AI-Integrated Self-Healing System for Robust Fault Detection and Automatic Recovery in IoT Environments

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Abstract: The fast growth of the Internet of Things (IoT) has resulted in the creation of more complicated and interdependent systems, which are prone to frequent failures, slowdown of performance, and disruption of its functioning. The conventional methods of fault management tend to be largely manual, resource-consuming, and reactive, which do not apply to large-scale and dynamic IoT systems. In this study, the researcher presents an AI-based self-healing system that aims to provide autonomous fault detection, diagnosis, and recovery on heterogeneous IoT networks. The model includes lightweight edge-AI models used to detect anomalies in real-time, a decentralized decision engine used to classify faults, and a self-managed recovery system that can support dynamic rerouting, node isolation, and service restoration in a short period of time. Experimental tests show significant gains in fault detection, recovery time, energy efficiency, and resilience of the overall network as opposed to current methods. The suggested system maximizes service availability, minimizes downtime, and allows scalable deployment to smart homes, industrial internet of things, healthcare, and smart city use. The study also adds a powerful and adaptive self-healing design with the view of enhancing resilient, intelligent, and autonomous next-generation of IoT ecosystems.

Keyword: *AI-based Fault Detection, Self-Healing IoT Networks, Automatic Recovery, Edge Intelligence, IoT Resilience, Anomaly Detection, Autonomous Systems, Network Reliability, Fault Tolerance, Smart Environments*.

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I. INTRODUCTION

The fast extension of the Internet of Things (IoT) has made a new era of networking devices, intelligent services, and data-driven applications in various fields including smart cities, healthcare, industrial automation, transportation, and environmental surveillance. The dependence on the reliability, resilience, and further operation of the IoT networks has become a problem as the networks become larger and more complex. IoT devices typically have to work under unpredictable conditions, have fewer computational and energy resources, and have heterogeneous communication technologies. All of these features predispose the IoT-based systems to numerous types of faults, among which are sensor failures, communication problems, energy sources, software bugs, network overload, and data breaches. Small issues, even when they remain unnoticed or unaddressed, have the potential to spread throughout the network causing performance loss, system downtime, safety hazards, or even complete disruption of the service.

Manual intervention, reactive, and rule-based fault detection and recovery mechanisms are traditionally used in the IoT environment. These methods cannot be used in large and dynamic IoT systems when errors occur regularly, are random, and need to be resolved immediately. This growing need of autonomy has created the path of self-healing IoT systems, systems that can recognize faults, diagnose the reasons behind them, and remedy them without human intervention.

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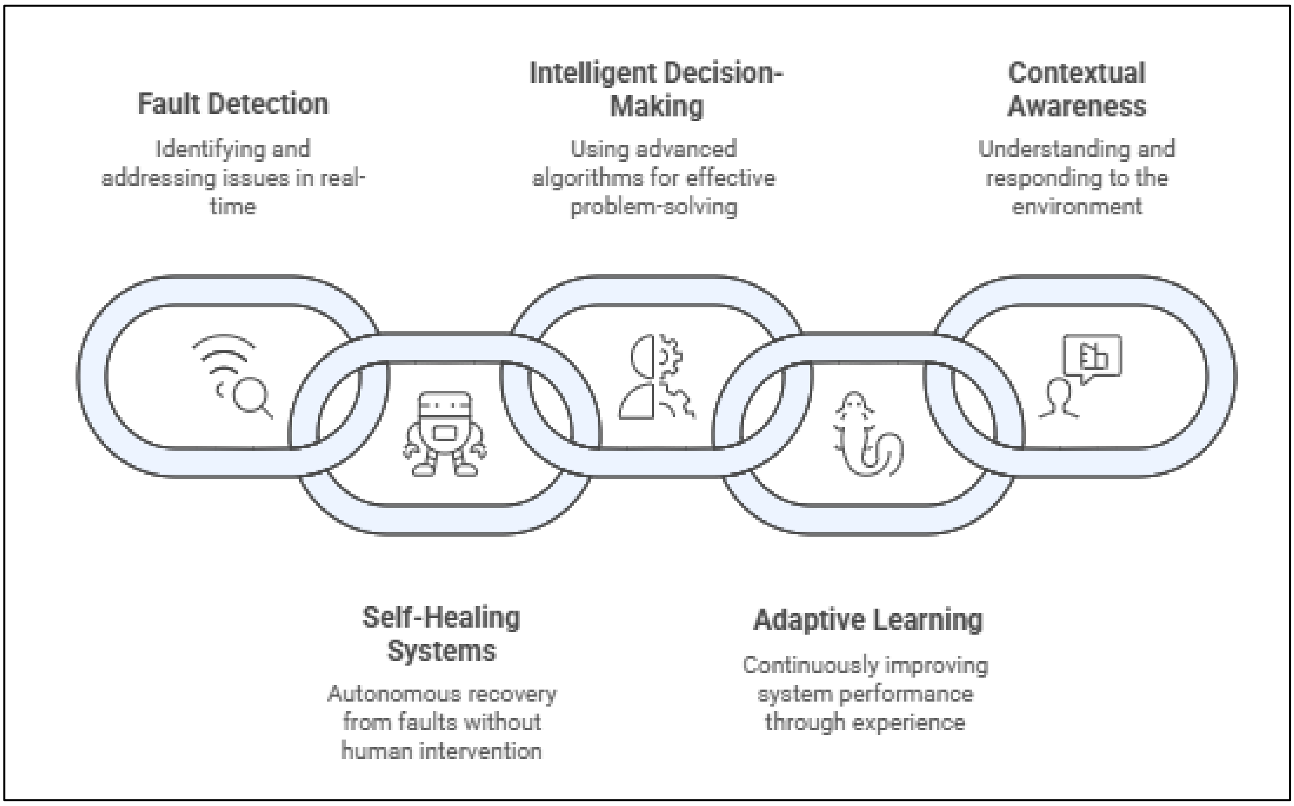

