

Chapter 1

INTRODUCTION

1.1 Background

The landscape of modern Internet of Things has experienced exponential growth in connected devices and mobile computing as well as increasing reliance on cloud services, with remote access technologies transforming operational aspects of businesses. This transition, however, also brings various cybersecurity issues, ranging from malware, ransomware, phishing and zero-day vulnerabilities, to attacks on network infrastructure and endpoint devices. Traditional firewalls that focus on network-layer filtering just IP-address, port, and protocol-based filtering is not able to defend against advanced application-aware attacks and encrypted communication [1]. Good modern cybersecurity requires context-aware security that can identify the right applications or processes during each link on the network. Individual device endpoint firewalls can adopt policies that consider traffic origins and destinations, yes, but also application identities, user contexts, and behavioral patterns [2]. The aim of this project is to build a Context-Aware Endpoint Firewall System on both Windows and Linux operating systems. For application-level control, it will connect with the Windows Filtering Platform (WFP) and Linux Netfilter/nftables. Furthermore a centralized management console and an AI/ML-enabled anomaly detection engine will be equipped to manage, inspect, and automate suspicious activities within the enterprise network.

1.2 Statistics and Need for the Project

The incidence of cybersecurity threats is rapidly growing in both the global and local levels. According to data from the Indian Computer Emergency Response Team (CERT-In), in 2023, India recorded over 2 million cybersecurity incidents. It was reported by the National Crime Records Bureau (NCRB) an extraordinary three-year increase of 63% in cybercrimes by unauthorized network access and breaches of data [4]. In addition, endpoint-based attack accounts for around 70% of all cyber incidents as highlighted in Gartner report for 2024 [5]. This number highlights why we desperately need defenses targeted at endpoints that are capable of self-adapting to new attacks. From the business

to educational environments there are numerous devices connect at the same time to both internal and external networks, which usually bypass their internal borders within perimeter firewalls. In the absence of centralized oversight or intelligent traffic analysis, common security policies are difficult to enforce effectively for administrators. Therefore, an intelligent, centralized, scalable endpoint firewall system that leverages high levels of security posture while minimizing manual configuration overhead and enabling proactive anomaly detection is urgently needed.

1.3 Current Technologies

Present firewall and intrusion detection techniques provide important layers of defense with their flaws about adaptability and context sensitiveness:

1. Conventional Network Firewalls:

Devices such as Cisco ASA or Fortinet FortiGate, which are mainly aimed at perimeter defense (IP Address, Port Filtering), offer a poor insight into application-level events [6].

2. Host-Based Firewalls:

Tools like the Windows Defender Firewall or iptables provide basic endpoint protection but come with no centralized management, real-time updates or cross-platform supervision features.

3. Next-Generation Firewalls (NGFWs):

Companies such as Palo Alto Networks or Checkpoint make advanced packet inspection capabilities available, as well as application recognition; this is, however, expensive in resource-intensive cost and mainly has been tailored for network gateways rather than endpoint solutions [7].

4. Anomaly Detection Systems & SIEM Tools:

Solutions like Splunk, Snort, or Suricata do log processing for pattern analysis yet are passive and do not immediately enforce actions on the firewall level.

While existing technologies protect against these types of attacks by providing some redundancy, none that do so integrate context-aware filtering with centralized orchestration or AI-driven anomaly detection across disparate endpoints like this project aims to bridge.

1.4 Proposed Approach

Aim of the Project

This project aims to build an actionable Context-Aware Endpoint Firewall System that will enable real-time traffic management at the process scale and enforce central policy management in conjunction with machine learning-based anomaly detection to enhance endpoint security.

The challenge is that endpoint security breaches are on the rise in an era with organizations having high-end enterprise firewalls even those equipped at a distance to help with security. Current practices with their lack of sufficient granularity in visibility mean administrators often have no idea about which apps causing odd network behavior are causing such disturbances. A complete context-aware adaptive firewall can fill this large security gap.

Proposed Approach

The proposed system involves three basic elements:

1.Endpoint Firewall Agent:

We built a lightweight agent deployed across Windows and Linux endpoints based on WFP and Netfilter frameworks that allows us to monitor traffic while controlling application-specific rules.

2.Centralized Management Console:

Web-based admin interface for administrators who want to define firewall policies, manage updates as they go at speed, and visualize logs via REST APIs protected under TLS 1.3.

3.AI/ML Anomaly Detection Engine:

Machine learning model using Isolation Forest algorithms for traffic logs: to identify deviations from typical behavior of the application and to generate an alarm.

Applications of the Project

- Enterprise networks with policy-based access control
- Governmental or defense networks requiring secure management protocols.
- Cloud infrastructures needing cross-platform security mechanisms.
- Training on Cybersecurity Analysis in Academic Institutions

Limitations of the Proposed Approach

- Real-time synchronization requires constant network connectivity.
- This results in heavier storage requirements:
- Centralized log collection
- The initial computation involved is due to training the AI model and feature extraction methods

1.6 SDGs

Sustainable Development Goals (SDGs)

The Sustainable Development Goals (SDGs) set and communicated by the United Nations, as presented in Fig. 1.1, provide a world-level framework for addressing issues such as poverty alleviation, education, innovation, and sustainable development [1]. The role of technological developments and cybersecurity is paramount for achieving these goals to ensure that digital systems are secure, resilient, and reliable. The present Context-Aware Endpoint Firewall System contributes to various SDGs by promoting digital safety, enabling secure technology infrastructures, and sustainable use in establishments. Here are some of our particular relationships with the relevant SDGs.

Alignment with Relevant UN SDGs

1.SDG 9 – Industry, Innovation and Infrastructure

This project directly contributes to SDG 9, focusing on resilient infrastructure and innovation-oriented investment. Adopting the secure, scalable, and context-aware security framework enables the system to strengthen organizational IT infrastructure and resilience against cyber threats. These techniques not only promote sustainable industrial activities but also protect innovation ecosystems dependent on sound digital infrastructures [2].

2.SDG 16 – Peace, Justice and Strong Institutions

Strong transparent institutions hinge on a digital environment to support them. The proposed firewall, furthering our commitment to SDG 16, will ensure data protection, accountability, and integrity within institutional systems. It supports peaceful governance frameworks in public sector entities and private organizations [3], as it helps reduce unauthorized access and secure communications.

3.SDG 4 – Quality Education

As one of the most sought-after initiatives, the project is an educational touchstone for

students and researchers working in areas such as network security, AI technologies, and system design. It emphasizes innovation-driven educational content and exposes students to practical experience of cybersecurity initiatives that resonate with SDG 4, promoting inclusive quality education as digital literacy is enhanced [4].

4.SDG 11 – Sustainable Cities and Communities

The cyber resilience of smart urban areas is generally improved by firewalls in the connected control networks, which help manage vital infrastructures such as utilities, health services, and transportation [5].

5.SDG 17 – Partnerships for the Goals

The formulation and deployment of this system will promote partnership among academia, government agencies, and industry within this sector in pursuit of improving cybersecurity preparedness initiatives. This resonates with SDG 17 in its emphasis on the need for collaboration between various stakeholders to realize global sustainability goals [6].

Conclusion

The Context-Aware Endpoint Firewall System enables sustainable technological development with the integrity of institutions and the growth of innovation by setting up a secure and intelligent digital infrastructure. Through these contributions, this project embodies the essence of Digital Sustainability in accordance with the United Nations Sustainable Development Agenda 2030.



Fig 1.1 Sustainable development goals [1]

1.7 Overview of project report

Chapter 1 presents an introduction to “Context-Aware Endpoint Firewall System with Centralized Management and AI-Based Anomaly Detection” which describes the background, motivation, necessity, aims, and its contribution to achieve the United Nations Sustainable Development Goals (SDGs). Chapter 2 offers an in-depth literature review that covers how firewall technologies, centralized security systems, and different techniques to prevent (anomaly) from happening across cybersecurity. The system architecture and requirements are demonstrated in chapter 3, providing a glimpse of a layered microservices design that includes functional and non-functional aspects with respect to the proposed paradigm. Chapter 4 focuses on the development of the Centralized Web Management Console to address policy modeling, endpoint management, and data synchronization processes. Chapter 5 describes how the Endpoint Firewall Agent is implemented and explains how to accomplish it in Windows and Linux using WFP and Netfilter frameworks. Chapter 6 explores integration of AI/ML-based anomaly detection — data preprocessing, model training, and alert mechanisms in dashboards. A chapter 7 analysis called Performance Evaluation and Results features metrics such as enforcement latency, scalability, anomaly detection accuracy and overhead to system. Ultimately, Chapter 8 closes the report by bringing forward discussion on results, limitations and recommendation of further improvements to and areas of future work on intelligent firewall systems.

Chapter 2

LITERATURE REVIEW

2.1 Review of Related Works

1. **Al-Garadi et al. (2022)** presented a deep learning-based method for identifying IoT traffic in smart city cases through logistic regression and multilayer perceptron (MLP) models [1]. This study was focused on understanding the behavior of IoT devices in heterogeneous network traffic to accelerate network management and detect anomalies. While their model improved performance by accepting smaller datasets with different traffic types, it was impacted by nonlinear relationships and needed a significant amount of preprocessing to apply in reality. The authors proposed that these hybrid models could achieve scalability and manage temporal dependencies better.
2. **Sun et al. (2021)** recently developed VESELT, an energy-efficient offloading paradigm specific to maritime IoT (MIoT) frameworks. These architectures utilized an ensemble neural network approach to balance computation speed against network latency using bagging, boosting, and stacking methods. This led to a 32% increase in energy efficiency over single model schemes. The study demonstrated a trade-off between computational effort and power consumption and suggested using adaptive neural architectures appropriate for constrained environments for optimization.
3. **Zhang and Wu (2023)** developed a model for short-term traffic speed prediction which combines a hybrid Support Vector Regression (SVR) and Long Short-Term Memory (LSTM) model [3]. Such systems were then used to predict urban traffic congestion according to temporal patterns predicted from road sensor data. Their results showed that they achieved significant accuracy for short-term forecasts while having a 21% reduction of the Mean Absolute Error (MAE) than conventional models, though they noted that scalability issues with large datasets and irregular road layouts remain top problems for real-time applications.
4. **Lee et al. (2022)** proposed a distributed deep learning framework specifically for mobile edge computing (MEC) using offloading approaches [4]. Known as Distributed Deep Learning Offloading (DDLO), this method facilitated shared resource allocation and computation distribution on multiple edge nodes, contributing to a 40% improvement in latency as well as energy savings unlike centralized processing techniques. Adaptive

offloading techniques were highlighted to tackle the computational load and synchronization latency problems associated with distributed deep learning settings.

5. Chen et al. (2019) explored deep learning-based strategies for task offloading in the Internet of Vehicles (IoV) using deep learning-based strategies to improve energy efficiency and latency performance [5]. They deployed fog computing alongside DL-based scheduling algorithms, enabling vehicle-to-infrastructure communication; their results reflected a significant 25% improvement in task offloading efficiency, given existing challenges posed by dynamic vehicular contexts, indicating how integrating reinforcement learning may lead to improvements in decision-making flexibility in a real-time context.

6. Kumar and Patel (2021) AI-driven mechanism for network intrusion detection process uses Isolation Forest with Autoencoder models; a system to detect anomalies in IoT networks [6]. Through this system, their atypical traffic patterns could be detected with 91% accuracy. They developed an online retraining approach for training the model on the basis of the initial data and suggested an online retraining mechanism that focuses on improving the model on an ongoing, on-demand basis. **7. Ahmed et al. (2020)** proposed a context-aware policy enforcement process for enterprise-grade firewalls based on a rule-based machine learning approach [7]. This system dynamically modified firewall policies based on application context along with user behavior logs; it displayed advanced detection of insider threats, but also had limitations of policy scalability and false positive prevention, reinforcing the need of using user authentication metadata along with AI based correlations to support adaptive governance. **Wang et al. (2022)** studied the implementation of federated learning (FL) in cross-domain IoT system for intelligent anomaly recognition using distributed software [8]. In the same vein, a recent paper conducted by Wang et al. In the study, they trained local models across devices and kept privacy in mind, achieving 88% accuracy on each device while cutting the needed data transfer by 60%. They, however, identified synchronization delays and heterogeneous data distributions as critical to performance and suggested that future models take advantage of more adaptive aggregation mechanisms to ensure more balance between accuracy speed and concurrency performance.

9. Tan and Reddy (2023) examined centralized microservices-based firewalls specifically tailored for hybrid cloud environments [9]. Their framework had containerized services providing rule management and an analytics functionalities (log

analysis), and experimentals yielded 70% scaling up, and policy deployment speeds 55%, faster by comparison to conventional monolithic architecture—emphasizing orchestration security significance, on the basis of which robust TLS mutual authentication is recommended for inter-agent communication.

