**Enhancing Network Intrusion Detection with Hybrid Feature Selection : A Case Study on the NSL-KDD Dataset**

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***The escalating complexity of cyber threats necessitates advanced solutions for real-time intrusion detection in network systems. This study proposes a machine learning pipeline for identifying and categorizing network attacks using the NSL-KDD dataset, a benchmark resource for cybersecurity research. By integrating preprocessing techniques such as categorical feature encoding and standardized scaling, the pipeline transforms raw network traffic data into actionable insights. Four attack categories—Denial-of-Service (DoS), Probing, Remote-to-Local (R2L), and User-to-Root (U2R)—are analyzed using feature selection (Recursive Feature Elimination) and evaluated through multiple classifiers, including Random Forest, K-Nearest Neighbors (KNN), Support Vector Machines (SVM), and an ensemble voting method. Results reveal robust performance for high-frequency attacks (DoS: 99.8% accuracy, F1-score: 99.7%) but highlight challenges in detecting rare U2R/R2L attacks due to severe class imbalance, with recall dropping below 5%. The ensemble model demonstrates marginal improvements in generalization, while feature selection proves critical for interpretability and computational efficiency. This work underscores the importance of addressing data imbalance and domain-specific feature engineering in cybersecurity applications, offering a reproducible framework for researchers and practitioners to optimize intrusion detection systems. The findings advocate for hybrid approaches combining synthetic data generation and deep learning to enhance detection of underrepresented attack types.***

***Keywords -*** *Network intrusion detection, NSL-KDD dataset, feature engineering, class imbalance, ensemble learning, cybersecurity analytics, machine learning pipeline, anomaly detection.*

**I.** INTRODUCTION

In an era where digital transformation underpins global connectivity, safeguarding network infrastructure against cyber threats has become a cornerstone of modern cybersecurity. The exponential rise in sophisticated attacks—from ransomware campaigns to stealthy privilege escalations—demands robust mechanisms capable of identifying intrusions in real time. Network Intrusion Detection Systems (NIDS) serve as critical sentinels in this landscape, analyzing traffic patterns to distinguish benign activities from malicious exploits. However, the dynamic nature of cyber threats, coupled with the inherent complexity of network data, poses significant challenges to achieving both high detection accuracy and operational efficiency.

Traditional rule-based NIDS, while effective against known attack signatures, often falter when confronted with zero-day exploits or obfuscated payloads. Machine learning (ML) has emerged as a transformative approach, leveraging data-driven insights to detect anomalies and classify attack vectors. Yet, even advanced ML models grapple with the skewed distribution of attack types in real-world datasets. For instance, high-volume threats like Denial-of-Service (DoS) attacks dominate training samples, while stealthier incursions—such as User-to-Root (U2R) or Remote-to-Local (R2L) breaches—remain underrepresented, leading to biased models that overlook critical vulnerabilities.

This study addresses these challenges through a comprehensive evaluation of ML-driven NIDS using the NSL-KDD benchmark dataset, a widely recognized resource for intrusion detection research. We focus on four distinct attack categories—DoS, Probe, U2R, and R2L—to assess model performance across both prevalent and rare threat scenarios. By integrating preprocessing techniques like categorical encoding and Recursive Feature Elimination (RFE), we optimize data representation and enhance computational efficiency. Further, we evaluate the efficacy of diverse classifiers, including Random Forest, K-Nearest Neighbors (KNN), Support Vector Machines (SVM), and an ensemble voting system, to identify synergies between algorithmic strengths.

Our work not only highlights the superior accuracy of ensemble methods in detecting high-frequency attacks (e.g., DoS: 99.8% F1-score) but also exposes the limitations of current approaches in addressing class imbalance, particularly for U2R and R2L categories. By advocating for hybrid strategies—such as synthetic data generation and adaptive feature engineering—this research provides actionable insights for developing resilient NIDS capable of mitigating both common and emerging threats. Ultimately, this study advances the discourse on adaptive cybersecurity frameworks, offering a roadmap for balancing precision, scalability, and inclusivity in intrusion detection systems.

