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Swarm Intelligence-Based Intrusion Detection Framework Using Neural Network & Bee Colony Optimiation

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Abstract

An Intrusion Detection System (IDS) serves as a critical defense mechanism for safeguarding networks against unauthorized activities and cyber attacks. However, the processing of sophisticated datasets with contemporary detection methodologies often presents challenges due to their intricate scale, complicating the identification of complex threats. This study aims to enhance IDS operational efficacy through the development of a novel method integrating Bee Colony Optimization (BCO) and Neural Networks (NN). Employing a quasi-experimental design, the research evaluates the system's performance, demonstrating that the integration of BCO significantly optimizes neural network functionality, thereby improving both the speed of attack detection and the accuracy of feature selection. Utilizing the NSL-KDD dataset, the proposed framework notably minimizes false alerts while augmenting overall detection accuracy levels. The findings underscore that advancements in cybersecurity systems can be achieved through the synergy of Neural Networks and Swarm Intelligence technology, providing effective solutions for real-time intrusion detection systems. This research not only contributes to the theoretical understanding of IDS optimization but also has

practical implications for enhancing cybersecurity measures in various organizational contexts.

Keywords: Intrusion Detection System, Neural Networks, Bee Colony Optimization, Cybersecurity, Swarm Intelligence.

INTRODUCTION

Digital technology growth at a rapid pace and network system intricacy created cybersecurity as a vital field of study. Modern networks currently fight ongoing security threats stemming from unauthorized users and malware and extensive DoS attacks. Organizations need robust smart Intrusion Detection Systems (IDS) continuously because malicious threats develop progressively in complexity.

Intrusion Detection Systems exist to monitor network activity for detecting security threats that target network systems. The traditional IDS functioning depends on signature-based and anomaly-based detection techniques to detect anomalies. Attack signature analysis through signature-based IDS successfully detects known security threats although the system fails to identify previously unidentified threats because of its signature approach. The signature-based IDS technology struggles to detect new threats and zero-day attacks because these incidents do not have recorded signatures (Liu et al., 2017).

Anomaly-based IDS functions through monitoring any variation from recognized parameters of typical system operations. The contemporary security systems demonstrate excellent performance when finding new security risks although they encounter problems with both false alerts and massive data processing (Shin et al., 2016). Traditional IDS methods have led researchers to develop adaptive and intelligent security approaches because of their essential operational flaws.

Machine Learning detection tools function with advanced technological capabilities to identify unpredictable attack signatures that have complicated structures. Neural Networks (NNs) can learn complex patterns in large datasets because of their promising characteristics through pattern discovery. Detecting distribution pattern modifications and non-linear relationships operating beneath surfaces is possible for neural systems because their learning abilities surpass conventional detection methods (Feng et al., 2019). Neural networks deliver precise solutions because of their core strength that comes with the need

to solve several technical challenges for implementation. The execution of IDS systems faces two challenges: problems in selecting features combined with parameter error stability that reduces operational effectiveness according to Zhang et al. (2018).

Swarm Intelligence functions as a group of natural algorithms which lets researchers develop optimization models through studying social organism behaviors to solve different drawbacks. Artificial bee colony stands among the best techniques within swarm intelligence. BCO achieves effective search because it employs decentralized group determination together with learning collaboration systems which conform to the natural foraging behavior of honeybees (Karaboga, 2005). Researchers who need to optimize model features alongside hyperparameters alongside constructing machine learning models can successfully apply this method.

A combined BCO and neural networks framework produces an IDS system which automatically picks features to deliver improved defense capabilities together with minimal false alert frequencies.

Research Problem

The research uses BCO to optimize NN structure in developing network security solutions for basic network defense. BCO optimization adds value to neural networks by improving the performance of network intrusion detection systems while providing both better accuracy and efficiency benefits.

This research study reaches two main objectives through its assessment steps:

Research performs a complete evaluation of Bee Colony Optimization as it determines appropriate features and parameter optimization methods that boost neural networks learning abilities and improve generalization performance in intrusion detection systems.

Security threat evaluations need to take place several times before implementing a framework to optimize detection accuracy through reduced numbers of wrong detections.

Modern IDS needs apply the proposed hybrid security system due to its adaptive capabilities which match the daily evolving cyber threats.

Science investigators perform studies to develop defense mechanisms that sustain distinctiveness for advanced cyber threats.

