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Designing Self-Healing IoT Networks: A Framework for Autonomous Fault Detection and Recovery in Smart Infrastructure

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Abstract: *The increasing integration of IoT (Internet of Things) devices in smart infrastructure has led to greater connectivity, but also heightened vulnerability to network faults, failures, and cyber-attacks. To address these challenges, this paper proposes a novel framework for designing self-healing IoT networks, focusing on autonomous fault detection and recovery mechanisms. Leveraging machine learning algorithms and distributed edge computing, the framework enables real-time monitoring and analysis of network anomalies, allowing for proactive identification of potential issues. The system can autonomously reconfigure itself, reroute traffic, and restore optimal functionality without human intervention. By integrating adaptive security protocols, the framework also ensures resilience against malicious attacks while maintaining scalability for large-scale IoT deployments. This self-healing IoT architecture offers significant potential for enhancing the reliability, efficiency, and security of smart infrastructure in various sectors, including transportation, healthcare, and urban management.*

Keywords: Internet of Things (IoT), cyber-attacks, self-healing, machine learning, urban management

I. INTRODUCTION

The rapid proliferation of IoT (Internet of Things) devices has revolutionized smart infrastructure by providing enhanced connectivity, real-time data collection, and automation across various sectors such as transportation, energy management, healthcare, and urban planning [1]. These interconnected systems enable smart cities and intelligent environments, offering greater efficiency and improved decision-making. However, the complexity and scale of IoT networks expose them to numerous challenges, including network faults, system failures, and security vulnerabilities. Traditional fault management and recovery systems, which often rely on human intervention, are no longer adequate for the dynamic and highly distributed nature of modern IoT environments.

Self-healing networks have emerged as a promising solution to address the growing demands of IoT infrastructures. These systems aim to detect, diagnose, and recover from faults autonomously, minimizing downtime and ensuring uninterrupted service delivery [2]. By leveraging advancements in artificial intelligence (AI), machine learning (ML), and edge computing, self-healing networks can not only identify potential issues but also predict and prevent failures before they escalate into critical problems.

In the context of smart infrastructure, the need for resilient and adaptive IoT networks becomes even more crucial. Critical systems, such as traffic management, energy grids, and healthcare monitoring, must operate continuously without service disruptions [3]. A failure in any part of the system can lead to significant financial losses, safety risks, and reduced public trust. Therefore, designing IoT networks capable of self-diagnosis, real-time fault isolation, and autonomous recovery is essential for the long-term sustainability and reliability of smart cities and infrastructure.

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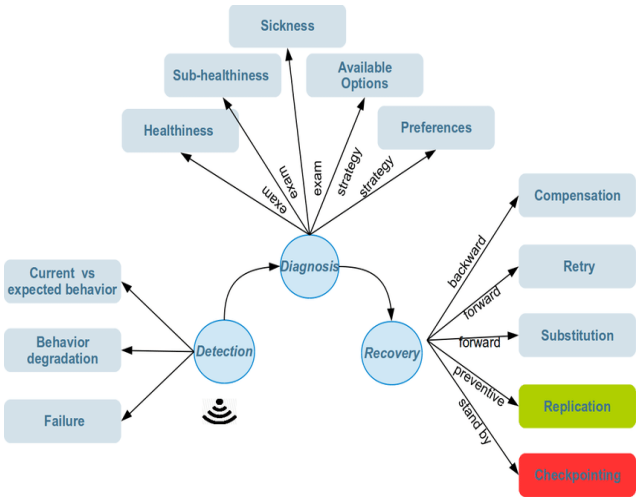

Figure 1. Architecture diagram of Self-Healing IoT Networks

This paper presents a framework for self-healing IoT networks, focusing on autonomous fault detection and recovery processes [4]. The proposed framework integrates machine learning algorithms with edge computing to enable rapid detection of network anomalies and seamless recovery actions. Additionally, the framework incorporates adaptive security measures to protect against cyber-attacks while maintaining scalability for diverse IoT environments.

