INTELLIGENCE SECURE ROUTING ALGORITHM FOR IOT NETWORKS

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Abstract

The advance in the IoT has brought new challenges in the area of communication in such networks especially in secure, efficient and reliable manner in constrained and dynamic environment. This work introduces the "Intelligent Secure Routing Algorithm which is a more layered solution in an attempt to solve these challenges by incorporating cryptographic methods, trust assessments, and machine learning classifiers to identify threats. The algorithm continuously calculates trust levels for IoT nodes depending on packet delivery, probability of communication, and energy efficiency that allows the exclusion of fake or unreliable nodes. With reinforcement learning, the algorithm selects the most suitable routing decision in order to achieve the best of both security and energy consumption as well as network performance. Realistic benchmarking proves the effectiveness of the use of an algorithmic approach over conventional strategies by providing higher network throughput, better PDR, decreased delay, and optimized energy utilization. It also successfully counteracts most of the IoT risks such as DoS and MITM attacks with real-time anomaly detection and immediate node isolation. It is also important to note how this algorithm can be implemented in critical IoT use cases: health, manufacturing, smart city. The results confirm the effectiveness of the algorithm, and the further study is recommended to be conducted toward practical application, blockchain and edge computing, and the use of deep learning for improving the algorithm performance. Thus, this work presents the Intelligent Secure Routing Algorithm as a reliable and efficient approach to improving the security and reliability of IoT networks communication.

1 Introduction

Internet of Things (IoT) is an emerging sophisticated concept to connect every day things and objects to the internet to facilitate the exchange of information and sharing of data in different fields. IoT networks consist of numerous connected devices such as sensors, actuators, and gateways that are connected with one another to offer real time data and command. They have become essential in the contemporary technologies, and are used widely in areas including homes, health, transportation, farming and industries. That is why IoT is meaningful – because it promises to make operations more efficient, resource use more effective and

efficient, and people's lives better. For instance, in healthcare, IoT connected devices allow for constant surveillance of patient vital signs including heart rate, glucose levels and blood pressure in order to prevent diseases and in the process reduce healthcare costs (Miorandi et al., 2012). Likewise, in smart cities, IoT is transforming the infrastructure of smart cities through the central management of utilities including energy, water and waste management, smart traffic system that addresses problems such as traffic jam and pollution (Gubbi et al., 2013).

The IoT networks include nodes of different capabilities and with different resource requirements, making the networks diverse and capable of implementation in various industries. However, this is so mainly because this diversity is also a source of problems, especially as concerns the scalability of the networks, their security and resource utilization. Many IoT devices are energy and processing constrained which makes it important to design protocols and algorithms that are efficient and secure. However, as more and more networks of IoT devices are deployed, the issues of security threats like unauthorized access, data leakage, and privacy infringement become even more significant. To unlock the potential of IoT and integrate it into the core systems all these challenges must be overcome.

The trends analyzed indicate that IoT has become crucial across contemporary societies because of its high growth rate. Research in this industry predicts that in the next coming years, billions of C2C connected devices will act as the support structure of smart environments, adding up to trillions of dollars to the world economy (Atzori et al., 2010). This proliferation provides the need to search for new solutions to address IoT-specific issues while realizing the enormous benefits of IoT in industries and in people's lives. For example, constant development of enhanced secure routing algorithms are vital in the IoT network reliability and security hence opening up the future for sustainable and scalable IoT applications.

2 Challenges of Secure Routing in IoT Environments

The IoT networks have opened a new horizon of connectivity in this world where connectivity has become crucial for a plethora of services and sectors. Nevertheless, secure routing is rather a difficult problem in these networks concerning the features of IoT devices and their surroundings. These challenges mainly arise from limited resources, variability in the network, changes in security threats, and competition between performance and security.

2.1 Resource Constraints

IoT devices are commonly developed to have constrained resources such as power, memory, processing power, and bandwidth. Such constraints limit the feasibility of deploying conventional security solutions that are usually capital-intensive. For instance, strong encryption and authentication processes call for a lot of computational power and energy. But many IoT devices are battery-powered, and thus, energy efficiency is one of the most important aspects to consider. This forms a trade-off which calls for lightweight security protocols that can offer protection without consuming much of the resource. Furthermore, low-end devices cannot run algorithms, which leaves them open to smart attacks (Zhang et al., 2014).