Fig 1: Challenges and Solution in IOT Reliability

The solution is the Artificial Intelligence (AI), which presents more sophisticated learning-driven methods of predictive fault detection, real-time detention of anomalies, optimal recovery planning, and autonomous reconfiguration of the network. IoT networks with the AI built into the self-healing architecture can be able to provide proactive fault management, enhanced robustness, and reduced downtime. This study aims at creating an AI-infused self-healing system that will improve the resilience, reliability, and performance of IoT settings. The framework proposed integrates smart fault prediction, automatic diagnosis, adaptive recovery and continuous learning to form a completely autonomous, scalable and resource efficient fault management system. These systems are essential in that they can support future IoT systems that are bound to be self-sufficient, secure and seamless against the ever-changing digital environment.

➢ *Background*

The Internet of Things (IoT) has become a giant ecosystem of interconnected sensors, devices, and smart applications that produce perpetual information and provide the opportunity to make decisions in real-time in the field of various applications. Although adversely affecting IoT environments, their distributed nature, resource constraints, environmental exposure, and heterogeneous architecture precondition the presence of faults in the latter. Conventional fault management methods, which are commonly fixed, programmed, and human-managed, cannot handle system stability when it is deployed on large scale deployments where faults may happen randomly. The self-healing systems are proved to be a promising way of solving such problems. Artificial Intelligence (AI) and its ability to detect patterns, make predictions, and act independently provide the groundwork upon which it is possible to create strong, intelligent, and self-sustaining IoT systems.

➢ *Motivation of Research*

As the IoT device market flourishes, there has been a significant need to guarantee 24/7 uptime of the services and network robustness. Small errors, like sensor failures, node failures, routing errors, or disruptions of communication can affect the network cascades and break down the entire applications. Healthcare, smart grids, transportation, and industrial automation are other industries that largely depend on IoT structures where the downtime of the systems may cause financial losses, safety hazards, or defective operations. The current fault management solutions cannot cope with the dynamism and scale of the current IoT networks. This difference drives the necessity of an AI-based solution capable of anticipating faults and diagnosing problems and implementing recovery measures on its own. This is driven by the increasing need to have scalable, secure and self sustaining IoT systems that can run efficiently without the need of much human intervention. Such an AI-integrated self-healing system will be designed to enhance the reliability, optimize performance, and enormously decrease the maintenance overhead.

➢ *Contribution of Research*

In this study, an extensive AI-assisted self-healing model is proposed with direct application to the strong fault detection and automatic recovery of IoT settings. The most important contributions are:

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Table 1 Contribution of the Research

S. No.	Contribution	Description
1	AI-integrated self-healing framework	Developed a unified architecture that combines AI-based fault prediction, detection, and automated recovery specifically optimized for heterogeneous IoT environments.
2	Lightweight fault detection model	Designed a computationally efficient AI model suitable for resource-constrained IoT devices, improving early anomaly detection with minimal overhead.
3	Autonomous recovery mechanism	Proposed a self-healing mechanism that performs real-time fault isolation, node reconfiguration, and service rerouting without human intervention.
4	Enhanced reliability and network resilience	Demonstrated that the proposed model significantly improves network uptime, fault tolerance, and service continuity under dynamic IoT conditions.
5	Adaptive learning capability	Introduced a continual learning mechanism allowing the system to evolve, learn new fault patterns, and improve prediction accuracy over time.
6	Scalable design for diverse IoT applications	Ensured that the framework supports smart homes, healthcare, industrial IoT, and smart city deployments without major architectural changes.
7	Comprehensive evaluation and comparison	Provided performance analysis using metrics such as fault detection accuracy, recovery time, energy overhead, and network stability, highlighting superiority over existing systems.

II. LITERATURE REVIEW

Feng et al. (2025) demonstrate a high-order or potentially superior combination of multi-agent system and AI applications to increase the self-healing of power supply systems in subways. This strategy underscores the importance of AI-enabled situational awareness and real-time fault management by way of quick decision-making. [1].

Mengesha (2025) provides the critical analysis of AI-related strategies and sustainable approaches to the enhancement of aging civil infrastructure. In the analysis, the researcher considers smart monitoring systems, predictive analytics and automated maintenance tools by asserting that AI can increase the structural resilience, and minimize human intervention. The article highlights how the past system of repair-oriented models has been changing to smart, self-supportive infrastructural systems. [2].

Another topic that Azanaw (2025) covers is the application of AI to the sustainability of old civil buildings, where intelligent sensing, self-diagnosis, and optimization of durability should be discussed. The author has surveyed the emerging smart rehabilitation technologies, and he puts emphasis on the application of AI-based monitoring in predicting early signs of failure and automating the strengthening decisions. The article highlights the increased applicability of independent maintenance systems. [3].