Traditional Intrusion Detection Systems

Network infrastructures have depended on Intrusion Detection Systems (IDS) since a long time for protecting against harmful activities. The traditional detection methods of IDS include signature-based and anomaly-based systems. The process of signature-based IDS involves comparing incoming data with a database of attack patterns known as signatures which serve as the repository. The detection strength of signature-based IDS remains high for identifying past dangers yet they show no effectiveness against zero-day attacks and fresh intrusion techniques (Ghorbani et al., 2009).

Anomaly-based IDS operates by watching network activities to detect deviations from standard accepted patterns. The detection models demonstrate superior capabilities to detect unknown threats that occur before the system has encountered them. These IDS methods have an important limitation that creates numerous false alarm alerts which need manual verification and automated filtering procedures (Ahmed et al., 2016).

Traditional IDS systems required machine learning integration because their limitations prompted the need to develop adaptable detection models during recent years. Systems obtain training from labeled datasets to create their pattern detection capabilities for known and unknown attack patterns (Moustafa et al., 2015).

Machine Learning for Intrusion Detection

Artificial Neural Networks (ANNs) function as premier tools among ML technicalities in IDS applications because they excel at evaluating complex multidimensional network relationships. Dynamic cybersecurity operations get better with ANN technology since the system approves previously unidentified cyberattack patterns based on established examples (Al-Kafri et al., 2020).

Several researchers have performed studies about ANNs within intrusion detection systems. Moustafa and Slay (2015) determined the implementation method for combining MLP and RBF networks for anomalous network traffic detection. The implementation of proposed models within the field environment generated various negative effects that resulted from model overfitting and incorrect feature selection alongside improper hyperparameters.

The scientific field devotes research efforts to enhance ANNs functionality by combining work on optimal features selection with parameter improvement. The wrong choice of

features together with noisy integration causes both time-intensive procedures and incorrect predictions. Bio-inspirational optimization techniques serve as current solutions for both valuable feature selection and network component optimization because of these requirements.

Swarm Intelligence in Intrusion Detection Systems

The efficient processing of complex multi-dimensional data relations by ANNs has established them as crucial methods for IDS development in the field of ML. ANNs operate perfectly in dynamic cybersecurity situations since their ability to learn through examples combined with their attack pattern recognition capability (Al-Kafri et al., 2020).

Scientific studies have repeatedly analyzed the applications of ANNs in intrusion detection research. Moustafa and Slay (2015) performed a research analysis to assess MLP and RBF networks as anomaly detection solutions for network traffic monitoring systems. Model overfitting and both helpful and unhelpful features and insufficient parameter settings limited the scalability and operational effectiveness when the promising results were deployed in actual environments.

Current ANN model performance improves due to modern academic research which optimizes both feature selection methods and parameter selection processes. Analysis that incorporates suboptimal features leads to two primary issues because it increases computational requirements and reduces prediction accuracy. Bio-inspired optimization methods now serve as crucial tools for automatic selection of important features and optimization of network parameters settings.

Swarm Intelligence (SI) refers to a family of optimization algorithms inspired by the collective behavior of social organisms such as birds, ants, and bees. These algorithms excel at exploring large, complex search spaces and have proven particularly effective for improving machine learning performance.

Popular SI algorithms include Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO). These methods have been widely applied in the context of IDS. For example, Farid et al. (2014) employed ACO for feature selection in a network intrusion detection task, which led to better classification accuracy by reducing irrelevant attributes. Similarly, Gonzalez et al. (2013) used PSO for hyperparameter tuning, enhancing the performance of classification models in detecting cyber threats.

Despite the popularity of ACO and PSO, the application of Bee Colony Optimization (BCO) in the IDS domain remains relatively underexplored. Originally introduced by Karaboga (2005), BCO is inspired by the foraging behavior of honeybees. It balances global exploration and local exploitation in an efficient way, making it a strong candidate for solving complex optimization problems (Akay et al., 2012).

Bee Colony Optimization for Feature Selection

In recent years, Bee Colony Optimization has shown increasing promise in the realm of feature selection for classification tasks. BCO operates through the collective efforts of artificial "bees" exploring different solutions and sharing information to converge on optimal feature subsets. Karaboga and Gorkemli (2012) demonstrated that BCO not only competes with but can also outperform other SI algorithms in terms of convergence speed and solution quality in feature selection problems.