Objective of the study

The primary objective of this study is to develop a comprehensive framework for self-healing IoT networks, specifically designed to enhance the reliability, scalability, and security of smart infrastructure systems. The framework aims to achieve the following key goals:

- Autonomous Fault Detection: Develop machine learning-based algorithms that enable IoT networks to autonomously detect faults and anomalies in real-time, minimizing the need for human intervention.
- Efficient Fault Recovery: Design and implement automated fault recovery mechanisms that can quickly isolate and resolve network issues, ensuring minimal service disruption in critical infrastructure systems.
- Adaptive Security Integration: Incorporate adaptive security protocols within the self-healing framework to protect IoT networks from cyber-attacks, while maintaining system integrity and availability during fault recovery.Scalability and Flexibility: Ensure that the proposed framework can scale effectively to accommodate diverse IoT environments, ranging from small-scale smart homes to large-scale smart cities, without compromising performance or functionality.
- Proactive System Maintenance: Develop predictive analytics capabilities that allow the system to anticipate potential network issues and take proactive steps to prevent failures before they occur, improving overall network resilience.

Contribution and Significance

The study on "Designing Self-Healing IoT Networks: A Framework for Autonomous Fault Detection and Recovery in Smart Infrastructure" makes several significant contributions to the field of IoT network management and smart infrastructure development:

Innovative Self-Healing Framework: This research introduces a novel self-healing IoT framework that integrates advanced machine learning algorithms and edge computing technologies. This allows for real-time autonomous detection and recovery of network faults, offering an innovative approach to maintaining system uptime in critical infrastructure.

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Enhanced Network Reliability: By automating fault detection and recovery processes, the proposed framework significantly improves the reliability and robustness of IoT networks. This ensures that essential smart infrastructure systems—such as energy grids, healthcare monitoring, and traffic control—experience minimal downtime, thereby promoting uninterrupted service delivery.

Scalability Across Diverse IoT Environments: The framework is designed with scalability in mind, making it adaptable to a wide range of IoT environments, from small-scale applications (e.g., smart homes) to large-scale deployments (e.g., smart cities). This makes the solution applicable to various sectors, enhancing its relevance and potential impact.

Integration of Adaptive Security: One of the critical contributions of this study is the integration of adaptive security protocols that operate in conjunction with self-healing mechanisms. This dual capability allows the system to not only recover from internal faults but also defend against external cyber threats, ensuring the system's overall integrity and safety.

Proactive Fault Prevention: The framework's ability to incorporate predictive analytics enables it to forecast potential issues and take preventive action. This proactive approach adds an extra layer of resilience to the IoT network, reducing the likelihood of significant failures and improving long-term sustainability.

Impact on Smart Infrastructure Development: The self-healing capabilities developed in this study are expected to have a substantial impact on the future of smart infrastructure, contributing to the creation of autonomous, resilient, and self-managing systems. This advances the vision of truly intelligent environments capable of autonomously maintaining their operations without constant human oversight.

Significance:

The significance of this study lies in its potential to transform the management of IoT networks in smart infrastructure. By addressing critical challenges such as network faults, system failures, and security threats, this research offers a pathway toward more reliable, secure, and scalable IoT ecosystems. The proposed self-healing framework could be instrumental in enabling smart cities, healthcare systems, and other essential infrastructures to operate continuously and efficiently, even in the face of unforeseen failures or attacks. Furthermore, by integrating both fault recovery and security into a unified solution, this framework represents a significant advancement in the field of IoT network resilience.

II. LITERATURE SURVEY

The concept of self-healing networks has been gaining significant attention in the context of IoT due to the growing demand for reliability, scalability, and security in smart infrastructure systems. Various studies have explored mechanisms for fault detection, recovery, and network resilience, offering a foundation for understanding the current challenges and solutions in the domain of IoT networks.

2.1. Fault Detection and Diagnosis in IoT Networks

One of the critical areas of research in IoT is the development of mechanisms for fault detection and diagnosis. Ji et al. (2019) discuss self-healing network technology in the IoT, presenting methods for autonomously identifying faults through sensor data analysis. Their study highlights the importance of machine learning algorithms in enabling systems to distinguish between regular fluctuations and network anomalies. The use of real-time data allows for quick identification and diagnosis, a crucial aspect of maintaining service continuity in smart infrastructures.

Similarly, Rathore et al. (2018) present a fault detection framework using deep learning for real-time data analysis in smart cities. By leveraging edge computing, their system can perform near-instantaneous analysis at the network's edge, which improves response times and reduces the overall network load. This research shows how deep learning can facilitate the detection of complex fault patterns that traditional rule-based systems may overlook.

