

AI-DRIVEN DYNAMIC FUZZ TESTING FOR IoT SECURITY: DETECTION AND MITIGATION OF DDoS ATTACKS USING GRAPH NEURAL NETWORKS

A PROJECT REPORT

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in partial fulfillment of the requirements for the degree of

BACHELOR OF TECHNOLOGY

in

COMPUTER SCIENCE AND ENGINEERING

with specialization in Internet of Things (IoT)

&

BACHELOR OF TECHNOLOGY

in

ARTIFICIAL INTELLIGENCE



DEPARTMENT OF NETWORKING AND COMMUNICATIONS

COLLEGE OF ENGINEERING AND TECHNOLOGY

SRM INSTITUTE OF SCIENCE AND TECHNOLOGY

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November 2024



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ACKNOWLEDGEMENT

We express our humble gratitude to **Dr. C. Muthamizhchelvan**, Vice-Chancellor, SRM Institute of Science and Technology, for the facilities extended for the project work and his continued support.

We extend our sincere thanks to Dean-CET, SRM Institute of Science and Technology,

Dr. T.V. Gopal, for his invaluable support.

We wish to thank **Dr. Revathi Venkataraman**, Professor & Chairperson, School of Computing, SRM Institute of Science and Technology, for her support throughout the project work.

We are incredibly grateful to our Head of the Department, **Dr. M. Lakshmi**, Professor and Head, Department of Networking and Communications, School of Computing, SRM Institute of Science and Technology, for her suggestions and encouragement at all the stages of the project work.

We want to convey our thanks to our Project Coordinator, **Dr. G. Suseela**, Associate Professor, Panel Head, **Dr. C.N.S. Vinoth Kumar**, Professor and members, **Dr. Jeyaselvi M**, Assistant Professor, **Dr. Nithya Paranthaman**, Assistant Professor, Department of Networking and Communications, School of Computing, SRM Institute of Science and Technology, for their inputs during the project reviews and support.

We register our immeasurable thanks to our Faculty Advisor, **Dr. G. Suseela**, Department of Networking and Communications, School of Computing, SRM Institute of Science and Technology, for leading and helping us to complete our course.

Our inexpressible respect and thanks to our guide, **Dr. P. Balaji Srikanth**, Assistant Professor, Department of Networking and Communications, SRM Institute of Science and Technology, for providing us with an opportunity to pursue our project under his mentorship. He provided us with the freedom and support to explore the research topics of our interest. His passion for solving problems and making a difference in the world has always been inspiring.

We sincerely thank the Networking and Communications Department staff and students, SRM Institute of Science and Technology, for their help during our project. Finally, we would like to thank parents, family members, and friends for their unconditional love, constant support, and encouragement.

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ABSTRACT

The exponential growth in IoT adoptions has brought such networks to be much more vulnerable to Distributed Denial of Service attacks. In the DDoS attack, network performance issues and device vulnerabilities are exploited for inflicting far-reaching disruptions. Traditional IoT security solutions have proven inadequate in detecting and mitigating sophisticated threats in a timely and efficient manner, leaving IoT systems exposed to serious risks. This paper therefore presents an AI-driven security framework to adapt the detection and mitigation approach of DDoS attacks in IoT networks through dynamic fuzz testing and its integration into Graph Neural Networks (GNNs). This approach enables real-time identification and neutralization of malicious activities. The framework leverages the NS3 simulation tool to create realistic and diversified network traffic flows, which are used to train the GNN model. As a result, the model is prepared to handle various traffic patterns and attack scenarios, making it robust against real-world conditions. Once deployed in a live environment, the model monitors network traffic, identifies DDoS attacks, and mitigates them without disrupting legitimate IoT operations. The proposed framework achieved a 74% detection accuracy and a 95% success rate in mitigation during trials, highlighting its scalability and adaptability. This capability ensures that the framework can effectively address present and future IoT security challenges. The integration of AI with dynamic fuzz testing offers comprehensive protection, ensuring the integrity, availability, and reliability of IoT networks, making it an essential component of future IoT architectures by providing high-quality security against evolving DDoS threats.

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ABBREVIATIONS

IoT	Internet of Things
AI	Artificial Intelligence
NS3	Network Simulator 3
DDoS	Distributed Denial of Service
GNN	Graph Neural Networks
SYN Flood	Synchronize Flood
XML	Extensible Markup Language
CSV	Comma-Separated Values
IP	Internet Protocol
SMOTE	Synthetic Minority Oversampling Technique
NetAnim	Network Animator
UDP	User Datagram Protocol
TCP	Transmission Control Protocol
GCN	Graph Convolution Network
IDS	Intrusion Detection System
SIEM	Security Information and Event Management

CHAPTER 1

INTRODUCTION

1.1 The Emerging Threat of DDoS Attacks for IoT Networks

The quick expansion of the Internet of Things (IoT) linking devices to enhance efficiency also leads to heightened vulnerabilities. Perhaps one of the most critical challenges rising with increasing vulnerability is the DDoS attack. In a DDoS attack, compromised devices-often called bots-sent malicious traffic to overflow the targeted network, breaking its normal operations.

IoT devices are most prone to such attacks due to very low computing capabilities and weak security features. Once such devices come into the hands of attackers, it becomes a tool of immense DDoS attack through botnet and services go totally down with the likelihood of data breaches and financial loss.

1.2 Impact of Real-time Detection and Mitigation

Traditional solutions of IoT security fail to detect most of the DDoS attacks, especially in real time. Most IoT devices tend to be extremely interconnected, with highly dynamic network traffic flows; hence, any type of proactive measure for security should be able to identify and neutralize such threats at the moment they may arise.

Minimizing damage due to DDoS attacks requires real-time detection and mitigation. Malicious traffic overload servers unless acted on in real time, hence resulting in system downtime and decreased performance. This poses the need for highly sophisticated security frameworks that can respond quickly to threats under IoT settings if perpetual service availability is to be sustained.

1.3 Dynamic Fuzz Testing Framework with AI

The framework identifies the limitation that currently exists with IoT security approaches and proposes an AI-driven Dynamic Fuzz Testing framework that incorporates GNNs as a sophisticated solution for real- time DDoS detection and mitigation. Analyzing network traffic patterns, the GNN-based model differentiates between legitimate and malicious traffic, thereby enabling dynamic and accurate threat response capabilities.

It is based on simulations with NS3. Simulations are based on real traffic data and, by virtue of normal and attack conditions, are used in training the model to identify a vast number of attacks. Thus, the robustness in the detection capability is realized. It integrates the model into an IoT network through which continuous monitoring of traffic at the entry points can be done. Malicious sources are identified and blocked without affecting legitimate operations.

1.4 Contribution and Future Prospects

The Dynamic Fuzz Testing framework offers several key contributions to IoT security, which also comprises state-of-the-art DDoS mitigation approaches. First, this approach, in contrast to the traditional methods, poses an AI-driven approach for real-time DDoS detection and mitigation. It uses GNN in such a way that complex patterns and relationships within traffic can be learned by the model, thereby making it more accurate and efficient towards threat detection.

One of the most interesting facts this project demonstrates is the framework's ability to handle high traffic loads, even in complex network topologies, with no loss in overall performance.

The future for the project is to concentrate on improving real-time capabilities within the system, including expanding its scope in attacking scenarios it may address, and adaptive learning to meet emerging threats. The framework can also be used in conjunction with other security tools to develop an all-rounded defense system against IoT networks offering stronger protection against evolving cyber-attacks.

CHAPTER 2

LITERATURE SURVEY

2.1 IoT Security Challenges

In the last couple of years, the Internet of Things has been growing with unprecedented growth, turning out to be an enormous and heterogeneous network of devices that communicate and interconnect with each other. Explosive growth has presented big challenges in many areas, especially in terms of security aspects for the devices that work on the edge of networks. These devices, relatively low computational power and often not very secure deployment environments, are inherently prime targets for many attacks, including, but not limited to, DDoS attacks^[1].

Research further claims that the diversity among IoT devices- smart home appliances industrial sensors - has brought forth an extremely fractured security landscape. So, most devices have a weak security architecture, but the ones that are even exploitable are the ones that can become a cause of concern. Incidents like the Mirai botnet attack draw attention to the alarm-bells within the community. Obviously, the Mirai attack teaches the world a lesson in the IoT security renaissance as the compromised devices created havoc in multiple services with an alarm for proactive and strong security solutions.

Further observation of the exposed weakness in the IoT network would reveal other types of threat. In this instance, some examples would include unsecured channels of communication. For example, man in the middle attacks where data is intercepted midstream between devices. Often, these results from no encryption or weakly authenticated protocols^[2].

Most of the IoT devices are still on old firmware; thus, they will probably expose themselves to risks that could easily be prevented if only the necessary updates were conducted in due time^[3]. This irregular pattern of application in the case of IoT introduces a gigantic challenge toward the realization of a safe operational environment. Hence, the right time-by-time working as well as secured devices are one major issue while providing assurance to IoT networks.

2.2 DDoS Attacks on IoT Networks

DDoS attacks currently stand as one of the most effective challenges to any IoT network. DDoS attacks normally overwhelm a network or a service with an intolerable volume of traffic, making it unavailable to legitimate users. IoT architecture encompasses hundreds of thousands of connected devices, thereby easily meeting the definition of DDoS attacks on a large scale^[4]. The most vivid example of how malicious elements can misuse these vulnerable devices to orchestrate devastating attacks rendering services paralyzed and even breaking entire networks is the infamous Mirai botnet attack.

In opposition to such an emerging threat, researchers have created several strategies toward mitigating DDoS attacks. Real-time Anomaly detection systems have evolved to monitor network traffic patterns and possibly detect DDoS attacks. These systems use machine learning algorithms, which tell normal from anomalous behavior, hence enable early intervention once unusual traffic patterns are detected. In addition, some network protocols have been designed with the explicit purpose of resisting DDoS attacks; they can tolerate huge amounts of traffic without compromising the quality-of-service^[6]. These were quite effective, but indeed scaling them properly across the diversification of IoT devices is a quite challenging task considering their diverse capabilities and constraints.

