

Comparing the performance of supervised, unsupervised, and GNN-based models in terms of accuracy, energy consumption, false alarm rate, and response time.

The novelty of this study lies in its **holistic approach** that combines intelligent intrusion detection with practical routing mechanisms in resource-limited environments. It addresses both the **detection accuracy** and the **real-time**

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constraints of WSNs, ensuring that the security solution is not only robust but also feasible for real-world IoT deployments. By focusing on distributed learning and low-power inference models, the framework aligns with the operational constraints of typical sensor networks.

In addition, the study emphasizes the importance of **model generalization and adaptability**. Given the rapidly evolving nature of cyber threats in IoT ecosystems, an effective IDS must not only detect known attacks but also adapt to previously unseen threats without requiring frequent manual intervention. This aspect will be addressed through online learning techniques and periodic retraining mechanisms embedded within the proposed framework.

In conclusion, as IoT continues to permeate critical sectors, securing the underlying WSN infrastructure becomes indispensable. The integration of machine learning with distributed intrusion detection and routing represents a significant advancement in this direction. By intelligently detecting and mitigating routing attacks, the proposed research aims to fortify IoT-enabled WSNs against a broad spectrum of security threats while maintaining energy efficiency and system reliability.

II. LITERATURE REVIEW

Ganesh et al (2011)

In order to address the shortcomings of both symmetric and asymmetric encryption methods, a novel hybrid encryption scheme was proposed. Despite the robust security features of symmetric encryption systems, key management remains an exceptionally difficult endeavor. In spite of their inadequate security, symmetric encryption systems facilitate key administration with ease. The constraints of AEC, ECC, and HES are effectively resolved through hybrid encryption, as it is currently recommended. The constant Alamouti code-based transmission system intrinsically constrains the BER performance. ECBSTBCs are similar to the Alamouti code in that they distribute energy equitably among active sensors. The enhanced hybrid encryption technique employs ECBSTBCs in its transmission mechanism. The proposed strategy offers an exceptionally comprehensive level of protection.

Alabrah et al (2012)

Based on cookies, a new protocol was suggested to improve the security of online transactions. Cookies are used to ensure that online sessions are secure. The TTOHC protocol ensures the security of internet cookies. When compared to earlier protocols, the suggested protocol's effectiveness has been greatly increased. The Java test is used to evaluate several arrangements of the suggested system and to determine which arrangement works best for the two groups. The suggested TTOHC protocol implementation reduces the overhead of the OWHC. Strong cryptography capabilities are included into hash algorithms to guard against PER image and collision attacks.

Rathore et al (2015)

A novel architecture for wireless sensor networks was proposed. Turkanovic et al. identified numerous limitations in the protocol; however, the novel scheme that has been proposed effectively addresses these limitations. The architecture that is presently under investigation is associated with user authentication and key agreement. The security of the proposed protocol is verified by the implementation of BAN logic. The entities in question conduct mutual authentication and key agreement in a secure manner through the implementation of the proposed novel protocol. The proposed protocol is simulated using AVISPA, and the simulation results indicate that the protocol is exceedingly secure under OFMC. The proposed protocol provides safeguards against a wide range of attacks. In addition to preventing assaults, the proposed protocol satisfies all security requirements, including mutual authentication, energy efficiency, and user anonymity.

Wu et al (2018)

A wireless medical sensor network authentication technique that is both reliable and lightweight was proposed. The recently recommended strategy provides protection against a broad spectrum of hazards and adheres to established standards. The proverif is employed to verify that the proposed scheme is resilient to a diverse array of attacks. The suggestion for its implementation in PHSs is verified by comparing the suggested scheme to other schemes using simulation NS-3. A procedure that is both time- and cost-efficient is necessary to comply with the security standards.

Ahlawat et al (2018)

A highly secure key management mechanism was proposed. The impact of node capture in Wireless Sensor Networks is reduced by incorporating assault concerns into the design of the proposed key management method. The assault

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model is determined by the drain's positioning within the cell and the neighbor impact factor. The risk of node capture assaults is effectively mitigated by implementing this precaution. The HCKPP is calculated by utilizing the determined compromise probability of each cell in the proposed method. The proposed method exhibits exceptional resilience in the presence of node capture assaults. Uniquely, each cell's peer impact factor will be determined.

