Evolution of Machine Learning Applications in IoT Security: A Critical Analysis and Future Perspectives

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Abstract: The continuously advancing field of Internet of Things (IoT) has given rise to technologies that are crucial to protect IoT systems from various attacks. Conventional security methods have their own bottlenecks and fail to effectively deal with the security of IoT systems. This review explores the existing Artificial Intelligence and Machine Learning (ML) based approaches for IoT security. Covering researches mainly done in 2023-24, we have discovered that AI-enabled security solutions have better accuracy in detecting threats, more than 90%. On the other hand, they keep a check on the computational cost to prevent any cost overruns. Our key takeaways include the integration of multiple ML algorithms as a hybrid system, adversarial attack handling mechanisms and other techniques to handle targeted attacks. However, challenges persist, including resource constraints, ease of deployment, adaptability, robustness etc. Our review addresses these challenges and provide direction for future research along with the aim to offer valuable insights from relevant researches aimed at enhancing IoT security through Machine Learning Techniques.

1 INTRODUCTION

The rapidly growing use of IoT devices in our daily lives has completely changed how we interact with such systems across homes, offices, and other spheres. While offering numerous advantages to users worldwide, the concern for security and data privacy needs be addressed properly. Our review highlights the bottlenecks of traditional IoT security systems and in accordance with the research by (Ali & Rani, 2024), where they have stated that current systems are not sufficient to protect against sophisticated and more advanced attacks targeting IoT network.

The shift towards Machine Learning based solutions is rapidly being preferred over traditional methods as a solution for security challenges in this domain. Unlike traditional approaches which are based on static-rules and pre-defined conditions, ML introduces dynamic and adaptable systems which can protect against threats which learning from the data continuously to keep itself updated with latest threats. This milestone is described in the paper by (Saumya et al.,2024) as a significant point in the building of IoT security architectures. Table 1 shows the Projected IoT connections worldwide.

The prime advantage of using machine learning and AI in IoT security is its ability to deal with big data and understand hidden patterns that normal systems fail to uncover. This allows for better protection in IoT environments where standard protocols aren't that much efficient in detecting advanced cyberattacks. However, integrating AI/ML in legacy IoT systems has its own set of challenges. Some of them are resource constraints, low-power operations, communication protocols, and interoperability with various IoT devices. (Omarov et al.,2024) have described these challenges in depth in their research where they indicated that traditional systems fail to maintain a balance between security and simplicity of algorithm and how Machine Learning based algorithms are better.

Rapid progress has been seen in past few years in the field of Machine Learning in IoT. Some use cases like real-time threat detection and prevention systems have achieved accuracy as high as 97%. Research by (Alomiri & AlShehri, 2024) describes how delay in identification of threat can cause serious data breaches and compromises in security.

Although research in this domain is going on, the practical implementation of theoretical models and systems has several challenges. One of the primary

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Table 1: Projected IoT Connections Worldwide.

Year	IoT Connections (Min, in billions)	IoT Connections (Max, in billions)	YoY Growth (%) (Min)	YoY Growth (%) (Max)	Key Observations
2022	13.8	13.8	-	-	Baseline Year
2023	15.9	16.6	15.2%	20.3%	Expansion of 5G and smart devices
2024	18.0	18.8	13.2%	13.3%	Increased industrial IoT adoption
2025	20.1	20.1	11.7%	6.9%	Growth in smart city projects
2026	22.4	22.4	11.4%	11.4%	IoT penetration in healthcare and AI
2027	24.7	24.7	10.3%	10.3%	Rise of edge computing and 6G research
2028	27.1	27.1	9.7%	9.7%	Autonomous vehicles and AIoT surge
2029	29.6	29.6	9.2%	9.2%	Mass adoption of industrial IoT
2030	32.1	40.0	8.5%	21.6%	IoT becoming mainstream in daily life
2031	34.6	34.6	7.8%	-13.5%	AI-driven IoT innovation
2032	37.1	37.1	7.2%	7.2%	Global IoT regulations evolve
2033	39.6	39.6	6.7%	6.7%	IoT surpasses 39 billion devices

challenges is adversarial attacks which manipulate the training process and introduce errors in the algorithm which makes it helpless against some targeted attacks. (Harbi et al., 2024) have described the risk of such attacks and how they disrupt the machine learning model. Moreover, they have highlighted the need for careful optimization of ML models so they can perform efficiently under limited resource conditions as well.