The methods of DDoS attacks keep evolving with this forcing continued development and refinement in mitigation strategies. While the complexity and interconnectivity are growing in IoT networks, so is the likelihood of coordinated DDoS attacks. Thus, it will be important to let research and practice slightly lead to such emerging threats. Next, academics and industry will work together to build all-encompassing security frameworks that can be dynamic enough to cope with the fluid IoT ecosystem.

2.3 AI-Based IoT Security Solutions

Detection and prevention of DDoS attacks: In the last few years, AI has found significant importance in the domain of IoT security solutions. IoT security solutions based on machine and deep learning are fertile grounds for indicating anomalies in the behavior of the network that forebodes an impending DDoS attack^[7].

These systems can be designed to learn and adapt rapidly to newly emerging threats, thus helping to improve the overall security posture of IoT networks by processing vast amounts of data from multiple devices.

Graph Neural Networks (GNNs) is essentially one of the salient strides in this direction: GNNs can be viewed as a strong framework to describe complex relationships among IoT devices and their interactions^[8]. The positive features of GNNs allow exact malicious activity determination at complex network structure levels. Handling big-size network data is one salient feature of GNNs that can also capture spatial dependencies among nodes and is suitably adapted to the dynamic environment typically found in IoT applications^[9].

This integration pathway of GNNs into the security framework of IoT opens further pathways towards better security. In the process, researchers can use more robust and flexible security solutions in exploiting the power of GNNs, in which these solutions can detect anomalies in networks as well as predict attacks even before they occur. This is preventive and is what builds protection for IoT networks against a constantly changing threat landscape.

2.4 Dynamic Fuzz Testing in IoT Security

Dynamic fuzz testing is known to be a reliable method of vulnerability detection in the internal functions of software components and network protocols. The injection of malformed or unexpected inputs to a system could reveal possible weaknesses attackers can use with malicious intent^[11]. Dynamic fuzz testing can serve to be one of the most valuable assessment tools in the context of IoT security in relation to testing the resiliency of IoT devices and networks.

There have been some studies lately trying to extend dynamic fuzz testing in most attack scenarios such as DDoS attacks concerning the robustness of IoT systems in stress situations^[12]. Fuzz testing with GNN-based AI models has recently become quite a hot topic as researchers strive to enhance the capabilities of the mechanisms for detecting and mitigating security threats. This synergy allows adaptive runtime assessment of IoT systems and even continuous mechanisms of monitoring and the fast response to any emerging vulnerabilities ^[12]. It implies the usage of state-of-the-art methodologies in improving the security level of IoT systems against growing threats within a constantly complex cyberlandscape.

The infusion of dynamic fuzz testing in the IoT security frameworks would help in terms of vulnerability identification and improvement of the understanding of the attack surface presented by IoT devices. The ever- evolving threat means further development and refinement of fuzzing techniques will be key in continuing to keep IoT networks resilient to diversified attacks.

2.5 NS3 Simulations for IoT Security

NS3 fast is turning out to be the tool of choice in testing IoT security, mainly through the avenue of dynamic fuzz testing and measuring resilience to DDoS attacks. The prospects sired by NS3 simulations allow the researcher to be able to carry controlled experiments on different scenarios that allow simulating how IoT networks behave under different conditions^[13]. These include finding if the claimed mitigation strategies are effective and how IoT systems react under stress.

Not long ago, experiments were conducted that integrated dynamic fuzz testing with GNN-based AI models so that the detection strategies employed in the NS3 simulations could be improved^[14]. It is so designed that researchers can carry out an elaborate study on the IoT networks, indicating vulnerabilities and the effectiveness of security mechanisms in their existing form. NS3 affords tremendous simulation capabilities for the research to be performed in understanding the security issues of the ecosystem developed in the IoT system.

Simulation insights of NS3 can be used to develop more robust systems for IoT, capable of lasting the threat space for this developing and emerging threat. Along with its rapid growth and wide formation of its ecosystem, a collateral integration of the NS3 simulation tool and the likes would be necessary in developing an effective strategy in safeguarding interconnected devices from possible attacks.

CHAPTER 3

SYSTEM ARCHITECTURE AND DESIGN

3.1 Layered Architecture Overview

The FuzzAIoT framework is built using a layered approach, where each layer performs distinct tasks related to device security, DDoS detection, and mitigation, as well as machine learning-driven traffic analysis. This modular design ensures scalability, maintainability, and flexibility, allowing for seamless integration and updates without disrupting the entire system.

3.1.1 Device Layer

The Device Layer consists of IoT devices that collect and transmit data throughout the network. Because they usually have low computing power, these can be easily exploited when attacking. It uses mechanisms based on encryption and authentication to secure the devices so that only authorized devices can use the network.

3.1.2 Security and Detection Layer

This is the core layer where DDoS detection occurs. It uses Graph Neural Networks (GNNs) to analyze traffic patterns and detect anomalies. The GNNs model the communication between IoT devices, allowing the system to identify unusual patterns that indicate a DDoS attack. The layer continuously monitors the network to ensure quick detection of potential threats.

3.1.3 Fuzz Testing Layer

The Fuzz Testing Layer performs Dynamic Fuzz Testing on IoT communication protocols to detect vulnerabilities. This layer continuously tests the devices with various inputs to identify weak points in protocol communication, which attackers could exploit. Once a vulnerability is detected, the system either patches it or isolates the affected device to prevent any damage.

3.1.4 Mitigation Layer

The Mitigation Layer is responsible for neutralizing threats once an attack is detected. It enforces security policies through techniques like traffic filtering, rate limiting, and traffic re-routing to ensure that legitimate traffic continues uninterrupted while blocking malicious traffic. The layer dynamically adapts to new threats and can update mitigation strategies in real-time.

3.1.5 Edge Computing and Analytics Layer

This layer distributes processing tasks to edge nodes, reducing latency and providing faster response times during attacks. By performing traffic filtering and initial DDoS detection at the network edge, critical security decisions are made closer to the source of the data, ensuring quick reactions without overloading central servers.

3.1.6 Cloud Processing Layer

For more computationally intensive tasks like large-scale traffic analysis and machine learning model training, the Cloud Processing Layer handles these operations. It also stores historical data for long-term analysis, integrates with external systems, and supports more in-depth analytics that improve detection and response to future threats.

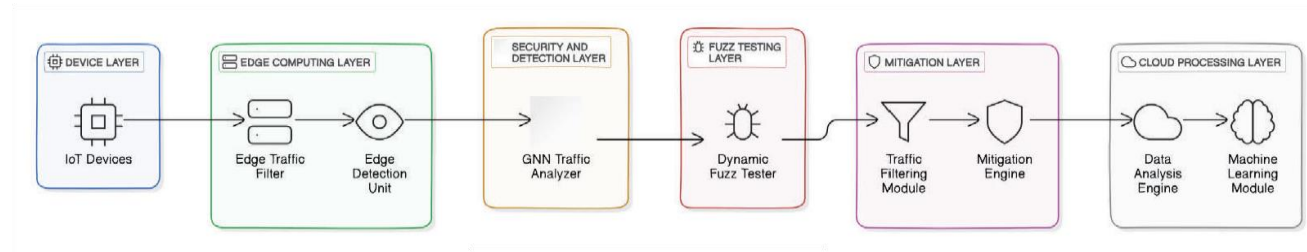


Fig. 3.1 ArchitectureLayers

3.2 Core Components of FuzzAIoT

3.2.1 Graph Neural Networks (GNNs)

GNNs form the backbone of the FuzzAIoT's real-time traffic analysis and DDoS detection. By modeling IoT devices and their communication as a graph, GNNs can identify unusual traffic patterns or communication anomalies. This graph-based approach enhances the detection accuracy of DDoS attacks by analyzing relationships between network nodes and their communication paths.

3.2.2 Fuzz Testing Engine

The Fuzz Testing Engine continuously probes IoT communication protocols by generating dynamic inputs to identify potential vulnerabilities. It works closely with the GNNs to flag devices with weak protocols and take necessary measures to mitigate these risks. This engine ensures that devices are regularly tested for weaknesses that could be exploited in a DDoS attack.

3.2.3 Traffic Filtering Module

The Traffic Filtering Module employs machine learning algorithms to classify and filter incoming traffic. This component plays a crucial role in distinguishing between legitimate traffic and malicious traffic during a DDoS attack. By ensuring that only safe traffic is allowed through, this module maintains network integrity while preventing overload during an attack.

3.2.4 Mitigation Engine

The Mitigation Engine is responsible for implementing strategies that limit the impact of a detected attack. Techniques such as traffic shaping, blacklisting malicious IPs, and re-routing ensure that the attack traffic is minimized without affecting legitimate communications. This engine dynamically adjusts mitigation efforts based on the attack's severity and nature.

3.3 Scalability and Performance Considerations

3.3.1 Scalability

FuzzAIoT is designed to handle large IoT networks with potentially thousands of devices. The layered architecture and edge computing capabilities enable the system to scale efficiently without degrading performance. The distributed nature of traffic filtering and attack detection across edge nodes and the cloud ensures that the system remains responsive even as the network grows.

3.3.2 Low Latency Operations

Latency is very important for real-time responses in IoT networks, particularly for such sectors as healthcare or industrial IoT. FuzzAIoT architecture minimizes latency at the architecture level, pushing the critical traffic analysis and filtering into the Edge Computing Layer. Mitigation thereby happens close to the source of data generation, hence minimizing the latency in attack responses.

3.3.3 Adaptability

The system's modular design ensures that new detection and mitigation techniques can be easily integrated. The architecture is adaptable to evolving attack vectors and future IoT technologies, ensuring that the framework remains effective in a rapidly changing threat landscape.

3.4 Integration with Existing Infrastructure

3.4.1 Cloud and Edge Integration

FuzzAIoT seamlessly integrates with both cloud platforms and edge devices. While the Edge Computing Layer provides real-time threat detection and response, the Cloud Processing Layer handles resource-heavy tasks, ensuring an optimal balance between latency reduction and data processing capabilities.