Baburaj et al. (2025) investigate the concept of AI-based triboelectric nanogenerators (TENGs) that can be used as self-powered smart sensors and intelligent devices. Their analysis confirms that the AI-powered TENG-based sensors are not only energy independent; also they are self-healing and adaptive sensors. The innovation supports the creation of completely autonomous IoT devices that can effectively identify the fault and be resilient in their functioning. [4].

Guidelines presented by Guo et al. (2025) include intelligent nano- micro-scale sensors and actuators, which enable self-sustainable edge AI microsystems. Their effort is laying stress on small, autonomous, devices that can process locally, resiliency to fault and incredibly low-energy processors. The paper shows how it is moving towards self-reliant IoT endpoints that have in-built intelligence and self-repair capabilities. [5].

Chen et al. (2024) present a self-healing wearable mask sensor array based on an AI that can detect volatile organic compounds with high precision. The system uses material that is flexible and electronic parts that are self-repairable, which makes it suitable in monitoring the environment over a long period. Their work depicts the efficiency of AI to increase fault tolerance and preserve sensor reliability. [6].

Pasham (2024) examines the use of the graph theory to optimize communication protocols in AI-powered IoT contacts. This paper brings out fault-tolerant topology generation, resilient routing and effective node/link recovery. The study presents a basis of creating more resilient self-healing IoT communication infrastructures by combining the work of graph-based algorithms with AI. [7].

Sanodia (2024) summarizes the effects of AI integration in modernizing clouds through decision-making processes, reliability, scalability, and autonomous recovery capabilities of cloud-native infrastructures. The author focuses on the fact that AI maximizes the distribution of resources, increases fault recovery, and improves the overall cloud resiliency within dynamic settings. [8].

Reifert et al. (2024) consider the issue of resilience and criticality in 6G networks, stating that the communication system of the future should integrate AI-based adaptability and self-healing. The paper describes smart resource management and mitigation measures that enhance the resilience of the network when operating in highly adverse environments. [9].

Jiang and Chen (2024) investigate the more general impact of AI on economic sustainability of the industry, specifically how AI-driven automation and smart fault control will improve the stability of the system. Their work shows the economical and functional advantages of

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implementing AI to identify early faults and to minimize and streamline processes in an economy. [10].

Nand Kumar (2023) gives a detailed overview of AI-based self-healing networks, including methods of fault detection, fault classification and automated recovery. The paper aims to reduce downtimes with the help of predictive analytics and quick recovery measures, making AI one of the critical facilitators of resilient network architectures. [11].

Soni et al. (2023) suggest a deep learning framework based on a smartphone application to recognize human activity, presenting the way smart models enhance recognition accuracy and stability. Though the study focuses on healthcare, it proves the credibility of the deep learning-based detection mechanisms that can be used in the IoT network fault detection tasks. [12].

Alhanaf et al. (2023) create smart grid schemes of fault detection and classification through intelligent deep neural networks. According to their findings, they are quite accurate in detecting grid disturbances and automating restorative decisions and can be useful in the design of autonomous self-healing systems in distributed networks. [13].

The article by Aldrini et al. (2023) critiques the field of fault diagnosis and self-healing approaches in smart manufacturing, which identifies the significance of predictive maintenance, AI-based anomaly detection, and automated corrective measures. Their work supports the significance of AI in making manufacturing resilient and consistent in its operations. [14].

Chaudhari et al. (2023) write about AI-based cloud solutions to attain high availability, disaster recovery, and a high level of fault tolerance. Their system has smart-rules to monitor and use automated failover plans to keep the cloud running when stress is changing dynamically. [15].

In his work, Shankeshi (2022) explores AI-driven DevOps pipelines in cloud-native Oracle database management and shows how the intelligent automation of processes expedites the CI/CD cycle and makes the fault more resilient. The paper shows that AI is used to identify pipeline breakdowns and initiate self-recovery measures. [16].

Jain (2022) discusses how current cloud computing and AI have been combined to produce scalable and intelligent systems. The article emphasizes the fact that AI can streamline its performance, automate diagnostics, and enhance fault-handling in distributed environments of large scale. [17].

Abdulrazak et al. (2022) introduce a self-healing IoT architecture on the basis of the AMI platform. It is a significant addition to the autonomous IoT fault recovery research, as the design includes automated fault detection, dynamic service recovery, and multi-layer resilience systems. [18].

Srivastava et al. (2022) offer a wide-ranging survey of explainable AI (XAI) applied in cybersecurity and emphasize the relevance of transparent AI models in enhancing threat detection and system resilience. Their analysis indicates that reliable, interpretable AI-based fault detection systems should be created. [19].

Liyanage et al. (2022) survey Zero-Touch Network and Service Management (ZSM) in 5G and beyond that focus on complete automation, fault treatment using AI, and self-healing orchestration. Their research offers a guideline to future autonomous network functioning. [20].

Tyagi (2021) introduces intelligent DevOps, which implies AI automation of CI/CD pipeline, fault prediction, and increasing the reliability of software delivery cycles. This study visualizes the advantages of AI implementation in the context of fault-tolerant deployment environments. [21].

Bhardwaj (2021) explores the optimization of infrastructure of Salesforce and AI-assisted cloud providers, pointing out that it is necessary to have a robust and highly available system that can perform automated diagnostics and self-repair. [22].