2.2 Diverse Network Conditions

communication in IoT networks is always heterogeneous because the devices' capabilities differ and use multiple protocols like Wi-Fi, Zigbee, Bluetooth. This diversity poses a problem in establishing routing protocols that could be compatible with these devices in the most optimal manner. Also, IoT networks are characterized by dynamic topologies because nodes may be mobile, connectivity may be intermittent or some devices may fail. Such changes can distort the routing processes and demand algorithms that would be able to ensure the secure connection under these circumstances. Another problem that arises as IoT networks expand in size and denseness is scalability since routing protocols must accommodate an ever-increasing number of devices without undermining security or efficiency (Al-Turjman et al., 2019).

2.3 Security Threats

In view of this, IoT networks are prone to a number of security threats due to their distributed nature and the fact that they operate wirelessly. Snooping over the wireless communications is a simple activity and attackers can easily get hold of the intended wireless communications. Similarly, spoofing attack in which the entities pretend to be legal nodes poses a threat to the routing procedures and data integrity. One more typical threat is the Sybil attack that is implemented by the single dishonest participant who created several fake accounts in order to negatively affect the functionality of the network. Moreover, IoT devices are vulnerable to the DoS attack because the attack can exhaust the device's resources and makes the device unresponsive. These threats clearly point that IoT routing protocols need to have robust and proactive security solutions (Miettinen et al., 2017).

2.4 Limited Standardization

This makes the issue of security in IoT system designs even more complex because there are no best practices on how to secure routing across the IoT network. The absence of well defined protocols that are implemented across the devices is the cause of compatibility; devices that were manufactured by different companies cannot easily interconnect. This fragmentation also affects the ability to create integrated security solutions that can be implemented on IoT settings that vary greatly. Therefore, the formation of a safe and inter-operational IoT environment has needed global cooperative attempts for the standardization of IoT (Raza et al., 2013).

2.5 Trade-offs Between Performance and Security

Many IoT networks are deployed in places where parameters like latency, throughput, and energy consumption are acutely significant. For example, in the healthcare use cases, the slightest latency in data sharing might result in very dangerous effects. However, put in place measures such as encryption or multi-factor authentication, they will slow down the processing further, creating a time and security conundrum. It is a challenging task to design the routing protocols which can balance both the aspects; such problem demands new solutions (Basha et al., 2020).

Security in IoT routing is a complex problem, which requires solutions to several problems including the resource limitations of IoT devices, variability of network conditions, new threats, and standardization. Though these challenges may appear very demanding, they also offer a great potential for introducing new ideas in designing robust, lightweight, and adaptive routing algorithms. They will be helpful for making IoT networks secure, reliable, and scalable toward achieving the envisioned applications of today's IoT systems.

3 Review of Existing Secure Routing Protocols and Algorithms in IoT Networks

The security of the routing of data in IoT networks is crucial in order to protect the privacy, confidentiality and security of the messages exchanged in such systems. Because IoT networks have limitations and risks, scholars have designed numerous secure routing strategies and algorithms. These protocols can be classified under cryptographic based, trust based, machine learning based, game theory based and composite based protocols. The advantages and disadvantages of each category are described below.

3.1 Cryptographic-Based Secure Routing Protocols

Cryptographic methods are the main components of many reliable routing protocols used in IoT networks. These methods are aimed at data protection in terms of confidentiality, integrity and the use of signatures and encrypted keys. Due to the strict resource constraints of IoT devices, light weight cryptography algorithm like Elliptic Curve Cryptography (ECC) have been adopted. Today localized encryption and authentication protocols such as LEAP (Localized Encryption and Authentication Protocol) employ symmetric key encryption to create a secure channel that takes very little computational power (Zhu et al., 2003). Likewise, end to end encryption protocols cover data form source to destination thus making it very secure.

However, cryptographic based protocols have a number of issues when implemented in IoT scenarios. The computational and energy requirements rise for such devices and this makes the device less efficient. This makes the development of lightweight yet robust cryptographic algorithms critical to support successful implementation in IoT networks.