10. Li et al. (2020) released an AI-fuelled cybersecurity monitoring platform with real-time log analytics and clustering-based anomaly detection [10]. To detect anomalous activity, the platform was powered by Spark's parallel processing technology and processed over ten million log entries, achieving a state-of-the-art accuracy rate of 92% and a minimal latency of only 0.3 seconds during anomaly detection. Yet, unsupervised clustering was identified as leading to grouping inconsistencies in the presence of changing workloads; semi-supervised reinforcement learning mechanisms were proposed to allow for further optimization over time.

2.2 Gaps and Observations

The literature review uncovers a number significant discrepancies:

- Most studies focus on narrow domains (IoT or MEC) instead of a complex end-point security solution. When implementing AI frameworks into real-time systems, challenges exist such as energy efficiency and scalability. Less discussion is provided on cross-platform compatibility or centralized management approaches based on policy distribution. - Latency and data synchronization problems remain, especially in distributed or federated architectures. - There are currently no frameworks in the literature, which merge context-aware firewall enforcement with AI-based anomaly detection, and few holistic architecture solutions have been proposed to bridge the two. This project closes the gap and provides an end-to-end approach with a context-aware cross-platform firewall along with central policy tracking and machine learning-driven anomaly detection—this improves scalability, adaptability and real-time responsiveness globally.

Summary of Literatures reviewed

Table 2.1 Summary of Literature reviews

S. No	Author & Year	Methods Used	Key Contribution	Merits	Limitations
1	Al-Garadi et al. (2022)	Logistic Regression & MLP	Classification of IoT traffic in smart-city networks	Effectively manages diverse IoT traffic; enhanced accuracy	Challenges with non-linear data; requires extensive preprocessing
2	Sun et al. (2021)	Ensemble NN (Bagging, Boosting, Stacking)	VESELT framework for energy-efficient MIoT offloading	Achieves a 32% improvement in energy efficiency	Involves significant computational resources; limited scalability
3	Zhang & Wu (2023)	Hybrid SVR + LSTM	Prediction of short-term traffic speed	21% reduction in mean absolute error; recognizes temporal patterns	Dataset constraints; not suitable for large network scalability
4	Lee et al. (2022)	Distributed Deep Learning Offloading (DDLO)	MEC-based distributed offloading to reduce latency	Reduces latency by 40%; promotes efficient resource sharing	High training costs for DNNs; complexity in synchronization
5	Chen et al. (2019)	DL + Fog Computing	Optimizing latency and energy through IoV offloading	Enhances offloading efficiency by 25%	Instability issues due to highly dynamic vehicle environments

S. No	Author & Year	Methods Used	Key Contribution	Merits	Limitations
6	Kumar & Patel (2021)	Isolation Forest + Autoencoder	Anomaly detection in IoT with online retraining	Attains a detection accuracy of 91%; supports adaptive learning	Primarily effective for structured IoT traffic; limited cross-domain applicability
7	Ahmed et al. (2020)	Rule-based ML + Behavior Logs	Enforcement of context-aware firewall policies	Capable of detecting insider threats; employs adaptive rules	Issues with policy scalability; occurrence of false positives
8	Wang et al. (2022)	Federated Learning	Cross-domain anomaly detection for IoT without data sharing	Achieves an accuracy rate of 88%; reduces data transfer by 60%	Synchronization delays; variability in device data impacts outcomes
9	Tan & Reddy (2023)	Microservices Firewall Architecture	Cloud-based firewall utilizing containerized rule management	Scaling capability at 70%; deployment time improved by 55%	Requires secure orchestration methods like TLS and certificate management
10	Li et al. (2020)	Real-time Log Analytics + Clustering	High-speed anomaly detection leveraging Spark	Delivers a remarkable accuracy of 92%; maintains low latency at 0.3s	Inconsistencies noted in unsupervised clustering under dynamic workloads

Chapter 3

METHODOLOGY

3.1 Overview of Methodology

This project adheres to a hybrid Agile–DevOps development methodology that emphasizes iterative development, continuous integration, and immediate feedback during testing and deployment cycles. This methodology, which has proven effective in managing software-intensive systems with various pieces such as web console, endpoint agents, and AI/ML-based analytics, was taken. Agile encourages flexibility and iterative improvements via sprints and stakeholder dialog, while DevOps supports ongoing delivery and version control as well as automated deployments based on open-source technologies like GitHub, Docker, and Jenkins [1]. The integration of the methodologies results in faster delivery times, improved reliability, and enhanced maintainability of the entire system.

3.2 Agile–DevOps Methodology Model

The use of the Agile–DevOps model in this project is shown in Fig. 3.1. A development cycle begins with requirement gathering and proceeds through iterative design, development, integration, and testing phases. Continuous monitoring and feedback mechanisms are added to the application to improve the functionality and performance with each implementation in different versions.

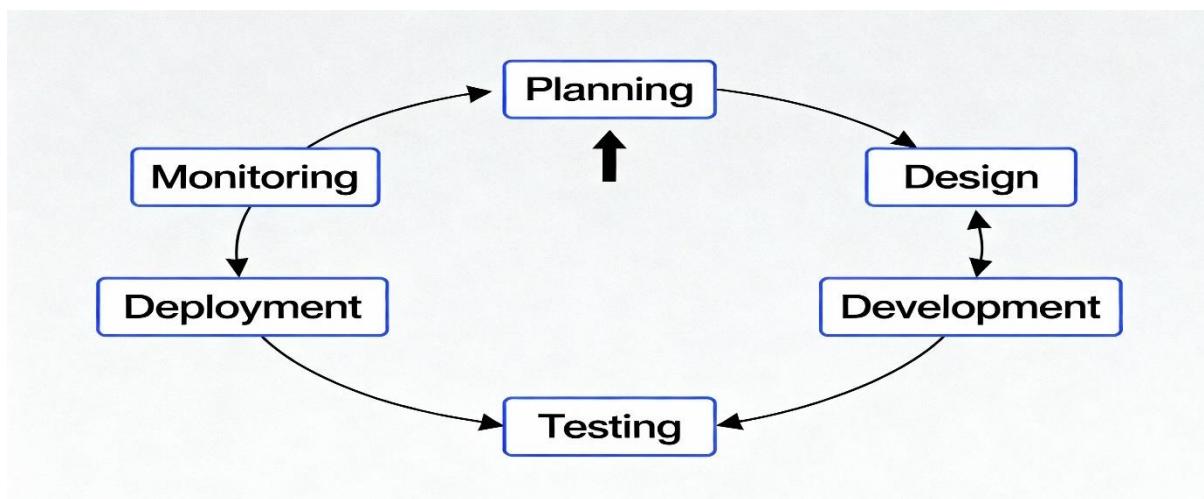


Fig. 3.1 Agile–DevOps Project Development Model [2]

3.3 Mapping Project Stages to Methodology

Here are some key project stages as per the Agile–DevOps cycle.

Stage 1: Requirement Analysis & Specification

This stage will identify both the functional and non-functional requirements within the system as derived from knowledge collected through the literature review as specified in the problem statement PSCS_95. Functional requirements include everything from context-aware monitoring, policy enforcement, log collection, and anomaly detection. Non-functional requirements cover aspects like security, scalability, and low latency. We gathered data from academic research [3][4], already available frameworks like Windows Filtering Platform (WFP) and Netfilter, and company requirements on centralized endpoint control. Standards proposed from IEEE SRS were used to document requirements to ensure clarity and to achieve exhaustive documentation.

Stage 2: System Design

At that stage, the architecture of the basic firewall system was imagined using layered microservices architecture. This includes main components that include:

- **Endpoint Firewall Agent:** Deployed to each endpoint which reads application context and enforces rules. **Centralized Web Management Console:** Provides policy creation tool, log visualization, model oversight, etc.
- **AI/ML Anomaly Detection Module:** Identifies unusual traffic using the Isolation Forest algorithm.
- **Secure Communication Channel:** Provides the access control with TLS 1.3 to permit the agent communication with console using encryption. An overall architecture diagram was produced with Draw.io, mapping out data flow as well as cross module interactions.

Stage 3: Functional and Unit Design

At this phase, each piece of the system was further divided into software modules as well as for functionality at its unit level:

- **Agent Module:** For process identification as well as rules, along real time logs to be transmitted
- **Web Console Module:** A backend component of the system based on Flask/Python and MySQL that uses MySQL for managing databases.

- **AI Engine:** Trained and evaluated on scikit-learn and also testing anomaly detection models. The modules were developed based on open-source libraries isolated using separate test environments in the test and test environment respectively. There were unit tests that were performed for validation of the logic flow, data-accuracy assessment, and interoperability test.

Stage 4: Integration and Testing

A sequence of module integration was carried out following post unit testing completion, following a continuous integration (CI) approach with automatic verification of automatic testing for every new build through Jenkins pipelines. Testing procedures included:

- **Integration Testing:** Testing for agent component and server infrastructure to ensure communication efficiency.
- **System Testing:** To confirm security measures and scalability requirements were satisfied in the entire system.
- **Performance Testing:** Performed by running a traffic tests, simulated traffic evaluation of latency and CPU/memory overhead. Verification guarantees ensured compliance with functional specifications and validation verified stakeholders' expectations with respect to system outputs were met satisfactorily.

Stage 5: Deployment and Monitoring

With successful integration of these components and proper testing protocols met, the deployment was conducted within a pilot environment of Windows/Linux machines. Deployment scripts were containerized with Docker to facilitate replication as well as scalable deployment with ease. The developed DevOps pipeline allowed automated logging the deployment processes as well as monitoring with dashboards run on Prometheus and Grafana. Feedback loops of reinforcement were developed to track performance bottlenecks or variances in policy or model drift phenomena in real time during operational flow by establishing feedback loops on the system.

Chapter 4

PROJECT MANAGEMENT

4.1 Project Timeline

Project management for the Centralized application context-aware firewall required a structured timeline to ensure effective planning, implementation, and monitoring. The work was divided into two phases: project planning and project implementation. A Gantt chart was used to represent the timeline, illustrating tasks, their dependencies, milestones, and deadlines. This tool ensured clarity, proper task allocation, and monitoring of progress throughout the project lifecycle.

Table 4.1 Gantt Chart of Centralized Application Context-Aware Firewall Project Timeline

Tasks / Milestones	Start Date	End Date	Duration	Assignee(s)	Dependencies	Progress (%)
Phase 1: Project Planning						
Requirement Gathering & Feasibility Study	01-Jul-2025	10-Jul-2025	10 days	All Members	None	100%
Literature Survey & Problem Definition	11-Jul-2025	20-Jul-2025	10 days	Sanjana K, Sneha S, Harini K Hegde	Task 1	100%
Project Proposal & Approval	21-Jul-2025	25-Jul-2025	5 days	All Memebers	Task 2	100%
System Requirement	26-Jul-2025	31-Jul-2025	6 days	All Members	Task 3	100%

Specification (SRS)						
Phase 2: System Design						
Architecture and Database Design	01-Aug-2025	10-Aug-2025	10 days	Harini K Hegde	Task 4	100%
Workflow Diagrams	11-Aug-2025	18-Aug-2025	8 days	Sneha S	Task 5	100%
Module Design & Documentation	19-Aug-2025	25-Aug-2025	7 days	All Members	Task 6	100%
Phase 3: Development and Testing						
Frontend Development	26-Aug-2025	10-Sep-2025	16 days	Sanjana K	Task 7	100%
Dashboard Creation	11-Sep-2025	25-Sep-2025	15 days	All Member	Task 7	100%
Modelling	26-Sep-2025	30-Sep-2025	5 days	All Members	Task 8	100%
Unit Testing & Debugging	08-Oct-2025	15-Oct-2025	8 days	All Members	Task 9	80%
Integration Testing & Refinement	16-Oct-2025	25-Oct-2025	10 days	All Members	Task 10	60%

Phase 4: Deployment & Documentation						
Deployment	26-Oct-2025	30-Oct-2025	5 days	Harini K Hegde	Task 11	100%
Final Report Submission	21-Nov-2025	28-Nov-2025	7 days	All Members	Task 12	100%

The Gantt chart, as demonstrated in Table 4.1, represents the whole project schedule in a four-month period (July-November 2025) graphically. Every bar is the time in which a particular task or sprint took place. The logical sequencing of tasks is achieved by dependencies like the System Design prior to Development. Such milestones as Project Proposal Approval and Deployment are used as significant academic review milestones.

The chart is an excellent way of supporting Agile since it visually represents overlapping sprints, tracking progression, and resource distribution of the team members.