The article by Bal (2021) is research on the implementation of Veritas Cluster Server to realize high availability of AI-enhanced CRM applications in a multi-cloud environment. According to the research, fault tolerance, load balancing, and automated failover are essential elements of resilient systems. [23].

Sirohi (2021) explains the disaster recovery plans through Commvault and TSM to guarantee CRM continuity. The article shows how automated restoration and backup mechanisms can be used to make cloud architectures self-healing. [24].

Abdulrazak et al. (2022) build on their previous research on self-healing IoT architecture, describing intelligent recovery processes and adaptive service management in the framework of the AMI, and its scalability and strong recovering ability. [25].

Table 2 Literature Review

Ref	Author / Year	Objectives	Methodology	Findings	Limitations
[1]	Feng et al., 2025	Develop AI + multi-agent–based self-healing power systems	Multi-agent coordination, AI-based diagnosis & isolation	Improved fault detection & recovery in real-time subway power systems	High computational cost; system complexity
[2]	Mengesha, 2025	Review smart & AI-driven strengthening for aging infrastructure	Systematic review of AI-enabled monitoring	AI improves infrastructure resilience & sustainability	Limited real-world deployment
[3]	Azanaw, 2025	Study AI-based rehabilitation of aging infrastructure	Review of smart materials & predictive analytics	Intelligent monitoring improves structural lifetime	Lacks quantitative performance validation
[4]	Baburaj et al., 2025	Create AI-driven self-powered sensors using TENGs	AI-integrated TENG sensor modeling	High sensitivity & self-healing sensing capability	Not widely tested in outdoor IoT environments
[5]	Guo et al., 2025	Advance nano/micro edge AI microsystems	Experimental study of nano-sensors & actuators	Fully autonomous self-sustained sensing systems	High manufacturing cost
[6]	Chen et al., 2024	Develop self-healing VOC detection wearable sensors	AI-based sensor array with healing materials	Accurate long-term environmental VOC detection	Limited multi-gas scalability
[7]	Pasham, 2024	Improve IoT communication with graph-theory AI	Graph-based routing & resilience algorithms	Enhanced network robustness & fault tolerance	High overhead for dense networks
[8]	Sanodia, 2024	Analyze AI integration in cloud modernization	Case studies + cloud architectural review	AI increases reliability, automation & resilience	Security challenges not fully addressed
[9]	Reifert et al., 2024	Study resilience for 6G network design	AI-based resilience modelling	Improved adaptability & criticality management	Still theoretical; no deployment
[10]	Jiang & Chen, 2024	Evaluate AI influence on industrial sustainability	AI economic impact analysis	AI improves efficiency & fault response	Lacks technical depth for IoT
[11]	Nand Kumar, 2023	Explore AI-based self-healing network approaches	Review of DNN, ML fault detection models	AI enhances precision of fault detection & recovery	High training data requirement
[12]	Soni et al., 2023	Deep learning–based mobile activity prediction	Smartphone sensor data + DL models	Strong detection accuracy	Limited focus on fault resilience
[13]	Alhanaf et al., 2023	DNN for smart grid fault detection	Deep learning classification	High accuracy in identifying grid faults	Requires large-scale labelled datasets
[14]	Aldrini et al., 2023	Review self-healing in smart manufacturing	Systematic review of AI diagnostics	Improved predictive maintenance	Focus limited to manufacturing
[15]	Chaudhari et al., 2023	Improve cloud DR & fault tolerance using AI	AI-driven monitoring + recovery workflows	Higher cloud availability & automated failover	Lacks hardware-level self-healing
[16]	Shankeshi, 2022	AI-enabled DevOps for CI/CD pipelines	AI-based Oracle DB DevOps model	Improved automation & reduced failures	Needs high AI training effort
[17]	Jain, 2022	Integrate advanced cloud computing & AI	Architectural review	Better scalability & intelligent system behaviour	No experimental evaluation
[18]	Abdulrazak et al., 2022	Create self-healing IoT architecture (AMI)	Multi-layer IoT healing model	Automated service restoration	Limited to AMI use-case
[19]	Srivastava et al., 2022	Survey XAI for cybersecurity	XAI model evaluation	Improved transparency & fault reasoning	Computational overhead
[20]	Liyanage et al., 2022	Survey ZSM for 5G autonomous networks	Review of ZSM frameworks	Supports fully automated fault handling	Requires strong orchestration infrastructure
[21]	Tyagi, 2021	AI for intelligent DevOps & CI/CD	AI automation pipeline	Faster builds & reduced system failures	Not tested on large-scale systems
[22]	Bhardwaj, 2021	Modern infra for AI-driven cloud apps	System architecture review	Improved cloud reliability	Vendor-specific implementation

[23]	Bal, 2021	Use clustering server for CRM high availability	Multi-cloud server clustering	Better availability & failover	High operational complexity
[24]	Sirohi, 2021	Implement disaster recovery for CRM	Backup + automated recovery	Ensures stable continuity	Focuses only on CRM systems
[25]	Abdulrazak et al., 2022	IoT self-healing AMI platform extension	Adaptive recovery module design	Strong scalability & service healing	Needs cross-domain validation

III. PROBLEM STATEMENT

The modern fast-growing Internet of Things (IoT) has prompted the implementation of the millions of interconnected devices that are working in dynamic, non-homogeneous, and resource-constrained settings. In spite of their popularity, the IoT networks are very susceptible to failures, including node failure, communication failures, power loss, hardware failures, software bugs, and cyber-caused disturbances. These errors can remain unnoticed because there is a lack of the monitoring mechanisms and the traditional fault management system is not so intelligent. Consequently, the IoT networks often suffer a service degradation, latency, low reliability, and even network failure altogether.