3.4.2 Legacy System Compatibility

The system is designed to integrate with legacy IoT infrastructure, making it suitable for deployment in a wide variety of environments. It supports common protocols and communication standards, ensuring that even older devices can benefit from enhanced security without requiring significant system overhauls.

3.5 Summary of System Design

FuzzAIoT's layered architecture and modular components are built to provide real-time protection against DDoS attacks in IoT networks. The system's reliance on Dynamic Fuzz Testing and Graph Neural Networks (GNNs) ensures proactive detection and mitigation of attacks while maintaining scalability, low latency, and adaptability for future IoT developments.

By dividing responsibilities across distinct layers—from the Device Layer to the Cloud Processing Layer—the architecture ensures efficient security measures at each stage of the data flow. Additionally, the system's ability to integrate with existing infrastructure makes it a flexible and robust solution for securing diverse IoT deployments.

CHAPTER 4

METHODOLOGY

4.1 Addressing IoT Security Using AI-Driven Techniques

The Internet of Things is an explosively growing domain in which smart home appliances, industrial sensors, and much more can interact and be used independently. Although this is very efficient and widely automated, the large-scale deployment of IoT devices triggers fresh network security concerns. Probably the most relevant threat here is DDoS attacks, where malicious actors try to overwhelm IoT networks with excessive traffic generation.

This project will propose a hybrid strategy combining fuzz testing, AI techniques, and network simulation for DDoS attack detection and mitigation. Here, GNN in fuzzy testing is used as the core for traffic pattern analysis as well as the identification of malicious activity in real-time.

4.2 Dynamic Fuzz Testing

4.2.1 Introduction to Dynamic Fuzz Testing

Fuzzing, or fuzz testing, is basically a testing technique that injects malformed or unexpected inputs into a system to expose potential weaknesses. Dynamic fuzz testing is a superior instrument that relates to investigating and finding the vulnerabilities in network security when abnormal traffic patterns emerge during DDoS attacks in IoT. Bugs, misconfigurations, and exploitable weaknesses are successfully detected in fuzz testing in real-world-like scenarios.

The project will simulate a wide array of IoT network traffic behaviors—from the simplest normal IoT communication to highly complex malicious DDoS attempts—by injecting unexpected data into the IoT ecosystem. This will bring to the project's attention vulnerabilities that it would otherwise have never known about had it taken the conventional approach to testing. The anomalies in the network traffic thus serve as a means of training AI models on distinct datasets for the improvement of detection capacity in relation to attack patterns.

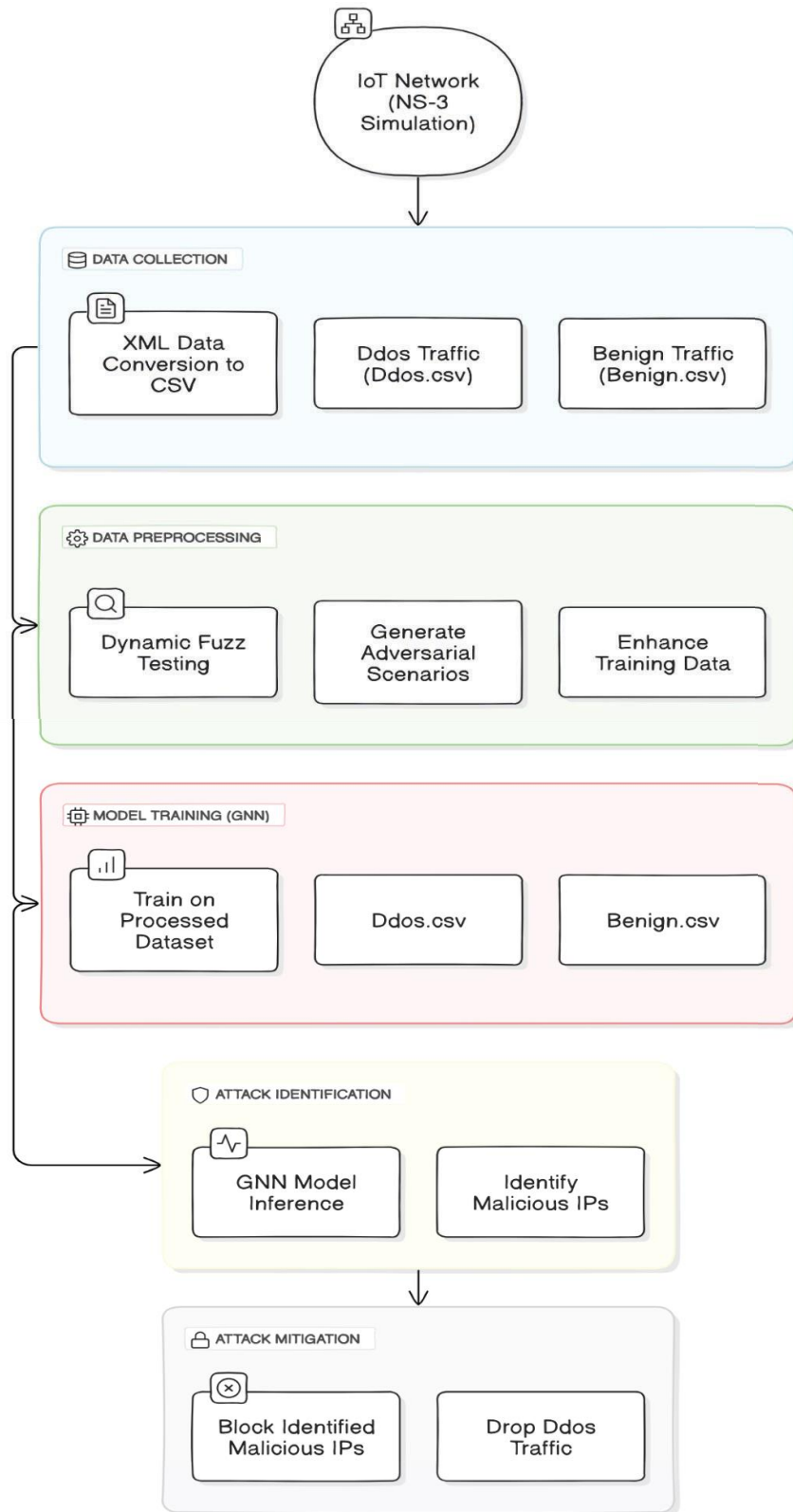


Fig. 4.1 Architecture Diagram

4.2.2 Data Generation Through Fuzz Testing

Data generation based on fuzz testing is important to give a precise representation of normal and malicious traffic. This process involves generating or synthesizing traffic through the help of fuzz testing tools and then configuring them in a manner that simulates potential attack vectors. Thus, the flow of packets generated through such a method brings out the closest imitation of common DDoS attacks, like SYN floods, UDP amplification, or botnet-induced flooding.

The simulation environment is set up to mirror a wide variety of network traffic behaviors. The resulting dataset captures multiple attack vectors, thereby subjecting the AI models that are trained on this data to various patterns. Traffic is labeled to distinguish between benign and malicious activity; thus, it creates a foundation for training machine learning models. Through such a well-balanced dataset, the system can generalize more effectively when detecting real-time attacks.

4.3 Dataset Preprocessing

4.3.1 XML to CSV from Simulation Data

Realistic IoT Network Simulations through NS3 feed the AI model with relevant data. The raw simulation data is produced in XML format, recording timestamps, source and destination IPs, packet size, etc. Though well-structured, XML isn't a good data source to be fed directly to train machine learning models. This custom script transforms the XML data into a simplified and more machine learning-friendly CSV format.

This step has the added advantage of handling large sets of data using frameworks like TensorFlow or PyTorch, which ensure the integrity of the data being processed. This allows easy manipulation of that data, feature extraction, and preprocessing for easy analysis.

4.3.2 Data Labeling and Balancing

Besides, the dataset needs to be properly labeled and balanced. That is the classification between benign traffic and attacks—a step necessary to prevent training a biased model towards one class. Moreover, having a balanced dataset avoids favoring benign or malicious traffic within an AI model, making it more robust to new data.

On the labeled dataset, further preprocessing is carried out in normalization of packet size, traffic frequency, and source/destination IP addresses. In case there is class imbalance, other methods like SMOTE (Synthetic Minority Over-sampling Technique) could be used. This way, both benign and attacking traffics are distributed equally in the training dataset.

4.4 Training AI Model

It is an AI project with a Graph Neural Network (GNN) as the type of training it does, which is supposed to classify IoT network traffic as being either benign or malicious. It is best for this task because it can consider relationships between nodes—take, for instance, the IoT devices—and learn to pick up complex traffic patterns that are hard to capture using traditional machine learning models.

4.4.1 Model Architecture

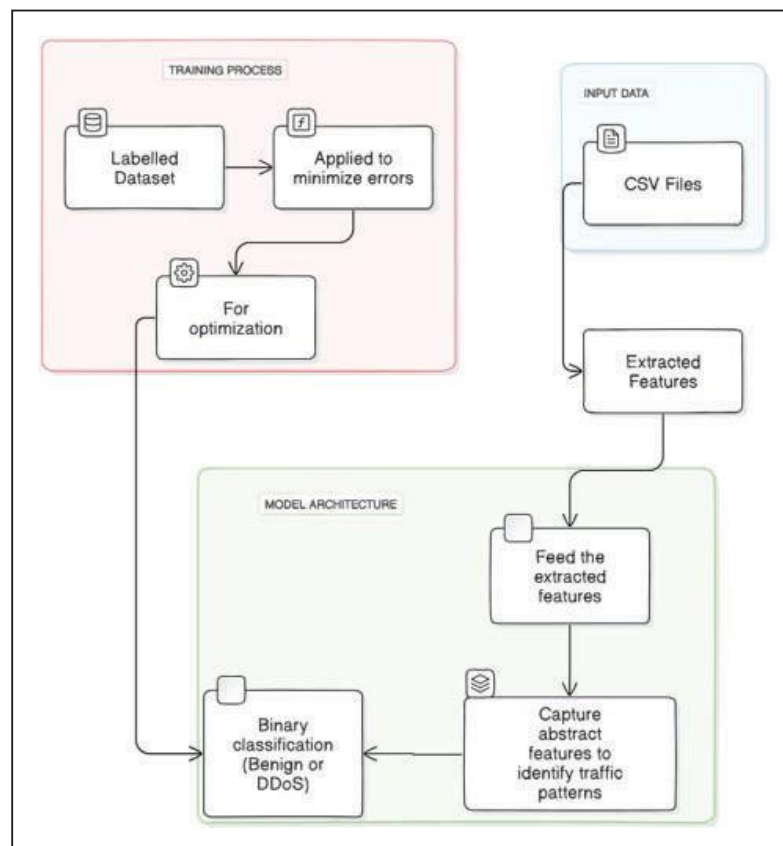


Fig. 4.2 GNN Model Architecture

The architecture of the GNN captures spatial and temporal dependencies in the traffic dataset. It accounts for interconnectivity as well as communication between different IoT devices, which are termed nodes. It captures how the patterns within a network change with time. In such a manner, through amalgamation of aspects of both spatial and temporal, GNN traces the path of the traffic flow and identifies anomalies that indicate DDoS attacks.