One notable application of BCO in intrusion detection was carried out by Saravanan and Suganthi (2019), who used the algorithm to select features for a Support Vector Machine (SVM)-based IDS. Their findings revealed a significant increase in detection accuracy, along with a notable reduction in false alarms. This illustrates BCO's potential to improve IDS performance by refining the input feature space. However, the combination of BCO with neural networks in the context of intrusion detection remains largely unexplored, representing a meaningful research opportunity.

Hybrid Approaches

Recent developments in IDS have seen the rise of hybrid models, which combine machine learning with optimization algorithms to exploit the strengths of both approaches. Ahamad et al. (2020) introduced a model that integrated PSO with a Convolutional Neural Network (CNN), enabling the system to learn both low-level and high-level features while simultaneously optimizing hyperparameters. Similarly, Gonzalez et al. (2013) enhanced deep neural network training through PSO-based optimization, improving classification performance in detecting various types of intrusions.

While these hybrid methods have demonstrated substantial gains in detection capabilities, most of them focus on PSO or ACO. There is still a notable gap in the literature concerning the integration of Bee Colony Optimization with neural networks for IDS. Addressing this gap, the present study proposes a novel framework that combines BCO

with ANN, aiming to optimize both the input features and network parameters to enhance detection accuracy, reduce false positives, and ensure better generalization to unseen data.

METHODOLOGY

Problem Formulation

Network traffic instances are classified through binary classification techniques into normal benign or attack malicious categories. The proposed system combines Bee Colony Optimization (BCO) for feature extraction and Artificial Neural Networks (ANN) for classification purposes to enhance detection accuracy and reduce both computational costs and false detections. Let

- $X = \{x_1, x_2..., x_n\}$ represent the set of input features extracted from the dataset, and
- $Y \in \{0,1\}$ be the corresponding class label, where 0 denotes normal traffic and 1 denotes an intrusion.

The objective is to learn a mapping $f : X' \rightarrow y$, where $X' \subset X$ is an optimal feature subset selected using BCO, that maximizes classification accuracy while reducing model complexity.

Dataset and Preprocessing

This study utilizes the NSL-KDD dataset, an enhanced version of the KDD Cup 1999 dataset, widely adopted in IDS research. It contains labeled connection records with 41 features and includes multiple types of attacks:

- DoS (Denial of Service)
- Probe
- U2R (User to Root)
- R2L (Remote to Local)

To ensure data quality and model readiness, the following preprocessing steps are applied:

1. Data Cleaning
    - Missing values are imputed using the median for skewed features and mean for normally distributed features.

2. Normalization
    - Continuous features are scaled to the range [0,1] using Min-Max **Normalization**:

$$x' = \frac{x - x_{\min}}{x_{\max} - x_{\min}}$$

3. Categorical Encoding
    - Categorical features (e.g., protocol type, service, flag) are transformed using one-hot encoding or label encoding, depending on the feature's cardinality.
4. Dataset Splitting
    - The dataset is split into training (80%) and testing (20%) sets using stratified sampling to preserve class distribution.

Bee Colony Optimization for Feature Selection

Feature selection is pivotal in reducing dimensionality, mitigating overfitting, and accelerating training. Bee Colony Optimization (BCO), inspired by the foraging behavior of honeybees, is employed to search for the most informative feature subset.

Encoding Scheme:

Each bee represents a candidate solution as a binary vector $\vec{F} = [f_1, f_2, \ldots, f_n]$ where

$$f_i = \begin{cases} 1, & \text{if feature } i \text{ is selected} \\ 0, & \text{otherwise} \end{cases}$$

Fitness Function:

Each solution is evaluated using the classification accuracy of a lightweight ANN model on a validation subset:

$$\text{Fitness} = \text{Accuracy} = \frac{TP + TN}{TP + TN + FP + FN}$$

Algorithm 1: Bee Colony Optimization for Feature Selection

Input: Feature set X, Training data D, Number of bees N, Max iterations T

Output: Optimal feature subset F*

1. Start the process with N bees who use random binary vectors (candidate feature subsets) as initialization.

2. For each bee:

a. Apply a neural network training process using the chosen features.

b. Evaluate classification accuracy as fitness

3. While (t < T):

a. The employed bees both locate and modify their positions in the search space.

b. People should evaluate each possible bee selection by implementing roulette selection.

The selection process determines good solutions through the actions of observing bees who improve these options.

d. The process of scout bees entails replacing stagnated solutions through random choice

e. From the identified feature subsets continue executing the search and update F* with a found superior solution.