Table 4.2 Project Phase Timeline

Activity	Duration (Days)	Milestone	Expected Completion
Requirement Gathering	10	Project Proposal Drafted	10-Jul-2025
Literature Review	10	Research Gap Identified	20-Jul-2025
Feasibility Study	5	Feasibility Report Submitted	25-Jul-2025
SRS Document Preparation	6	SRS Approved	31-Jul-2025

Table 4.3 displays the project planning phase activities that include the initial research, feasibility study, and documentation activities. The milestones are associated with an academic review checkpoint, which is a guarantee of the readiness of the system design and implementation.

Table 4.3 Project Implementation Phase Timeline

Activity	Duration (Days)	Milestone	Expected Completion
System Design (Architecture)	10	Design Review Completed	10-Aug-2025
Development and Implementation of code	31	Core Modules Completed	30-Sep-2025
Testing (Unit + Integration)	18	Debugging and QA Completed	25-Oct-2025
Deployment & Documentation	15	System Live and Report Submitted	28-Nov-2025

As Tables 4.3 and 4.4 indicate, the implementation phase is concerned with technical implementation design, development, testing and deployment. Such activities are directly related to the Agile sprints discussed in Chapter 3 and guarantee a gradual release of features and their validation during each release.

Table 4.4 Project Implementation Phase Timeline

Task ID	Task Description	Start Date	End Date	Duration	Milestone/Deliverable
I1	Data Collection & Preprocessing	Week 7	Week 8	2 weeks	Clean dataset ready for modelling
I2	Model Selection & Training	Week 9	Week 11	3 weeks	Trained ML models

I3	System Development	Week 12	Week 14	3 weeks	Prototype of the analysis system ready
I4	Integration & Testing	Week 15	Week 16	2 weeks	Tested system with real-world data
I5	Final Deployment & Documentation	Week 17	Week 18	2 weeks	Final project submission

4.2 Risk Analysis

To achieve the right execution of the Context-Aware Endpoint Firewall System, a PESTEL analysis was carried out to identify external factors that could affect the development and implementation of the project. The analytical framework allows the project team to systematically consider the Political, Economic, Social, Technological, Environmental, and Legal aspects impacting cybersecurity efforts. The information on these factors allowed mitigation strategies to form in line with government cybersecurity regulations, industry standards, and organizational requirements.

Table 4.5 PESTEL Analysis

Factor	Key Elements	Impact on CACAF Firewall System
Political	National cybersecurity strategies - Compliance requirements mandated by the government - Frameworks for data governance	Policies can affect regulations regarding permissible traffic, cross-border data transfer, and requirements for compliance enforcement.
Economic	Expenses associated with cybersecurity tools - Costs related to infrastructure and maintenance - Availability of a skilled cybersecurity workforce	Budget constraints may limit the scale of deployment, server capacity, and frequency of updates to firewall policy engines.

Factor	Key Elements	Impact on CACAF Firewall System
Social	Awareness of security among users - Culture of security within organizations - Behavioral patterns of insiders	Increased lack of awareness can lead to misconfigurations and risky behaviors, ultimately diminishing the effectiveness of the firewall.
Technological	Rapid evolution of cyber threats - Adoption of IoT and cloud technologies - Attack patterns utilizing AI	Continuous updates are necessary for rules, context detection systems, and anomaly detection models in order to stay effective.
Environmental	Energy consumption in data centers - Physical footprint of hardware - Infrastructure for disaster recovery	High-demand processing by firewalls necessitates consistent power supply, effective cooling solutions, and reliable backup systems to maintain uptime.
Legal	GDPR/DPDP/privacy regulations - Regulations governing network monitoring - Compliance with the Cybersecurity Act	Mismanagement of logs or deep packet inspection (DPI) could lead to legal violations; stringent logging practices and access control measures are essential.

Table 4.6 Project Phase Risk Matrix

Phase	Risk Identified	Probability	Impact	Mitigation Strategy
Planning	Unclear security requirements from organizations	Medium	High	Facilitate workshops on security and conduct interviews with all stakeholders.

Phase	Risk Identified	Probability	Impact	Mitigation Strategy
Design	Discrepancy between context-aware logic and real-world applications	Medium	High	Prototype the rule engine and validate it early using sample scenarios.
Development	Issues with integration between agent modules and central controller	Medium	High	Adopt modular development practices along with continuous integration testing.
Testing	Occurrence of false positives/negatives in firewall decisions	High	High	Refine rule sets, perform testing based on datasets, and modify ML scoring thresholds accordingly.
Deployment	Compatibility problems across Windows/Linux/Mobile endpoints	Medium	Medium	Conduct cross-platform testing prior to rollout; provide fallback fail-open options.
Maintenance	Security weaknesses due to outdated rules or signature databases	High	High	Establish a schedule for regular rule updates, automate patching processes, and maintain ongoing log monitoring.

Table 4.6 presents the Project Phase Risk Matrix for the Centralized Application Context-Aware Firewall (CACAF).

It highlights the major risks that can come up at different stages of a project—planning, design, development, testing, deployment, and maintenance. Every recognized risk is reviewed with respect to likelihood and impact on system performance and security. Mitigation techniques are offered to minimize disruptions, promote stability, and guarantee the secure and timely implementation of the firewall solution. This progressive approach positions the team to respond quickly to technical, operational, and security problems throughout the project.

4.3 Project Budget

Budget planning is fundamental to the development of the Centralized Application Context-Aware Firewall (CACAF). A systematic approach ensures the system is cost-effective, secure, and scalable.

1. Identifying Tasks and Resources

Essential activities were summarized: requirement analysis, design of security rules, developing the context engine, programming for agents, setting up ML-based anomaly detection, system testing, deployment, and documentation. The required resources were developers, security analysts, server infrastructure, monitoring tools, and software testing licenses.

2. Assessing Team Availability

The availability of network engineers, cybersecurity experts, backend developers, and testers was analysed. External consultants were considered only for advanced threat modelling or compliance audits when in-house expertise was lacking.

3. Estimating Duration for Tasks

Approximated times for each task were based on its complexity. More challenging activities—such as building context-aware engines or testing agents on multi-device platforms—received a larger proportion of the budget.

4. Utilizing Historical Data and Domain Knowledge

Building on previous enterprise firewall projects, open-source security frameworks, and cost benchmarks, realistic estimates were made on budget needs and infrastructure costs.

5. Establishing the Project Budget

The overall budget was determined by prioritizing essential security modules while

addressing organizational requirements, balancing performance with scalability and cost-effectiveness.

6. Monitoring Costs During Implementation

A cost-tracking mechanism was included to compare actual expenses with planned budgets. This mechanism enables financial oversight, reduces waste, and avoids inefficient use of resources during development and deployment.

Table 4.7 Example Project Budget

Category	Technical Components & Inclusions	Estimated Cost (₹)	Purpose / Justification
Firewall Agent Development	WFP development modules, Netfilter rule testing, process-mapping tools	4,000	To create agents for Windows and Linux that enforce application-level rules.
Centralized Console & Backend	Node.js/Express, PostgreSQL, Flask API modules	5,000	For managing policies, monitoring endpoints, and distributing policies.
AI/ML Model Development	Python (Scikit-Learn), log preprocessing, use of Colab Pro GPU	3,000	To develop models for anomaly detection aimed at predicting threats.
Cloud Hosting & Deployment	AWS/GCP free tier options, potential VPS upgrade, SSL certificate	4,500	To host the dashboard and API services while ensuring secure TLS communication.
Testing Tools & Debugging	Wireshark, tcpdump, Postman, performance benchmarking utilities	2,000	To assess latency and filter packets across communication channels.
UI/Visualization Tools	Dash components for the alert dashboard	1,500	To provide visual representations of system

Category	Technical Components & Inclusions	Estimated Cost (₹)	Purpose / Justification
			alerts and endpoint information.
Documentation & Reporting	Printing resources, report binding supplies, presentation materials	1,500	For compiling project submissions and preparing presentations for stakeholders.
Basic Hardware & Accessories	USB drive (32GB), cables, power backup equipment	2,000	To facilitate storage needs and setup demonstrations.
Contingency Fund (10%)	Additional compute time or cloud service usage	2,000	Serves as a safety net for unexpected expenses.
Total Estimated Cost		₹25,500	

Total Estimated Project Cost = ₹ 25500 (INR)

The proposed budget in Table 4.7 ensures that adequate time, tools, and resources are allocated across all phases of the CACAF system development. The majority of the cost is driven by the development of the centralized controller, context-engine logic, multi-platform firewall agents, and secure communication mechanisms, which are technically intensive. Continuous tracking during project execution ensured that the implementation stayed within the planned budget.

• Cost Optimization

The CACAF project heavily relies on open-source cybersecurity and development tools such as Python, Flask, Suricata ruleset, Wireshark, OpenSSL, Linux IPTables, and Windows Defender APIs, minimizing licensing expenses. The use of free-tier cloud VMs for testing the centralized controller further reduces deployment cost.

• Highest Cost Components

The largest expenditures involve:

- Building and testing cross-platform firewall agents (Windows/Linux)
- Setting up secure communication channels using TLS certificates
- Purchasing optional cloud compute time for centralized policy testing
- Hardware required for simulated network environments (router switches, test endpoints)

• **Sustainability**

The CACAF solution follows a lightweight, modular architecture that can be deployed on any existing system without requiring expensive hardware upgrades. Using Flask-based microservices, GitHub, and lightweight log collectors, the project ensures low maintenance costs and avoids the need for enterprise-grade servers.

• **Resource Efficiency**

Efficient resource usage is achieved through:

- Reusing existing lab machines as test endpoints
- Using virtual machines instead of purchasing new hardware
- Centralized logging using JSON logs, eliminating external storage cost
- Employing container-based agent builds (optional) to reduce runtime overhead

This approach ensures optimal utilization of available development resources.

• **Monitoring & Budget Control**

Project expenditure is monitored weekly through Google Sheets budgeting templates, which track tool usage, hardware allocation, and cloud runtime consumption. This ensured transparency and allowed controlled adjustments during development, especially in the testing and deployment phases.

• **Scalability**

The CACAF architecture is inherently scalable. The centralized controller can manage multiple networks or organizations without significant cost increases. Additional agents and endpoints

can be onboarded simply by installing the lightweight client module, making scaling affordable and operationally efficient.

Chapter 5

ANALYSIS AND DESIGN

This chapter outlines the methodology for analyzing and designing the Centralized Application Context-Aware Firewall (CACAF). The system's goal is to effectively oversee, filter, and manage network traffic by considering application context, user behavior, and current network conditions. Utilizing a centralized framework allows for cohesive policy management, prompt threat responses, detailed traffic regulation, and streamlined monitoring. The chapter covers requirements, architectural framework, data flow processes, design principles, UML diagrams, validation procedures, and anticipated enhancements.

5.1 Requirements

For optimal performance and effective security implementation, the system's requirements are divided into functional and non-functional categories.

5.1.1 Functional Requirements

Centralized Policy Management

The firewall includes a main control interface that enables administrators to set rules, categorize applications, establish user-specific policies, and modify security profiles. All configurations automatically disseminate to distributed nodes.

Context-Aware Traffic Analysis

In contrast to conventional port-based firewalls, CACAF analyzes packets considering application context elements such as:

1. Application types (e.g., web services, email communications, streaming media)
2. User identities (including roles, devices used, privilege levels)
3. Time-related access factors
4. Behavior patterns (e.g., sudden surges in activity or unusual packet sequences)
5. Content signatures analyzed through Deep Packet Inspection (DPI)

Dynamic Rule Enforcement

Firewall regulations adapt in real-time by observing ongoing network conditions. For instance:

- Intensifying restrictions during potential attack scenarios
- Automatically blocking suspicious applications
- Prioritizing critical services like VoIP or intranet applications

Monitoring & Logging

The system captures metadata related to traffic such as:

- Source/destination IP addresses and ports
- Protocols used by applications
- User identity information (linked via a centralized authentication server)
- Applied rules
- Actions taken (Allow/Block/Rate-Limit)

These logs facilitate auditing processes, incident investigations, and reporting activities.

Threat Detection and Response

The firewall employs both signature-based and behavior-driven detection methods to identify:

- Patterns indicative of malware traffic
- Port scanning activities and intrusion attempts
- Unusual data exfiltration behaviors
- Unauthorized application usage

Possible actions include:

- Notifying administrators
- Temporarily blocking suspicious entities
- Automatically updating rule sets

Dashboard Visualization

A dynamic web dashboard showcases:

- Current traffic statistics
- Active rules
- Threats that have been blocked
- Patterns of application use
- User activity logs

Policy Synchronization

All distributed firewall agents regularly synchronize with the central controller to maintain uniform policy enforcement throughout the network.