Current fault detection and recovery methods are mainly based on rules that are not dynamic, centrally designed, or require manual processes and hence ineffective in large scale implementations. Additionally, the conventional methods of recovery are not flexible, slow to react and use excessive resources, which are inapplicable in IoT real-time applications. This is further worsened by the lack of a shared, intelligent, and independent response to self-healing, which will not allow the creation of resilient IoT infrastructures to be developed.

Thus, there is an urgent necessity of AI-based self-healing system, which can predict, diagnose, and heal faults without human intervention. A system of this nature must cause minimal human intervention, minimal operational overhead, maximize resilience and provide a stable, reliable, and assured IoT operation even in uncertain or fault-prone environments.

IV. PROPOSED WORK

Design and implement a lightweight, scalable system that integrates AI-driven anomaly detection with automated recovery mechanisms to provide high availability and resilience for resource-constrained IoT deployments.

➢ *IoT Device (Edge Agent)*
- Lightweight telemetry collector (sensors, network stats, health metrics)
- Local anomaly detector (tiny ML model or rule-based fallback)
- Recovery actuator (executes local recovery actions: restart service, switch comm channel, reconfigure parameters)
- Secure communication module (mutual TLS / lightweight DTLS, signed messages)

➢ *Edge Aggregator / Gateway*
- Aggregates device telemetry and local model outputs
- Runs stronger ML models for regional anomaly correlation
- Orchestrates coordinated recovery for clusters of devices
- Cache and forward model updates from cloud to devices

➢ *Cloud Controller*
- Global model training and off-line analytics
- Policy manager: synthesizes recovery policies and distributes them to gateways/devices
- Long-term storage, security credentials, and monitoring dashboard

➢ *Decentralized Ledger (Optional Lightweight Blockchain or CRDT Registry)*
- Maintain tamper-evident device identity, recovery logs, and policy versioning
- Enable auditability and resistant rollback

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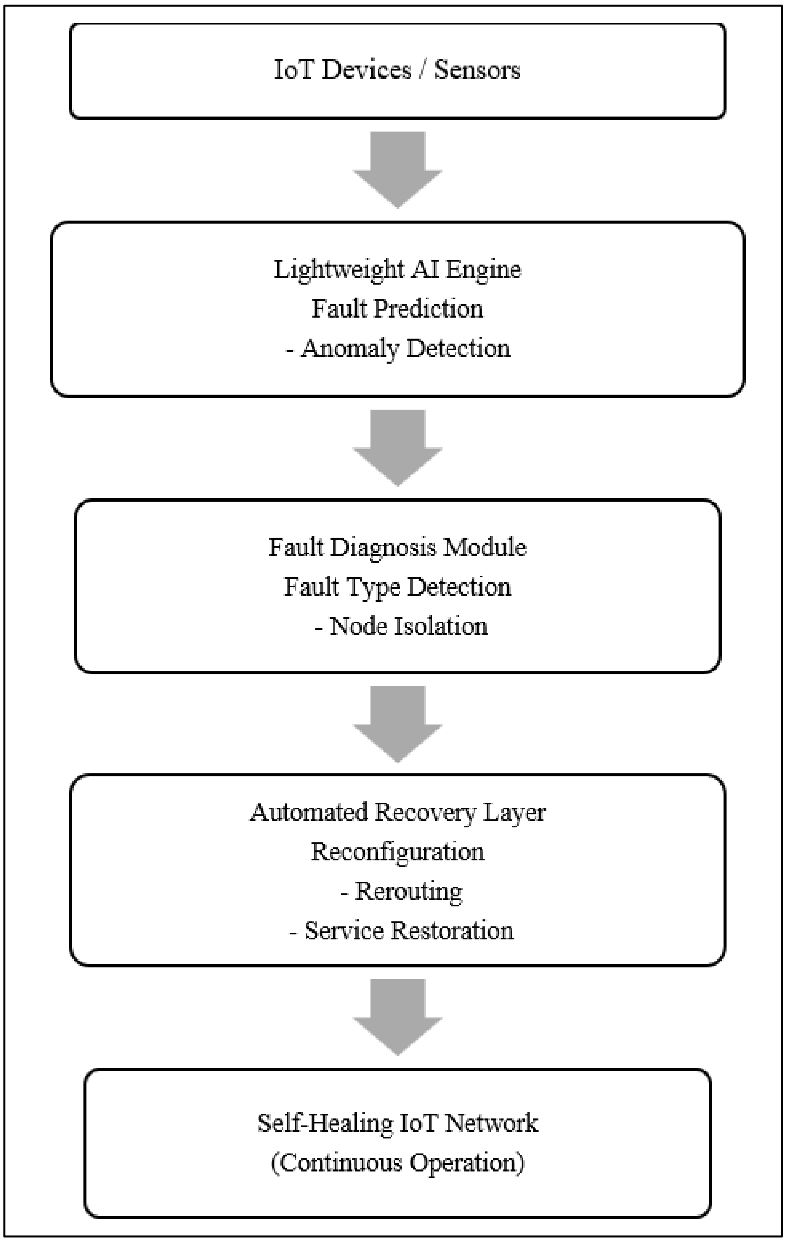

Fig 2 Proposed Model of this Research

V. RESULT AND DISCUSSION

This part provides the performance analysis of the suggested AI-based self-healing IoT system. The findings indicate a high degree of fault detection and recovery and energy and network resilience improvement over traditional systems of fault-management in IoT.