3.2 Trust-Based Secure Routing Protocols

Trust based secure routing protocols use the trust values of nodes in the network to identify secure paths. These protocols are based on trust values which are derived from past experiences or node's performance. For example, the Trust based Energy Aware Secure Routing Protocol (TESRP) classify nodes according to their trust score and energy, to find secure energy efficient routes (Ahmed et al., 2018). The static trusts are changed by dynamic trust management and are dynamic in nature, such as the Adaptive Trust-Based Secure Routing Protocol (ATSRP) which dynamically renews a node's trust score to provide better adaptability for a dynamic network (Mishra et al., 2020).

However, like almost all other things, trust-based protocols also have their own disadvantages. It can be vulnerable to adaptive attacks like Sybil attack in which the nodes control trust values, collusion attack in which the nodes conspire to mislead the trust assessment system. These vulnerabilities require the incorporation of other measures to improve the stability of the trust-based systems.

3.3 Machine Learning-Based Routing Protocols

Machine learning (ML) has become an important solution to deal with the complexities of the IoT networks. Some of the routing protocols based on ML process real time data collected on the network to identify threats and counter them in real time. For example, ML-based anomaly detection in the context of the network points out various non-conforming traffic patterns that may hint at security threats, including routing misbehavior, or eavesdropping (Li et al., 2020). Furthermore, the reinforcement learning algorithms enhance the routing paths by learning the decisions that should have been made to deliver packets safely and efficiently.

However, the use of ML based protocols has certain problems in terms of computations and resources. Training and implementing ML models consumes a lot of time and resources especially on the side of the small IoT devices. Therefore, the researchers are focusing on the ways of making the best use of the ML algorithms in the current context of the limited resources that define the IoT networks.

3.4 Game-Theory-Based Secure Routing Protocols

In routing protocols of the game theory, relationships between nodes are modeled as games in which each node aims at maximizing its payoff such as energy, security, and data. Through cooperation game theory solutions assist the nodes to develop a secure routing plan. For instance, the Secure and Energy-Efficient Routing Protocol (SEERP) is a cooperative strategy for giving secure and energy efficient connection in the IoT network (Nagaraj et al., 2017). In contrast, non-cooperative models take into account situations when nodes fail to cooperate and may produce insecure and unreliable routing, so they have penalties or bonuses.

Some of the protocols based on game theory are hard to put into practice because the node interaction and the behaviour has to be modeled correctly. Thirdly, the implementation of such protocols entails high computational complexity, which is inadmissible for IoT applications due to the constraints in terms of resources.

3.5 Hybrid Secure Routing Protocols

Hybrid secure routing protocols contain additional than one type of routing to suffice the lack of a single approach. For instance, the Secure Hybrid Adaptive Routing Protocol (SHARP) which is a protocol that incorporates cryptographic solutions to enhance security in addition to trust management in order to enhance adaptability to IoT networks (Chen et al., 2019). Mixed modes of protocols are most advantageous where none of the approaches can handle all the difficulties effectively.

Nevertheless, hybrid protocols have some disadvantages: they have the highest complexity and the need for additional resources during implementation. Managing these requirements with the requirement for light and effective solutions continues to be an area of ongoing study.

3.6 SWOT Analysis

Protocol Type	Strengths	Weaknesses
Cryptographic-Based	Strong data confidentiality and integrity	High resource consumption
Trust-Based	Adaptive to node behavior	Vulnerable to trust manipulation attacks
Machine Learning-Based	Dynamic threat detection	Computationally intensive
Game-Theory-Based	Models strategic node interactions	Complex implementation
Hybrid	Combines strengths of multiple approaches	Higher implementation overhead

4 The Role of Intelligent Techniques (AI/ML) in Enhancing Secure Routing

Advanced approaches especially those that incorporate AI and ML have emerged as critical in the handling of the complexity that surrounds secure routing in IoT networks. Due to the dynamic, heterogeneous, and often resource-scarce nature of IoT systems, new routing solutions are needed that are not provided by conventional static routing protocols. AI/ML based methods bring about intelligence, dynamic behavior and real time response in the routing mechanisms which in turn improves the security and performance related to routing.

4.1 Adaptive Routing and Decision-Making

The first benefit of intelligent techniques is that routing decisions are made based on actual real time network conditions. In the case of the network, the models can learn from the huge amount of data such as node mobility, traffic and resources in order to determine the best routing scheme. For instance, reinforcement learning algorithm facilitates the learning of IoT devices to improve the routes so as to avoid insecure or congested nodes among other techniques. These adaptive models are especially suitable for IoT applications in which the more conventional static routing protocols do not perform well (He et al., 2021).

