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**MDDM**

Master’s Degree Program in

**Data-Driven Marketing**

**Improving Intrusion Detection Systems: Challenges with Public Datasets and the Role of Explainable AI**

A Practical Guide Using NFS-2023-TE and HIKARI-2021

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Master Thesis

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# **Statement of Integrity**

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism, any form of undue use of information or falsification of results along the process leading to its elaboration. I further declare that I have fully acknowledged the Rules of Conduct and Code of Honor from the NOVA Information Management School.

*Rome, 27/06/2024*

Abstract

Intrusion detection systems based on public datasets deliver results only in academic papers but not in the real world because of flaws in how they are made. Should explainable algorithms be essential when building intrusion detection systems based on a machine learning model? A new paper highlights some of the deficiencies of these studies, but new datasets came out, and practical guides on tackling the problem are missing. Following the paper mentioned above, we have tried to see what improvements have been made and added new suggestions based on our findings. This work found issues on an existing dataset; moreover, we prove with explainable AI why building an intrusion detection system with these datasets should be avoided. Besides adding a contribution on what to avoid while making an intrusion detection system, we also show how some aspects of the process need to be deeply analyzed before proposing a new model.

**Keywords**

intrusion detection; explainable AI; NIDS; public dataset, HIKARI-2021, NFS-2023-TE, Cybersecurity

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# **Introduction**

In recent years, the global landscape of internet usage has undergone a dramatic transformation, with the number of users experiencing significant growth (Xiong et al., 2021). This expansion, driven by technological advancements and worldwide digitalization, has brought numerous benefits to society, including enhanced data sharing, network efficiency, and improved decision-making processes (Ahmetoglu et al., 2022).

However, this digital transformation has also introduced new challenges, particularly in cybersecurity. As the reliance on internet-connected systems grows, so does the potential for network threats and cyber-attacks (Walter et al., 2022). This trend has been further exacerbated by recent global events, such as the COVID-19 pandemic, which led to a surge in internet traffic due to increased remote work and stay-at-home activities. In 2022, global internet traffic reached a staggering 997,301 Gbps, a 30% increase from 2018 (TeleGeography, 2023).

The escalating threat landscape is evidenced by alarming statistics, such as a 29% increase in global cyber-attacks in 2021 (check point, 2021). This underscores the need for robust cybersecurity measures to protect individuals, businesses, and critical infrastructure.

In response to these growing threats, cybersecurity has evolved rapidly. Network Intrusion Detection Systems (NIDS) have become integral to organizational cybersecurity strategies. However, traditional signature-based and rule-based defensive mechanisms face challenges in coping with the increasing volume and complexity of information flowing through the internet (Gümüşbaş et al., 2021).

Researchers and computer engineers have turned to more advanced solutions to address these challenges, particularly in Artificial Intelligence (AI). Machine Learning (ML) and Deep Learning (DL) algorithms have shown promise in enhancing the performance of cyber defensive systems (Louk & Tama, 2023). These AI-based approaches offer the potential for more effective prediction and high-accuracy detection of emerging threats that may be difficult to identify using conventional antivirus programs.

While AI techniques have demonstrated impressive performance in various cybersecurity applications, such as intrusion detection, spam filtering, and malware identification (Sahakyan et al., 2021), a significant challenge lies in the trade-off between model performance and explainability. Interpretability and transparency have come to the forefront, particularly in light of regulations like the European Union's General Data Protection Regulation, which emphasizes the importance of understanding the logic behind AI-driven decisions (Goodman & Flaxman, 2017).

The field of Explainable AI (XAI) has emerged to address these concerns, offering strategies to make AI decisions more intelligible to humans. It has already been implemented in various domains, such as healthcare, business processes, financial and legal decisions, and autonomous vehicle (Nazar et al., 2021).

Building on the issue of explainability, this study practically addresses some specific criticisms raised by (Catillo et al., 2023). Starting from the premise that today, there are ML models that perform IDS work with incredible results, this study highlights how these academic results do not translate into real-world implementation of these models. The problem lies in a series of issues related to public datasets. Besides being a simplified version of reality, these datasets include errors in creating the dataset itself, leading to the easy achievement of good results by machine learning models. A dataset taken as an example in this study is CIC-IDS 2017 (Sharafaldin et al., 2018). The reason this dataset was chosen is that among the various datasets released in recent years, it is the most cited.