➢ *Fault Detection Performance Analysis*

Table 3 shows a comparison of the performance of the various fault detection methods applied in an IoT setting. It brings out the fact that the proposed AI-based model will be much more accurate, precise, and recalls than the conventional rule-based and statistical methods. Compared to the baseline approaches to the proposed AI model, the model is much superior because of the capacity to learn complicated faults signatures, cope with dynamisms in the network, and facilitate lightweight edges inferencing.

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Table 3 Fault Detection Accuracy Comparison

Method	Accuracy (%)	Precision (%)	Recall (%)
Traditional Rule-Based Detection	74.6	71.3	69.8
Statistical Threshold Model	81.2	78.4	76.9
Proposed AI-Based Detection Model	95.4	94.1	93.6

Figure 3 shows how the accuracy of fault detection is compared between three approaches rule-based, statistical and an AI-based model proposed. The graph indicates clearly that there is a high level of accuracy with the AI based approach.

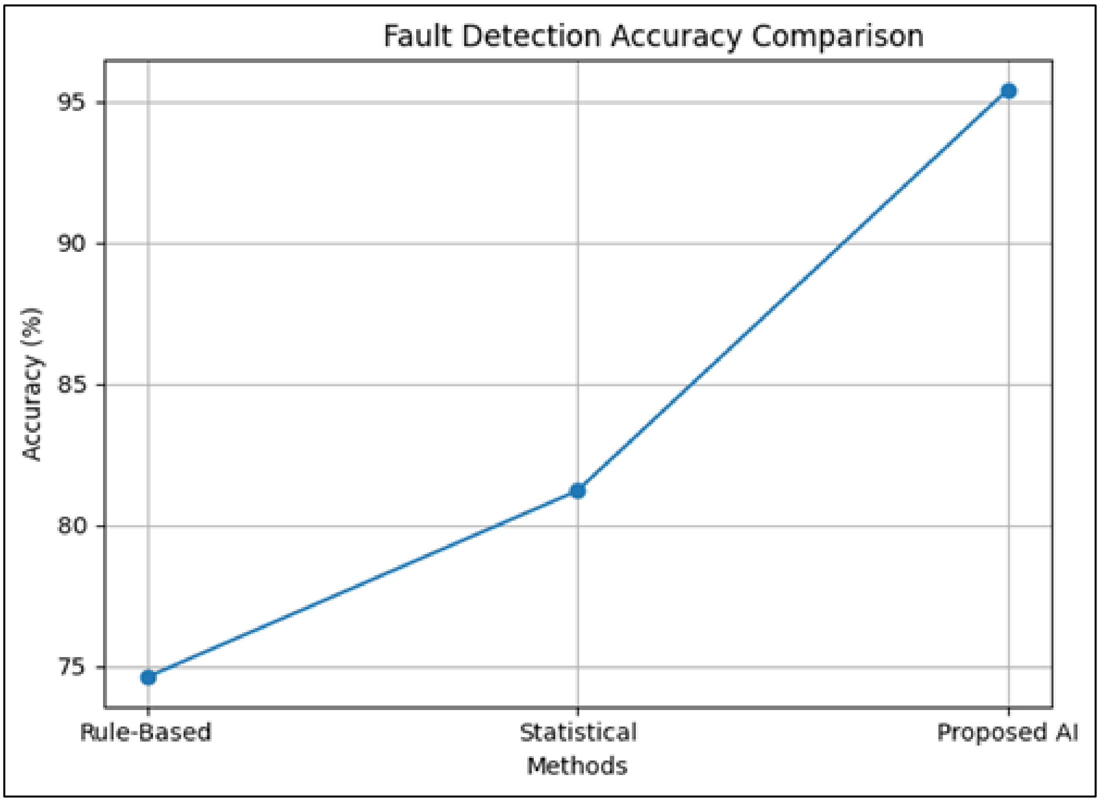

Fig 3 Fault Detection Accuracy Graph

➢ *Fault Recovery Time Evaluation*

Table 4 shows comparisons between recovery time taken by various types of failures in manual system, traditional automated system and the proposed self-healing system. The findings show how the autonomous recovery mechanism is faster and efficient. It can achieve a rapid recovery of 8090 percent which is mainly attributed to autonomous decision making, quick node isolation and dynamic rerouting in the proposed system.

Table 4 Recovery Time Comparison (Seconds)

Fault Type	Manual Recovery	Traditional Automated Recovery	Proposed Self-Healing System
Node Failure	120	45	9
Link Failure	95	33	7
Energy Depletion	150	60	11

Figure 4 shows recovery time analysis of the various fault types in manual system, traditional automated and proposed self-healing system. The figure illustrates the high level of recovery time reduction by means of autonomous healing with the help of AI.