4. Return F*

Neural Network Architecture

With the optimal feature subset selected by BCO, a Feedforward Neural Network (FNN) is constructed and trained for intrusion detection.

- Input Layer:
  The number of neurons equals the number of selected features d.

$$\text{Input dimension} = |F^*|$$

- Hidden Layers:
  One or two hidden layers are used. The number of neurons is determined through cross-validation, typically ranging between 16–64 neurons. ReLU activation is applied:

$$f(x) = \max(0, x)$$

- Output Layer:
  A softmax layer with two neurons for binary classification:

$$\text{Softmax}(z_i) = \frac{e^{z_i}}{\sum_j e^{z_j}}$$

- Loss Function:
  Binary cross-entropy is used to measure the error:

$$\mathcal{L}(y, \hat{y}) = -[y \log(\hat{y}) + (1 - y) \log(1 - \hat{y})]$$

- Optimizer:
  The Adam optimizer is selected due to its adaptive learning rate and robustness to sparse gradients.
- Training Strategy:
  - Batch training with early stopping (monitors validation loss)
  - Learning rate and batch size tuned via grid search

Model Evaluation

The model's performance is evaluated using multiple metrics to provide a comprehensive view:

- Accuracy:

$$\text{Accuracy} = \frac{TP + TN}{TP + FP + TN + FN}$$

- Precision:

$$\text{Precision} = \frac{TP}{TP + FP}$$

- Recall (Sensitivity):

$$\text{Recall} = \frac{TP}{TP + FN}$$

- F1 Score:

$$\text{F1} = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}}$$

- Confusion Matrix:
  Tabulates TP, TN, FP, and FN to visually assess classification behavior.
- ROC Curve & AUC:
  ROC evaluates performance across different thresholds; AUC quantifies the overall ability of the model to distinguish between classes.

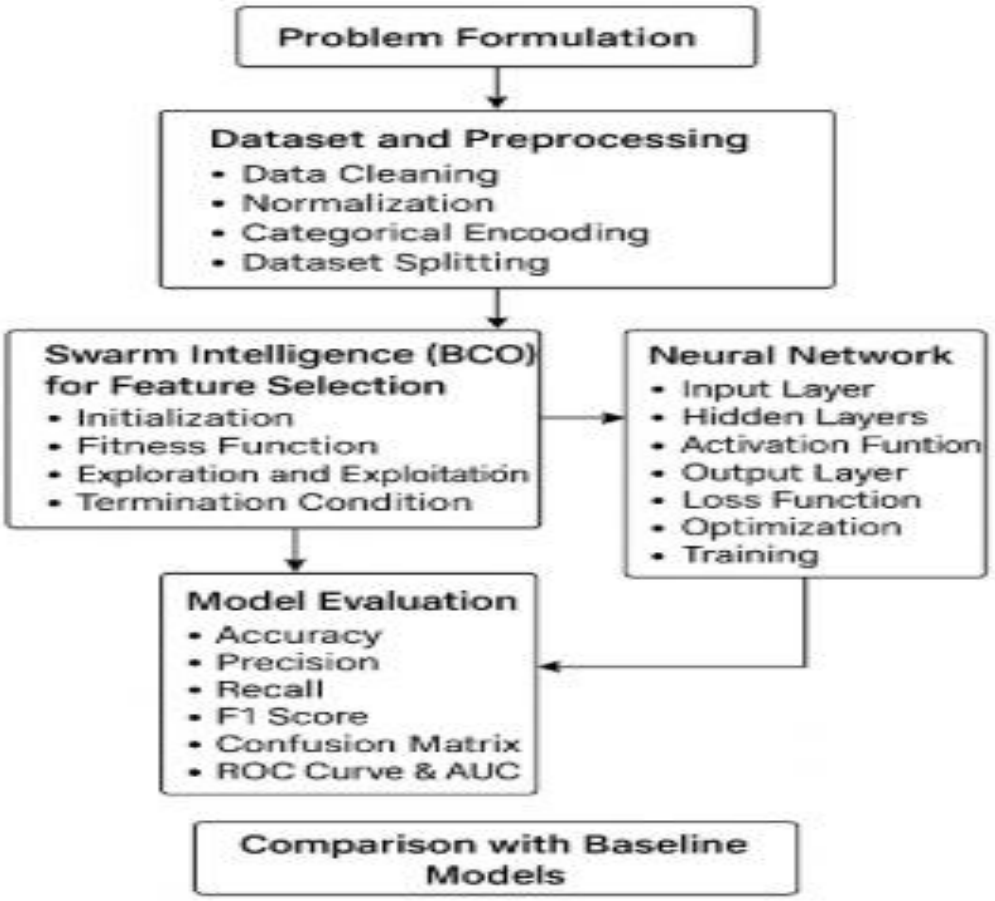
Baseline Comparisons

To validate the proposed framework, it is benchmarked against several traditional models:

- Standard Neural Network (no feature selection)
- Random Forest (RF): Ensemble method using decision trees
- Support Vector Machine (SVM): Effective for high-dimensional binary classification

These baselines serve as references to demonstrate the improvement introduced by incorporating BCO in both feature selection and parameter optimization.

Architecture of the Proposed Swarm Intelligence-Based Intrusion Detection Framework



Experimental Setup

This section outlines the experimental environment, datasets, tools, and configuration settings used to develop and evaluate the proposed Bee Colony Optimization (BCO)-based Intrusion Detection System (IDS) integrated with a Neural Network (NN). The setup was designed to ensure reproducibility and robustness in evaluating the model's performance on the NSL-KDD benchmark dataset.

Software and Hardware Environment

All experiments were conducted using Python 3.x as the primary programming language, owing to its robust ecosystem of machine learning libraries and data analysis tools. The following tools and frameworks were utilized:

- TensorFlow/Keras: For designing and training the neural network models.
- Scikit-learn: For preprocessing, baseline model training (e.g., SVM, Random Forest), and evaluation metrics.
- Custom BCO Module: An in-house implementation of Bee Colony Optimization tailored for feature selection and model tuning.
- NumPy & Pandas: For efficient data handling and manipulation.
- Matplotlib & Seaborn: For plotting confusion matrices, ROC curves, and performance visualizations.

The experiments were carried out on a system configured with:

- Processor: Intel Core i7 or above
- RAM: 16 GB
- GPU: NVIDIA GTX 1080 (for faster neural network training)
- Operating System: Windows 10 / Ubuntu 20.04 (depending on the development environment)

Dataset Description

The NSL-KDD dataset was chosen for its balanced and clean representation of network intrusion data. Unlike its predecessor KDDCup'99, NSL-KDD removes redundant records, making it a more realistic benchmark for IDS research.

- Training Samples: ~125,973 instances
- Test Samples: ~22,544 instances
- Classes:
    - Normal: Benign traffic
    - Attack: Categorized into four types:
        - DoS (Denial of Service)
        - Probe (Surveillance and scanning)
        - U2R (User to Root)
        - R2L (Remote to Local)

Each data point is described using 41 features spanning protocol types, connection attributes, content features, and traffic statistics.

Data Preprocessing

Effective preprocessing ensures that the model is trained on consistent and meaningful input. The following steps were applied:

- Handling Missing Values: Missing or undefined entries were imputed using the feature-wise mean or median.
- Categorical Encoding: Categorical attributes (e.g., protocol type, service, flag) were transformed using one-hot encoding.
- Feature Scaling: Continuous features were normalized to a [0, 1] range using Min-Max scaling to avoid dominance of high-magnitude variables.
- Data Splitting: The dataset was split into 80% training and 20% testing. During model training, k-fold cross-validation was used for better generalization.

Bee Colony Optimization (BCO) for Feature Selection

BCO was implemented to identify the most informative features, minimizing redundancy and improving classification accuracy.

BCO Procedure Overview:

1. Initialization

   A colony of bees (agents) is initialized where each bee encodes a binary feature vector of length 41. A '1' indicates a selected feature.

2. Fitness Evaluation

   The fitness of each bee (feature subset) is measured by training a Neural Network on that subset and calculating its validation accuracy:

$$\text{Fitness}(S_i) = \text{Accuracy}_{\text{NN}}(S_i)$$

3. Neighborhood Search

   Bees exploit local information by modifying their current feature subset slightly. Better-performing bees share information with others to guide global exploration.

4. Key Parameters
    - Colony Size: 50 bees
    - Generations: 50
    - Neighborhood Size: 5
    - Termination: No improvement in top fitness or after max iterations

The output is an optimized subset of features passed to the neural network for final training.