Another area of application, the Industrial Internet of Things or IIoT has benefitted from the provision of AI/ML based security systems. Adaptive models allow autonomous handling of attacks, minimizing human intervention. These systems can detect various cyber threats including both known and new, improving real-time monitoring and mitigation of threats. (Wankhade et al., 2024) have described the advancements in the field of IIoT and security measures focusing mainly on precision, reliability and real-time functioning.

Current trends mainly focus on the development of hybrid machine learning models, combining more than one algorithm to enhance it while overcoming the limitations of one single algorithm. For instance, combination of supervised and unsupervised Machine Learning Algorithms has resulted in increased threat detection accuracy and reduced false positives as evaluated by (Iqbal et al., 2024). Additionally, Pareto-optimal models have also been discussed.

Significance of the Study. Understanding the role of ML in IoT security and its impact, are crucial for designing and developing advanced security solutions. As cyber threats are getting advanced day by day, so as the need to have adaptive and intelligent security systems. This review summarizes the current state of ML in IoT security highlighting various techniques, major trends and key inferences which can be derived from the study alone. The limitations, challenges and future directions are clearly discussed to help the researchers infer and conclude. Moreover, it acts as a fundamental base, by providing the directions of future research which can focus on safety and reliability of IoT Environments and optimization of complex ML algorithms to work better with IoT units.

2 CURRENT STATE OF ML IN IoT SECURITY

2.1 Intrusion Detection Systems

Intrusion detection systems (IDS) have emerged as powerful tools for identifying and classifying threats in IoT ecosystems. Their job is to detect any anomaly in the system or network and alert the user before the threat actually affects the system. Recent studies show that Random Forest has displayed the accuracy of 92.72% in binary classification of threats and 92.40% in multiclass classification tasks. Therefore, it can be considered as a reliable choice for threat detection systems. This review and comparison have been done by (Saumya et al., 2024).

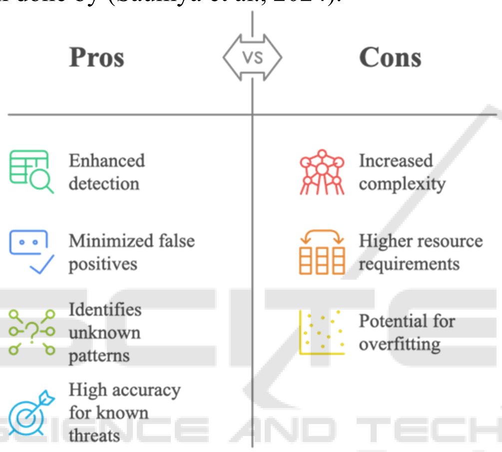

Figure 1: Advantages and disadvantages of Hybrid approaches in IDS.

Similarly, other algorithms like Support Vector Machines (SVM) have shown notable accuracy in recall metrics, which makes them highly preferable for detecting variety of tasks that too with greater precision.

The performance of IDS can be further improved using hybrid approaches. (Iqbal et al., 2024) have experimented that integration of Supervised and Unsupervised machine learning algorithms have improved the detection accuracy and adaptability of system to detect new and unknown threats, which the traditional systems fail to identify. Advantages and Disadvantages of Hybrid approaches in IDS is given in figure 1.

2.2 Feature Selection and Performance Optimization

Feature Engineering is crucial when we have mixed and heterogeneous data to work upon. Since ML model's performance is determined by the quality of training data, having features in bulk require Feature selection and optimizing the process of feature selection is a key requirement to identify which weight vector is most important. According to (Htwe et al., 2024), combining one-hot encoding with Pearson correlation can achieve high accuracy while maintaining computational load. This helps in applications where we have limited resources like computation, storage and network.