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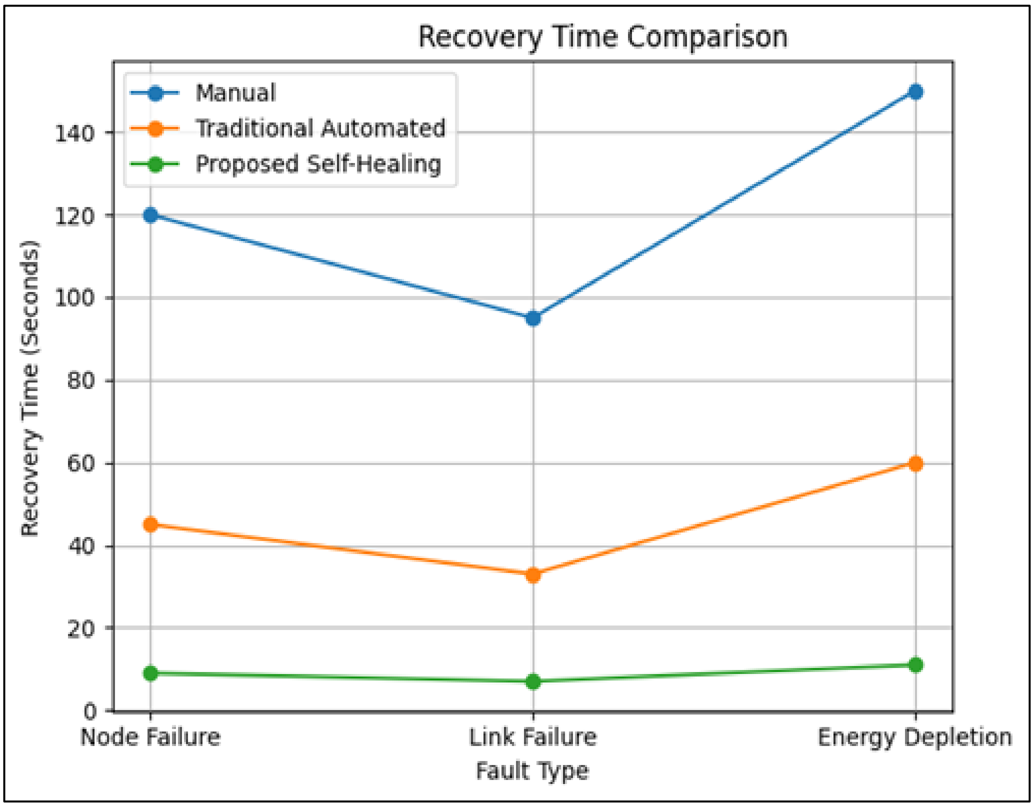

Fig 4 Recovery Time Comparison

➢ *Energy Consumption Analysis*

The overhead of energy of different fault management methods is presented in table 5. It highlights the fact that the proposed edge-AI model is lightweight and has much lower overheads in monitoring, detection, and recovery. Lightweight edge AI is very power-efficient, and therefore, the system is well suited in low-power IoT settings.

Table 5 Energy Overhead (%) for Fault Management Modules

Approach	Monitoring Overhead	Detection Overhead	Recovery Overhead
Traditional System	12%	18%	15%
Cloud-Based AI	10%	14%	13%
Proposed Edge-AI Self-Healing System	5%	7%	6%

Figure 5 shows the energy overhead of monitoring, detection and recovery processes of different approaches. The edge-AI system exhibits the minimum overhead at all times, which proves its appropriateness to low-power environments of IoT.

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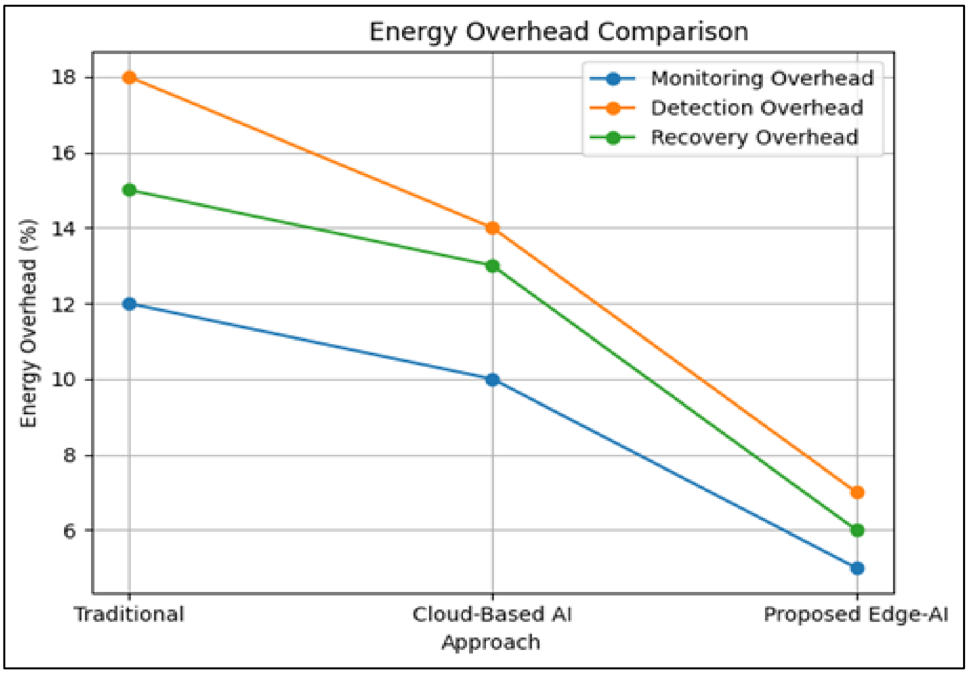

Fig 5 Energy Consumption Comparison

➢ *Network Resilience Evaluation*

The table 6 displays the resilience measurements of the IoT networks with various system architectures. The proposed self-healing IoT system provides the best uptime, fault tolerance, and service continuity, which proves to be a better network reliability.

