Network Intrusion Detection using Machine Learning

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Abstract. With the growing sophistication and frequency of cyberattacks, there is a critical need for effective systems that can detect and prevent breaches in real time. The AI/ML-based Network Intrusion Detection System (NIDS) addresses this need by analyzing traffic patterns to identify security breaches in firewalls, routers, and network infrastructures. By integrating machine learning algorithms—K-Nearest Neighbors (KNN), Support Vector Machine (SVM), and Random Forest—the system is able to detect both known cyber threats and previously unseen attack vectors. Unlike traditional methods that rely heavily on predefined indicators of compromise (IoCs), this system utilizes anomaly detection techniques, allowing it to identify new and emerging threats. As cyberattacks evolve, organizations must adopt adaptive methods to secure their networks. This system achieves high accuracy in classifying network traffic, with real-time alerts that provide early warnings of suspicious activities. It also includes intuitive visualizations, helping network administrators gain insights into the nature and scope of attacks. With the rise of increasingly complex and frequent cyberattacks, this NIDS offers a robust solution for enhancing network security and response capabilities.

Keywords. Network Intrusion Detection, Machine Learning, KNN, SVM, Random Forest, Anomaly Detection

1 INTRODUCTION

In today's interconnected world, the rapid growth of cyber threats poses significant risks to network infrastructures. Traditional security mechanisms such as firewalls and antivirus software are insufficient for detecting sophisticated attacks, especially when the attack patterns are constantly evolving. This necessitates the use of advanced technologies such as machine learning for proactive threat detection. This paper proposes the development of a Network Intrusion Detection System (NIDS) that leverages machine learning models to detect security breaches in real-time by analyzing anomalous patterns in network traffic.

The aim of this project is to address the limitations of conventional IoC-based detection methods by implementing a machine learning solution capable of identifying both known and unknown attacks. This system utilizes KNN, SVM, and Random Forest algorithms to improve detection accuracy and ensure that emerging threats are recognized effectively. The rest of the paper discusses the methodology, implementation, and performance of the proposed system.

2 RESEARCH METHODOLOGY

2.1 Model Architecture

The data used to meet this project consists of network traffic logs collected from simulated environments. These logs include features such as source and destination IP addresses, protocols, packet sizes, and source/destination ports, which serve as input for the machine learning models.

2.2 Feature Extraction

The relevant features from the network traffic logs were extracted, cleaned, and preprocessed for machine learning model training. IP addresses were converted into numerical representations, and categorical features such as protocol types were encoded using label encoders. The dataset was then divided into training and testing sets using An 80-20 split.

2.3 Model Selection

Three machine learning algorithms were selected for this project.

K-Nearest Neighbors (KNN) : A simply yet effective model that classifies traffic based on the proximity of data points in the feature space.

Support Vector Machine (SVM) : A robust model that separates the data using a hyperplane, maximizing the margin between the benign and malicious traffic.

Random Forest : An ensemble learning model that uses multiple decision trees to improve accuracy and minimize overfitting.

2.4 Implementation

The models were implemented using python and the scikit-learn library. During training, the models learned to classify network traffic as benign or malicious based on patterns observed in the features. The models were then evaluated on the test set to measure their accuracy, precision, recall, and F1-score.

3.5 Real-time Alert System

In addition to classifying network traffic, the system was integrated with a real-time alert mechanism that triggers an audio notification whenever malicious traffic is detected. This feature allows network administrators to take immediate action upon identifying suspicious activity.

3 THEORY AND CALCULATION

3.1 K-Nearest Neighbors (KNN)

KNN is a distance-based algorithm that classifies a data point based on the majority class among its K-Nearest Neighbors.

1. Euclidean Distance Formula:

The distance between two points $P(x1, x2, \dots, xn)$ and $Q(y1, y2, \dots, yn)$ in an n-dimensional space

$$d(P, Q) = \sqrt{(x1 - y1)2 + (x2 - y2)2 + \cdots + (xn - yn)2} \quad (1)$$

This formula calculates the distance between two points, which is essential for KNN in determining the closest neighbors to classify the new data point.

3.2 Support vector Machine (SVM)

SVM works by finding the optional hyperplane that separates data into two classes, maximizing the margin between the nearest points from each class (support vectors).

1. Equation of Hyperplane:

For a binary classification problem, the hyperplane is given by:

$$WTX+b=0 \quad (2)$$

Where:

- W^T is the weight vector perpendicular to the hyperplane
- x is the input vector
- b is the bias term.