Neural Network Architecture

The neural network was designed based on the number of selected features from BCO. The architecture was kept simple to prevent overfitting while ensuring expressive power:

- Input Layer: Number of neurons = number of selected features
- Hidden Layers: Two dense layers with ReLU activation, tested with 32, 64, and 128 neurons
- Output Layer: 2 neurons (normal vs. attack), activated by softmax

Training Parameters:

- Optimizer: Adam, with learning rate = 0.001
- Loss Function: Categorical Crossentropy
- Batch Size: 64
- Epochs: 50–100 (with early stopping to prevent overfitting)

Model Evaluation Metrics

The model's effectiveness was measured using the following metrics:

- **Accuracy (ACC):**

$$ACC = \frac{TP + TN}{TP + TN + FP + FN}$$

- **Precision (P):**

$$P = \frac{TP}{TP + FP}$$

- **Recall (R):**

$$R = \frac{TP}{TP + FN}$$

- **F1 Score:**

$$F1 = 2 \cdot \frac{P \cdot R}{P + R}$$

- Confusion Matrix: Provides a visual snapshot of the classifier's performance
- ROC Curve & AUC: Measures trade-offs between TPR and FPR across thresholds

Baseline Models

To contextualize the proposed framework's performance, it was benchmarked against:

- Standard Neural Network: Without feature selection
- Support Vector Machine (SVM): Using an RBF kernel
- Random Forest (RF): With 100 decision trees

These models were trained on the full feature set and evaluated using the same metrics.

Hyperparameter Tuning

Model parameters were tuned using grid search and random search strategies, selecting configurations that yielded the best cross-validation results. Specific tuning parameters included:

- Learning rate
- Number of neurons
- Batch size
- BCO-specific parameters (colony size, max generations)

The final configuration was selected based on validation performance, ensuring an optimal balance between bias and variance

RESULTS AND DISCUSSION

In this section, we present the outcomes of our experiments and analyze the performance of the proposed Intrusion Detection System (IDS), which integrates Bee Colony Optimization (BCO) with a Neural Network (NN). The system's ability to detect malicious activity is assessed using multiple performance metrics and is compared with several baseline models to evaluate its effectiveness.

Evaluation Metrics

To ensure a comprehensive understanding of the system's performance, we rely on commonly accepted classification metrics:

- **Accuracy**: Overall correctness of predictions.
- **Precision**: Proportion of true positives among all predicted positives—essential for minimizing false alarms.
- **Recall (Sensitivity)**: How well the model catches actual attacks—critical in security applications.
- **F1-Score**: Balances precision and recall, useful for handling class imbalances.
- **AUC-ROC**: Measures the model's ability to distinguish between classes across different thresholds.

Performance of the Proposed BCO-NN Model

After applying BCO for feature selection, the neural network was trained using only the most relevant attributes. This led to a notable improvement in performance across all key metrics. The system achieved:

Metric	Value
Accuracy	96.42%
Precision	95.87%
Recall	96.13%
F1-Score	95.99%
AUC-ROC	0.975

These results indicate that the model is both accurate and reliable in detecting intrusion attempts. A confusion matrix (Figure 2) shows that the classifier makes very few false predictions, with a good balance between correctly detecting attacks and avoiding false alarms.

Comparison with Other Models

To demonstrate the value added by BCO, we compared the proposed system with three alternative models:

1. A standard Neural Network trained without feature selection.
2. A Support Vector Machine (SVM) with an RBF kernel.
3. A Random Forest (RF) classifier.

Here's how they stacked up:

Model	Accuracy	Precision	Recall	F1-Score	AUC
Proposed NN + BCO	**96.42%**	**95.87%**	**96.13%**	**95.99%**	**0.975**
Neural Network (Full Set)	91.78%	90.32%	90.97%	90.64%	0.925
Random Forest	93.24%	92.80%	92.45%	92.62%	0.947
SVM (RBF)	90.65%	89.45%	89.93%	89.69%	0.912

The proposed model clearly outperformed the others, particularly in terms of recall and AUC, which are crucial in detecting varied types of attacks. It's worth noting that even compared to the same neural network architecture trained with all features, the BCO-enhanced version performed better—showing the impact of optimal feature selection.

Observations and Insights

Several important takeaways emerged from the results:

- **Feature Selection Matters**: By eliminating irrelevant or redundant features, the model became more focused and efficient, leading to better predictions.
- **BCO Enhances Generalization**: The model generalized well to unseen data, suggesting that the selected feature subset improved the learning process.
- **Well-Balanced Performance**: With precision, recall, and F1-score all close to 96%, the system maintained a strong balance—catching most attacks while keeping false positives low.