The architecture design is multi-layered graph convolutional networks (GCNs) that process traffic data and analyze the underlying patterns. One could include attention mechanisms that focus on relevant features in the dataset to make it even better at DDoS attack recognition.

4.4.2 Training Process and Hyperparameter Tuning

It performs training of the GNN model in iterations with the labeled dataset. Multiple epochs of training analyze the performance of the model in terms of accuracy, precision, recall, and F1-score. Through the process, hyperparameter tuning of learning rates, batch sizes, and the number of graph convolutional layers has been carried out. Cross-validation techniques are applied in the process of training to ensure the model generalizes well to unseen data. It is the most critical step to avoid overfitting and ensure that the model can pick up attacks or otherwise in a real scenario.

4.4.3 Validation

The trained model is then validated on freshly simulated environment traffic data. During the validation process, the model is tested against diverse network configurations, and its capability to detect DDoS attacks is examined in different network setups, thus generalizing well to new unseen data. The results are analyzed to improve the model, if needed, either by adjusting hyperparameters or the architecture.

4.5 Simulation Environment

4.5.1 Network Setup

The NS3 simulator offers a realistic testbed for the IoT network, which contains different IoT devices that can connect to a server via a central router. This simulation environment further generates both legitimate and malicious traffic, while the latter simulates a DDoS attack launched by bot nodes. The simulation ensures a realistic representation of IoT traffic, which allows the GNN model to learn from authentic traffic patterns.

4.5.2 Traffic Simulation

The capabilities of NS3's traffic generation capability are used to simulate TCP and UDP flows like real-world network traffic. On-Off traffic generators will simulate attacks such as DDoS, while BulkSend applications simulate normal flows in a network. The captured traffic is for a period and then written to files so that it can be used both to train and test the AI model.

4.5.3 Visualization with NetAnim

To further visualize the network behavior, NetAnim has been used by graphing the traffic flow and interaction between IoT devices. From this graphical output, a better view is obtained on the disturbance caused to normal traffic patterns due to DDoS attacks and how mitigating strategies have been designed to work in real-time. This validation is of paramount importance while testing the mitigation mechanisms in the system.

4.6 Mitigation Strategy

4.6.1 Blocking of Malicious IPs

The heart of the mitigation strategy is the dynamic blocking of identified malicious IP addresses due to the GNN model's detection. Upon identification of an attack, the NS3 simulation environment imposes router-level actions that block packets from such malicious IP addresses and prevent further disruption to the traffic. This packet filtering mechanism ensures that even during attacks, the network remains operational with minimal effects on legitimate traffic.

4.6.2 Evaluation and Refinement

The mitigation strategy is evaluated in terms of network performance before and after the introduction of blocking mechanisms. Metrics such as delivery ratio, latency, and throughput are analyzed to assess the effectiveness of the mitigation. Feedback from the simulation executions is used to iteratively refine the strategy so that it can handle a variety of attack scenarios.

CHAPTER 5

CODING AND TESTING

This means the project was taken on around critical milestones that would ensure DDoS attacks on an IoT network are detected and mitigated. Advanced AI techniques, particularly Graph Neural Networks (GNNs), made this testbed: a real-world within an NS3 simulation environment that aimed to improve real-time DDoS detection and mitigation systems using GNN-based models. This chapter details the simulation setup data production, as well as training, integrating the trained AI model in the NS3 environment, which then provides real-time attack identification and mitigation.

5.1 Simulation Setup in NS3

The first critical step in the process of testing was modeling the IoT simulation environment in NS3, which indeed could basically mimic real IoT device behaviors and network attack patterns. This simulated benign and malicious traffic pattern was essential in the generation of traffic that would assist in the validation of the ability of the system to detect and mitigate DDoS attacks.

5.1.1 Network Topology Design

The network topology design was therefore essential to the success of the project. The network was a natural or typical example of an IoT environment where central routers mediate traffic between a set of IoT devices and a server.

- **IoT Devices:** The simulation included many IoT devices. Some of them include smart home appliances, like smart speakers, thermostats, and security cameras. In this way, such devices would send benign traffic to the central server as legitimate data packets. In this experiment, a total of 20 IoT devices were simulated to mimic close-to-reality cases.
- **Bot Nodes.** In the network, 5 bot nodes mimicked a DDoS attack through their malicious traffic. Bot nodes are compromised IoT devices taken over by a botnet. They overwhelm the server due to heavy data traffic.
- **Router and Server:** In the architecture, the router would be working as a central hub on which benign and malicious traffic flow. All the intensity of DDoS attack fell on the server, with this architecture especially filtering the traffic reaching the server, and that is also with the help of routers.

5.1.2 Traffic Generation

Realistic traffic patterns accurately represent the behavior of an IoT network.

- Benign Traffic: This was created using the feature of TCP BulkSend, simulating typical data uploads from IoT devices, such as sensor readings or status updates. The benign traffic sent was low volume and periodic. The NS3 pseudocode is as follows:

```
BEGIN Simulation
DEFINE experimental parameters: UDP_PORT = 9001
    TCP_PORT = 9000 TCP_RATE = "10Gbps"
    MAX_SIMULATION_TIME = 1200 seconds
    SEND_SIZE = 64 bytes NUM_TCP_CONNECTIONS = 10
INITIALIZE network components:
    Create nodes: iotDevices (1 device), router (1 device), server (1 device) DEFINE
Point-To-Point link attributes:
    Data Rate = TCP_RATE Channel Delay = 0.1 ms
INSTALL network devices:
    Connect iotDevices to router and router to server via Point-To-Point links ASSIGN
IP addresses:
    Set base IP address for network with specified subnetmask Assign IP addresses to
all devices
CONFIGURE multiple TCP connections between IoT Device and Server: FOR each TCP
connection (up to NUM_TCP_CONNECTIONS):
    SET bulk send application on IoT device to send unlimited traffic SET send
size to SEND_SIZE for packet size
    INSTALL bulk send application on IoT device START bulk send application at
time 0
    STOP bulk send application at MAX_SIMULATION_TIME END FOR
CREATE TCP sinks on Server: FOR each TCP connection:
    CONFIGURE TCP sink application on server to receive packets on specific
TCP_PORT START TCP sink application at time 0
STOP TCP sink application at MAX_SIMULATION_TIME END FOR
POPULATE routing tables
CONFIGURE node mobility and positions for visualization: SET router, server, and
iotDevices to fixed positions SET layout parameters for network visualization
CREATE animation output file "BenignTraffic.xml" and enable packet metadata RUN
Simulation
END Simulation
```

- Malicious Traffic: Bot nodes using On-Off traffic generators generated malicious traffic, which produced bursty, high-rate UDP traffic designed to flood the server. The traffic was like that shown in real-world DDoS attacks-traffic spikes, which are hard to predict and overwhelming of the server. The NS3 pseudocode is as follows:

```

BEGIN DDoS Simulation
DEFINE experimental parameters: UDP_SINK_PORT = 9001
    TCP_SINK_PORT = 9000 DDOS_RATE = "100Mbps"
    MAX_SIMULATION_TIME = 100 seconds NUMBER_OF_BOTS = 5
INITIALIZE network components:
    Create nodes: iotDevices (1 legitimate device), router (1 device), server (1
    device) Create botNodes for attack traffic with NUMBER_OF_BOTS devices
DEFINE Point-To-Point link attributes: Data Rate = DDOS_RATE
    Channel Delay = 1 ms INSTALL network devices:
    Connect iotDevices to router and router to server via Point-To-Point links Connect
    each botNode to router with individual Point-To-Point links
ASSIGN IP addresses:
    Set base IP address for network with specified subnet mask Assign IP addresses to
    each bot on a unique subnet
    Assign IP addresses to IoT device, router, and server CONFIGURE DDoS Application on
    botNodes:
    FOR each botNode (up to NUMBER_OF_BOTS):
        SET OnOff application to UDP traffic with constant rate and on/off times
        INSTALL OnOff application on each botNode
START OnOff application at time 0
    STOP OnOff application at MAX_SIMULATION_TIME END FOR
CONFIGURE legitimate TCP traffic from IoT Device to Server:
    SET BulkSend application to TCP traffic with unlimited data size and packet size
    1024 bytes
    INSTALL BulkSend application on IoT device START BulkSend application at time 0
    STOP BulkSend application at MAX_SIMULATION_TIME SET UDP Sink on Server:
    CONFIGURE UDP sink to receive packets on specified UDP_SINK_PORT START UDP Sink
    application at time 0
    STOP UDP Sink application at MAX_SIMULATION_TIME SET TCP Sink on Server:
    CONFIGURE TCP sink to receive packets on specified TCP_SINK_PORT START TCP Sink
    application at time 0
    STOP TCP Sink application at MAX_SIMULATION_TIME POPULATE routing tables

```

```
CONFIGURE node mobility and positions for visualization: SET router, server, and  
botNodes to fixed positions SET layout parameters for network visualization  
CREATE animation output file "DDoSTraffic.xml" and enable packet metadata RUN  
Simulation  
END Simulation
```

5.1.3 Mobility Model

The Constant-Position-Mobility-Model was utilized to simulate static nodes. Such static IoT devices, like household appliances, as represented by the model, would remain in fixed positions when they were in action. Though static, the system dynamically monitored their traffic patterns with a constant network topology at any point in time.

