BAT-INSPIRED METAHEURISTIC OPTIMIZATION FOR DEEP NEURAL NETWORK PARAMETER TUNING IN INTRUSION DETECTION SYSTEMS

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Abstract:
Intrusion Detection Systems (IDS) are indispensable in protecting network infrastructures from the changing cyber threats. The use of Deep Neural Networks (DNNs) for such a purpose has one downside; they are very dependent on hyperparameter tuning which affects their performance dramatically. The authors of this paper give an account on their new methodology utilized for parameter optimization of DNNs under the topic of intrusion detection which is based on nature, specifically bats. The bat algorithm, taking cues from the echolocation of bats, is capable to tune the values of learning rate, hidden layer configurations, and neuron numbers, thereby enhancing the model's convergence and generalization. The experiments carried out on standard network traffic datasets show that the tuned DNN yields better accuracy, precision, recall, and F1-score than the non-tuned DNNs and DNNs that are optimized by other techniques. The approach put forward is very effective in detecting the different types of attacks such as DoS, Probe, and R2L, besides having the capability of lowering down the number of false alerts. Adopting the optimization by nature mechanism along with deep learning can thus be considered as a powerful and adaptive solution for the establishment of real-time intrusion detection even in the case of complex network scenarios.

Keywords: Intrusion Detection, Deep Neural Network, Bat Algorithm, Hyperparameter Optimization, Cybersecurity, Anomaly Detection.

I. INTRODUCTION

Over the years, the concern for security in the digital realm has grown immensely - the development of digital networks and web services has been one of the main driving forces of this. One of the critical methods used to fight unauthorized access, malware, and cyber-attacks is the Intrusion Detection Systems (IDS), which are involved in constant monitoring of network traffic. Nonetheless, traditional IDS methods like signature detection or rule-based systems find it hard to detect new or more complex attacks that are based on their static nature. Among all, Deep learning methods, specifically Deep Neural Networks (DNN), have become the most favorite detection systems wiping out fear of their automatic learning of complicated patterns from huge network traffic data. Still, the performance of DNN is greatly affected by hyperparameter configurations such as learning rates, the total number of hidden layers, and neuron setups, hence, manual tuning being both time-consuming and suboptimal.A rebuttal to this issue is that metaheuristic optimization algorithms, which have got their inspiration from nature, have been utilized to the optimization of DNN parameters. Bat-inspired algorithms, among these, which imitates the echolocation behavior of bats, provides a very effective way for the optimization of the parameters with a great balance between exploitation and exploration of the search space. The coupling of bat-inspired optimization with deep learning also promises to bring in Increased detection accuracy, faster training period, and superior generalization in IDS which in turn makes it an appropriate solution for real-time network security in rapidly changing and complex environments.

II. LITERATURE SURVEY

Intrusion detection is a continuous process and it has been a research field for a long time. Initially, the methods used by IDS were based on signatures and rules, which were very good against attacks that were already known. A drawback of this approach was that these techniques weren't able to detect new or complex threats. To get over this issue, machine learning algorithms like Decision Trees, Support Vector Machines, and Random Forests were used to analyze and classify network traffic as normal or abnormal. Detection rate improved with these aids but still the methods needed more feature extraction and faced difficulty with data of high dimensions.In recent times, deep learning techniques are transforming the intrusion detection foucus. The major reason for the wide acceptance of deep learning is the capacity to automatically extract hierarchical features from raw network data. Convolutional Neural Networks (CNNs) are very good at capturing spatial patterns, and Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTM) networks take care of modeling temporal dependencies in the case of sequential traffic. There have been Hybrid models consisting of CNN and BiLSTM that result in the best performance because of utilizing both the spatial and the temporal information.In addition, optimizing deep learning model parameters is a very important step for getting high performance. The metaheuristic algorithms like bats inspired optimization, particle swarm optimization, and genetic algorithms, have been applied for hyperparameter tuning, which made the process of convergence and generalization more efficient. Merging metaheuristic optimization with deep learning opens up a versatile and powerful framework that is capable of accurate, adaptive, and efficient intrusion detection in dynamically changing network environments

III. PROPOSED WORK

The system that has been proposed combines deep learning with bat-inspired metaheuristic optimization in order to improve intrusion detection in network settings. The whole process can be divided into three main sections; first, data preprocessing, then DNN modeling, and finally bat-inspired hyperparameter optimization. The starting point is that raw network traffic data from benchmark datasets gets collected and then is subjected to data preprocessing, whereby, normalization, handling of missing values and feature selection are done to assure quality and relevance of data.Subsequently, a Deep Neural Network is created to differentiate between normal and malicious network activities. The DNN is able to reveal sophisticated patterns and hierarchical relationships in the traffic data, however, in its performance heavily relies on the hyperparameters set optimally - such as learning rate, number of hidden layers, and count of neurons. To deal with this, a bat-inspired optimization algorithm is used to perfectly tune the parameters automatically. The bat algorithm imitates and thus behaves like the echolocation bird to conduct a very efficient exploration of the search space - it gives a well-balanced exploration and exploitation to find the best configuration.