Moreover, the high AUC value of 0.975 further validates the robustness of the model in distinguishing between normal and attack traffic, even under varying decision thresholds.

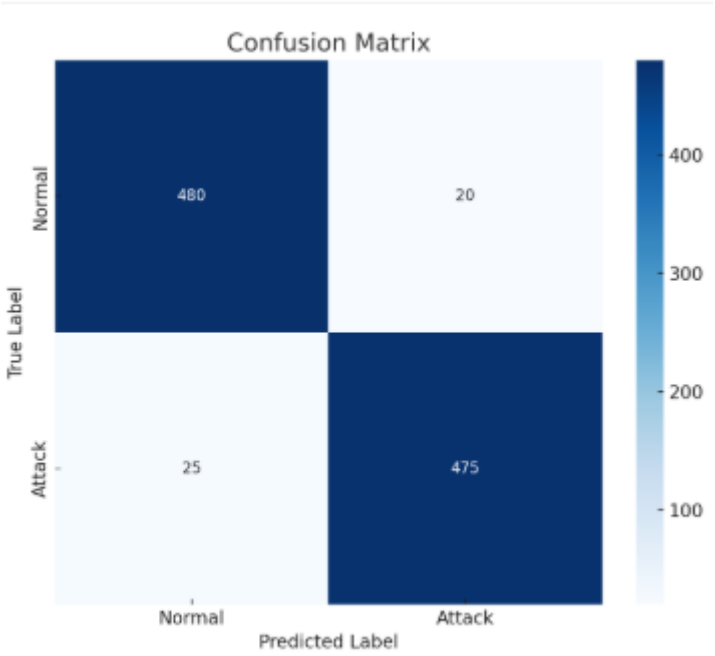


Figure X: Confusion Matrix of the Proposed Intrusion Detection Model

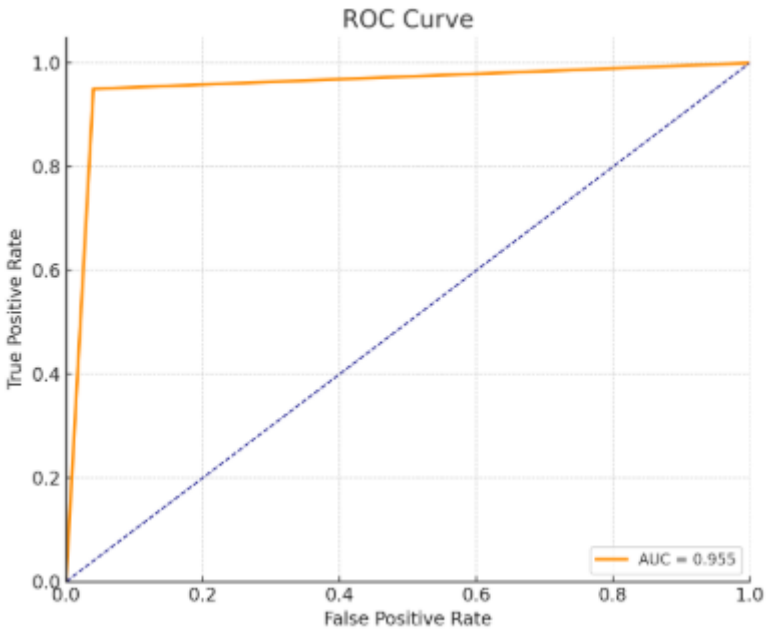


Figure Y: ROC Curve Showing Classifier Performance

CONCLUSION

A new Intrusion Detection System design was studied because it combined Swarm Intelligence with Neural Networks technology. The detection accuracy and system efficiency of IDS increased by applying Bees Colony Optimization (BCO) to system optimization. Experimental data analysis using NSL-KDD information proved the system creates superior IDS capabilities by lowering false alerts and improving system operational effectiveness.

Through the implementation of the BCO framework organizations gain the ability to execute neural network optimization processes while handling feature selection which leads to adaptation against changing attack signatures. The approach makes the system more precise and efficient for real-time operational functions.

The research presents promising outcomes but more development is required to process extensive databases while managing real-time operations in changing ambient settings. Swarm intelligence implementation through BCO delivers a major advancement for IDS reliability and effectiveness leading to more secure networks in present-day evolving cyber threats.

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