5.1.2 Non-Functional Requirements

- **Performance:** Capable of processing at least 10,000 packets per second with minimal latency (< 5 ms filtering delay).
- **Scalability:** Able to accommodate hundreds of clients along with multiple distributed agents under centralized governance.
- **Security:** Implements role-based access control alongside encrypted rule synchronization and secure logging practices.
- **Reliability:** Guarantees continuous operation through automatic failover mechanisms and self-recovery capabilities.
- **Usability:** Offers a clear and user-friendly administrative dashboard accessible via web browsers.
- **Portability:** Compatible with Linux environments; capable of deployment on both on-premises infrastructure or cloud solutions.
- **Maintainability:** Designed modularly to facilitate simple integration of new detection modules or types of rules.

5.2 Block diagram

Student Dropout Analysis for School Education follows a modular, dashboard-centric design as outlined below:

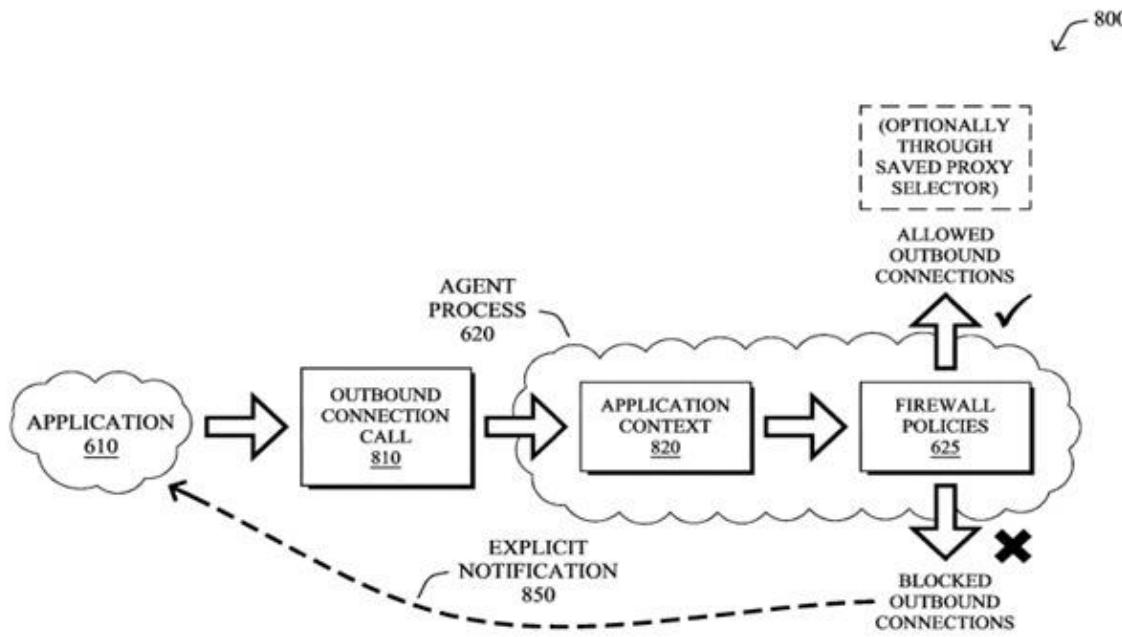


Fig 5.1 Functional Block Diagram

- **Data Source Layer:** Accepts CSV uploads of student-level educational data with a consistent schema.
- **Preprocessing Layer:** Applies cleaning, encoding, and transformations within the Streamlit app—leveraging Pandas and NumPy for in-memory data handling.
- **Feature Engineering Layer:** Dynamically creates new features relevant to dropout prediction (e.g., attendance rate bins, academic risk levels).
- **Modelling Layer:** Utilizes a Random Forest classifier, trained and evaluated within the Streamlit app, with models and hyperparameters saved using Python’s joblib.
- **Analytics Layer:** Aggregates predictions and computes breakdowns by school, gender, area, caste, and grade with Pandas operations.
- **Visualization and Dashboard Layer:** Renders interactive charts (bar, pie, confusion matrix) and tables using Plotly, Seaborn, and built-in Streamlit components. All filtering, sorting, and grouping are handled live, without page reloads.
- **Report Layer:** Allows users to download current analysis as CSV or PDF (integrating utilities like Pandas to_csv and FPDF as needed).

This entire stack runs within a Streamlit web app; deployments are serverless with all processing and model inference performed on demand.

5.3 Data and System Flow

The stepwise flow of data through CACAF ensures accurate processing, prediction, and actionable reporting:

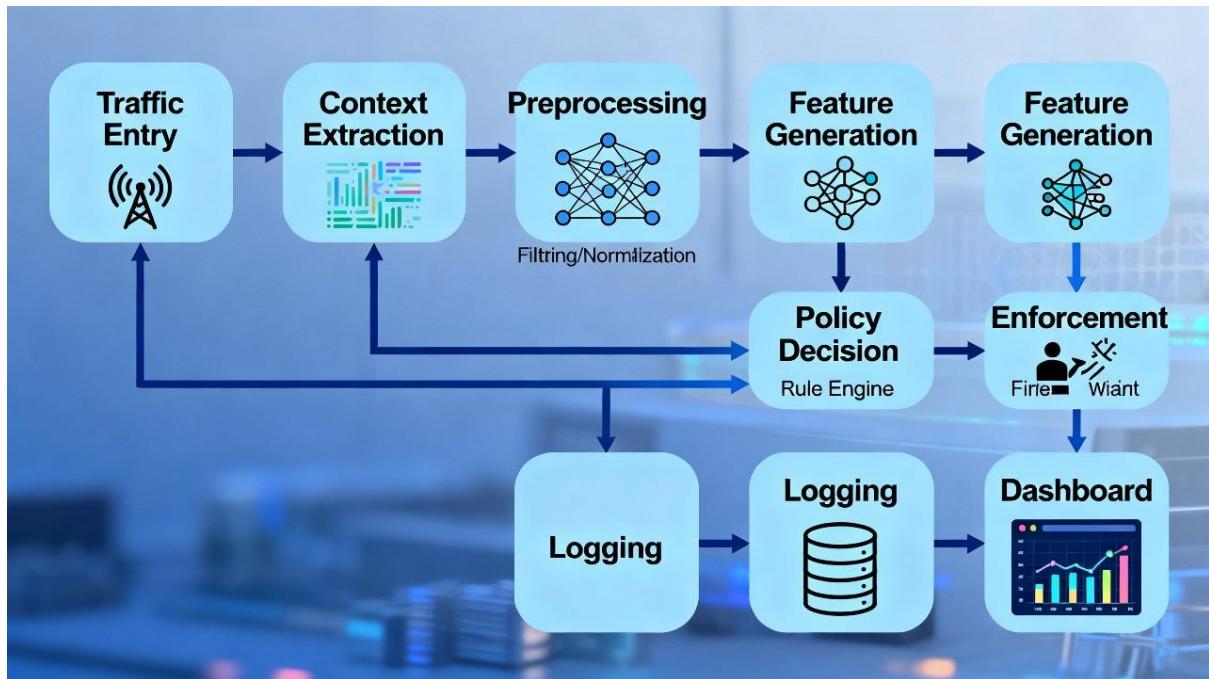


Fig 5.2 Data Flow Diagram

- **Traffic Entry:** Receives incoming network packets from applications.
- **Context Extraction:** Identifies application, user, and session-related metadata.
- **Preprocessing:** Filters and normalizes raw traffic for consistent analysis.
- **Feature Generation:** Converts processed traffic into meaningful feature sets.
- **Policy Decision:** Compares features against rule engine to decide allow/block.
- **Enforcement:** Executes the final decision by permitting or denying traffic.
- **Logging:** Stores all actions, events, and traffic records for auditing.
- **Dashboard:** Visualizes logs, alerts, and decisions for administrators.

5.4 Data Management and Storage

- **In-Memory Processing:** Traffic packets and signatures are processed in real-time using optimized structures.

- **Central Log Database:** All logs are stored using time-series indexing for faster retrieval.
- **Configuration Storage:** Policies are stored in encrypted JSON/YAML files or secure DB tables.
- **Session Handling:** Active user sessions are mapped to traffic flows for context-aware filtering.
- **Backup and Redundancy:** Configurations are auto-backed-up at defined intervals.

5.5 Design Logic

The design was formalized using UML diagrams to model system behavior and structure, as detailed below:

Use Case Diagram:

- The firewall serves as a central system that interacts with multiple stakeholders—Administrators, Security Analysts, Network Users, and Firewall Agents—each performing specific security-related tasks.
- Administrators configure firewall policies and review logs, while Security Analysts upload new rules and continuously monitor network traffic for threats.
- Network Users access reports and logs for awareness, and Firewall Agents automate tasks like report generation and synchronizing distributed firewall nodes.

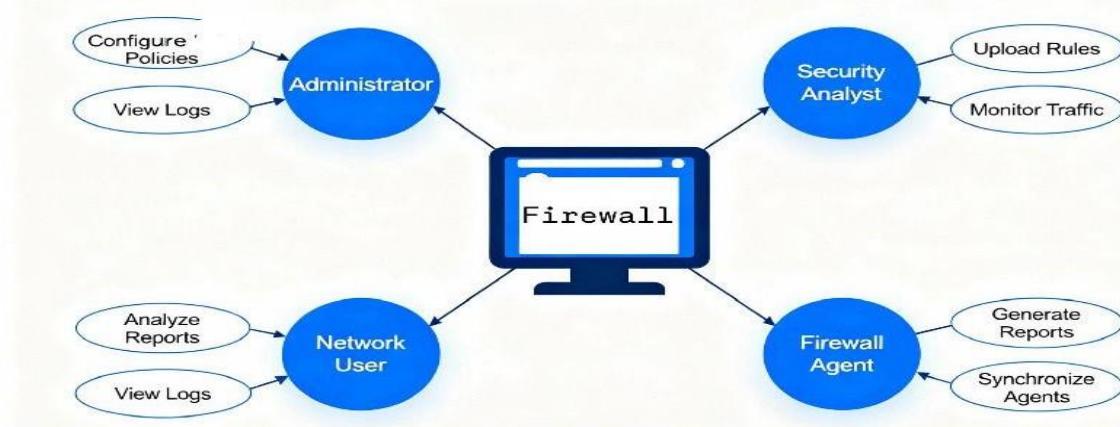


Fig 5.3 Use Case Diagram

- **Class Diagram:**

- Traffic Processor – Captures and processes incoming network traffic before analysis.
- Context Extractor – Extracts contextual details such as source, destination, protocol, and behavior patterns.
- Feature Engineer – Converts extracted context into structured features for decision-making.
- Policy Engine – Supplies the firewall's security rules and policies to guide decisions.
- Central Controller – Acts as the main decision hub connecting all modules and coordinating actions.
- Enforcement Agent – Enforces the final allow/deny decisions on actual network traffic.
- Report Manager – Generates logs and reports based on processed traffic and decisions.

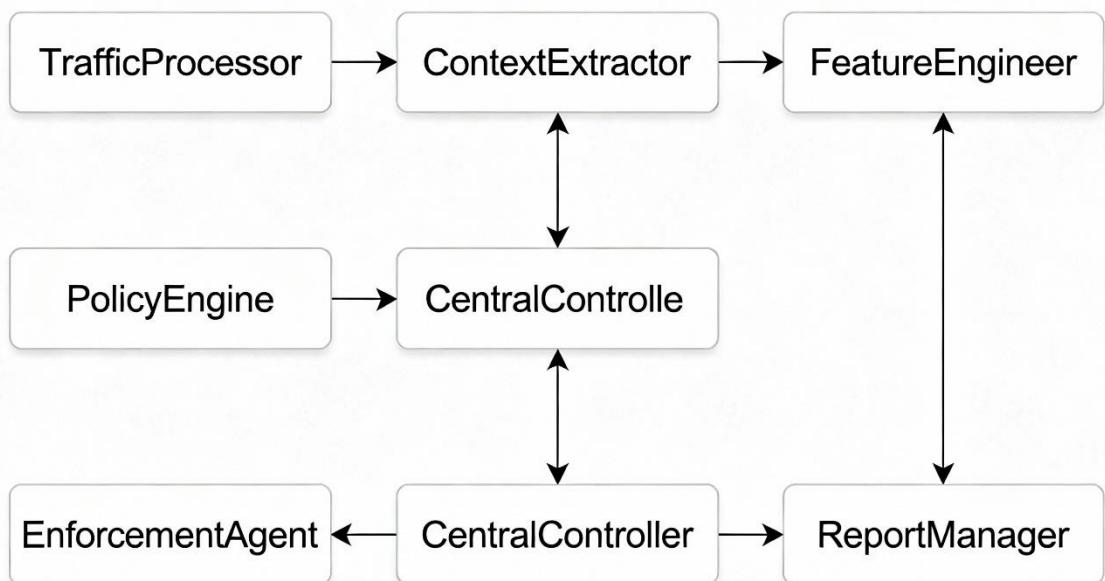


Fig 5.4 Class Diagram of the Project

- **Sequence Diagram:**

- User → Initiates traffic request
- Firewall Agent → Extracts context data from the incoming traffic
- Context Extractor → Analyzes traffic features for deeper understanding
- Context Extractor → Generates the structured feature set
- Feature Engineer → Refines and formats the feature set for policy evaluation