Starting from the criticisms developed by (Catillo et al., 2023), we will analyze two new datasets, NFS-2023-TE (Pekar & Jozsa, 2024) and HIKARI-2021 (Ferriyan et al., 2021). The choice of these datasets is not random, as NFS-2023-TE is the latest in a series of datasets created using the same data as CIC-IDS 2017, correcting some issues found in the original dataset. These issues have been addressed by WMTC-2021 (Engelen et al., 2021; L. Liu et al., 2022) and CRiSIS-2022 (Lanvin et al., 2023), leading to NFS-2023-TE, the latest in this series of improvements. Meanwhile, HIKARI-2021 is an entirely new dataset inspired by CIC-IDS 2017 that adds seven new requirements to the eleven used (Gharib et al., 2016) by CIC-IDS 2017.

The need to analyze new datasets instead of a more famous one arises for two reasons. The first is that NFS-2023-TE assumes that CIC-IDS 2017 contains errors, while the other most cited datasets are nowadays outdated. The second reason is that these datasets become obsolete quite quickly (Guerra et al., 2022), so it makes no sense to insist on working on old datasets.

This work aims to minimize the trade-off between explainability of these algorithms and performance. To achieve this result, we will demonstrate how even classical machine learning algorithms can achieve results comparable to deep learning models. After that, we will show how XAI algorithms like Shap (Lundberg & Lee, 2017) are fundamental in demonstrating the validity of a model or the dataset on which this model is based. We will then analyze the HIKARI-2021 dataset, which, to our knowledge, has never been done before. This analysis has led to the discovery of serious problems that make any model developed on these data unsuitable for real-world usage. This analysis will be conducted partly by verifying that the problems found in CIC-IDS 2017 are not present in HIKARI-2021, partly following what is exposed in (Catillo et al., 2023), and finally, use Shap as an XAI algorithm.

Consequently, this study does not want to be yet another attempt to obtain good results with a new model, as starting from flawed data would be a useless exercise. However, it wants to be practical work that brings together some issues already seen in the past to contribute to the drafting of some guidelines that can help develop better datasets in the future.

# **technical Knowledge**

This section contains some technical knowledge needed for those who are not computer scientists. Some of these explanations can be argued, but a more technical explanation is out of scope and will lead to a longer and more complex explanation.

* 1. **What does an IDS do?**

An Intrusion Detection System (IDS) is a security tool that monitors network traffic for suspicious activities. Its main job is to:

1. Watch all network connections passing through a specific point, usually near the router.

2. Analyze this traffic to identify potential threats or attacks.

3. Alert security teams or automatically respond when it detects something suspicious.

Traditionally, many IDS systems used signature-based detection, which could only identify known attacks. However, according to recent research, machine learning (ML) models are increasingly being used to build more effective IDS. The critical advantage of ML-based IDS is their ability to understand the underlying patterns of attacks. This allows them to potentially detect new, previously unseen threats, unlike signature-based systems limited to recognizing only known attack patterns.

In our analysis, we will focus on how to evaluate the performance of ML models used in IDS. Specifically, we will explore:

1. Metrics for model accuracy: We will examine the advantages and limitations of using different evaluation metrics such as accuracy, precision, recall, and F1 score. This comparison will help us understand which metrics are most suitable for assessing IDS performance in different scenarios.

2. Inference time: We will evaluate the speed at which the model can make predictions. This is crucial for an IDS, as faster detection allows for quicker response to potential threats, minimizing the impact of an attack. For instance, in a data theft scenario, reducing detection time directly correlates with reducing the amount of data that could be stolen.

By focusing on these aspects, we aim to develop a comprehensive understanding of building and evaluating effective ML-based Intrusion Detection Systems that can adapt to new threats and provide robust protection against evolving cyber risks.

* 1. **What is an IP address, and what is a port?**

In the context of a dataset for an Intrusion Detection System (IDS), IP addresses and ports are represented as features. Each host (computer or device on a network) is identified by an IP address, which can be called its network "address". However, it is essential to note that a single host can have multiple active ports, which act like "doors" for different types of network traffic.

Ports, ranging from 0 to 65535, serve specific purposes. For example, port 80 is typically used for HTTP traffic, port 443 for HTTPS, and port 22 for SSH. This means one host can communicate using multiple services simultaneously, each through a different port.

In our dataset, we typically find four key pieces of information for each connection: the source IP address, source port, destination IP address, and destination port. While this information is crucial for network analysis, using it directly in machine learning model training can lead to problems.

The main issue is that IP addresses are often dynamically assigned and can change over time. They are also limited in number, especially with IPv4 (though IPv6 vastly expands this range). Similarly, while there are 65,536 possible ports, many are standardized for specific uses. Training a model on these specific values could create a bias where the model associates certain IPs or ports with malicious activity rather than learning the underlying patterns of the attack.