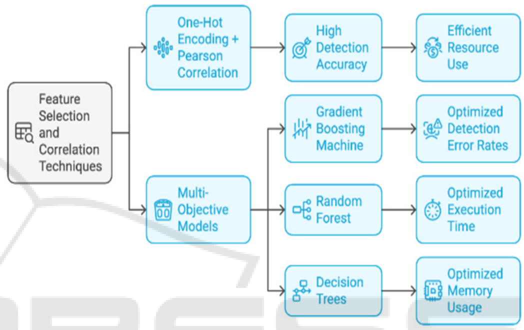

Figure 2: Enhancing ML Models in IoT security.

Pareto-optimal machine learning work best when you have multiple performance objectives. (Wu et al., 2024) highlights Gradient Boosting, Random Forest and Decision Trees as some of the highly effective machine learning approaches for building an anomaly detection model. They primarily deal with the detection accuracy, execution time and memory usage and are mainly used in resource-constrained environments. Enhancing ML Models in IoT Security is shown in figure 2.

2.3 Real-Time Threat Detection

Another key feature of ML-based models is Threat detection in real-time. Some systems have resulted accuracy of over 97% in identification of network threats (Alomiri & AlShehri, 2024). Also, in IIoT systems, adaptive models have demonstrated high accuracy and better threat response, by monitoring data streams and based on that pattern, detect anomaly in data and behavior. (Wankhade et al., 2024) have explained how these models continuously upgrade their threat detection capabilities, thus providing robust security in dynamic environments.

Figure 4 depicts the Real-time threat detection in IIoT.

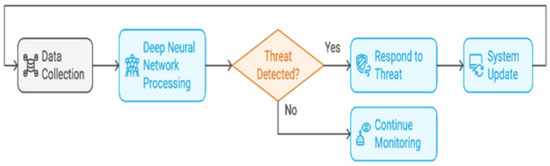

Figure 3: Real-time threat detection in IoT.

2.4 DDoS Attack Detection and Mitigation

Distributed Denial of Service (DDoS) attacks pose a significant threat to network-based IoT systems. It works by disrupting the availability of services and data to various nodes. This is done by tampering data nodes at network level. Recent studies have down that Machine Learning based techniques have better performance in detection and mitigation of DDoS attacks (table 2).

Table 2: ML approaches for DDoS attack detection in IoT.

ML Technique	Detection Rate	False Positive Rate	Key Features	Reference
Deep Neural Networks	97.3%	2.1%	Real-time detection capabilities	Kumar et al., 2024
Ensemble Learning	95.8%	1.8%	Multi-vector attack detection	Wankhade et al., 2024
SVM	94.2%	2.8%	Low computational overhead	Saumya et al., 2024
Random Forest	96.5%	1.5%	Effective for volumetric attacks	Omarov et al., 2024

3 KEY TAKEAWAYS

The table 3 shows a comparative analysis of various machine learning models where we can infer that Tree-based algorithms, particularly Random Forest and Decision Trees, deliver best performance with different datasets. Even with default parameters, these models prove to be highly effective for IoT Security in Cyber-attack detection with an accuracy close to 99% in CIC-IoT2023 dataset. (Islam Jony & Arnib, 2024).

Table 3: Performance comparison of ML algorithms in IoT security.

Algorithm	Accuracy	Use Case	Dataset	Reference
Random Forest	92.72%	Binary Classification	UNSW-NB15	Saumya et al., 2024
Random Forest	92.40%	Multiclass Classification	UNSW-NB15	Saumya et al., 2024
Ridge Classifier	97.00%	Real-time Threat Detection	IoT Network Traffic	Alomiri&AlShehri, 2024
Decision Tree	99.19%	Cyber-attack Detection	CIC-IoT2023	Islam Jony&Arnob, 2024
Random Forest	99.16%	Cyber-attack Detection	CIC-IoT2023	Islam Jony&Arnob, 2024

4 CHALLENGES AND LIMITATIONS

4.1 Adversarial Attacks

One of the key challenges in using Machine Learning models is their vulnerability to adversarial attacks. (Harbi et al., 2024) highlights one of such attacks named Fast Gradient Signed Method (FGSM) which is a common attack technique that disrupts and manipulate the training process by introducing certain samples, that obfuscate the security systems and cause the model to make incorrect predictions bypassing security. (Ibitoye, 2024).