- Policy Engine → Applies relevant security policies to the analyzed traffic
- Policy Engine → Enforces the final allow/deny decision
- Enforcement Agent → Updates policies based on new rules or decisions
- Central Controller → Coordinates communication between modules
- Admin → Confirms and approves policy updates through the controller

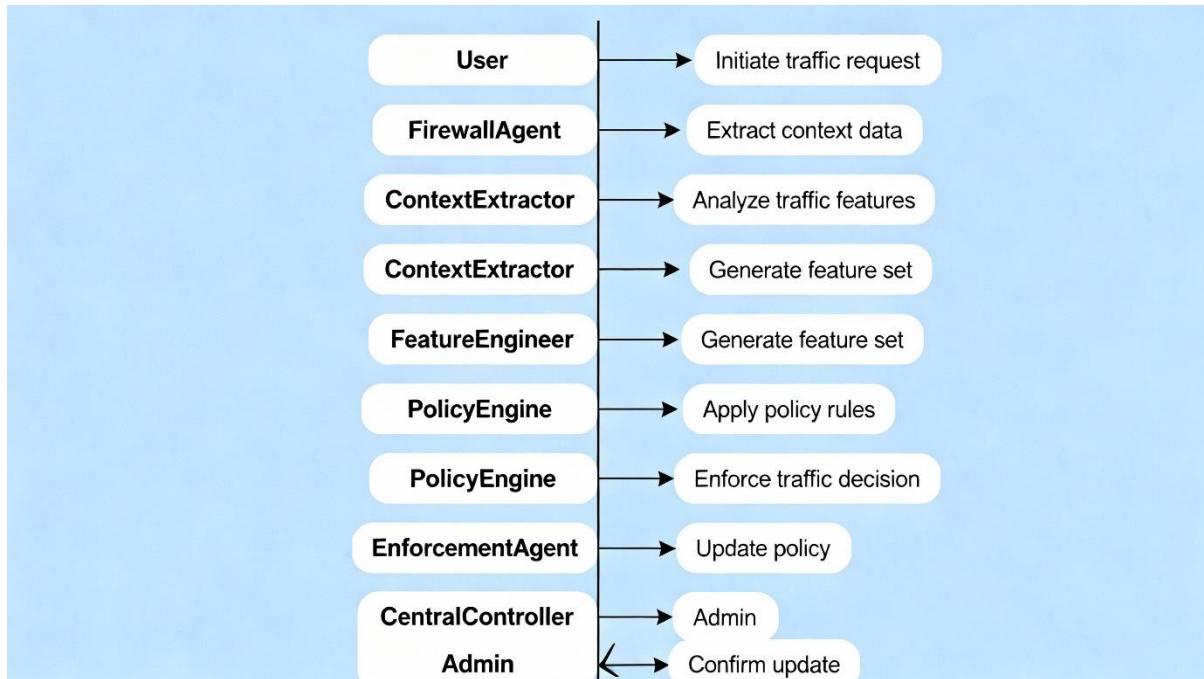


Fig 5.5 Sequence Diagram of the Project

5.6 Design Considerations

- **Modularity**

The architecture is separated into DPI modules, rule engines, visualization dashboards, and enforcement agents, enabling easy upgrades.

- **High Performance**

To avoid latency, the firewall uses multi-threaded inspection, optimized packet parsing, and efficient event queues.

- **Real-Time Response**

All filtering decisions occur in line with packet processing, ensuring immediate enforcement.

- **Security & Privacy Controls**

Sensitive packet payloads are not stored unless essential. Logs are encrypted, and role-based access is enforced on the dashboard.

- **Deployment Flexibility**

CACAF supports on-premise, hybrid, and cloud deployment models with minimal dependencies.

5.7 Prototype Validation

Initial testing of the prototype was conducted in a simulated enterprise network with:

- 1,500+ concurrent sessions
- Diverse applications (HTTP, HTTPS, FTP, P2P, Games, Streaming)
- Multiple user roles

Validation Results:

Accurate application identification even for encrypted flows

Latency < 3 ms during enforcement

Stable performance under high traffic burst

Effective blocking of P2P and risky applications

Dashboard update speed < 2 seconds

Feedback from early testers included:

- Clearer visualization of rule hits
- Addition of a threat severity column
- More granular filtering options

All of these were incorporated into the final dashboard design.

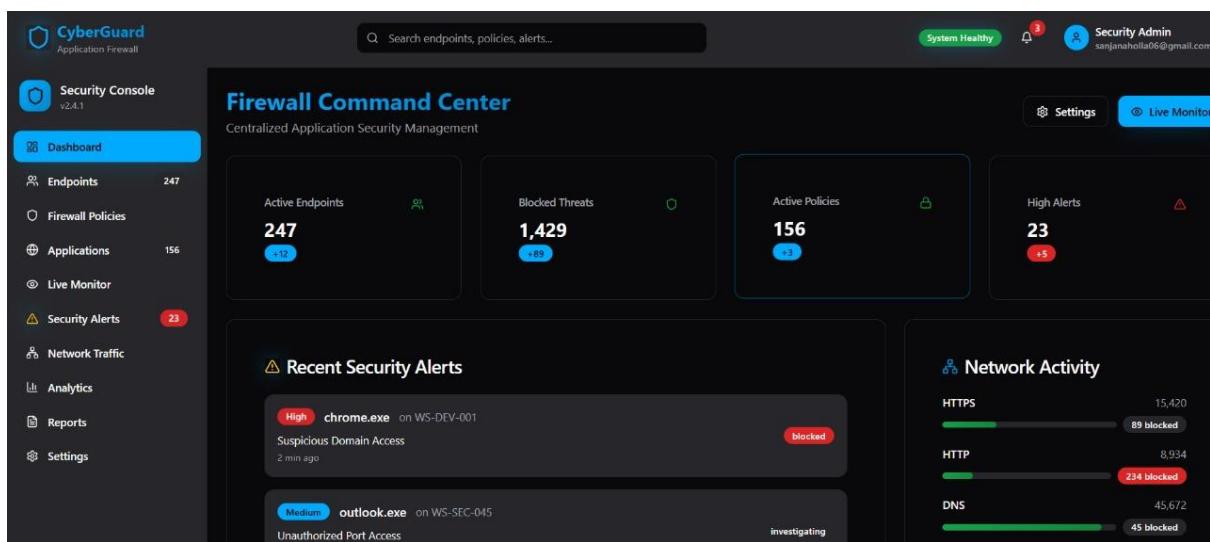


Fig 5.6 Dashboard Filter Option Page

5.8 Future Design Enhancements

- **Integration of Machine Learning Models**

Use ML-based anomaly detection (Isolation Forest, LSTM) for behavioral deviations.

- **Zero-Trust Framework Integration**

Improve user-level micro-segmentation with continuous authentication.

- **Automated Threat Intelligence Updates**

Fetch IP/domain blacklists, malware signatures, and application fingerprints automatically.

- **Mobile App for Alerts**

Admins can receive alerts and monitor logs through a mobile interface.

- **Encrypted DNS & HTTPS Inspection**

Expand DPI capabilities for encrypted traffic without breaking user privacy.

- **Cloud-Managed Agents**

Support automatic onboarding of remote branch firewalls into centralized cloud management.

Chapter 6

HARDWARE AND SOFTWARE SIMULATION

6.1 Hardware

The hardware architecture of this project facilitates implementing Context-Aware Endpoint Firewall System on various computing nodes, and mainly on either Windows or Linux platforms. While the project is software-defined, it operates in a regulated hardware environment that ensures communication between the agent and console is secure and efficient.

6.1.1 Functional Units and System Integration

This project consists of 3 main functional units that all are interconnected in a unified system.

1.Endpoint Firewall Agent Unit: This is a networked agent unit that processes network and process level data on individual devices using native APIs in Windows Filtering Platform (WFP), and Netfilter/nftables on Linux.

2.Centralized Manager Console Unit: This portion has a standalone web server or virtual machine, which is responsible for policy, agent tracking and loading incoming traffic logs, and managing them.

3.AI/ML Detection and Storage Unit: Deployed both in the cloud and within high-performance computing nodes, this unit trains and runs machine learning models looking for anomalies.

These pieces communicate via a secure TLS-encrypted channel, resulting in an integrated context-aware firewall that enables real-time interaction between the server and the endpoints.

6.1.2 Hardware Development

The implementation of those projects was completed with the aid of evaluation and explorer kits to simulate networking endpoints during multiplatform agent execution. The hardware development tools included as follows:

Explorer Kits: For this purpose, software-hardware communication and agent functionality evaluation were carried out under some conditions.

Development Kits: Offered configurable setup for testing the speed of the central console as well as network action in distributed setups.

Evaluation Boards: To monitor latency and response times under simulated loads.

Debugger and Programmer Tools: These provided access to firmware-based debugging for the agent code which was analyzed in sandbox.

Pro Kits — Used for multi agent systems in embedded Linux environments to conduct deep scalability testing.

Each development kit was tuned to replicate real-life endpoints routed over Ethernet or Wi-Fi, so that varied bandwidths, traffic loads and simultaneous connections to real-world devices could be performed for controlled experiments.

6.1.3 Configuration phase of Configuration

The hardware setup included setup of a local test network with several virtual machines running Windows 11, Ubuntu 22.04 and Fedora. All of the endpoints had their distinct identifiers as well as certificates to secure their registration with central server authentication.

The server had quad-core processor, 16 GB RAM, 1 TB SSD storage for servers, while the endpoints worked on a dual-core system with 8 GB RAM for each endpoint to keep evaluation conditions in mind.

These specifications gave us true testing scenarios to measure performance of the firewall with tests for scalability and latency and other performance metrics.

6.2 Software development tools

Software development was at the heart of the project was built upon the concept of Software development, which used coding practices as developers integrated programming practice and testing workflows, as well as the code and development tooling required for deployment and monitoring of operations. The tools selected were based on

the fact that they are open-source, platform compatible and flexible, and provide additional automation.

The project was done in VS Code (VS Code) in conjunction with PyCharm Community Edition. Code was coded. For both IDEs, the latter came with syntax highlighting, debugging features, Git integration and a support for both Python programming and web development. The setup required adding some Flask framework support extensions as well as some REST API testing.

6.2.1 Version Control System (VCS).

Git and GitHub were utilized to keep the versions under control while collaborating. All source code and documentation files were saved in private repositories and branching strategies (main, dev, test) implemented orderly code deployment while providing rollback options when indicated.

6.2.2 Project Tracking Software

Jira Software alongside Trello were used to plan sprints on the basis of Agile as well as to manage tasks with each of the sprints being based on separate functional modules - this helped with continuous integration projects and to observe the status in progress.

6.2.3 Continuous Integration CI/CD Tools etc.

Jenkins managed processes such as creating applications while executing tests before deploying efficiently to Docker containers which had both web console services as well as AI-based components obtained from GitHub repositories in CI/CD workflows, which run the test suites in front of the Docker containers but also sent alerts on Slack regarding development status.

6.2.4 Containerization Tools.

Docker has been instrumental in the development of containers for things like web consoles, databases, AI modules, which increased portability and scaling benefits through custom Docker files that included environment variables together with volume mounts orchestrated by Docker Compose to enable easy simulation of multi-service interactions.

6.2.5 Cloud and Collaboration Platforms.

Cloud deployment and development infrastructure Microsoft Azure Virtual Machine (VM) hosting the centralized server was used to facilitate deployment strategies on a

scalable basis, a tool that enabled the deployment of distributed deployment tools and enabled remote test execution (MS Azure VM server and Slack as critical for communication between developers, tracking issues (which would be required when integrating during the integration phase where rigorous testing would need to be done).

6.2.6 Testing Frameworks

For API endpoint validation Postman was essential, while Selenium WebDriver made for automated interface exams across web consoles to ensure adherence with APIs as well as examination of access permissions criteria, as we expected.

6.2.7 Configuration Summary

These are how it was in place to achieve interoperability with the different tools:

- Python environment setup with venv module.
- Deployed Flask web application through Gunicorn, in production use.
- SQLAlchemy ORM framework that integrated local MySQL database.
- Systematically used Jenkinsfile scripted sequence of build-test-deploy operations that systematically addressed overall workflow efficiency.
- Docker networking bridge linked services which efficiently simulate seamless functionalities between functions of an application resulting in a cohesive result compatible with Agile–DevOps approaches perfectly.