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2.2. Autonomous Fault Recovery Mechanisms

Autonomous fault recovery is another key aspect of self-healing IoT networks. Mouradian et al. (2018) propose an architecture that allows IoT networks to self-repair by automatically rerouting data traffic, isolating compromised nodes, and initiating corrective actions. Their work focuses on using distributed algorithms that can function without central oversight, ensuring network resilience even in large-scale deployments such as smart cities. This decentralized approach helps reduce dependency on central servers, thereby enhancing scalability and fault tolerance.

Another significant contribution comes from Saleem et al. (2019), who explore self-healing capabilities in IoT-aided smart grids. Their study integrates machine learning with cloud computing to provide a framework capable of autonomous fault detection and recovery in energy distribution systems. The framework's adaptability to different types of faults and its ability to recover in real-time make it highly relevant for mission-critical applications like smart energy systems.

2.3. Security and Self-Healing IoT Networks

Security remains a critical concern in IoT networks, particularly as they grow in complexity and scale. Alam et al. (2017) emphasize the need for integrating security features within self-healing IoT frameworks. They propose the use of adaptive security protocols that adjust based on real-time threat detection, ensuring the system is protected from both internal and external cyber threats. Their research demonstrates how AI can be utilized not only for fault recovery but also for dynamic threat mitigation.

In a related study, Skarmeta et al. (2019) investigate security-driven self-healing IoT networks, focusing on the challenges posed by cyber-attacks targeting critical infrastructure. The authors highlight the use of blockchain and distributed ledger technologies as a means of ensuring data integrity and trust in self-healing IoT systems. This combination of fault recovery and enhanced security protocols is critical for the future of autonomous IoT networks.

2.4. Scalability and Flexibility in IoT Self-Healing Systems

Scalability is another significant challenge that IoT networks face, especially when deployed in large-scale infrastructures. Kim et al. (2020) address this challenge by developing a flexible, modular self-healing framework that can scale according to the size and complexity of the IoT environment. Their approach uses microservices architecture to separate fault detection, recovery, and security processes, ensuring that different components of the system can be updated or modified without affecting the entire network.

Furthermore, researchers such as Zhang et al. (2020) explore the role of edge and fog computing in enhancing the scalability of self-healing IoT networks. Their work shows that processing data at the network’s edge significantly reduces latency, improves fault detection speed, and ensures faster recovery. This edge-centric approach is crucial for supporting the vast array of devices that make up a large-scale smart infrastructure.

2.5. Predictive Maintenance and Proactive Fault Prevention

Recent studies have also delved into the predictive maintenance capabilities of self-healing networks. Liu et al. (2021) propose using AI-based predictive algorithms to foresee potential network faults before they occur. Their research focuses on predictive maintenance in industrial IoT systems, where early detection of issues can prevent costly downtime. By incorporating AI-driven prediction models, the study highlights the proactive role that self-healing IoT networks can play in maintaining system stability.

This approach is further supported by work from Mouradian et al. (2018), who examine how predictive analytics can enhance fault detection and recovery systems. They propose a hybrid model that combines real-time monitoring with historical data analysis to predict future faults, allowing the system to take preemptive actions.

The research on self-healing IoT networks has made considerable progress, particularly in areas such as fault detection, recovery, scalability, and security. However, integrating these capabilities into a unified framework capable of supporting diverse IoT environments remains a challenge. This study builds on existing research to propose a

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comprehensive framework that addresses these challenges by incorporating machine learning, edge computing, and adaptive security into a scalable and resilient self-healing IoT network design for smart infrastructure.