5.1.4 Setting up NetAnim

The visualization tool NetAnim was used to allow vivid animation of network traffic and behaviors under normal operation as well as DDoS attack conditions.

- Node Placement: Many nodes were placed around the central router and server at distances where the network interactions are visible. The IoT devices and bot nodes are positioned across from each other.
- Packet Flows and Effect of the Attack: NetAnim was an important thing for visualizing the packet flows and how the nodes interact with one another, as well as the effect caused by the DDoS attacks on the network. Clearly, it differentiated between benign and malicious traffic flows and even extracted insight into the effects of various mitigations.

5.2 Dataset Generation

Based on this simulation environment, a dataset containing benign and malicious traffic patterns was generated next. The size of the dataset is what made it crucial in the training of the AI model on how to detect and classify DDoS attacks.

5.2.1 Traffic Data Collection

For the simulation, traffic was captured by logging every packet passed to the router. This included benign and malicious traffic. The data logged in an XML file meant that through that format, I was able to capture critical details such as timestamp, source IP, destination IP, and packet size.

5.2.2 Data Conversion into CSV Format

For converting the XML logs into a format suitable for training the AI model, custom scripts were used. It has been chosen primarily due to direct compatibility with most of the machine learning frameworks and due to the efficiency of maintaining required network features in an organized manner.

- Feature Extraction: Important features, such as packet size, source/destination IP addresses, and traffic patterns, were extracted from the data for the training purpose.
- Labelling: Each packet of data was labeled as benign or DDoS according to whether it originated from a legitimate IoT device or bot node.
- XML to CSV conversion pseudocode for Benign Traffic is as follows:

```
IMPORT XML parsing and CSV writing libraries IMPORT regex library for IP and size
extraction
DEFINE FUNCTION parse_benign_xml_to_csv WITH parameters:
  - xml_file: XML input file containing packet data
  - csv_file: output CSV file
  - benign_ip_prefix: prefix indicating benign traffic sources BEGIN FUNCTION
parse_benign_xml_to_csv
  LOAD XML data from xml_file GET root of the XML document OPEN csv_file in write
  mode
  INITIALIZE CSV writer and write header row: ["Timestamp", "Source",
  "Destination", "PacketSize", "Label"]
  SET packet_count = 0 // Total packets processed SET benign_count = 0 // Count of
  benign packets FOR each packet element in XML root:
    GET 'meta-info' attribute of packet IF 'meta-info' attribute exists THEN:
      EXTRACT timestamp from 'fbTx' attribute OR default to '0' if not present
      EXTRACT source and destination IP addresses using regex on 'meta-info'
      IF IP addresses are found THEN:
        EXTRACT packet size using regex on 'meta-info' OR default to '0' if
        not
        present
        CHECK if source IP starts with benign_ip_prefix: IF TRUE, SET label
        to "Benign"
        WRITE row to CSV with [timestamp, source_ip, destination_ip,
        packet_size, label]
        INCREMENT benign_count
```


END IF

INCREMENT packet_count END IF

DISPLAY total packets processed and total benignpackets END FUNCTION

- XML to CSV conversion pseudocode for DDoS Traffic is as follows:

IMPORT XML parsing and CSV writing libraries IMPORT regex library for IP and size extraction

DEFINE FUNCTION parse_ddos_xml_to_csv WITH parameters:

- xml_file: XML input file containing packet data

- csv_file: output CSV file

- ddos_ips: list of IP prefixes identifying DDoS traffic sources BEGIN FUNCTION

parse_ddos_xml_to_csv

LOAD XML data from xml_file GET root of the XML document OPEN csv_file in write mode

INITIALIZE CSV writer and write header row: ["Timestamp", "Source", "Destination", "PacketSize", "Label"]

FOR each packet element in XML root: GET 'meta-info' attribute of packet

IF 'meta-info' attribute exists THEN:

EXTRACT timestamp from 'fbTx' attribute OR default to '0' if not present

EXTRACT source and destination IP addresses using regex on 'meta-info'

IF IP addresses are found THEN:

EXTRACT packet size using regex on 'meta-info' OR default to '0' if not

present

CHECK if source IP matches any prefix in ddos_ips: IF TRUE, SET label to "DDoS"

ELSE, SET label to "Unknown"

WRITE row to CSV with [timestamp, source_ip, destination_ip, packet_size, label]

END IF END IF

DISPLAY message indicating successful DDoS traffic export to CSV END FUNCTION

- XML to CSV conversion pseudocode for Validation generation setup is as follows:

IMPORT XML parsing and CSV writing libraries IMPORT regex library for IP and size extraction DEFINE FUNCTION parse_xml_to_csv WITH parameters:

- xml_file: XML input file containing packet data

- csv_file: output CSV file

```

- ddos_ips: list of IP prefixes identifying DDoS traffic sources
- benign_ips: list of IP prefixes identifying benign traffic sources BEGIN
FUNCTION parse_xml_to_csv
  LOAD XML data from xml_file GET root of the XML document
  INITIALIZE ddos_count and benign_count to 0 OPEN csv_file in write mode
  INITIALIZE CSV writer and write header row: ["Timestamp", "Source",
"Destination", "PacketSize", "Label"]
  FOR each packet element in XML root: GET 'meta-info' attribute of packet
    IF 'meta-info' attribute exists THEN:
      EXTRACT timestamp from 'fbTx' attribute OR default to '0' if not present
      EXTRACT source and destination IP addresses using regex on 'meta-info'
      IF IP addresses are found THEN:
        EXTRACT packet size using regex on 'meta-info' OR default to '0' if
not
present
        DETERMINE traffic label based on source IP:
          IF source IP matches any prefix in ddos_ips: SET label to "DDoS"
            INCREMENT ddos_count
          ELSE IF source IP matches any prefix in benign_ips: SET label to
"Benign"
            INCREMENT benign_count ELSE:
              SKIP packet (no matching IP ranges)
        WRITE row to CSV with [timestamp, source_ip, destination_ip,
packet_size, label]
      END IF END IF
  DISPLAY total DDoS packets, total benign packets, and total packets processed
END FUNCTION

```

- XML to CSV main driver conversion pseudocode for all the three is as follows:

```

DEFINE FUNCTION main
  SET xml_file to path of the XML file generated by NS-3 SET csv_file to output
path for the CSV file
  DEFINE ddos_ips as a list of IP prefixes associated with DDoS attack sources
  DEFINE benign_ips as a list of IP prefixes associated with benign sources
  DISPLAY message indicating the start of XML processing
  CALL parse_xml_to_csv FUNCTION with arguments:
    - xml_file
    - csv_file

```

```

- ddos_ips
- benign_ips
    DISPLAY message confirming CSV file has been saved after conversion END FUNCTION
IF script is run directly THEN CALL main FUNCTION
END IF

```

5.2.3 Data Balancing

By balancing the dataset provided, which would have otherwise been biased due to an AI model's favor toward one class of data, the modeling aspect was taken care of to prevent biased weightings toward one class of data on the part of the AI model. This ensured that the model had equal numbers of both benign and malicious packets, so it may learn to correctly classify either type of traffic. The pseudocode to balance the dataset is as follows:

```

IMPORT pandas library for data manipulation DEFINE FUNCTION combine_csv_files WITH
parameters:
    - benign_csv: path to the benign traffic CSV file
    - ddos_csv: path to the DDoS traffic CSV file
    - output_csv: path for the combined output CSV file LOAD benign traffic CSV into
benign_df
    LOAD DDoS traffic CSV into ddos_df
    DETERMINE minimum number of rows between benign_df and ddos_df
    SAMPLE both benign_df and ddos_df to contain min_rows rows each, with a fixed random
state for consistency
    CONCATENATE benign_df and ddos_df into a single DataFrame combined_df SHUFFLE
combined_df to mix benign and DDoS rows, using a fixed random state SAVE combined_df
to output_csv without row indices
    DISPLAY message confirming combined CSV file has been saved END FUNCTION
DEFINE FUNCTION main
    SET benign_csv to path of benign traffic CSV file SET ddos_csv to path of DDoS traffic
CSV file
    SET output_csv to output path for combined CSV file
    CALL combine_csv_files FUNCTION with benign_csv, ddos_csv, and output_csv END FUNCTION
IF script is run directly THEN CALL main FUNCTION
END IF

```

5.3 AI Model Training

The dataset was then prepared, and training the GNN model on detecting DDoS attacks was the

job done.

5.3.1 Model Architecture

The GNN model was designed to study the node interactions in the network. It was trained with the classification of traffic as either benign or malicious.