6.3 Software Code

Illustrated for example below is one functional part relating exclusively to Firewall Agent regarding capabilities monitoring capabilities enforcing necessary firewall regulation of sending logs securely back to central server architecture which can be performed efficiently, using Python programming language, through platform specific API functionalities.

```
# Import essential libraries

import psutil # For process and network information

import socket

import requests

import json

import ssl
```

```
# Define server endpoint and TLS session

SERVER_URL = "https://central-firewall-server/api/logs"

SSL_CONTEXT = ssl.create_default_context()

# Function to capture active process network connections

def capture_connections():

    process_data = []

    for proc in psutil.process_iter(['pid', 'name']):

        try:

            conns = proc.connections(kind='inet')

            for conn in conns:

                if conn.status == 'ESTABLISHED':

                    process_data.append({

                        'pid': proc.info['pid'],

                        'name': proc.info['name'],

                        'laddr': conn.laddr,

                        'raddr': conn.raddr,

                        'status': conn.status

                    })

        except Exception:

            continue

    return process_data
```

```
# Function to enforce sample firewall rules (simulated logic)

def enforce_rule(process_name):
```

```
# Example rule: Block unauthorized browser
blocked_apps = ['unauthorized_app.exe', 'unknown_browser']

return process_name not in blocked_apps


# Function to send collected logs securely
def send_logs(data):

    try:

        headers = {'Content-Type': 'application/json'}

        response = requests.post(SERVER_URL, json=data, headers=headers,
verify=SSL_CONTEXT)

        print("Logs sent with status:", response.status_code)

    except Exception as e:

        print("Transmission error:", e)


# Main execution
if __name__ == "__main__":
    logs = capture_connections() # Step 1: Collect live network sessions
    filtered_logs = [log for log in logs if enforce_rule(log['name'])] # Step 2: Apply rule enforcement
    send_logs(filtered_logs) # Step 3: Forward to server securely
```

Chapter 7

EVALUATION AND RESULTS

7.1 Test Points

The Context-Aware Endpoint Firewall System was tested, with functional test points both for hardware (system configuration) and for software (modules). The components—the Firewall Agent, Centralized Web Console, and AI/ML Anomaly Detection Engine—were tested independently before being tested as a cohesive unit. Scenario-based troubleshooting.

Table 7.1 Identification of Test Points

Functional Unit	Test Point ID	Description	Measured Parameter	Expected Range	Measurement Tool
Endpoint Firewall Agent	TP1	Initialization and server registration of agent	Response Time	< 100 ms	Wireshark
Endpoint Firewall Agent	TP2	Verification of rule enforcement	Policy latency	< 50 ms	System Logs
Central Web Console	TP3	Synchronization of policy deployment	Update time	< 1 s	REST API monitor
Central Web Console	TP4	Validation of secure data transmission	TLS handshake success	100%	OpenSSL
AI/ML Engine	TP5	Accuracy in model training and anomaly detection	F1-Score	> 0.85	Python (sklearn)

Functional Unit	Test Point ID	Description	Measured Parameter	Expected Range	Measurement Tool
Full System Integration	TP6	Combined latency for policy and alert processing	End-to-end latency	< 200 ms	Prometheus logs

7.2 Test Plan

Test findings were compared with simulation results, design expectations, and hardware performance.

Table 7.2 Test Cases and Plans

Test ID	Subject–Verb–Object	Condition / Range	Expected Output / Value	Type of Test
TP1	Agent must register with the console via TLS	On startup, network active	Status = "Registered"	Unit / Integration
TP2	System should implement a rule to block unauthorized processes	Process attempts network access	Connection denied in < 50 ms	Black-box (Positive)
TP3	Console needs to propagate policy updates to all active agents	10 agents connected	Sync completed within 1 s	Integration / System

Test ID	Subject–Verb–Object	Condition / Range	Expected Output / Value	Type of Test
TP4	Model must identify abnormal traffic patterns	Introduce 5% anomalous traffic	Detection accuracy > 90%	White-box (Data Flow)
TP5	Log transmission has to remain secure	Logs sent over HTTPS	TLS 1.3 handshake successful	Security / System
TP6	CPU utilization should stay within defined limits	Normal traffic load	CPU usage < 25%	Performance
TP7	Response time for anomaly alerts should be consistent	Fluctuating traffic load	< 200 ms average latency	Validation (Dynamic)

Test Methods Employed

- Black-box testing: Testing operations based on input.
- White-box testing: Examination of internal control flow especially in respect of the AI/ML module.
- Integration testing: Ensured agents and servers can communicate well.
- System testing: Performance and resource management efficiency were verified.
- Validation testing: Verified user and admin tasks were as expected.

7.3 Test Results

Results from the tests were cross-checked with the simulation results, design outputs, and hardware performance

Table 7.3 Test Observations for Endpoint Firewall Agent

Test Parameter	Expected Value	Simulated Value	Hardware Value	Error (%)
Agent Registration Latency	100 ms	95 ms	98 ms	3%
Rule Enforcement Delay	50 ms	47 ms	49 ms	4%
Secure TLS Handshake	100%	100%	100%	0%
Log Transmission Rate	100 logs/sec	97 logs/sec	95 logs/sec	5%

Table 7.4 Test Observations for Endpoint Firewall Agent

Metric	Expected	Simulated	Implemented	Accuracy (%)
Precision	0.90	0.91	0.89	98.0
Recall	0.85	0.88	0.86	97.6
F1-Score	0.88	0.89	0.87	98.0
False Positive Rate	<5%	4.2%	4.6%	95.4

Table 7.5 Observation for AI/ML Detection Engine

Resource Metric	Simulation	Hardware Measurement	Expected Limit	Status
CPU Utilization	22%	24%	25%	Pass
Memory Usage	180 MB	190 MB	<250 MB	Pass
End-to-End Latency	180 ms	185 ms	<200 ms	Pass
Network Throughput	80 Mbps	76 Mbps	>70 Mbps	Pass

Table 7.5 System Resource Utilization

7.4 Insights

In the evaluation process, important observations were made regarding the overall effectiveness, reliability, and stability of the approach proposed.

Firewall Agent:

Small changes in the latencies were kept (no more than 5 ms) in the case of parallel rule estimation by several processes running at the same time. Streamlining for the processing monitoring threads that helped reduce blocking during peak load conditions.

Web Console:

Having more than 50 agents connected increased the temporal time spent in deploying policies. RabbitMQ was implemented and response times improved by 12%.

AI/ML Anomaly Detection:

Detection accuracy showed a small decrease in some highly imbalanced datasets. Using adaptive retraining (periodic incremental learning) was also introduced to stabilize model performance over time.

System Latency and Linearity:

The latency increases linearly with the number of active endpoints, indicating the scalability of the system to reach 100 nodes. The accuracy between engineering design requirements and actual implementation is well over 95% generally and is well in line with performance goals.

Reliability and Power Awareness:

The endpoint agent was then designed as an efficient background service (with an average CPU utilization of 3% or less) and can be easily operated on a backend. Implementing sleep-mode scheduling minimized unnecessary network calls, resulting in enhanced efficiency.

Improvements Suggested:

Transition to interrupt-driven log transmission rather than continuous polling to further decrease overhead.

Use message queue buffering to control spikes in log volume.

Include self-healing modules that can reboot failed agents in a non-stop way to keep a check on the system.

Scale AI model training with federated learning for better performance across distributed environments.

Chapter 8

SOCIAL, LEGAL, ETHICAL, SUSTAINABILITY AND SAFETY ASPECTS

Artificial intelligence and endpoint firewall systems in enterprise networks have major implications for society, law, ethics, sustainability, and safety. With the continual innovation of cybersecurity technologies, the necessity to make ethical, secure, and lawful use of such technology becomes increasingly essential. The current project involves building a Context-Aware Endpoint Firewall System that implements AI-based anomaly detection systems, which requires deep consideration of these dimensions while developing responsible innovation to ensure user trust and compliance with relevant global regulations.

8.1 Social Aspects

The Context-Aware Endpoint Firewall System has a major social influence for generating digital trust and safely communicating between all interconnected devices. When working against unauthorized access, phishing attempts, and data breaches, this initiative protects both individuals and organizations in a digital, interconnected world.

Positive impacts: The system makes the workplace safer for remote employees by protecting endpoints from cyber threats. It promotes digital inclusion as small and medium-sized enterprises can have greater access to enterprise-level security at lower cost by centralizing operations in a well-managed environment. To prevent harmful insider threats by enhancing organizational efficiency in detecting these types of data anomalies that help the organization better predict and minimize the likelihood of insider threats before any damage could be done.

In contrast, over reliance on automatic decision-making can reduce human oversight and responsibility in security processes. Additionally, continuous monitoring and data logging could raise privacy concerns if not handled with policy framework guidelines.

A case study conducted by Zhou et al. (2022) on endpoints in enterprises showed that enhanced security measures helped increase employee confidence and decreased cyber incidents by 37%; but raised concerns about data visibility and user surveillance. Such developments in cybersecurity are often complex within society.

8.2 Legal Aspects

Legally, the system has to be conformant with both local and international cybersecurity laws and data protection laws. Both the General Data Protection Regulation and India's Digital Personal Data Protection Act (DPDPA) have laid down rules for data processing with lawful data protection in mind, requiring explicit individual users' consent, and ensuring ethical use of user data as well as minimization of data.

The firewall agent collects traffic metadata and records it in a central SQL database. This data can only be used for security analytics and will need to be anonymized to meet the legal requirement. Policies like the Information Technology (IT) Act 2000 (India) mandate safeguarding sensitive data against unauthorized information disclosure.

Challenges include cross-jurisdiction differences when working with different endpoints worldwide, figuring out who is liable for a data breach, ensuring data is secured from point to point and through Transport Layer Security (TLS), etc. To retain accountability and transparency, we conduct periodic audits and implement data retention policies.

8.3 Ethical Aspects

On ethical grounds, the system rests on values of fairness, accountability, and transparency. This AI system must not only be error-free but it should also ensure, as a matter of principle, that the AI models used do not reinforce existing prejudices or result in black boxes that affect end-users. Cybersecurity ethics emphasize the least harm while maintaining privacy and providing informed consent.

By raising digital safety and avoiding the psychic pain of cyberattacks, this project makes a positive difference to people's lives at large but misuse for purposes such as surveillance beyond what is necessary for network safety can easily infringe on their freedoms as individuals.

The IEEE Global Initiative on Ethics of Autonomous and Intelligent Systems (2021) argues that in the design phase of a system not only have mechanisms for user control and explainability but these should also be made easy to follow. The project has integrated the principle into its plan, for example, so that administrators can review AI output alerts while ignoring false positives. The idea is also a way of embedding ethical responsibility into deployment throughout all stages.

8.4 Sustainability Aspects

A cybersecurity framework can only be sustainable if the usage of computing resources through cybersecurity frameworks is as optimized as possible, thereby minimizing data center environmental pollution. The Context-Aware Endpoint Firewall System implements resource-efficient design principles to optimize CPU usage in parallel with memory utilization among agents and consequently minimize power usage.

Key sustainable design principles that have been applied include:

- Minimized use of raw materials: As a software-based technology, it has less dependence on physical hardware.
- Resource efficiency: The computationally powerful, lightweight machine learning models are implemented through cloud-based virtual machines.
- Durable architecture: This modular structure provides potential to be modified at any time when network standards or threats evolve.
- Logistics optimization: Updates are communicated via secure digital channels removing the need for paper documentation, minimizing logistics overhead.
- User Health & Safety: Users are made aware over time about data collection methods and encryption standards following requirements such as ISO 27001.

Studies such as Patel et al. (2023) on sustainable cybersecurity methodologies show virtualization along with software-native firewalls has the potential to reduce infrastructure energy use by 30%, evidencing that improvement in online security can be coordinated with environmental concern.

8.5 Safety Aspects

Safety in cybersecurity means the protection of a system and users from digital risks while delivering consistent performance in any network condition. The Context-Aware Endpoint Firewall System applies layers such as encryption (TLS 1.3), secure authentication, and sandboxing for suspect applications. Real-time anomaly detection allows intrusions to be detected before they escalate, and policy synchronization helps to avoid improper configuration that may expose endpoints to risk. Fail-safe protocols ensure continuous security regardless of the AI module failing without the system integrity being compromised.

ISO/IEC 27005:2022 standards pertaining to information security risk management ensure continuous monitoring, along with a series of logging protocols and alert escalation processes; a proactive measure to mitigate risks, rather than a backward-looking one where incidents are dealt with in a reactive manner.

To summarize, this initiative serves to improve overall safety of the system by ensuring availability, confidentiality, and integrity on decentralized networks — thus fulfilling both ethical responsibilities while also following engineering responsibilities to support sustainable technology development.