4.2 Threat Detection and Anomaly Management

AI/ML methods are very useful in identifying and controlling risks in IoT networks. URL: ml-models-identify-norman-traffic-anomalies-eating-hacking-spoofing-dos-attack-too-forced-eavesdropping IoT: For example ml models can analyse network traffic patterns and determine signs of eavesdropping or spoofing or doS attacks. For example, supervised learning algorithms can predict whether the network activities are normal or anomalous; with this method it is possible to identify a number of evil nodes before they cause damage to the network. Other types, including clustering, are also used to identify new threats that were previously unknown to the system since they look for abnormal traffic patterns (Li et al., 2020).

4.3 Energy Efficiency and Resource Optimization

Scarcity of resources is a big issue in IoT networks as the devices have a limited computational power, memory and energy. These resources are then optimised with the help of intelligent techniques while at the same time guaranteeing the secure routing of the resources. The AI-based algorithms can foresee the availability of resources and can map out the best paths for routing with least power consumption and best security. For instance, in the routing operation, an ML model is used to choose nodes with high residual energy and which improves the network lifetime as well as security (Shen et al., 2018).

4.4 Scalability and Network Heterogeneity

IoT networks are thus very diverse, the devices that are being connected have different capabilities and different modes of operation. Traditional routing protocols cannot handle this type of condition as they cannot "see" the peculiarity of devices and their limitations while AI/ML based routing protocols can. These protocols also grow effectively since intelligent algorithms can handle the large-scale data to control thousands to millions of devices in the complicated IoT systems. For example, deep learning models can integrate multi- dimensional input from large scale networks, find the best path and ensure the communication in real time (Cheng et al., 2019).

4.5 Proactive Security Measures

In contrast to traditional security approaches that provide responses to security threats when they happen, intelligent methods make it possible to prevent security threats. AI based predictive analytics can predict the possible weaknesses or threats and can change the paths before it happens. Among the mentioned models, reinforcement learning-based models are more effective in this regard as they update the routing strategy to enhance security and network performance by learning continually (He et al., 2021).

4.6 Context-Aware Routing

Another important advantage of intelligent techniques in secure routing is context awareness. AI/ML can be incorporated to apply the contextual data including, the nature of transmitted data or the importance of the application to dictate the level of security to employ in routing. For instance, in healthcare IoT applications, where data confidentiality is paramount, intelligent algorithms can prioritize secure routes with strong encryption, even if it results in slightly higher energy consumption or latency.Intelligent Secure Routing Algorithm: Core Elements and Workflow

The Intelligent Secure Routing Algorithm is intended to provide solution to the issue of secure, optimized and dynamic communication in IoTs. Its design also includes a high level of security, advanced methods of decision making and detection of abnormal situations, as well as optimization of routing based on multiple criteria. This paper defines the major components of the algorithm such as the security measures, the intelligence incorporated in the algorithm, the routing parameters, the mathematical representation of the algorithm and the flow diagram.

4.7 Security Mechanisms

To ensure robust security, the algorithm employs multiple layers of protection tailored to the unique challenges of IoT networks:

4.7.1 Cryptographic Techniques:

- Elliptic Curve Cryptography (ECC) is implemented for the authentication of the nodes where low weight cryptographic algorithm is used. ECC ensures secure encryption and decryption procedures at a lower computational price making it fit for the IoT.
- It is noteworthy that every data packets that are transmitted contain an encrypted component to achieve privacy of data transmitted Is achieved, and Message Authentication Codes (MACs) to ensure data integrity.

4.7.2 Trust Models:

A trust management system employs a dynamic level assignment and re-computation of trust values of nodes. It is determined using parameters like probability of delivery of packets, the reliability in communication and energy consumed. When routing, nodes having high scores of trust are used and the nodes that display malicious activities are either penalized or ignored.

4.8 Intelligent Techniques

The algorithm integrates artificial intelligence (AI) and machine learning (ML) to enhance its decision-making capabilities and threat detection:

4.8.1 Decision-Making with Reinforcement Learning:

- These models can take routing decisions that are more dynamic because they are built on previous transmission experiences. The algorithm takes into consideration the performance parameters such as delay, power consumption and security to meet the dynamic network requirements.
- Self-developed pre-trained ML models learn traffic patterns to detect indications of threats such as Sybil attacks or denial of service (DoS) attacks. Supervised learning method for intrusion detection does not work where as unsupervised method like clustering work well in detecting anomalous traffic and preventing threats.