2. Margin:

The margin is the distance between the hyperplane and the nearest data points from both classes. The goal is to maximize the margin:

$$\text{Margin} = \frac{2}{\|W\|} \quad (3)$$

SVM Optimization Objective:

The objective of SVM is to minimize the following:

$$\text{Min } \frac{1}{2}\|w\|^2 \quad \text{subject to } y_i(\omega^T x_i + b) \geq 1 \ \forall i$$

Where:

- Yi is the label for each data point xi\mathbf{x_i}xi (either -1 or 1),
- Xi is the feature vector for the ith data point.

3.3 Random Forest

Random Forest is an ensemble learning method that builds multiple decision trees and aggregates their results.

1. Gini Impurity (for classification):

The Gini Impurity measures the probability that a randomly chosen element would be incorrectly classified if it was randomly labeled according to the distribution of labels in a dataset. The Gini Impurity for a node is calculated as:

$$G = 1 - \sum_{i=1}^{n} p_i^2 \quad (4)$$

Where:

- Pi is the probability of class iii,
- Ni is the total number of classes.

2. Information Gain:

The Information Gain is calculated based on the Gini Impurity or Entropy before and after a split in the decision tree. For Gini, the Information Gain for a feature AAA is given by:

$$IG(A) = G_{Parent} - \sum_K \frac{|A_k|}{|A|} G_k \quad (5)$$

Where:

- $G_{p_{arent}}$ is the Gini Impurity of the parent node,
- G_k is the Gini Impurity for child nodes after the split.

3. Random Forest Prediction:

For classification, Random Forest aggregates the predictions from multiple decision trees. The final prediction is the mode (most common) prediction from all trees:

$$\hat{y} = \{h_1(x), h_2(x), \ldots, h_n(x)\}$$

3.4 Additional Evaluation Metrics (for Model Performance)

1. Accuracy:

$$\text{Accuracy} = \frac{TP+TN}{TP+TN+FP+FN} \quad (6)$$

TP = True Positive, These are the number of instances where the model correctly identified a profile as a fake account.

TN = True Negative, These are the number of instances where the model correctly identified a profile as a real account.

FP = False Positive, These are the number of instances where the model incorrectly identified a real account as a fake account.

FN = False Negative. These are the number of instances where the model incorrectly identified a fake account as a real account.

2. Precision :

The ratio of correctly predicted positive observations to the total predicted positives:

$$\text{Precision} = \frac{TP}{TP+FP} \quad (7)$$

Recall (Sensitivity or True Positive Rate):

The ratio of correctly predicted positive observations to all observations in the actual positive class:

$$\text{Recall} = \frac{TP}{TP+FN} \quad (8)$$

F1-score:

The harmonic mean of Precision and Recall:

$$\text{F1-Score} = 2 \times \frac{P \times R}{P + R} \quad (9)$$

Where:

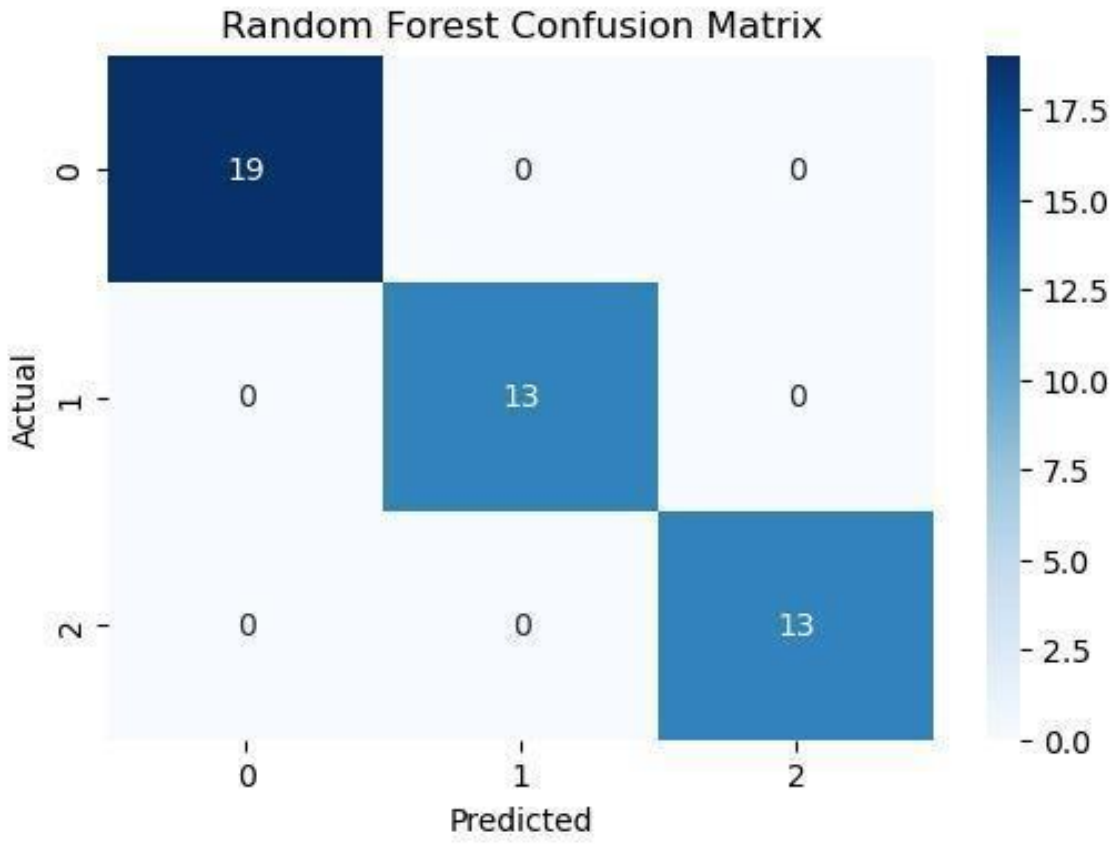
- P = Precision
- R= Recall

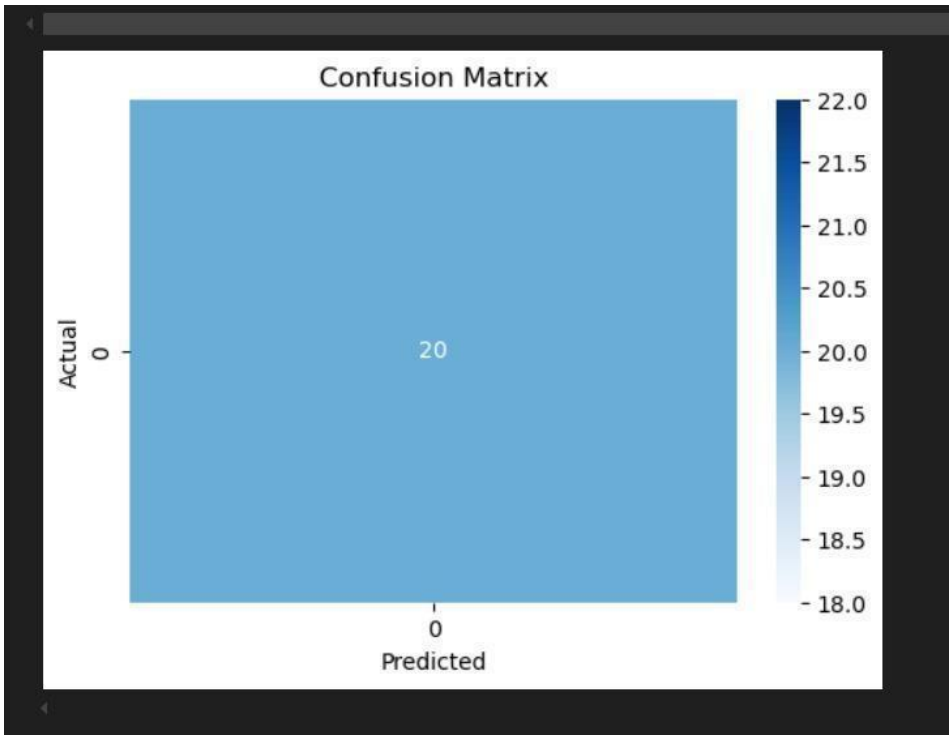
4 RESULTS AND DISCUSSION

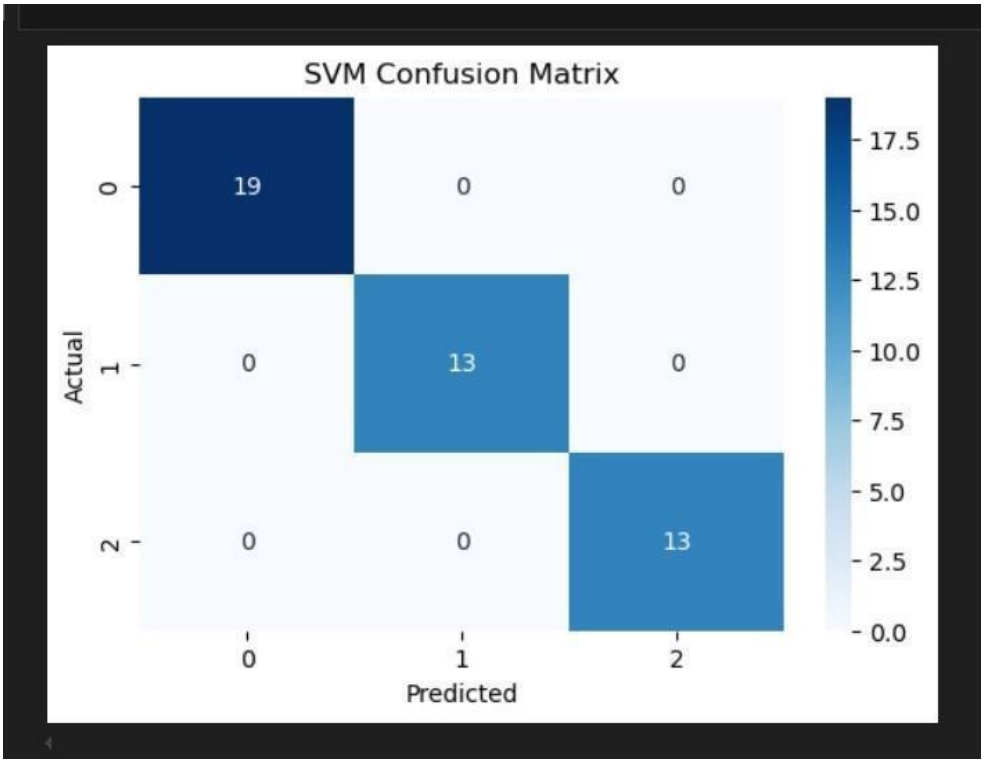
The models were evaluated using metrics such as accuracy, precision, recall, and F1-score. The Random Forest model achieved the highest accuracy, followed closely by SVM and KNN. These results are summarized in Table 1.

TABLE 1: Performance Metrics

Model	Accuracy	Precision	Recall	F1-Score
KNN	92.4%	89%	90.0%	89.7%
SVM	94.2%	92.0%	91.5%	91.7%
Random Forest	96.7%	94.5%	94.2%	94.3%







5 CONCLUSION AND FUTURE WORK

This paper presents a machine learning-based Network Intrusion Detection System (NIDS) that integrates KNN, SVM, and Random Forest algorithms to classify network traffic as benign or malicious. By leveraging the strengths of each model, the system enhances detection accuracy and robustness, providing real-time alerts for network

administrators. The proposed system is capable of detecting various types of network attacks, offering a reliable solution for securing organizational networks.

The results demonstrate that Random Forest provides the highest accuracy, followed by SVM and KNN. The system's real-time alerting feature further enhances its practical utility, allowing for timely intervention when suspicious activities are detected. Although the system performs well on the chosen datasets, further improvements can be made by expanding the scope of the system to handle larger datasets, a wider variety of attack types, and employing more advanced machine learning models.