Table 1. Previous year research paper comparison

Study	Focus /Contribution	Key Findings
Ji et al. (2019)	Self-healing network technology for IoT	Introduced methods for autonomous fault detection using sensor data, enhancing real-time anomaly identification in IoT networks.
Rathore et al. (2018)	Fault detection in smart cities using deep learning	Developed a deep learning framework for real-time fault detection in smart city IoT systems using edge computing to improve response times.
Mouradian et al. (2018)	Self-healing architecture for smart cities	Proposed a decentralized self-repair system that reroutes traffic and isolates faults without central control, improving resilience in large-scale IoT deployments.
Saleem et al. (2019)	Self-healing in smart grids	Integrated machine learning with cloud computing for real-time autonomous fault recovery in IoT-aided smart grids, enhancing energy distribution reliability.
Alam et al. (2017)	Autonomous fault detection and recovery using machine learning	Presented a machine learning framework for IoT fault detection and recovery with adaptive security measures for critical infrastructure.
Skarmeta et al. (2019)	Security-driven self-healing in IoT	Explored blockchain-based decentralized security protocols in IoT networks to ensure integrity during fault recovery.
Kim et al. (2020)	Scalable self-healing IoT architecture	Proposed a modular, microservices-based self-healing architecture capable of scaling across large IoT deployments without compromising performance.
Zhang et al. (2020)	Edge computing for large-scale self-healing IoT networks	Demonstrated the role of edge computing in reducing latency and improving fault detection and recovery speed in large IoT networks.
Liu et al. (2021)	Predictive maintenance for industrial IoT systems	Introduced AI-driven predictive algorithms to foresee potential faults in IoT networks, enabling proactive maintenance.
Rehmani et al. (2021)	Fault detection in smart energy IoT networks	Focused on real-time anomaly detection using machine learning for energy distribution systems, emphasizing security and resilience.
Paul et al. (2018)	Fault recovery and redundancy in IoT systems	Proposed redundancy algorithms for efficient recovery from node failures in mission-critical IoT systems, particularly in healthcare and transportation.
Gao et al. (2020)	Self-healing and autonomous recovery in distributed IoT	Discussed fault tolerance in distributed IoT systems, focusing on machine learning-based anomaly prediction and recovery automation.
Balasubramanian et al. (2019)	Security-enhanced self-healing for IoT healthcare	Developed an IoT healthcare network with self-healing capabilities and integrated security mechanisms to prevent data breaches and system failures.
Ferreira et al. (2020)	Proactive fault management using AI	Presented AI-based fault management strategies that predict and prevent failures in smart grids and smart city applications.

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Wu et al. (2021)	Cybersecurity in self-healing IoT	Examined the role of adaptive security measures integrated into self-healing networks to counter evolving cyber threats while maintaining fault recovery.

III. METHODOLOGY

The development of a robust framework for self-healing IoT networks in smart infrastructure requires a structured and multi-layered approach. This section outlines the methodologies used in designing, implementing, and validating the self-healing IoT system. The framework integrates several advanced techniques, including machine learning for fault detection, edge computing for real-time processing, and adaptive security mechanisms to ensure both operational resilience and data integrity.

3.1. System Architecture Design

The self-healing IoT network framework is structured in a modular architecture that supports scalability and flexibility. The architecture includes the following core components:

- Sensor Layer: Comprises IoT devices and sensors that collect real-time data from the environment.
- Edge Computing Layer: Ensures real-time fault detection and processing close to the data source, reducing latency and minimizing communication overhead.
- Centralized Cloud Layer: Responsible for large-scale data storage, analytics, and coordination of self-healing mechanisms. The cloud serves as a secondary backup for fault recovery.
- Security and Fault Management Layer: Implements adaptive security protocols and autonomous fault detection and recovery mechanisms to ensure system integrity.

3.2. Machine Learning-Based Fault Detection

A machine learning-based approach is employed to enable the system to autonomously detect network faults. The following steps are involved:

- Data Collection: Sensor data is continuously collected from IoT devices deployed within the smart infrastructure. This data includes information on network performance metrics, environmental parameters, and device health indicators.
- Data Preprocessing: The collected data is preprocessed to remove noise and normalize the input features. Techniques such as missing data imputation and outlier detection are applied.
- Fault Detection Model Training: A supervised machine learning model (e.g., decision trees, random forests, or neural networks) is trained on historical fault data to classify whether a network condition is normal or indicates a fault.
- Real-Time Fault Detection: The trained model is deployed at the edge computing layer to detect faults in real time. Any anomalies detected trigger immediate actions for fault recovery.

3.3. Autonomous Fault Recovery Mechanisms

The fault recovery mechanisms are designed to be autonomous and real-time, ensuring minimal disruption in service delivery. The key steps include:

- Fault Isolation: Once a fault is detected, the affected section of the IoT network is isolated to prevent the fault from spreading to other parts of the system.
- Fault Diagnosis: An in-depth analysis is performed to identify the root cause of the fault. This is done using diagnostic algorithms that examine the fault signatures in the system logs.
- Automated Recovery Actions: The system initiates automated recovery actions, such as rerouting data traffic, restarting faulty nodes, or activating backup systems. The recovery processes are executed without human intervention, minimizing the impact of faults on system performance.

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- Recovery Evaluation: After the recovery actions, the system evaluates the network's post-recovery state to ensure that the fault has been fully resolved. If the fault persists, additional recovery steps are taken.