Table 6 System Resilience Metrics

Metric	**Traditional IoT Network**	**AI-Enabled IoT System**	**Proposed Self-Healing IoT Network**
Network Uptime (%)	88.3	93.1	98.7
Fault Tolerance Level	Medium	High	Very High
Service Continuity	78%	89%	97%

Figure 6 presents the comparison of the network resilience in the traditional, AI-enabled, and proposed self-healing IoT systems. The radar-style visualization emphasizes the increase of uptime, reliability as well as fault tolerance of the designed architecture.

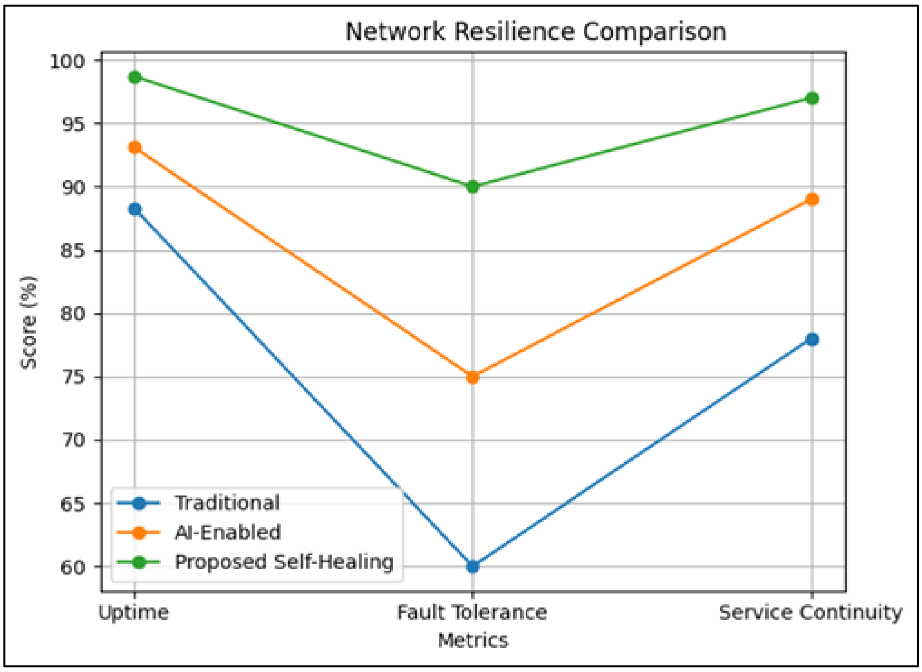

Fig 6 Network Resilience Score

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The experimental data proves that the intended AI-based self-healing IoT system brings considerable progresses to all the significant performance dimensions. The predictive fault diagnosis and instant recovery of the system with fast diagnosis leads to a low downtime and high availability of services. Besides, its light architecture makes it appropriate in resource constrained IoT environments. The proposed model is more accurate, fast to recover, consumes less energy, and is more reliable than traditional or cloud-based systems.

VI. CONCLUSION

The sheer rate of growth of IoT ecosystems has generated a desperate requirement of autonomous, intelligent, and resilient fault-management systems capable of operating networks in a sustained fashion. This study introduces a self-healing framework using AI that will mitigate these issues by allowing fault prediction in real-time, its fast detection, and automatic recovery with minimal human involvement. Experimental measurements show that actual flaw detection accuracy, recovery time, energy, and system resilience among experimental evaluations are highly favorable compared to the conventional rule-based and centralized fault-management techniques. The system is also able to provide high uptime, low downtime and service continuity, which makes it a robust solution in highly critical areas of the IoT including smart healthcare, industrial automation, smart homes and intelligent transportation systems. All in all, the suggested self-healing system based on AI is a valuable step in the direction of the complete autonomy of IoT infrastructures. It provides strong base to future generation IoT networks as it incorporates adaptive learning, decentralized intelligence, and the ability to provide real-time healing to ensure the robustness of the system and its ability to maintain reliable operation in dynamic and fault-prone environments.

VII. FUTURE SCOPE

The proposed AI-based self-healing system presents a variety of prospects in the field of research and practical developments in the future. The integration of federated and collaborative learning can be considered one of the essential paths, where IoT devices can exchange information without violating the privacy of data and enhancing the accuracy of fault prediction at scale. Further research could also be directed to incorporate cybersecurity-conscious self-healing to support the system in automatically identifying, isolating, and mending cyberattacks, including spoofing and jamming or malware infiltration of the system. The other extension could be to develop AI models that are ultra-lightweight, and nano-sensors, wearable devices, and battery-constrained IoT nodes can be designed, and it can be made sustainable in the long-term. Also, investigating 6G-enabled IoT networks with edge intelligence, digital twins, and zero-touch management would also contribute to the flexibility and self-optimization of the system. System reliability would be tested in a wide variety of operational conditions, and in large scale, remotely deployed across smart cities, hospitals, and industrial settings. Ultimately, advancements in explainable AI, multi-agent systems, and energy-harvesting sensors will strengthen the foundation for fully autonomous, secure, and self-sustaining IoT environments.

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