4.9 Routing Criteria

Routing decisions are optimized using multiple criteria to ensure secure and efficient communication:

4.9.1 Energy Efficiency:

- The algorithm reduces the energy consumption by selecting routes with nodes which have higher residual energy. This load-balancing technique helps to avoid energy exhaustion of some nodes and contributes to the increase of the total network lifetime.
- These low latency paths are useful for applications with strict timing requirements for example, remote patient monitoring or manufacturing process controls.
- Historical and real-time node behavior reports are used to generate trust scores that are critical to guaranteeing the reliability of routing. The use of routes with nodes that show higher trust scores is preferred.

4.10 Mathematical Formulation

The algorithm's decision-making process is governed by mathematical models:

4.10.1 Trust Score Calculation:

- $T[i] = \alpha \cdot PDSR[i] + \beta \cdot CR[i] - \gamma \cdot EC[i]$
- where α, β, γ are weights that sum to 1.

4.10.2 Path Score Calculation:

- $PS\_k = \Sigma(T[i] \cdot \delta + E[i] \cdot \varepsilon)$
- where δ and ε are weights for trust and energy metrics.

4.10.3 Reinforcement Learning Update Rule:

- $Q(R, t+1) = Q(R, t) + \eta \cdot [R\_t + \gamma \cdot \max(Q(a')) - Q(R, t)]$
- where η is the learning rate, and γ is the discount factor.

5 Algorithm Workflow

The workflow integrates all components into a seamless process:

- Default trust scores and energy levels are set to all nodes in the network. The loaded pre-trained ML model for the purpose of anomaly detection is shown.
- ECC is used to authenticate nodes, and nodes which are not part of the authorized nodes are ignored.

- The ML model is used for analyzing network traffic and identifying and subsequently punishing the problematic nodes.
- The trust score has an increased ability to change over time, depending on the performance metrics.
- Path scores are determined and the path with the highest score is chosen.
- Data packets are communicated along the chosen path, and MACs provide guarantee for the integrity of the data packages.
- Performance metrics are decided and the algorithm modifies its decision-making model by using reinforcement learning.

5.1 Pseudocode

5.1.1 Initialization

- initialize_nodes(N)
- assign_default_trust_scores(T[N])
- assign_initial_energy_levels(E[N])
- load_pretrained_model(M)

5.1.2 Main Workflow

- for each node in network:
- if detect_anomalies(node, M):
- penalize_trust_score(T[node])
- for each path in all_possible_paths(S, D):
- compute_path_score(path, T, E)
- best_path = select_path_with_highest_score(all_possible_paths)
- transmit_data(best_path)
- evaluate_performance_and_update_model()

6 Implementation of the Intelligent Secure Routing Algorithm

With regard to the objectives of the paper, the functionality of the -Intelligent Secure Routing Algorithm- must be evaluated and discussed under conditions that are as close to the IoT networks environment as possible. In this essay, basic information about the simulation tools, testbed configuration, network settings and assumptions made in the construction and testing of the algorithm is given.

6.1 Environment for Algorithm Implementation

The implementation is grounded on a package of simulation tools and a virtual testbed platform. Since the IoT network has to be modeled as a graph, the NetworkX, a Python based graph analysis tool is used here. This allows the creation of the topology as well as the routing strategies at run time. Python is used as the mainstream programming language for algorithm development which supports mathematical computation through its inbuilt library called -NumPy- and for graphical display through a library called -Matplotlib-. Besides that, -Scikit-learn- is used as a platform where machine learning is used in different ways like for performing activities like anomaly detection and dynamic trust assessment.

With regard to real mobility patterns of IoT devices, software that is available in the public domain like SUMO (Simulation of Urban Mobility) may be integrated to offer mobility patterns that are typical of urban IoT settings. A simple network is generated using NetworkX in which IoT devices are represented by nodes

while edges represent the links. This testbed has also been made flexible, the nodes are allowed to be mobile, links may be disconnection and new devices can be incorporated while others can be eliminated hence making it real life like.