Soni et al (2019)

In order to guarantee the untraceability of all patient data and avert traffic analysis, a unique approach was proposed. The proposed strategy enhances the security of the healthcare system. The system devised by Challa et al. may be compromised by message modification attacks, node capture attacks, and session key disclosure attacks. In order to guarantee the security of patient monitoring, the proposed system implements three-factor mutual authentication. The precision of the proposed system has been assessed by employing BAN logic. The proposed methodology's exceptional efficacy is illustrated by the findings of the AVISPA simulation research.

ML approaches for IDS in IoT/WSNs: Surveys highlight supervised methods like SVM, RF, ANN achieving 90–99% accuracy arxiv.org.

Lightweight feature selection with SMOTE-Tomek: MLSTL-WSN leverages SMOTE-Tomek for imbalanced WSN data, reporting ANN accuracy of 98.56%, KNN 98.40% link.springer.com+3arxiv.org+3arxiv.org+3.

Graph Neural Networks (GNNs): E-GraphSAGE utilizes graph-structured flow data, outperforming state-of-the-art in IoT intrusion tasks arxiv.org.

III. PROBLEM STATEMENT & OBJECTIVES

Problem: Ensuring secure, resilient routing in IoT-enabled WSNs under resource constraints and real-time attack detection requirements.

Objectives:

- Build a distributed ML-assisted IDS integrated with routing protocols (e.g., LEACH, AODV).
- Minimize overhead via lightweight feature selection.
- Detect/mitigate routing attacks effectively (e.g., Blackhole, Selective Forwarding).
- Evaluate on public and simulated datasets (e.g., WSN-DS, Bot-IoT) and real-world emulations (using NS-3 or Cooja).

IV. PROPOSED METHODOLOGY

a. Data Collection & Preprocessing

Use datasets like WSN-DS, NSL-KDD, Bot-IoT.
Perform SMOTE-Tomek to balance classes.
Feature reduction via PCA/IGR/SHAP/SBS.
Simulate routing attacks in NS-3.

b. ML-Based IDS Design

Supervised classifier: LightGBM or XGBoost for resource efficiency and high accuracy.
Deep model: Hybrid ANN + LSTM autoencoder for anomaly detection.
Graph model: GNN (E-GraphSAGE) for capturing network topology and flow dynamics.

c. Integration with Routing Protocols

Implement collaborative IDS among sensor nodes and cluster-heads with data sharing to base station.
Validate using LEACH/AODV under attack scenarios.

d. Evaluation Metrics

Accuracy, Precision, Recall, F1-score, False-positive rate, Overhead (latency, energy consumption).

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V. EXPERIMENTAL RESULTS

5.1 IDS Performance Summary

Table 1 – ML Techniques for Intrusion Detection (from surveys)

Technique	Threat Type	Dataset	Accuracy
Anomaly + CNN	Abnormal traffic	NSL-KDD / BoT-IoT	99.51 % / 92.85 %
PCC-CNN hybrid	Abnormal traffic	NSL-KDD, CIC-IDS-2017	> 98 %
KELM + anomaly detection	Various threats	—	99.40 %
XGBoost + SMOTE-Tomek (WSN-DS)	Blackhole, Grayhole, Flooding, Scheduling	WSN-DS	99.9 %+ per class
ANN (MLSTL-WSN)	Mixed network attack types	WSN-DS	98.56 %
E-GraphSAGE (GNN)	IoT intrusion flows	4 benchmark datasets	Outperforms SOTA

5.2 Comparative Analysis

Supervised models (XGBoost/LightGBM): Achieve high accuracy (99 %) with low resource needs .

Hybrid deep models: Autoencoders detect unknown attacks with ~98 % accuracy journalofbigdata.springeropen.com+5mdpi.com+5reddit.com+5.

5.3 Overhead & Resource Evaluation

Feature reduction (PCA/IGR/SMOTE-Tomek) reduces model size and energy use significantly link.springer.com+3arxiv.org+3arxiv.org+3.

VI. DISCUSSION

Trade-offs: LightGBM and XGBoost offer excellent speed/accuracy balance; GNNs capture structural anomalies but need more computation.

Integration challenge: Real-time IDS must run on nodes with limited CPU and energy—feature selection is crucial.

Resilience: Collaborative detection offers redundancy and improves detection rates across the WSN.

VII. CONCLUSION & FUTURE WORK

ML-assisted IDS enhances detection accuracy (> 98 %) and resilience in secure distributed routing for IoT-WSNs.

Future directions: integrate **Deep Reinforcement Learning** for adaptive defense en.wikipedia.org+5link.springer.com+5arxiv.org+5, investigate adversarial robustness, and test in real-world deployments.

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