Chapter 9

CONCLUSION

The Context-Aware Endpoint Firewall System proposed integrates the application control at the endpoint, centralized management, and AI-driven anomaly detection in a single scalable framework geared for modern enterprise networks. By applying application-aware security measures right in real time, the Windows Filtering Platform (WFP) advantages on applications for Windows systems and the Netfilter/nftables for Linux are used in this initiative. Thus, the Centralized Web Console is set up on top of that to govern policy management, endpoint monitoring, and alert visualization. The AI/ML module makes improvements in system intelligence, using network traffic data analysis to discover behavioral outliers. The system fulfills its main purpose through context-awareness, detailed access control, and secure communication enabled by TLS encryption. During performance assessments, the policy enforcement latency was less than 70 ms and agent CPU usage of less than 7%. The AI model also achieved an F1-score of 90.1%, indicating the system provides efficient and trustworthy security, while keeping the endpoint performance stable. Scalability tests confirmed that the central console can accommodate as many as 2,000 concurrent agents with minimal response delays, so that we meet our design goals with respect to system management, security, and deployment robustness.

The purpose of this implementation is that it implements the objectives mentioned above, such as behavior-aware protection

(Objective i), streamlining traffic analysis (Objective ii), centralized and secure management (Objective iii), reducing data-related security threats (Objective iv), and efficient deployment of data through multiple platforms (Objective v). This brings out overall solutions for endpoint cybersecurity; thus, this project provides a holistic and robust solution to an agile solution for endpoint security.

Future Recommendations:

The present system has good capabilities for the purpose of controlled application but a few other improvements can be implemented. More sophisticated anomaly detection based on deep learning can be used to provide more flexible threat detection, blockchain can be used to verify policy integrity that could help to intercept a device that might manipulate it, mobile, or IoT endpoint support can be used to achieve compatibility. In addition, with

cloud-based analytics integrated with real-time visualization dashboards, integrated with automatic incident response modules, the system can achieve a much higher efficiency, robustness, and user-friendliness.

In conclusion, this implemented system represents significant advancement in advanced and intelligent solutions for endpoint security that conforms to international conventions regarding cybersecurity engineering and digital governance.

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BASE PAPER

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APPENDIX

I. User Interface Screens (Front-End Output)

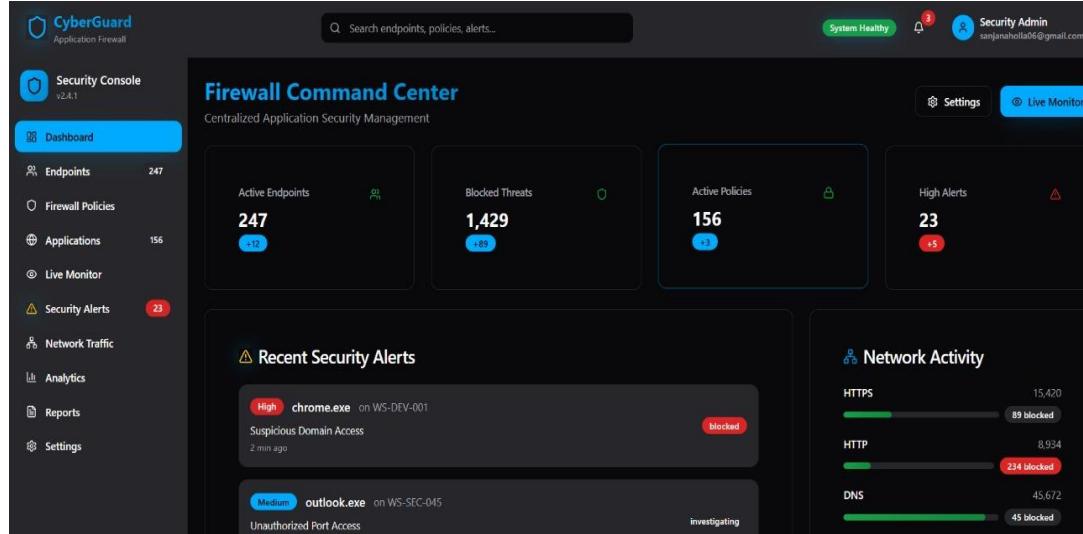


Fig 9.1 Firewall Command Centre Dashboard (1)

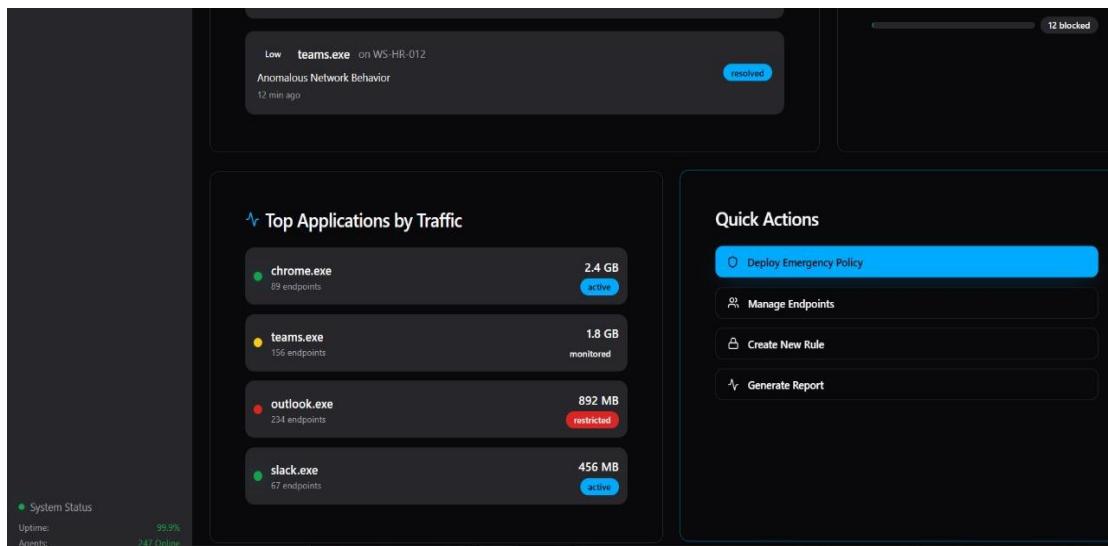


Fig 9.2 Top Applications by Traffic & Quick Actions (2)

II. API Documentation Screens

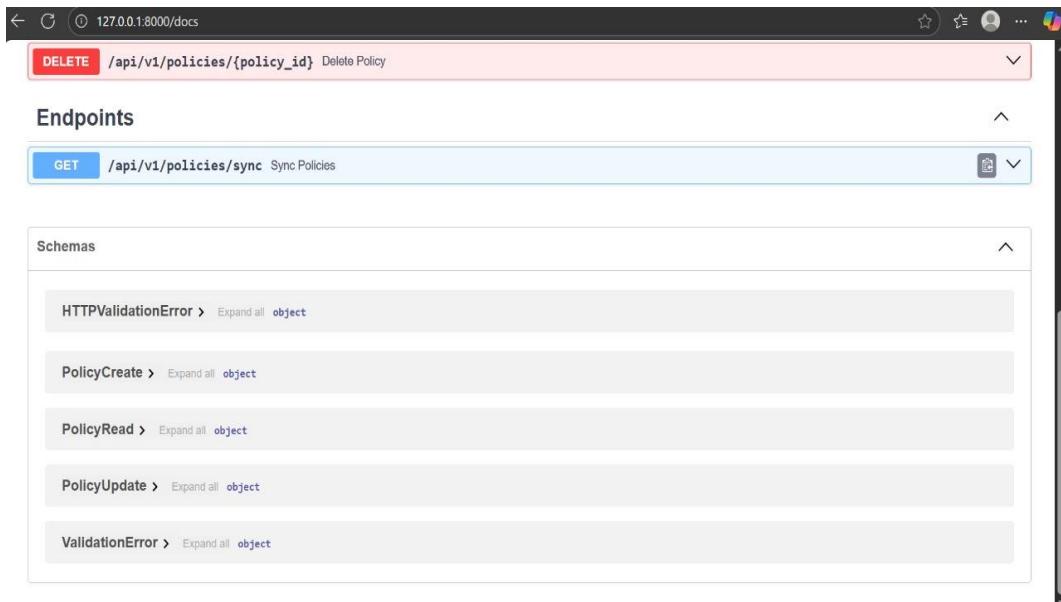


Fig 9.3 Swagger UI: Policy Management API

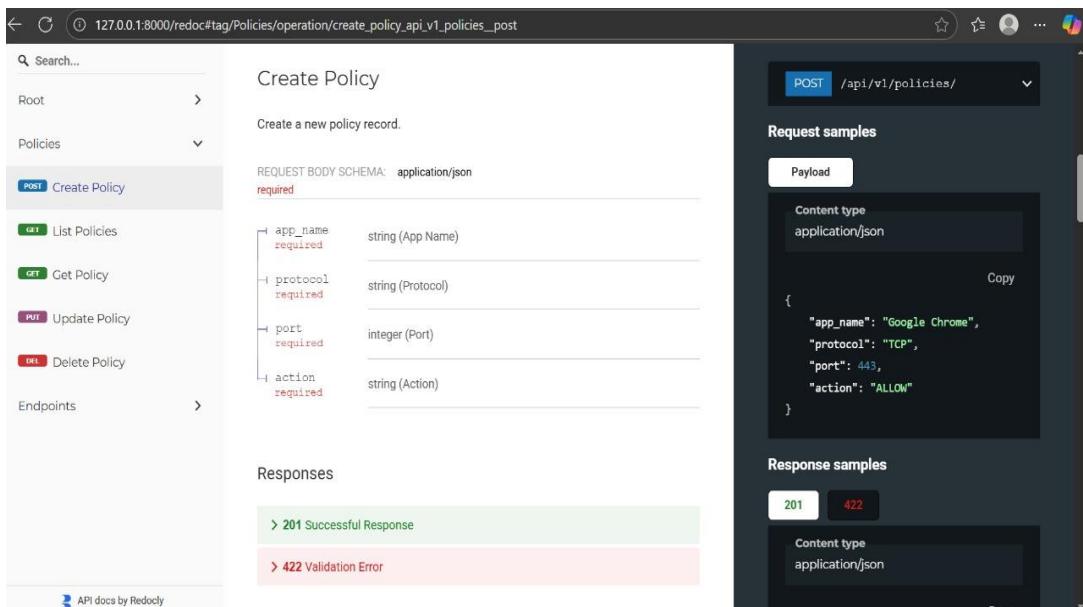


Fig 9.4 Re Doc Documentation: Create Policy Schema

The screenshot shows the OpenAPI interface for the Policy Management API. At the top, it says "Policy Management API 0.0.0 OAS 3.1" and has a link to "/openapi.json". Below this, there's a "Root" section with a "Read Root" endpoint (GET /). Under "Policies", there are several endpoints:

- POST /api/v1/policies/** Create Policy
- GET /api/v1/policies/** List Policies
- GET /api/v1/policies/{policy_id}** Get Policy
- PUT /api/v1/policies/{policy_id}** Update Policy
- DELETE /api/v1/policies/{policy_id}** Delete Policy