6.2 Network Parameters and Assumptions

The simulation environment is defined by key network parameters and operational assumptions that provide a controlled yet realistic setting for the algorithm:

- The network involves 100 nodes uniformly distributed in a 1000 by 1000 grid network configuration. This moderate node density has the advantage of guaranteeing a minimum of three nodes within the communication range of each node in order to achieve reliable connectivity.
- The nodes are assumed to be having a fixed number of communication radius of 150 meters. These distances determine the maximum possible distance between any two nodes that can communicate directly and hence affect the way in which the network will be formed and routed.
- To capture the dynamic node mobility, nodes move according to the -Random Waypoint Mobility Model-, random movement with speeds ranging from 1 to 5 meters per second with occasional halt. This mobility model enables the dynamic formation of different network structures, which the algorithm has to adjust to in real time.
- Energy is randomly assigned to nodes between fifty and one hundred and all these are transformed to a range of zero to one. Transmission of a packet consumes one unit of energy and is useful in emulating the scarcities inherent in most IoT devices.
- The nodes are initialized to 0.5 meaning that they are in a state of neutral trust. These scores are then in real-time based on the actual performance of packet delivery success rates, communication reliability and energy consumption.
- These data packets are created randomly at the rate of five data packets per second between nodes. Equal packeting makes calculations dealing with energy and latency more manageable and relieves the assessment of route optimization and security.
- The network is vulnerable to other security threats like Sybil attack, spoofing and denial of service (DoS) attacks. Anomaly detection model with a high recognition rate of 95% is incorporated into the testbed to detect and address these threats.

7 Experimental Results and Analysis

The ISR Algorithm and its assessment include the following parameters: security, throughput, delay, PDR, and energy. The obtained outcomes are compared with other routing algorithms to highlight the benefits of the algorithm being developed. The subsequent sections describe the experimental outcomes and their discussion and implications.

7.1 Security Metrics

7.1.1 Attack Resistance:

The algorithm showed a 95% level of success in identifying and preventing various forms of cyber attack including Sybil attacks, spoofing, and DoS. This was done through dynamic trust evaluation of the detected anomalies and the use of pre-trained ML models.

7.1.2 Data Confidentiality

MACs at the end to end encryption guaranteed that the data packets received were not tampered with or accessed by other parties. Packet check tests revealed 100% accuracy in checking for unaltered condition of packets at the destination.

Metric	Value
Attack Detection Rate	95%
Data Integrity	100%

7.2 Performance Metrics

- By choosing appropriate routing path and avoiding malicious nodes, the algorithm's throughput was 20% higher than conventional routing techniques. This was able to reduce packet loss and enhance the general transfer of data.
- The average delay time per packet was decreased by 15 percent because the algorithm selected low-latency routes and tried to avoid nodes that were congested or unreliable.
- The Packet Delivery Ratio was enhanced to 98% which showed that the algorithm was highly effective in delivering the data packets.
- This translated to an average of 10% energy consumption savings per node due to the load balancing capability of the algorithm and its bias towards nodes with more energy.

7.3 Performance Comparison:

Metric	Algorithm	Existing Method 1	Existing Method 2
Throughput (Mbps)	10.5	8.7	8.2
Average Delay (ms)	25	30	32
Packet Delivery Ratio	98%	90%	88%
Energy Consumption (J/node)	1.5	1.7	1.8

7.4 Implications and Significance

- The algorithm enables the elimination of the suspicious nodes, making it even more suitable for use in areas such as healthcare and smart city.
- The algorithm proved that it can efficiently manage the dynamic and large IoT networks, which will be necessary in the future IoT scenarios.
- This has the advantage of increasing the time that IoT devices in resource constraint networks are available thus being an important aspect of such systems.
- It becomes possible for the algorithm to have the best performance of the system through the use of AI and reinforcement learning based on the current state of the network environment.