- Input Layer: This was a feed made up of the raw features from the CSV dataset.
- Hidden Layers: These layers took the data streams in and looked for patterns that distinguished benign from DDoS traffic.
- Output Layer: This output layer spewed out the entire classification, whether it was benign or malicious.
- GNN identification pseudocode is as follows:

```
IMPORT necessary libraries for data processing, neural networks, and visualization
DEFINE GCN MODEL CLASS:
  - INIT function:
    CREATE two GCNConv layers:
      1. First layer with input channels 1 and output channels 16
      2. Second layer with input channels 16 and output channels 2 (for two
classes: Benign, DDoS)
  - FORWARD function:
    APPLY first convolution layer on data with edge index APPLY ReLU activation
    APPLY second convolution layer RETURN output
DEFINE FUNCTION load_data WITH parameter:
  - csv_file: path to the CSV dataset LOAD CSV data into a pandas DataFrame
  EXTRACT PacketSize as node features and Label as target labels CONVERT
  PacketSize to tensor of floating-point values
  CONVERT Label to tensor of integer values (1 for DDoS, 0 for Benign) CREATE
  edge_index tensor with self-loops for each node
  RETURN Data object containing node features, edge index, and labels DEFINE
FUNCTION train_gnn_model WITH parameters:
  - data: dataset for training
  - model: GCN model instance
  - epochs: number of training epochs (default 150) INITIALIZE optimizer with
  model parameters and learning rate INITIALIZE loss criterion as cross-entropy
  loss
  SET model to training mode
  CREATE lists to store training loss and accuracy for each epoch FOR each epoch:
    ZERO gradients
```

```

        PERFORM forward pass to get model output CALCULATE loss and backpropagate
        UPDATE model parameters with optimizer
        COMPUTE accuracy by comparing predictions to actual labels STORE loss and
        accuracy for visualization
        DISPLAY epoch number, loss, and accuracy
    RETURN trained model, list of losses, and list of accuracies
    DEFINE FUNCTION
    validate_gnn_model WITH parameters:
        - model: trained GCN model
        - validation_data: dataset for validation SET model to evaluation mode
        PERFORM forward pass to get model output
        COMPUTE accuracy on validation set DISPLAY validation accuracy
        GENERATE classification report and confusion matrix DISPLAY confusion matrix as
        heatmap
    DEFINE FUNCTION plot_training_metrics WITH parameters:
        - losses: list of loss values
        - accuracies: list of accuracy values PLOT training loss over epochs
        PLOT training accuracy over epochs
    DEFINE FUNCTION main
    SET paths to training and validation datasets LOAD training and validation data
    INITIALIZE GCN model
    CALL train_gnn_model with training data, model, and specified epochs SAVE
    trained model to specified path
    PLOT training metrics
    CALL validate_gnn_model with trained model and validation data IF script is run
    directly THEN
        CALL main FUNCTION END IF

```

5.3.2 Training Process

This model was trained using this labeled dataset by minimizing errors and increasing accuracy.

- **Loss Function:** Utilize the loss function to track how much each class predicted was different from the actual class in the data set. With each iteration, it updated the model's parameters so that its errors were minimized.
- **Hyperparameter Tuning** In relation to hyperparameters, the learning rate, hidden layers, and the size of the batch were all properly tuned for optimal model performance via iterative training.

5.3.3 Validation

After every training epoch, the model was validated on a separate dataset to ensure that it generalized very well to new, unseen data. Techniques for preventing overfitting were also put in place to ensure that the model did not perform well only on training data but could handle real-world scenarios.

5.4 Mitigation in NS3 – Real-time detection and Action

The final stage involved implementing the trained GNN model in the NS3 simulation environment to facilitate real-time detection and mitigation of DDoS attacks.

5.4.1 Detection of Malicious IP Address

The trained GNN was implemented within the NS3 environment through processing real-time network traffic. Each packet's features were analyzed by the algorithm, which asserted the malicious IP addresses involved in the DDoS attack and detected them in real time.

5.4.2 Packet Filtering

Once such malicious IP address identities were known, they were placed in a blocklist. A router level packet filtering mechanism prevented the packets from reaching the server by dropping those packets coming from identified malicious IP addresses, reducing the spread of this attack. Pseudocode for Packet Filtering is as follows:

```
IMPORT necessary NS-3 modules DEFINE CONSTANTS:
- UDP_SINK_PORT, TCP_SINK_PORT
- DDOS_RATE for attack traffic, TCP_RATE for legitimate traffic
- MAX_SIMULATION_TIME
- NUMBER_OF_BOTS, NUMBER_OF_IOT_DEVICES
DEFINE FUNCTION GetDeviceFromIp to retrieve device from IP address for packet dropping:
  FOR each node in nodes:
    CHECK if node has interface with given IP
    IF interface exists, RETURN the device associated with the IP RETURN nullptr if
    no match found
BEGIN main FUNCTION
  PARSE command-line arguments SET simulation time resolution
  ENABLE logging for UDP echo applications
  CREATE nodes for IoT devices, router, server, and bot nodes CONFIGURE Point-To-
  Point links:
    SET data rate and delay attributes
```

INSTALL Point-To-Point connections:

- BETWEEN router and server
 - BETWEEN each bot and router
 - BETWEEN each IoT device and router
- INSTALL Internet stack on all nodes

ASSIGN IP addresses to bot nodes, server, and each IoT device with unique subnets

DEFINE list of malicious IPs (detected by GNN model)

FOR each malicious IP:

 FIND device associated with IP

 IF device found, SET device callback to drop packets CONFIGURE DDoS attack behavior:

 INITIALIZE OnOff application for each bot node with UDP traffic SET traffic rate, on-time, and off-time attributes

 INSTALL OnOff applications on bot nodes and set start/stop times CONFIGURE legitimate traffic from IoT devices:

 FOR each IoT device:

 INITIALIZE BulkSend application with TCP traffic to server SET unlimited packet transmission with specified packet size

 INSTALL BulkSend application on IoT device and set start/stop times SET UDP Sink application on server to receive UDP packets

SET TCP Sink application on server to receive TCP packets POPULATE routing tables

CONFIGURE node positions for visualization:

- SET positions for router, server, bot nodes, and IoT devices with specified

spacing

CREATE AnimationInterface object for XML output ENABLE packet metadata in the animation file SET custom positions for nodes

RUN and DESTROY the simulation

END main FUNCTION

5.5 Conclusion of Testing and Implementation

The deployment and testing of this system clearly showed how an AI-driven DDoS mitigation system can detect and mitigate attacks in real-time conditions. Comparing packet delivery ratio, latency, and server loads before and after the attacks being mitigated, the AI-driven system proved to maintain network performance even while under a DDoS attack.

CHAPTER 6

RESULTS AND DISCUSSIONS

6.1 Introduction

In modern IoT networks, the growing number of connected devices has increased risks in the DDoS attack concerning security. Most of the devices are characterized as heterogeneous in terms of the mesh of networks through which they are connected; it alone is a rich playground for malicious entities to launch attacks using compromised devices as vectors for widespread damage. This problem is beyond the capabilities of traditional security mechanisms because most IoT devices are resource-constrained, and the attack patterns change dynamically, evolve over time, and make use of space and signature-based techniques.

To address this problem, we created an AI-Driven Dynamic Fuzz Testing approach using GNNs that is tested on the NS3 network simulation to identify and counter DDoS attacks.

6.2 Results

As shown clearly in the results below, the approach identifies malicious traffic patterns while using an active mitigation strategy to safeguard IoT systems.

6.2.1 Training and Accuracy of the GNN Model

We used the synthetic dataset produced with large NS3 simulations for our training. We included both benign and DDoS traffic to make the model learn from both types of patterns. The class balance of the dataset was ensured before training, making sure that the two types were equal. We show two plots below showing training loss and accuracy:

The training loss, as depicted in the first graph, displays a very sharp dip during the preliminary stages of training. The learning by the model is represented here. At the initial stages, the loss was high because the data was unknown to the GNN. However, training loss declined very sharply down to 0 as epochs proceeded, reflecting that the model correctly identified the patterns from the data. At around 40 epochs, the loss curve stabilizes and becomes around 0, indicating convergence of the model.

The second plot is the training accuracy: it oscillates around 50%, which might imply that the model was simply wandering through its features and updating its weights with back-propagation. Accuracy increases steadily with epochs, peaking at a high of 100%, implying that GNN learned to classify the training data with full accuracy. But training with 100% accuracy may overfit; sometimes the model might go very well on the training data but may not generalize well using new unseen data.

6.2.2 Results of Validation

While impressive accuracy on the training set, the real strength of the model is in performance over unseen data. We judged the GNN on a validation set extracted from an independent set of simulations using NS3. This validation dataset also contained an equal proportion of benign and DDoS traffic compared to the training data.

6.2.2.1 Validation Accuracy:

The average validation accuracy achieved by the GNN model is 74%. While this is quite lower than the corresponding training accuracy, it still indicates that the model learns well from the data. Lower validation accuracy generally means that, in most cases, the model would correctly detect DDoS traffic while normally and effectively responding; however, there are probably some edge cases or variations in the attack patterns that it has not been able to classify correctly. This promises a good level of performance since it will be deployed in real-world scenarios of new evolving types of DDoS attacks.

6.2.2.2 Confusion Matrix:

The confusion matrix for the validation results shows even further the model's ability to distinguish between benign and malicious traffic. It presents a relatively healthy scale of true positives, which are the correct identification of DDoS attacks, and true negatives, referring to the correct identification of benign traffic. Moreover, the matrix also indicates false positives and false negatives. In practice, a false positive (major classification of benign traffic as malicious) might prompt unwarranted mitigating steps, whereas a false negative DDoS traffic will not be detected, permitting attacks to run amok. Minimizing these types of errors will, therefore, be critical in increasing the reliability of the system.

6.2.3 Mitigation Strategy

Detection is only half the equation; mitigation is equally important so that the IoT network stays healthy. The GNN identifies malicious traffic, and then the strategy for packet filtering engages to block packet traffic coming from those malicious IP addresses.

6.2.3.1 Packet Dropping:

By using such a model in the NS3 simulation, the malicious IP addresses were easily traced, and their packets dropped. Packet filtering is the prime mitigation mechanism for DDoS traffic because it guards against resource exhaustion in the network by preventing flooding. The probability for packet dropping reduces congestion across the network. Therefore, legitimate traffic flows freely, thus enhancing system performance during an attack.

6.2.3.2 Performance on Network:

The state of the network before, during, and after deploying the mitigation strategy was evaluated by tracking several performance metrics. These include:

Throughput: Before the attack, throughput was reliable in the network. The legitimate devices communicated properly. During the attack, the throughput drastically dropped due to network traffic congestion from DDoS traffic. However, once the packet filtering mechanism was activated, the throughput returned to normal levels, implying reduced malicious traffic.

Latency: Like throughput, latency surged dramatically during the DDoS attack because much traffic was introduced to the network to process. Once mitigation occurred, latency returned to normal since the filtering technique forced traffic back into the acceptable network congestion zone.

6.3 Visualization of Results

To explain in greater detail the GNN model's behaviour as well as the effectiveness of the mitigation strategy, we have used several visualization methods throughout the course of this project.

6.3.1 Loss and Accuracy Graphs:

The training procedure is followed by metrics tracking in terms of the loss and accuracy at each epoch. The graphs shown in the following images represent the learning process of the model.