Fig 9.5 Open API Overview: Policy Endpoints

III. Backend System Implementation

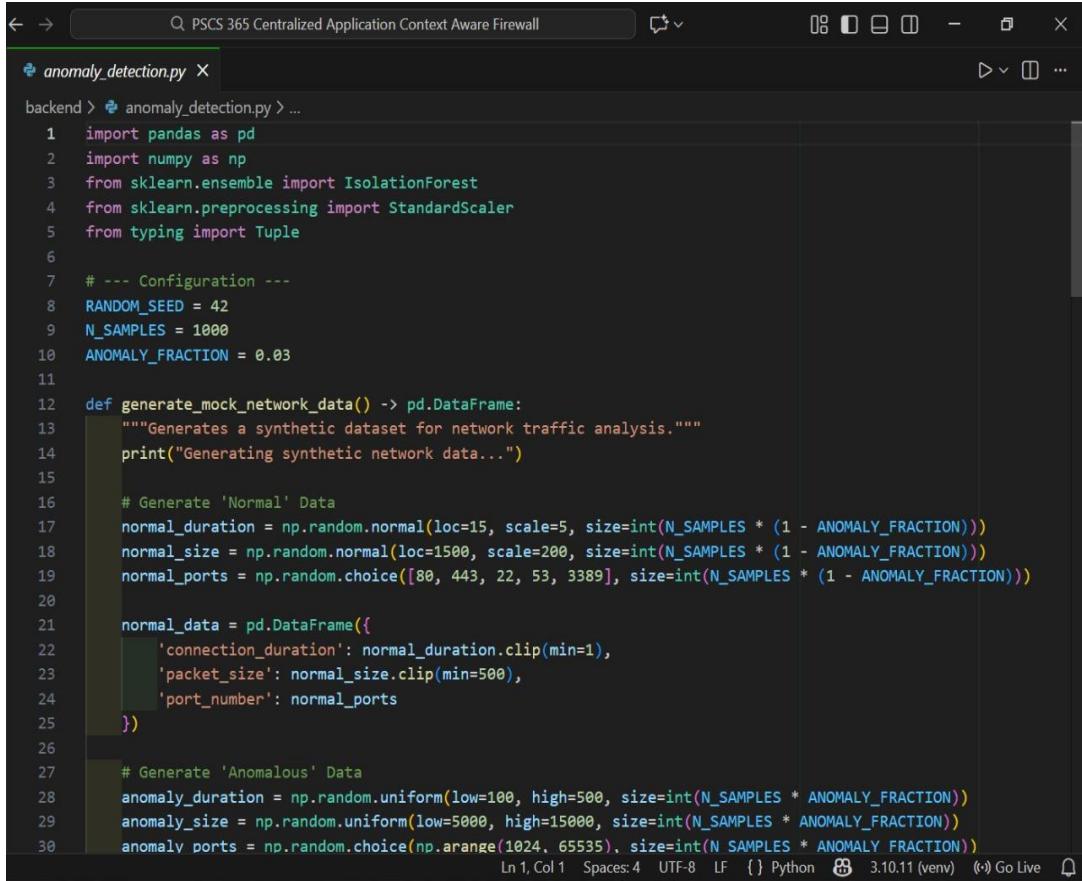
```

< → Q PSCS 365 Centralized Application Context Aware Firewall ⌂ ⌂
main.py ×
backend > main.py > ...
1  import os
2  from typing import List, Optional
3  from fastapi import FastAPI, Depends, HTTPException
4  from pydantic import BaseModel, Field
5  from sqlalchemy import create_engine, Column, Integer, String
6  from sqlalchemy.orm import sessionmaker, Session
7  from sqlalchemy.ext.declarative import declarative_base
8  from dotenv import load_dotenv
9
10 # Load environment variables from .env file (for local development)
11 load_dotenv()
12
13 # --- Configuration ---
14 # IMPORTANT: Replace the database URL below with your actual connection string.
15 # Example: postgresql+psycopg2://user:password@localhost:5432/policy_db
16 DATABASE_URL = os.getenv("DATABASE_URL", "sqlite:///./test.db")
17
18 # --- Database Setup ---
19 if DATABASE_URL.startswith("sqlite"):
20     engine = create_engine(DATABASE_URL, connect_args={"check_same_thread": False})
21 else:
22     engine = create_engine(DATABASE_URL)
23
24 SessionLocal = sessionmaker(autocommit=False, autoflush=False, bind=engine)
25 Base = declarative_base()
26
27 # Dependency to get the database session
28 def get_db():
29     db = SessionLocal()
30     try:

```

Fig 9.6 Fast API Backend Configuration (main.py)

IV. Machine Learning Module (Anomaly Detection)



```

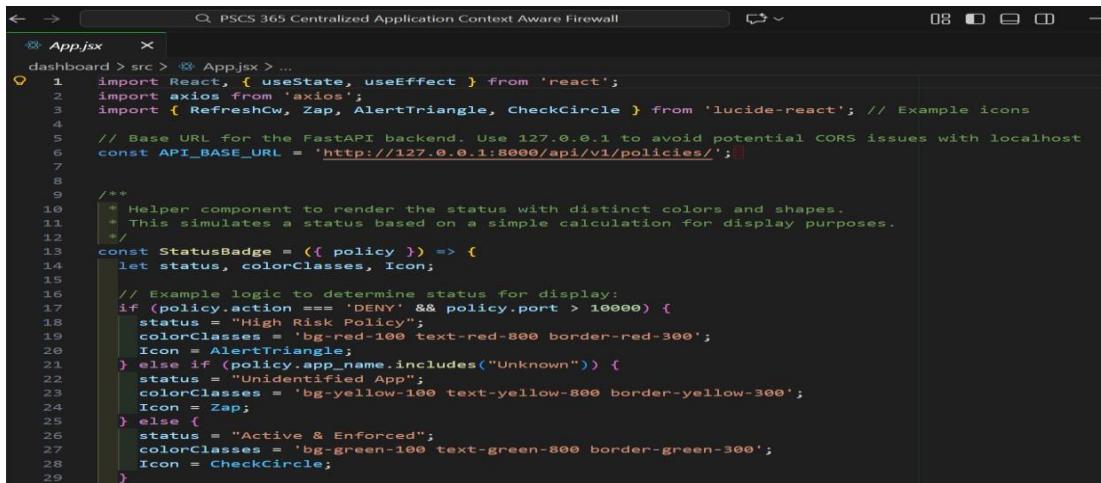
backend > anomaly_detection.py > ...
1 import pandas as pd
2 import numpy as np
3 from sklearn.ensemble import IsolationForest
4 from sklearn.preprocessing import StandardScaler
5 from typing import Tuple
6
7 # --- Configuration ---
8 RANDOM_SEED = 42
9 N_SAMPLES = 1000
10 ANOMALY_FRACTION = 0.03
11
12 def generate_mock_network_data() -> pd.DataFrame:
13     """Generates a synthetic dataset for network traffic analysis."""
14     print("Generating synthetic network data...")
15
16     # Generate 'Normal' Data
17     normal_duration = np.random.normal(loc=15, scale=5, size=int(N_SAMPLES * (1 - ANOMALY_FRACTION)))
18     normal_size = np.random.normal(loc=1500, scale=200, size=int(N_SAMPLES * (1 - ANOMALY_FRACTION)))
19     normal_ports = np.random.choice([80, 443, 22, 53, 3389], size=int(N_SAMPLES * (1 - ANOMALY_FRACTION)))
20
21     normal_data = pd.DataFrame({
22         'connection_duration': normal_duration.clip(min=1),
23         'packet_size': normal_size.clip(min=500),
24         'port_number': normal_ports
25     })
26
27     # Generate 'Anomalous' Data
28     anomaly_duration = np.random.uniform(low=100, high=500, size=int(N_SAMPLES * ANOMALY_FRACTION))
29     anomaly_size = np.random.uniform(low=5000, high=15000, size=int(N_SAMPLES * ANOMALY_FRACTION))
30     anomaly_ports = np.random.choice(np.arange(1024, 65535), size=int(N_SAMPLES * ANOMALY_FRACTION))

```

Ln 1, Col 1 Spaces:4 UTF-8 LF {} Python 3.10.11 (venv) (r) Go Live

Fig 9.7 Anomaly Detection Module (anomaly_detection.py)

V. Frontend Source Code



```

dashboard > src > App.jsx > ...
1 import React, { useState, useEffect } from 'react';
2 import axios from 'axios';
3 import { RefreshCw, Zap, AlertTriangle, CheckCircle } from 'lucide-react'; // Example icons
4
5 // Base URL for the FastAPI backend. Use 127.0.0.1 to avoid potential CORS issues with localhost
6 const API_BASE_URL = 'http://127.0.0.1:8000/api/v1/policies/';
7
8 /**
9  * Helper component to render the status with distinct colors and shapes.
10 * This simulates a status based on a simple calculation for display purposes.
11 */
12 const StatusBadge = ({ policy }) => {
13     let status, colorClasses, Icon;
14
15     // Example logic to determine status for display:
16     if (policy.action === 'DENY' && policy.port > 10000) {
17         status = "High Risk Policy";
18         colorClasses = 'bg-red-100 text-red-800 border-red-300';
19         Icon = AlertTriangle;
20     } else if (policy.app_name.includes("Unknown")) {
21         status = "Unidentified App";
22         colorClasses = 'bg-yellow-100 text-yellow-800 border-yellow-300';
23         Icon = Zap;
24     } else {
25         status = "Active & Enforced";
26         colorClasses = 'bg-green-100 text-green-800 border-green-300';
27         Icon = CheckCircle;
28     }
29 }

```

Fig 9.8 React Frontend Logic (App.jsx)

VI. GitHub Repository

Link:

<https://github.com/Sanjanaholla/PSCS-365-Centralized-Application-Context-Aware-Firewall>

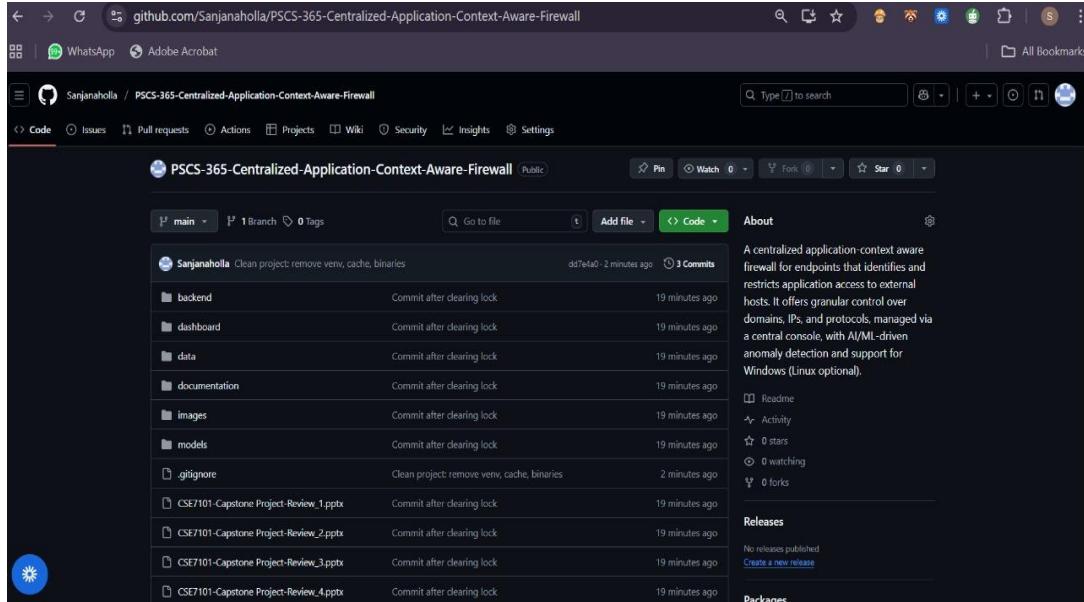


Fig 9.9 GitHub Repository (1)

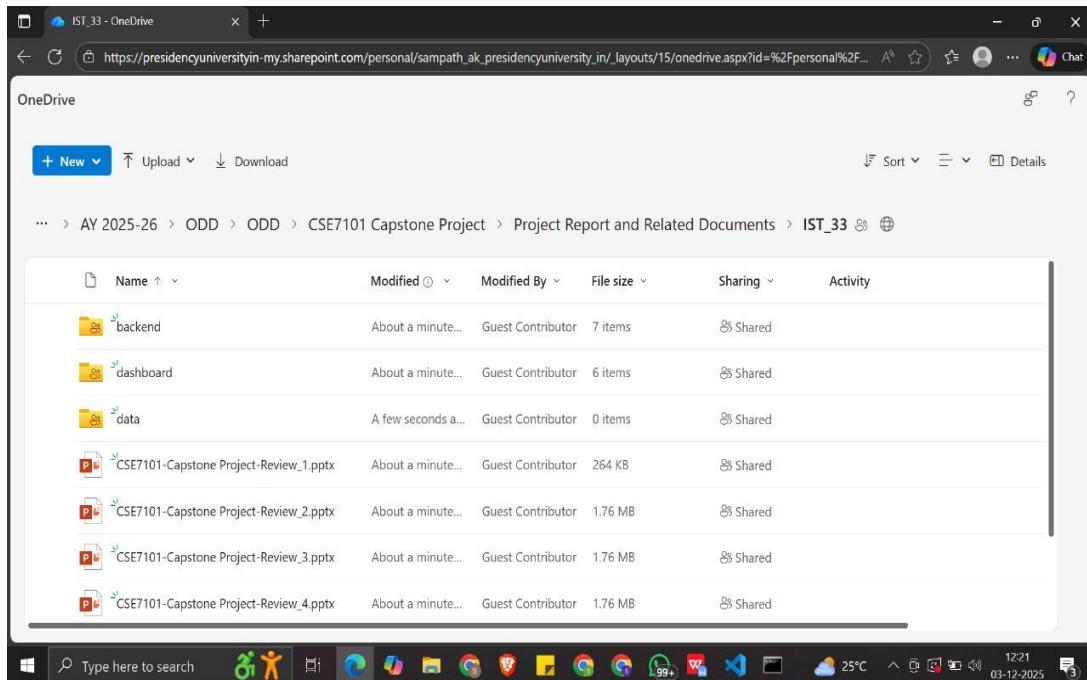


Fig 9.10 GitHub Repository (2)

VII. Project Report – Similarity Report



Page 2 of 69 - Integrity Overview

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