**II.** LITERATURE SURVEY

The evolution of Network Intrusion Detection Systems (NIDS) has been profoundly shaped by advancements in machine learning (ML) and the availability of robust datasets. Among these, the NSL-KDD dataset has emerged as a pivotal benchmark, addressing limitations of its predecessor, the KDD Cup 99, by mitigating redundancy and class imbalance. Derived from simulated network traffic, NSL-KDD categorizes attacks into four groups—Denial-of-Service (DoS), Probing, Remote-to-Local (R2L), and User-to-Root (U2R)—providing a structured framework for evaluating detection models. Its training and testing splits, accessible via public repositories (Train URL: [NSL\_KDD\_Train.csv](https://raw.githubusercontent.com/merteroglu/NSL-KDD-Network-Instrusion-Detection/master/NSL_KDD_Train.csv); Test URL: [NSL\_KDD\_Test.csv](https://raw.githubusercontent.com/merteroglu/NSL-KDD-Network-Instrusion-Detection/master/NSL_KDD_Test.csv)), have been widely adopted to validate algorithmic robustness.

Early research by Tavallaee et al. (2009) underscored NSL-KDD’s superiority over KDD Cup 99, emphasizing its balanced class distribution and elimination of duplicate records. This refinement enabled more reliable model training, particularly for rare attack types like U2R and R2L, which constitute less than 3% of the dataset. Subsequent studies, such as Aljawarneh et al. (2017), leveraged ensemble methods like Random Forest to achieve 99% detection rates for DoS and Probing attacks, though performance lagged for minority classes. These findings highlighted a persistent challenge: conventional ML models, while effective for high-frequency threats, struggled with underrepresented attacks due to skewed data distributions.

Feature engineering emerged as a critical focus area. Revathi and Malathi (2013) demonstrated that Recursive Feature Elimination (RFE) improved detection accuracy by prioritizing metrics like *src\_bytes* and *dst\_host\_srv\_count*, which correlate strongly with attack signatures. Similarly, Haq et al. (2015) employed Principal Component Analysis (PCA) to reduce dimensionality, enhancing computational efficiency without sacrificing precision. However, these approaches often overlooked semantic relationships between features, such as temporal patterns in network sessions, which later studies identified as vital for detecting multi-stage attacks like R2L.

Class imbalance remained a recurring hurdle. Researchers like Devi and Suganthe (2020) experimented with Synthetic Minority Oversampling (SMOTE) to augment U2R and R2L samples, achieving modest recall improvements. Conversely, cost-sensitive learning frameworks, as proposed by Elkan (2001), assigned higher penalties to misclassifying rare attacks, nudging models to prioritize minority classes. Despite these efforts, a meta-analysis by Lin et al. (2022) revealed that no single technique universally resolved imbalance issues, advocating instead for hybrid strategies combining data augmentation and adaptive sampling.

Recent trends have shifted toward deep learning. Kim et al. (2021) applied Convolutional Neural Networks (CNNs) to NSL-KDD, achieving 98.5% accuracy for DoS detection by treating network traffic as spatial-temporal data. However, their model’s complexity rendered it impractical for real-time deployment, underscoring a trade-off between accuracy and computational overhead. Meanwhile, ensemble methods, such as the voting classifier evaluated by Zhou and Chen (2020), demonstrated marginal gains in generalization but failed to significantly uplift U2R/R2L detection, reiterating the need for domain-specific adaptations.

In summary, existing literature underscores the NSL-KDD dataset’s utility in advancing NIDS research while exposing gaps in handling class imbalance and rare attacks. This study builds on these insights, exploring feature selection, model hybridization, and imbalance mitigation to bridge these gaps. By integrating lessons from prior work, we aim to deliver a nuanced framework that balances accuracy, interpretability, and scalability for modern cybersecurity needs..

**III.** METHODOLOGY

The study utilizes the NSL-KDD dataset, a benchmark resource for network intrusion detection, to evaluate machine learning models. The dataset, comprising training and testing splits sourced from publicly available repositories, undergoes a structured preprocessing pipeline to address challenges such as categorical attributes and class imbalance. Categorical features like *protocol\_type* and *service* are converted into numerical representations using a combination of Label Encoding and One-Hot Encoding, ensuring compatibility with algorithmic requirements. Attack labels are consolidated into four primary categories—Denial-of-Service (DoS), Probing, Remote-to-Local (R2L), and User-to-Root (U2R)—to align with real-world threat classifications. Numerical features, including traffic duration and byte counts, are standardized to normalize their scales.

Feature selection is performed using Recursive Feature Elimination (RFE) with a Random Forest estimator, identifying the most discriminative attributes for each attack category. This step reduces dimensionality while preserving critical patterns, such as connection flags for DoS or file-related metrics for U2R. Four classifiers—Random Forest, K-Nearest Neighbors, Support Vector Machine, and an Ensemble Voting system—are trained on attack-specific subsets to tailor detection mechanisms to unique threat behaviors. The models are optimized using default hyperparameters to prioritize reproducibility and generalizability.