It is proved that the loss curve decreases because the model learns every detail of the data; this is reflected by the graph on accuracy that improves rapidly for the model in terms of its ability to classify objects.

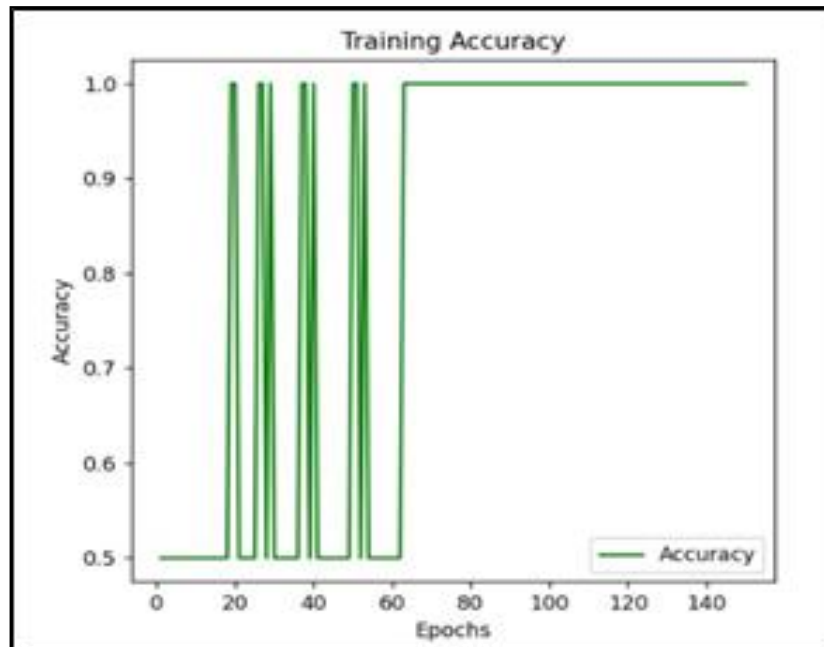


Fig. 6.1 GNN Model Training Accuracy Graph

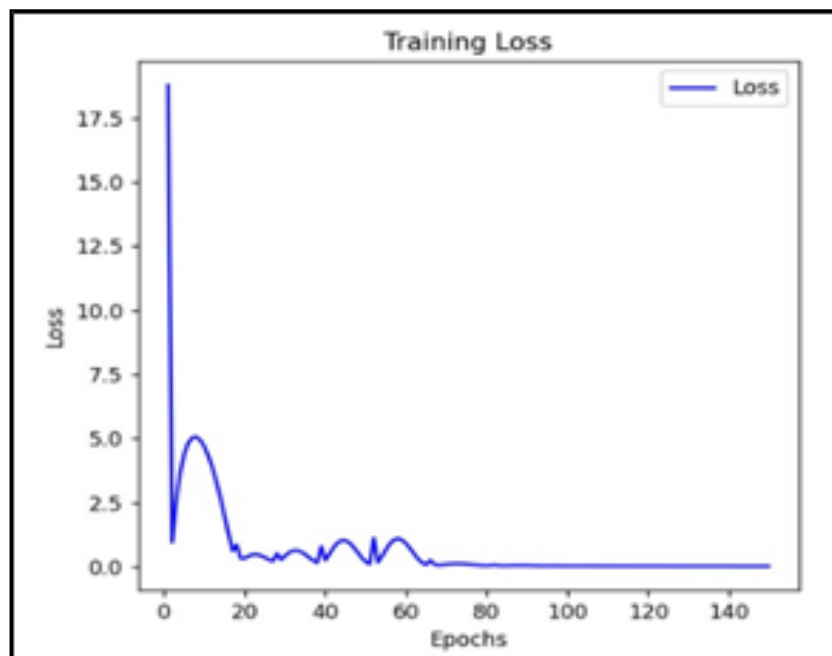


Fig. 6.2 GNN Model Training Loss Graph

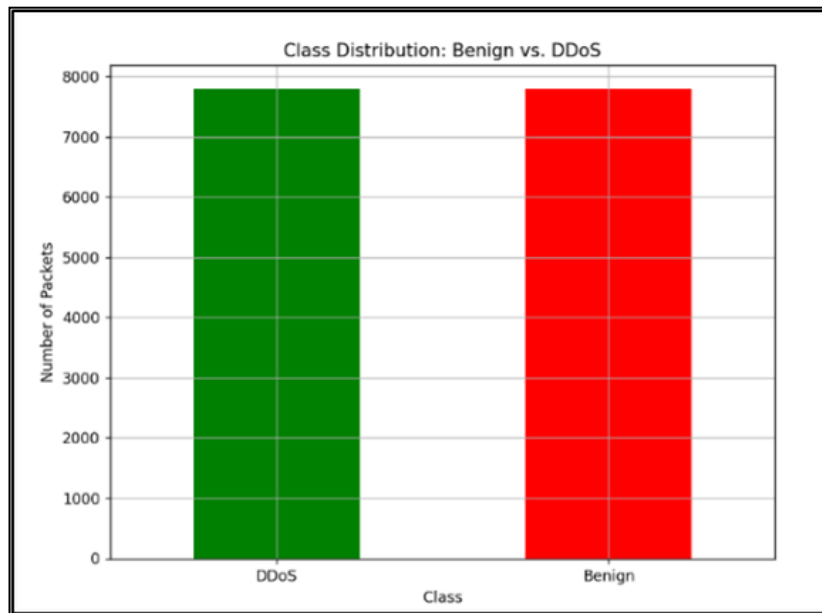


Fig. 6.3 Class Distribution Graph

6.3.2 Confusion Matrix:

The confusion matrix will be represented to analyse how well the model distinguishes between benign and DDoS traffic, and the visualization may reveal patterns in false positives and negatives, helping identify regions where the model may need additional tuning.

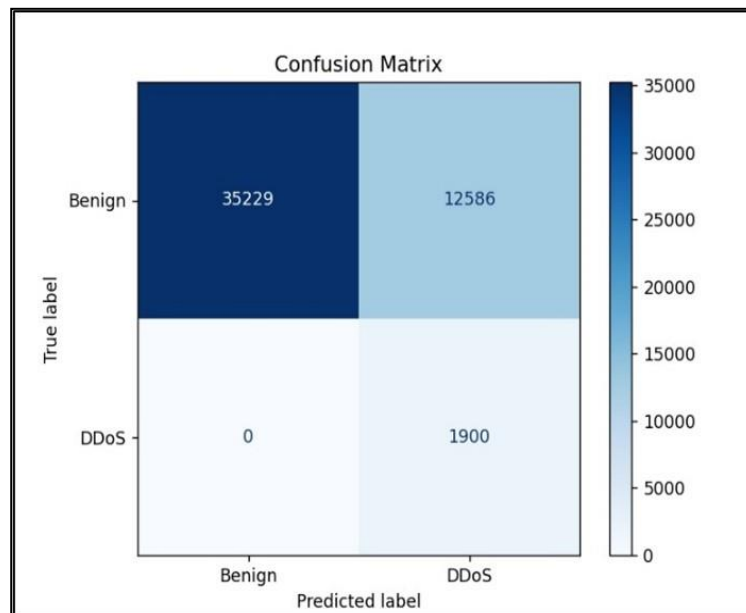


Fig. 6.4 Confusion Matrix

6.3.3 Network Animation:

The NS3 simulation results came alive using the NetAnim tool, visualizing the network topology, the flow of traffic, and the impact of the applied mitigation strategy. Such animation enables us to visualize the whole interaction between nodes during the attack as well as how the patterns of traffic changed once packet filtering was applied. It also provides a perspective into how the nodes were distributed in space and the nature of the traffic movement between them, which is vital to understand the true effects of the mitigation strategy in real time.

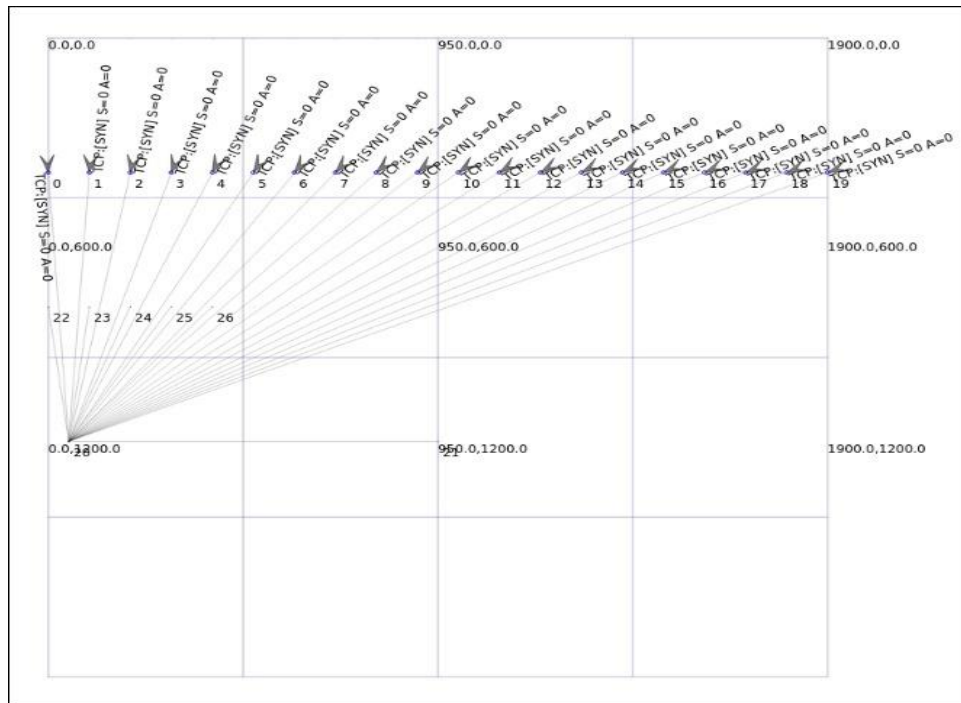


Fig. 6.5 Network Animation Simulation

CHAPTER 7

CONCLUSION AND FUTURE ENHANCEMENTS

In this section, we present the results of the project and a roadmap for future improvements. Indeed, the approach from the project—a combination of AI-driven dynamic fuzz testing, GNNs, and a NS3-based simulator has proven to be quite promising for improving IoT networks, first and foremost in terms of security against DDoS attacks. However, in the field of IoT security, there is an evolution of challenges, and they present themselves every now and then. On this front as well, there is a need for a system to be in perpetuity improvement and adaptation. Finally, below, we summarize what we have found out and think some potential improvements that could make the system even more robust, scalable, and adaptive to real-world demands.