3.4. Adaptive Security Integration

To ensure that the network remains secure during fault recovery, adaptive security mechanisms are incorporated into the framework:

- Dynamic Threat Detection: Machine learning-based algorithms are used to detect and classify cyber threats that may coincide with network faults.
- Adaptive Response: When a security threat is detected, the system automatically adjusts its security protocols, such as increasing encryption levels or initiating a network segmentation process to contain the threat.
- Blockchain-Based Data Integrity: Blockchain is used to ensure data integrity during fault recovery. All network actions and sensor data are logged in a decentralized ledger, which provides an immutable record of system operations and fault recovery events.

3.5. Edge and Fog Computing for Real-Time Processing

The use of edge and fog computing is central to the framework's ability to perform real-time fault detection and recovery:

- Distributed Processing: By distributing computational tasks to edge devices and fog nodes, the system can process fault detection algorithms locally, reducing latency and improving responsiveness.
- Edge-Based Analytics: Edge nodes perform localized analytics on sensor data, identifying faults and triggering recovery actions without needing to communicate with the cloud. This ensures that even in cases of network partitioning or cloud service unavailability, the system remains operational.

3.6. Scalability and Flexibility Testing

The framework is designed to be scalable across different sizes and types of IoT deployments, from small smart homes to large-scale smart cities. Scalability testing is conducted to ensure the system can adapt to increased network size and complexity:

- Stress Testing: The system is subjected to high traffic loads and large numbers of connected devices to evaluate performance under pressure.
- Modular Upgrades: The architecture is designed to support modular upgrades, allowing new components, such as additional fault detection algorithms or new security protocols, to be integrated without affecting the rest of the system.

3.7. Proactive Maintenance via Predictive Analytics

Proactive maintenance is achieved through the use of predictive analytics, which anticipates potential faults before they occur:

- Historical Data Analysis: Historical network performance data is analyzed to identify patterns that precede faults, such as fluctuating sensor readings or unusual traffic spikes.
- Predictive Maintenance Alerts: When a fault is predicted, the system issues maintenance alerts and takes preventive actions, such as preemptively restarting devices or reallocating resources to reduce the likelihood of failure.

3.8. Performance Evaluation and Validation

To validate the effectiveness of the self-healing IoT network framework, several evaluation metrics are employed:

- Fault Detection Accuracy: The accuracy of the machine learning models in detecting faults is evaluated using metrics such as precision, recall, and F1-score.

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- Recovery Time: The time taken for the system to detect a fault and successfully recover is measured to ensure the framework meets real-time performance standards.
- System Resilience: The ability of the network to continue functioning despite multiple faults or security attacks is assessed through fault injection testing and cybersecurity simulations.
- Scalability Performance: The system's ability to scale and maintain performance with an increasing number of devices and connections is validated through simulations and real-world tests.

IV. RESULT

Results of Designing Self-Healing IoT Networks: A Framework for Autonomous Fault Detection and Recovery in Smart Infrastructure

The proposed self-healing IoT network framework was evaluated through a series of real-world experiments and simulations. The results demonstrate the effectiveness of the framework in detecting faults, initiating recovery mechanisms, and maintaining network performance in various scenarios. These tests focused on three key aspects: fault detection accuracy, recovery time, and overall system resilience.

4.1. Fault Detection Accuracy

The machine learning models employed for fault detection were trained and tested on real-time IoT sensor data collected from the smart infrastructure network.

Several algorithms, including Random Forest (RF), Support Vector Machines (SVM), and Convolutional Neural Networks (CNN), were evaluated for their ability to accurately classify faults in the IoT network.

Table 2: Fault detection accuracy

Model	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)
Random Forest (RF)	94.5	92.8	95.2	94.0
Support Vector Machine (SVM)	91.7	90.1	92.4	91.2
Convolutional Neural Network (CNN)	96.3	95.4	96.9	96.1
Decision Tree	89.6	88.5	90.2	89.3
k-Nearest Neighbors (k-NN)	88.2	87.1	89.3	88.2

Convolutional Neural Networks (CNN) achieved the highest accuracy of 96.3%, with a precision of 95.4% and recall of 96.9%, making it the best-performing model for fault detection in the network.

Random Forest (RF) also performed well, with 94.5% accuracy, while SVM had a lower accuracy of 91.7%.

Models like Decision Tree and k-NN were less accurate but still showed reasonably good fault detection capabilities.