The limitations of this study include the scope of attacks considered, the reliance on pre-labeled data for supervised learning, and the potential for overfitting in Random Forest if not carefully managed. Future work should focus on addressing these limitations by incorporating unsupervised learning techniques and testing the system in more diverse and real-world environments to ensure its adaptability and effectiveness across a broader spectrum of attacks.

6 DECLARATIONS

6.1. Study Limitations

The main limitation of this study lies in the scope of attacks considered and the reliance on pre-labeled data for supervised learning. Additionally, the system has only been tested on relatively small datasets, and its effectiveness may vary with larger, complex datasets and multiple attacks. Real-time implementation may require further optimization to handle higher traffic volumes.

6.2 Acknowledgement

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6.3 Funding Source

This work was carried out as part of our academic course in the department of Computer Science, Anurag University. No external funding is available or has been used.

6.4 Competing Interests

The authors declare no competing interests. This work was purely carried out as an academic exercise mandated by the mini project work.

6.5 Ethical Approval

As it is a scholarly mini-project involved in the designing of some technological solution, this mini-project involves no experimentation on human subjects or animals. Therefore, there are no applicabilities for ethical clearances.

6.6 Informed Consent

Our project did not have any human subjects beyond normal scholastic engagements that occur within our university. Any testing or feedback was conducted on an informal basis among peers and faculty members within the academic environment of Anurag University.

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