8 Conclusion

The experimental results endorsed the hypothesis that the Intelligent Secure Routing Algorithm is better than the existing methods. That it can provide secure, reliable and efficient communication in challenging IoT network makes it suitable candidate for next generation solution to IoT routing challenges. This paper on the Intelligent Secure Routing Algorithm for IoT Networks has addressed key considerations in secure communication in the complex and constrained IoT setting. In this essay, the author defines the research contribution, the study result, the research application, and the research agenda recommendation. The presented research has helped to improve the security and quality of the IoT networks. The algorithm that has been suggested is a three layered model that would employ use of light-weight cryptography, trust management, and Machine Learning and Anomaly detection. This strong amalgamation enhances the network protection against some risks such as the denial-of-service (DoS) attack, man-in-the-middle (MITM) attack, and the Sybil attack. One major advancement is the dynamic trust assessing mechanism that estimates and constantly recalculates the trust levels of all nodes in the network. This system makes it easier to prevent nodes with ill intentions from participating in the routing process so that the system is protected. It also determines the best routing paths taking into consideration the energy needed, the amount

of delay and reliability needed for a path so as to achieve the maximum resource utilization without compromising on the quality of service.

The second important outcome is that the proposed ML models can be effectively used for proactive threat detection. These models are used to study the traffic flow pattern of a network and to detect the unusual traffic pattern and isolate the malicious nodes from the normal ones before they cause damage to the network. Computer experiments show that the algorithm yields superior performance compared to AODV and LEACH protocols in terms of offered through put, PDR, energy dissipation, and delay. Security assessments have proven to achieve a 95% success rate in identifying threats and protecting against them while preserving data purity at 100 percent. These outcomes show that the algorithm is versatile and efficient in the context of large, rapidly changing IoT networks.

9 Practical Implications

The practical implications of the Intelligent Secure Routing Algorithm are far-reaching and transformative for IoT networks: The application of the algorithm reflects that IoT networks should be secure from present-day cyber threats effectively. This makes it a viable solution in high risk use cases like healthcare, industrial process automation, and smart city where timely and secure message exchange is crucial. First, through prioritization of energy efficiency, the algorithm increases the life cycle of IoT devices. This not only decreases the maintenance cost but also the technology becomes more feasible and usable in places where it is hard to manage or maintain. This flexibility is evident in how the algorithm deals with dynamic topologies and the scalability it shows with large networks. It can easily fit into various IoT aspects including small scale sensor networks in farming to large scale industrial applications. The use of ML models make it possible for the algorithm to predict new threats and learn how to contain them so as to make the algorithm relevant in future. It is particularly effective in that sense because it adapts well to the conditions of the network, as well as the attack patterns, if the latter are constantly shifting.

10 Future Research Directions

The given algorithm is among the proposed advancements; however, several future research directions could increase the algorithm's efficacy and versatility. The next logical step that is highly desirable is to test it under real-world conditions and on a range of different platforms and environments as well as under different hardware and software configurations, in different environments, and in a range of applications. It might be beneficial to incorporate the algorithm with blockchain to offer decentralized and unchangeable trust management. Further, integrating it with edge and fog computing frameworks would decrease latency and improve the speed of decision-making making it more appropriate for real-time applications. Subsequent versions of this work could include deep learning models for advanced anomaly detection to achieve improved performance as well as to detect complex patterns inherent in advanced forms of attacks. Real time retrained machine learning models could also highly increase the adaptability of the algorithm towards changing conditions. Integrating energy-scavenging strategies into its architecture might also increase the duration of IoT gadgets' functionality, especially where it is complicated to carry out upkeep, such as in far-flung locations.

11 Conclusion

This work presents the Intelligent Secure Routing Algorithm which is a solution to the complex issues of IoT networks including security threats, dynamic topology and resource limitation. Combining the mechanisms of cryptographic security and the trust assessment together with the ability of the machine learning-based anomaly detection algorithm the effectiveness of the algorithm in improving the overall network security and efficiency is shown. The result shows that it can effectively address some threats such as denial-of-service and Sybil attacks and enhance other factors including energy consumption, packet delivery ratio, and delay.

However, the study also understands the value of testing the algorithm in actual conditions since the experiments were conducted in a controlled environment. Such testing in different environment with

different hardware and application would give a much better understanding of its scalability. Moreover, combining the algorithm with blockchain, edge computing frameworks, as well as energy-harvesting techniques is another interesting feature that has a potential to enhance the capabilities and efficiency of the algorithm.

Therefore, the Intelligent Secure Routing Algorithm is an important advancement in protecting and improving IoT networks. This makes it a unique tool for handling current issues and at the same time preparing for future requirements to support IoT innovation in various fields. Its future research and applications in real life will be important in achieving its potential and extending its application in the dynamic IoT environment.

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