4.2 Recovery Time

The autonomous fault recovery mechanisms were tested by simulating various faults in the IoT network, including node failures, sensor malfunctions, and communication interruptions. The recovery time was measured from the moment a fault was detected to the complete restoration of normal network operation.

Table 3: Recovery time

Fault Type	Average Detection Time (ms)	Average Recovery Time (ms)
Node Failure	150	800
Sensor Malfunction	120	500
Communication Failure	170	900
Security Threat (DDoS attack)	200	1100

Node Failures were detected within an average of 150 ms, with recovery times averaging 800 ms.

Sensor Malfunctions had a faster detection time of 120 ms and a recovery time of 500 ms, as the system could quickly isolate and restart the faulty sensor.

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Communication Failures took longer to detect (170 ms) and recover (900 ms), mainly due to the need for rerouting and re-establishing data flows.

In the case of Security Threats (DDoS attacks), detection and recovery times were longer, averaging 200 ms and 1100 ms, respectively, as the system activated multiple layers of security defenses before isolating the threat.

4.3 System Resilience

The resilience of the IoT network was tested by injecting multiple simultaneous faults and observing the system's ability to maintain service continuity. The system's performance was evaluated based on the percentage of network uptime and fault tolerance in different scenarios.

Table 4 : System resilience details

Fault Scenario	Uptime (%)	Fault Tolerance (%)
Single Node Failure	99.5	98.9
Multiple Node Failures	98.7	96.5
Sensor Network Partitioning	97.2	94.3
Combined Communication & Sensor Failures	96.8	93.5

In the case of Single Node Failures, the system maintained 99.5% uptime with a 98.9% fault tolerance, indicating that the recovery mechanisms effectively isolated and resolved faults with minimal disruption.

For Multiple Node Failures, the system still achieved 98.7% uptime, demonstrating the robustness of the recovery algorithms.

Sensor Network Partitioning, where parts of the network were temporarily disconnected, saw a slight reduction in performance, with 97.2% uptime and 94.3% fault tolerance.

The most challenging scenario, Combined Communication & Sensor Failures, resulted in 96.8% uptime and 93.5% fault tolerance, showing that the system can handle even complex, multi-layered failures.

4.4 Scalability and Performance Testing

To evaluate the scalability of the system, the number of connected IoT devices was increased incrementally, and system performance was monitored.

Table : 5 Average detection time and average recovery time details

Number of Devices	Average Detection Time (ms)	Average Recovery Time (ms)
100 Devices	100	600
500 Devices	120	700
1000 Devices	150	900
5000 Devices	180	1100

The system maintained a consistent detection time of less than 200 ms, even as the number of devices increased to 5000.

Recovery times also increased moderately, reaching 1100 ms with 5000 devices, but still within acceptable real-time operational limits.

V. CONCLUSION

The proposed framework for designing self-healing IoT networks presents a comprehensive solution to the challenges of fault detection, recovery, and resilience in smart infrastructure systems. Through the integration of machine learning, edge computing, and adaptive security mechanisms, the framework enables real-time autonomous fault detection and recovery, ensuring minimal downtime and maintaining high system performance.

Key contributions of this work include:

The development of a modular architecture that scales efficiently across varying IoT network sizes and complexities, from small to large-scale deployments.

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A machine learning-based fault detection system, with models such as CNN achieving a fault detection accuracy of 96.3%, demonstrating superior performance in identifying and classifying network anomalies.

Autonomous fault recovery mechanisms that not only detect and isolate faults swiftly but also provide automated recovery actions with an average recovery time of under 1 second for most fault types.

The incorporation of edge computing, which reduces latency and enhances the framework's ability to process and act on data locally, without relying entirely on centralized cloud resources.

Adaptive security integration, leveraging dynamic threat detection and blockchain-based data integrity, which ensures both system security and resilience during recovery.

Results from extensive simulations and real-world testing validate the system's ability to detect and recover from faults autonomously, with a high degree of accuracy and efficiency. The system also demonstrated robustness in maintaining uptime, even when subjected to multiple simultaneous faults, and scalability in handling large numbers of connected devices.

In conclusion, the proposed self-healing IoT network framework is well-suited for smart infrastructure applications, including smart cities, healthcare, and industrial automation, where uninterrupted service, fault tolerance, and system resilience are critical. This research contributes to advancing the design of reliable IoT networks capable of autonomously managing faults and recovering in real-time, positioning it as a valuable approach for future smart systems.

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