In order to overcome these attacks, proper adversarial training is needed. This can be done by training the model with some adversarial samples beforehand to ensure robustness against such attacks. However, this will further increase the training cost as additional samples need to be used for training process. This can become a bottleneck as IoT systems are generally designed with limited resource availability in mind.

4.2 Dataset Considerations

The UNSW-NB15 dataset has been widely used for evaluation and validation of proposed systems in real-world scenarios. Selecting the right dataset with balanced samples is crucial for validation of your model. (Omarov et al., 2024). Similarly, CIC-IoT2023 dataset has proved to be the most reliable dataset on which accuracy rates of 99.19% and 99.17 percent are achieved by (Islam Jony & Arnob, 2024) as mentioned in Table 3.

5 FUTURE RESEARCH DIRECTIONS

With the review of current state of ML in IoT Security, further researches can be based on resource optimization in Machine Learning models, aiming to create light-weight models which can operate efficiently in constrained environments. Research by (Wu et al, 2024) have focused on the Pareto-optimal solutions, which can be the key focus area for future researchers. Moreover, Hybridization of approaches can be done to improve performance of existing systems or to deal with challenges in existing systems. (Iqbal et al., 2024).

Network-based threats like DDoS needs innovative detection and mitigation strategies as a preventive measure in network systems. Future research can focus on adaptive and intelligent defense systems which can adapt to varying attack patterns and can function without manual intervention and rule base. (Wankhade et al., 2024) have laid the foundation by introducing these models in IIoT application, introducing real-time threat response systems.

According to Harbi et al. (2024), Adversarial attacks need to be addressed as they disrupt the fundamental functioning of ML-based security systems. New systems should balance out the efficiency and resource usage, for making it easier to deploy and integrating ML in existing IoT environments.

Advanced approaches like Federated learning and collaborative defense mechanisms can be used along with basic machine learning models, to further strengthen the system security and focusing on privacy of data while sharing it in IoT ecosystem. This will further reduce the risk of data breach and cyber-attack. Also, Explainable AI in security solutions can be researched upon as the present focus is on the model interpretability and the need to make the model more understandable by the user. (Islam Jony&Arnob, 2024).

6 CONCLUSIONS

With the comprehensive review of the various technologies being used to enhance security in IoT systems, we can conclude by saying that ML has made a profound impact this domain, particularly in IDS and threat response systems. Using AI/ML approaches, we can increase the efficiency of existing systems and make them autonomous, which will reduce human dependency and need to manually program rules for security systems to stay up to date with latest threats. Table 4 gives the Performance Comparison of ML Algorithms in IoT Security.

Table 4: Performance comparison of ML algorithms in IoT security.

Trend	Key Features	Benefits	References
Hybrid Learning Approaches	Combination of Supervised & Unsupervised Methods	Improved Detection Rates, Reduced False Positives	Iqbal et al., 2024
Adaptive ML Models	Real-time Learning Capabilities	Dynamic Threat Response	Wankhade et al., 2024
Feature Correlation	Optimized Feature Selection	Reduced Computational Overhead	Htwe et al., 2024
Adversarial Defense	Robust Model Training	Enhanced Security Against ML Attacks	Ibitoye, 2024

The Models will evolve along with the threats. Recent advancements highlight the exceptional performance of Random Forest with (92.72%) accuracy and other improvements like self-learning algorithms and hybrid systems which have transformed the scenario of security In IoT. Other improvements highlight the role of ML in proactive threat detection, real-time response systems and threat mitigation.

However, despite of all these benefits, some challenges like balancing the computational overload, integration into existing systems, vulnerability against adversarial attacks etc. is still there. Model manipulation prevention and feature selection optimization are crucial for training quality models.

Particularly in case of DDoS attacks, and other network-based attacks, it is crucial for a ML model to be adaptive, updated with the latest threats and resource-efficient. Moreover, hybrid systems are beneficial to overcome shortcoming and boosting efficiency of IoT security systems. Resource efficient defense mechanisms will play a major role in creating resilient frameworks that are well-suited for various IoT applications.

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