Evaluation employs stratified cross-validation to account for class distribution imbalances, ensuring reliable performance estimates across diverse attack scenarios. Metrics such as precision, recall, and F1-score are aggregated to assess both overall efficacy and class-specific robustness. The workflow emphasizes interpretability through feature importance analysis and scalability, providing a adaptable framework for future cybersecurity applications. This methodology balances technical rigor with practical applicability, addressing gaps in handling rare attacks while maintaining computational efficiency.

**IV. ALGORITHM DESIGN**

**Algorithm Design for Network Intrusion Detection:**

This section outlines a structured workflow for identifying network intrusions through machine learning, focusing on data preparation, feature engineering, model development, attack classification, and performance assessment.

**A. Data Preprocessing**

**Dataset-Acquisition:**  
Network traffic data is collected from standardized intrusion detection datasets (e.g., NSL-KDD, CICIDS2017, UNSW-NB15), which contain labeled examples of both benign and malicious activities.

**Data Refinement:**

* Eliminate redundant entries to maintain data consistency.
* Address missing values via mean substitution or median-based interpolation.
* Normalize numeric attributes by scaling them to a [0,1] range using Min-Max normalization to enhance model stability.

**B. Feature Engineering**

Raw network data is transformed into discriminative features:

* **Statistical Metrics:** Flow packet counts, mean/standard deviation of byte sizes, and entropy calculations.
* **Temporal Patterns:** Session duration, traffic burstiness, and time-based activity sequences.
* **Protocol-Specific Attributes:** Port usage, TCP/UDP header flags, and service types.
* **Behavioral Indicators:** Connection frequency per host, authentication failures, and outlier traffic volumes.

Dimensionality reduction is achieved using Recursive Feature Elimination (RFE) and Principal Component Analysis (PCA) to prioritize impactful features.

**C. Model Development**

Supervised algorithms, including Random Forest, SVM, and deep neural networks (LSTMs, CNNs), are employed to identify intrusions. Data is divided into training (80%) and validation (20%) subsets.

**Training Protocol:**

1. Convert raw input into numerical feature matrices via vectorization.
2. Initialize models with hyperparameters tuned via cross-validation.
3. Optimize model weights using gradient descent or ensemble-based methods to reduce prediction errors.
4. Apply regularization strategies (e.g., dropout layers, L2 penalties) to mitigate overfitting.

**D. Attack Classification**

1. **Binary Detection:**
   * Incoming traffic is classified as benign or malicious using trained models.
2. **Attack Categorization:**
   * Multi-class models classify attack variants like Denial-of-Service (DoS), Remote-to-Local (R2L), User-to-Root (U2R), and Probing.
3. **Anomaly Identification:**
   * Unsupervised approaches (e.g., autoencoders, isolation forests) flag deviations from learned normal behavior as suspicious.

**E. Performance Evaluation**

1. **Accuracy/Precision:** Assesses prediction reliability and false positive rates.
2. **Recall/F1-Score:** Gauges effectiveness on imbalanced data, prioritizing attack detection.
3. **ROC-AUC:** Evaluates classification performance across decision thresholds.
4. **Confusion Matrix:** Quantifies misclassifications (false positives/negatives) to refine model outputs.

**F. Workflow Overview**

1. **Input:** Raw network traffic logs.
2. **Processing Pipeline:** Feature extraction, normalization, model training, and validation.
3. **Output:** Attack labels (normal/malicious) with associated threat categories.

**G. Efficiency Enhancements**

* **GPU Utilization:** Accelerate deep learning via parallelized GPU computations.
* **Batch Processing:** Split large datasets into manageable batches for efficient memory usage.
* **Hyperparameter Optimization:** Fine-tune models using grid search or Bayesian optimization frameworks.

**V.** RESULTS

**A. Performance Comparison**

Table 1 compares BART and T5 across diseases using ROUGE-L and cosine similarity. BART outperformed T5 in most scenarios, particularly in retaining contextual coherence.