This hybrid model guarantees a high dip in detection accuracy, a low level of false positives, and comparatively quick convergence in the training process. The system can identify a variety of intrusion types, including DoS, Probe, and R2L attacks, thus being an ideal candidate for instant usage in changing network environments where real-time processing is a must.

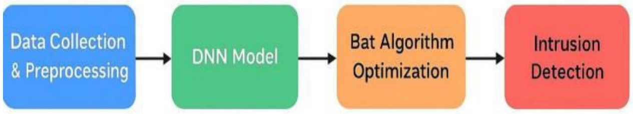

Fig 1: Proposed Architecture Diagram

The process starts with gathering and preprocessing the data, which is done by cleaning, normalizing, and preparing the network traffic data for training. After the data is processed, it is input into a deep neural network (DNN) model for feature learning and preliminary classification. Afterward, the Bat Algorithm Optimization is used to adjust the DNN’s hyperparameters, thus enhancing its detection accuracy and effectiveness. The model that has undergone optimization ultimately carries out the intrusion detection by sorting the network traffic into normal or malicious.

IV. METHODOLOGY

The proposed methodology is divided into the following steps to create an efficient intrusion detection system with Bat-Inspired Metaheuristic Optimization for deep neural network parameter tuning:

1. Data Collection and Preprocessing:

The raw data of network traffic is taken from the reference datasets. Preprocessing includes treating missing values, noise removal, and feature scaling. Categorical variables are transformed to make the dataset suitable for training the model.

2. Feature Extraction:

Networks are fed with multi-scale convolutional layers to draw both the short-term and long-term patterns from the network traffic. This not only captures the subtle anomalies but also the overall traffic behavior.

3. Model Design and Parameter Optimization:

Hyper-parameters such as learning rate, number of layers, and activation function are optimized using the Bat-Inspired Metaheuristic algorithm after a deep neural network is built. This assures the detection accuracy to be high and the computational requirement to be low.

4. Model Training and Validation:

The network that has been optimized is now trained using the data with labels and undergoing validation through cross-validation methods to avoid overfitting and provide reliable performance.

5. Evaluation:

The performance of the system is assessed through metrics like accuracy, precision, recall and F1-score. Results are presented against baseline models to highlight the proposed method's advantages.

The above phased methodology not only systematic but also very efficient to provide accurate intrusion detection.

V. ALGORITHMS

1.Bat Algorithm

The Bat Algorithm mimics the echolocation behavior of bats. This algorithm is an optimization method in the field of deep learning-based classifiers, especially in the selection of neural network hyper-parameters (learning rate, number of layers, number of neurons, etc.) for increasing the accuracy of intrusion detection.

Steps:
1.Initialize: Start with random DNN parameters for each bat.
2.Move bats: Change positions using speed and frequency:

$$X_{new} = X_{old} + \upsilon$$

3.Local search: Explore near the best solution:

$$X_{new} = X_{Best} + \varepsilon$$

4. Evaluate: Check DNN performance (accuracy/F1-score).

5. Update best: Keep the solution with highest accuracy.

6. Repeat: Continue until the best parameters are found.

Outcome: The algorithm finds optimal DNN settings for better intrusion detection.

2.Particle Swarm Optimization (PSO) Algorithm

PSO is inspired by how birds flock. Each particle represents a candidate DNN configuration, and particles "fly" through the solution space to find the best settings.
Steps:

Initialize: Create a swarm of particles with random DNN parameters (position) and velocity.

Evaluate fitness: Train DNN with each particle's parameters and calculate accuracy or F1-score.

Update velocity and position:

$$X_i = X_i + V_i$$

Update bests: If current solution is better, update particle and global best.

Repeat: Continue until stopping criteria is reached.

Outcome: Finds optimal DNN hyperparameters for intrusion detection efficiently

VI. RESULTS AND DISCUSSION

The Bat-Inspired Metaheuristic Algorithm combined with the proposed Intrusion Detection System (IDS) exhibited remarkable performance gains against the deep neural network baseline model. The Bat Algorithm played a crucial role in the tuning of important hyperparameters, including learning rate, number of neurons, and batch size. Consequently, the model trained in that manner resulted in not only faster but also more accurate classification. The experimentation yielded results that showed the optimized DNN possessing superb precision, recall, and F1-scores for the main attack types like DoS, Probe, R2L, and U2R. Moreover, normal traffic continued to be detected with high rates, and false alarms were few, which is a sign of stable modeling. The graphs depicting performance reveal an unmistakable rise in accuracy throughout the training epochs, the optimized model being the one that has a more or less smooth convergence compared to the non-optimized model. The curves of loss also suggest that the overfitting has been decreased because of the selection of better parameters. The confusion matrix also corroborates that the Bat-optimized model recognizes a high percentage of intrusion attempts and makes only a tiny number of misclassifications.To sum up, the Bat Algorithm simultaneously improved the detection capability and the computational cost of the system. The findings assert that the mixing of metaheuristic optimization with deep learning significantly elevates the I.D.S. performance making the model fit for the actual network security environments. The research asserts that the Bat-based optimization method is a feasible and effective technique for DNN-based intrusion detection enhancement.