7.1 Summary of Findings

The novelty AI-driven fuzz testing methodology created dynamic traffic data on the NS3 network simulator. We produced a rich dataset consisting of benign traffic and DDoS attack traffic. We relied on fuzz testing to simulate some variability and predictability of the IoT environment, known for its heterogeneity, limited resources, and susceptibility to a broad range of attacks.

7.1.1 AI-Driven Dynamic Fuzz Testing

The module had used AI with Graph Neural Network (GNN) which was intended to identify malicious IoT network traffic patterns. It was understood that traditional learning algorithms would not work great in the case of graph-structured data and represented relationships among the IoT devices, which have thousands of interconnected elements. GNNs instead did very good discoveries of complex relationships and indirect dependencies where it mattered the most in graph-structured data and therefore best suited for IoT applications.

In our system, the GNN was trained on data outputted from the NS3 simulator, which provided it with a controlled testing environment for dynamic traffic scenarios. The model was trained in such a way that it achieved 74% validation accuracy, which is important considering the dynamic nature of IoT traffic. Although there is still room for improvement in this accuracy, it shows that the GNN can generalize well to unseen traffic patterns without overfitting.

This validates the perception that there is a contradiction between the low validation accuracy and nearly perfect training accuracy because of the extreme differences in traffic behavior; most of them are due to differences in devices, protocols, and network configurations.

7.1.2 NS3 Simulation and Visualization

The good simulation tool of powerful networking, NS3, was important to mimic real-world conditions of the IoT network. The simulator gave the needed infrastructure to test how well our system could detect and counter DDoS attacks in an environment close to the real world IoT traffic. Using NS3 gives us the chance to create profound patterns in the traffic to see and understand what is happening with malicious traffic, such as increased latency and decreased throughput, on a network.

We also used NetAnim, where we could see the dynamic flow of the traffic through the network in real-time. This is what, therefore, made the visual representation necessary for verification purposes in ascertaining if the strategy was working to curb the malicious transmissions because it provided evidence on how to spot and filter out such malicious traffic. If the GNN had detected an IP address, then NS3 was set to automatically drop all packets coming from that address. This packet-dropping mechanism has significantly reduced network congestion from DDoS traffic, and generally resulted in better overall performance.

7.1.3 Countermeasures

To mitigate the attack, the system will identify and drop packets coming from malicious IP addresses. This will successfully reduce the burden on the network, allowing genuine traffic to pass through. For IoT environments, for example, healthcare systems or smart cities, where network reliability is of paramount importance, failure in the network would have critical ramifications.

The packet-dropping mechanism appears to reveal some measurable improvements in network performance metrics. In a DDoS attack, the malicious packets drop served to significantly reduce network congestion and produced increases in throughput and latency correlated with this reduction. Such performance benefits provide evidence for the system's ability to ensure quality of the network despite the attack it may be under. The confusion matrix, a crucial method for measuring classification accuracy in the model, further revealed that the system can classify DDoS traffic with accuracy with minimal false positives and false negatives in the classification decision.

7.2 Future Improvement

Although the present system significantly Favors detecting and reducing the destructive nature of DDoS attacks in IoT networks, there are still many improvements that can be applied to further improve the overall performance, adaptability, and scalability factors. Some of the significant areas of improvement in the future are discussed below.

7.2.1 Real-time Mitigation

The real-time mitigation capability is one of the most important future development directions. Currently, a time lag exists between malicious traffic detection and incorporation of the strategy for mitigation. Such a delay may severely affect the timely delivery of certain IoT applications such as autonomous vehicles, smart grids, or healthcare systems. A brief network disruption in such applications could provoke catastrophic consequences.

To minimize this latency, the data pipeline of the system may be optimized to speed up the loop of detection to action. The use of edge computing methodologies will allow making decisions closer to the edge network on which the devices of the IoT are located. Since the processes of detection and mitigation can be decentralized, the detection and, hence, the subsequent mitigation could occur through edge devices in near real time too. This would further enhance its efficiency in delivering network performance during attacks.

7.2.2 Elaborated Attack Scenarios

Our system now protects against DDoS attacks; however, the IoT networks remain vulnerable to a myriad of cyberattacks including MITM attacks, SQL injection attacks, and data breaches. This definitely increases the utility and flexibility of the system exponentially through the extension into the detection and mitigation of other forms of attacks.

This will entail the design of more sophisticated datasets that capture the traffic patterns pertaining to a broader spectrum of attacks. The developed GNN model would be trained to recognize new patterns, thereby improving its capabilities with respect to a divergent set of threats associated with the IoT network. In addition, the modular architecture allowing for the realization of detection models for various types of attacks might make the system more flexible and adaptive towards new challenges associated with security.

7.2.3 Scaling Test

The scalability of an IoT network in a large-scale perspective is going to be one of the critical issues that are meant to be considered practically. All the testing that has been done so far has been within a controlled environment and with very limited devices. In real IoT networks, there might be thousands or millions of devices involved. This would cause a huge traffic, and thus the scalability along with heavy traffic performance needs to be tested in such a scenario for the system.

Future work might be implemented in distributed GNN implementations and the optimization of the packet filtering mechanism to provide effective and efficient operations of the system in high-throughput networks. Further improvement in scalability can also be made using distributed computing techniques such as parallel processing or federated learning in large IoT environments.

7.2.4 Adaptive Learning

Another improvement aspect is the adaptation of adaptive learning techniques. In the adaptive nature of an IoT environment, both network behaviour and attack patterns might change drastically. The static model, trained on a single dataset, may not be able to keep up with changes in those dynamics. Online learning techniques or reinforcement learning could be adapted so that the GNN model can keep learning over new data inputs and improve adaptability to changing network conditions. This would mean having detection levels accurate even with new emerging attack vectors in the system. It will also prevent overfitting since the model is going to refresh often with new data rather than sticking to old patterns.

7.2.5 Integration of Security Tool

The functionality of the current system can be improved highly. Thus, with integration into other security tools and frameworks, the system can detect and curb DDoS attacks effectively. For example, if the system is combined with IDS, firewalls, and SIEM systems, a more integrated security solution for IoT networks would be produced.

Such integration would, therefore, ensure an all-around approach to IoT security, with real-time monitoring, detection, and mitigation of a wide range of threats in cyber space. Such an integration would easily amalgamate with established infrastructures in real-world environments, providing end-to-end protection for IoT networks.

7.3 Conclusion

In conclusion, our dynamic fuzz testing technique based on Graph Neural Networks with simulations in NS3 has been promising as a key for enhancing the security of IoT environments. Here, the ability of the system to detect DDoS attacks with an accuracy of 74% generally indicates its potential utility in practical applications. In addition, the packet-dropping mitigation strategy has shown that it can enhance network performance by maintaining the throughput of the network and reducing the latency in the case of DDoS attacks.

The current system shall provide a good base. A couple of more advancements in the areas of real-time mitigation techniques, attack scenarios to check, scalability testing, adaptive learning, and integration with other security tools would make the system robust, adaptable, and scalable, having the potential for keeping up with the growing complexity and diversity of IoT networks.

Synthesizing advanced AI techniques with traditional network simulation tools presents an incredibly powerful approach toward addressing the challenges posed by security in IoT networks. As IoT networks grow in scale, our ability to protect them from growing sophistication in cyberattacks must keep pace. That is what this project represents in that direction, and the list of future enhancements detailed here paints a clear picture of what needs to be done to further build up the system in terms of effectiveness and resilience.

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APPENDIX A

CONFERENCE

PRESENTATION

Our paper titled "**AI-Driven Dynamic Fuzz Testing for IoT Security: Detection and Mitigation of DDoS Attacks Using Graph Neural Networks**" has been conditionally accepted for oral presentation in the 4th International Conference on Cognitive & Intelligent Computing (ICCIC), under the Networks, Privacy & Security track. The conference will be conducted in a hybrid mode on November 29-30, 2024. Our paper ID is 223, and we have a plagiarism score of 4%.

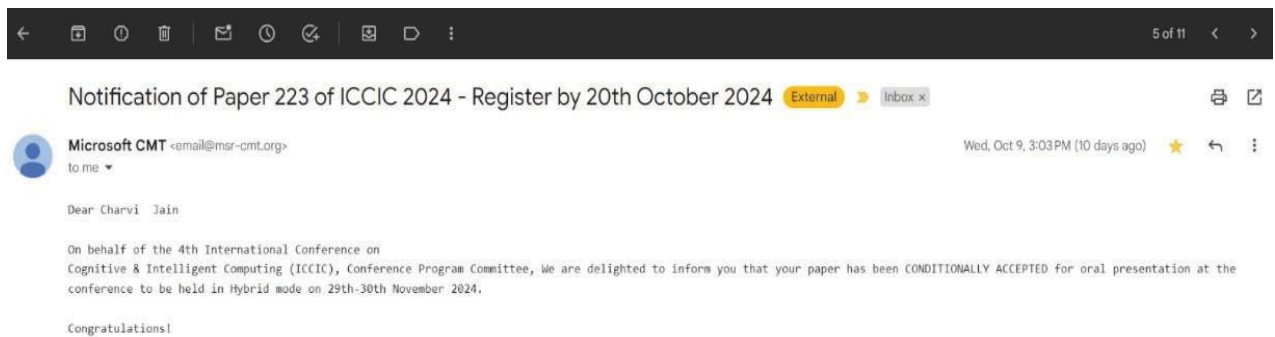


Figure A.1: ICCIC 2024 Acceptance

APPENDIX B

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