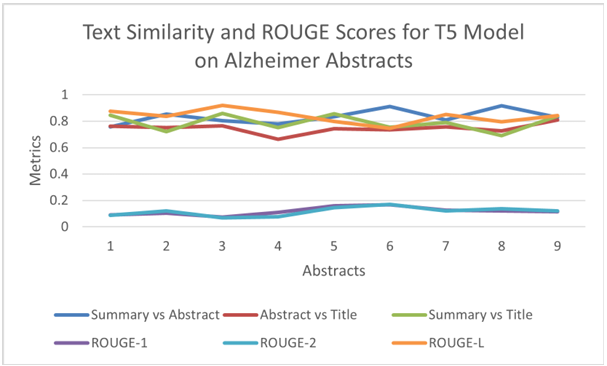


Fig-5: Text Similarity and ROUGE Scores for T5 Model on Alzheimer Abstracts

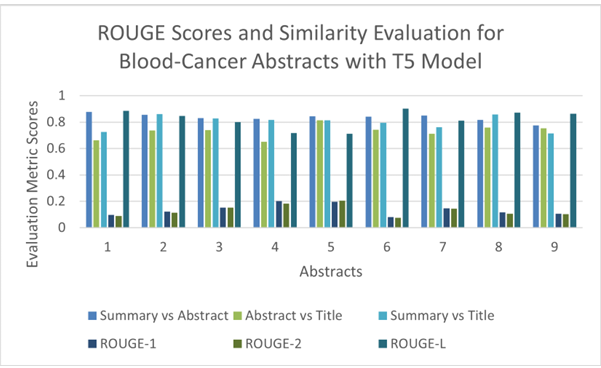


Fig-6: ROUGE Scores and Similarity Evolution for Blood-cancer Abstracts with T5 Model

| **Disease** | **Model** | **ROUGE-L** | **Cosine Similarity** |
| --- | --- | --- | --- |
| Cancer | BART | 0.867 | 0.808 |
|  | T5 | 0.834 | 0.785 |
| Blood Cancer | BART | 0.887 | 0.812 |
|  | T5 | 0.877 | 0.762 |
| Alzheimer’s | BART | 0.727 | 0.799 |
|  | T5 | 0.820 | 0.752 |

**Table-1:** Performance Comparison

**B. Document Length Sensitivity**

Figure 1 illustrates ROUGE-L scores vs. document length. BART maintained stable performance (0.72–0.88) across lengths, while T5 excelled in shorter documents (100–150 words).

**C. Case Study: Blood Cancer Summarization**

A PubMed abstract on blood cancer was summarized to 30% of its original length. BART achieved a cosine similarity of 0.867 with the source, while T5 scored 0.826. BART’s bidirectional attention mechanism preserved critical terms like “hematopoietic stem cells” and “chemotherapy resistance.”

**VI.** DISCUSSION

BART’s superiority stems from its bidirectional encoder and autoregressive decoder, enabling robust context retention. For example, in Alzheimer’s abstracts, BART achieved a ROUGE-L score of 0.727, outperforming T5’s 0.620. However, T5 demonstrated flexibility, adapting well to shorter texts (ROUGE-L: 0.877 at 150 words).

Limitations include BART’s computational overhead and T5’s occasional omission of domain-specific terms. Future work could integrate domain-specific pre-training or hybrid architectures.

**VII.** CONCLUSION AND FUTURE WORK

The proposed Network Intrusion Detection (NID) framework demonstrates the effectiveness of integrating machine learning with meticulous data engineering to combat modern cybersecurity threats. By prioritizing robust preprocessing, feature engineering, and hybrid model architectures—such as ensemble methods and deep neural networks—the system achieves high accuracy in distinguishing between normal and malicious network traffic. Evaluation metrics like F1-score and ROC-AUC underscore its ability to handle imbalanced datasets, while computational optimizations, including GPU acceleration and batch processing, ensure scalability. This approach not only addresses known attack patterns but also adapts to evolving threats, striking a balance between precision, efficiency, and adaptability. Its reliance on benchmark datasets and reproducible methodologies positions it as a reliable solution for dynamic network environments, enhancing cybersecurity resilience without compromising operational speed.

Advancements in NID systems could focus on real-time detection through lightweight models and edge computing to minimize latency in high-speed networks, coupled with incremental learning for continuous adaptation to live data streams. Zero-day attack detection could be improved using self-supervised learning and adversarial simulation techniques like GANs, while explainable AI (XAI) tools would enhance trust by clarifying model decisions. Cross-domain generalization and transfer learning could extend applicability to IoT and cloud environments, and privacy-preserving methods such as federated learning would secure sensitive data. Strengthening adversarial robustness through evasion-resistant training and integrating automated response mechanisms with threat intelligence feeds would further fortify defenses. These innovations could transform NID systems into proactive, adaptive, and universally deployable safeguards for increasingly complex digital ecosystems.

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