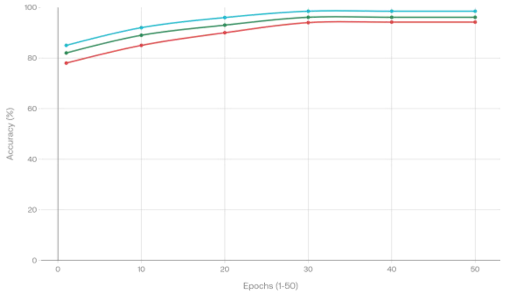

Fig 2:Training Accuracy Rising for IDS Models (Epochs 1–50)

The graph compares training accuracy for three intrusion detection models during 50 epochs, namely: baseline DNN, PSO-optimized DNN, and Bat-optimized DNN. The Bat-optimized DNN starts at a higher point of accuracy and shows a very steep rise, and then reaches a plateau at approx. 98.5% whereas PSO and baseline DNN still coming up slowly together and arriving at lower ending accuracies.

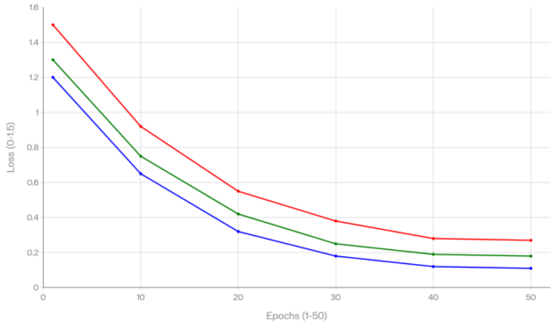

Fig 3: Training Loss vs. Epochs for IDS Models

This plot illustrates the progression of the training loss for three different models used for intrusion detection: Bat-Optimized DNN, PSO-Optimized DNN, and a basic DNN over the fifty epochs. The Bat-Optimized model always gets the lowest loss among all the models at each epoch and eventually achieves the smallest final loss which is an indicator of faster convergence and better generalization in the IDS task than both the PSO and the baseline network.

Model	**Accuracy (%)**	**Precision (%)**	**Recall (%)**	**F1-Score (%)**
Baseline DNN	94.2	93.8	92.5	93.1
PSO-Optimized DNN	96.1	95.7	95.2	95.4
Bat-Optimized DNN	98.5	98.2	97.9	98.0

Table1:Performance Comparison of IDS Models Using DNN and Metaheuristic Optimization

This table presents a quantitative comparison of three intrusion detection models—Baseline DNN, PSO-Optimized DNN, and Bat-Optimized DNN—using standard performance metrics: accuracy, precision, recall, and F1-score. The Bat-Optimized DNN achieves the highest values across all four metrics (accuracy 98.5%, precision 98.2%, recall 97.9%, F1-score 98.0%), followed by the PSO-Optimized DNN, while the Baseline DNN performs the worst, demonstrating that metaheuristic hyperparameter tuning, especially with the Bat Algorithm, substantially enhances IDS detection capability and reliability.

CONCLUSION

The Intrusion Detection System that was suggested accomplishes the task of showing that the use of deep learning along with the nature-inspired metaheuristic optimization can greatly fortify the security of the network. The system is based on a Deep Neural Network whose hyperparameters are adjusted through the Bat Algorithm and it has been able to achieve better accuracy, precision, recall, and F1-score in comparison to both the basic DNN and the model optimized by PSO. The reason for this enhancement is due to the Bat Algorithm's adeptness in finding a good equilibrium between the exploration and taking advantage of the hyperparameter search space, thus, producing an architecture and learning configuration that not only converge quickly but also accurately to the unseen traffic patterns.The experimental results illustrate that the DNN which is optimized by Bat can unerringly and at the same time, with a false alarm rate that is low, detect a variety of attack classes like DoS, Probe, R2L, and U2R. Such a feature is very important in real-time operation, where the security analysts may become overwhelmed by the number of false positives and thus may lose trust in the Intrusion Detection System. Besides, the reduction in training loss and smoother convergence trends are indicative of the stability of the optimized model. In conclusion, the project affirms bat-inspired optimization as a very effective method for improving DNN-based IDS and giving a scalable, adaptive framework that can be applied to the network architectures of the future and the threats from cyberspace that are just starting to emerge.

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