Attackers could exploit this bias. If they discover that the model considers specific IPs or ports as "safe," they could use these to bypass detection. Therefore, using these features for data correlation and initial analysis is generally better than training the detection model's core.

The primary reason for including IP addresses and ports in the dataset is to correlate records with the raw network traffic data, typically stored in pcap (packet capture) files. However, to make this correlation accurate, a timestamp is also necessary. The combination of IP, port, and timestamp uniquely identifies a specific network connection at a particular moment.

In summary, while IP addresses and ports are crucial for understanding network traffic, their direct use in machine learning models for cybersecurity can lead to vulnerabilities. Instead, they should be used carefully, primarily for data correlation and preprocessing, while the models should focus on more stable and generalizable features of network behavior.

## **What is a flow?**

A flow in these datasets typically represents a single TCP or UDP connection, recorded as one row in the dataset. Each flow is composed of multiple IP packets but is summarized into a single record with various features:

1. Identifier features: These include source and destination IP addresses, ports, and timestamps. They uniquely identify a connection.
2. Statistical features: These are derived from the connection data, such as flag counts, average packet size, maximum payload length, duration, etc. These features capture the behavior of the connection.

The number of features can vary significantly between datasets. Modern public datasets often have 80 or more features, with some new tools potentially offering up to 150 features.

There's a clear start (three-way handshake) and various defined endings for TCP connections. UDP, being connectionless, does not have standard open/close procedures. In datasets, UDP "connections" are typically defined as exchanges starting with the first observed packet and ending after a predefined timeout.

## **How these datasets are made**

Making a dataset for training an IDS starts with setting up a testbed to do the data capturing part, which will lead to storing the data captured in pcap files and processing them to make a csv file. All the steps we will discuss here are described in CIC-IDS 2017 and HIKARI 2021 papers.

The testbed consists of a network of devices, in our case, only computers and servers, but some datasets are specific to IoT devices. The main difference between IoT and generic datasets is the protocols used.

Once the testbed is set up, the capturing device starts to capture some session of regular traffic, which means that a computer is instructed to browse the Internet as an average person would do, and some session of attack, in which one or more hosts in the network are attacked.

The data we are talking about are IP packets containing TCP or UDP as payloads. Usually, this task is performed with tools such as tcpdump, which reads the flow of packets in the network and makes a pcap file of the data capturing session. These files contain the packet header, which includes all the packet metadata, such as destination, source, size of the packet, and a bunch of flags. Besides, the header packets also contain the payload, which is the data transported over the network.

Usually, these pcap files are released along with the dataset so that practitioners can analyze them and even create a new dataset from an existing pcap file. WTMC-2021, CRiSIS-2022, and NFS-2023-TE are all made from the pcap files of CIC-IDS 2017; their goal was not to create a new dataset from scratch but to improve an existing one.

Once we have made a pcap file, we can build our csv with a flowmeter tool, like CICFlowMeter (Lashkari et al., 2017), which was used for CIC-IDS 2017 or NFStream (Aouini & Pekar, 2022) used for NFS-2023-TE. These tools make the samples for our dataset; a sample is a flow composed of multiple packets. The samples are composed of flow statistics, like the packets' count, flow duration, timestamp, IP, port, and count of the flags.

We must label the samples once we have created a CSV file with all the connections. There are different ways to analyze the traffic, which are disclosed in the dataset papers. It is essential to know that once the attack's packet has been found, it will be labeled using the unique combination of IP, port, and timestamp. The timestamp of the flow is the same as the first packet that has started the flow.

## **Why do we use ML models?**

Historically, IDS were working based on the signature of the payload data. Signature-based IDS make a signature of the data in the payload and then check if the signature matches a known attack in a database. The problem with this kind of solution is that they can only detect known attacks, and with the growing dimension of attack databases, ML models have been proven faster. Moreover, since traffic is ciphered nowadays, this technique is less effective. ML models do not rely on the payload; instead, they use the flow statistics the flowmeter makes. So, if a new attack is created, it is possible that an ML model can detect the attack if it behaves similarly to a known attack.

## **What is a FIN and RST flag?**

IP packets, in addition to their payload, contain a series of metadata, including so-called flags. These flags perform various functions, including establishing or terminating the connection between two hosts. Specifically, to understand network traffic datasets, we need to know what the RST and FIN flags do.

There are three ways to close a TCP connection:

1. Exchanging a packet with the RST flag set
2. Exchanging two packets with the FIN flag set between the two hosts
3. A timeout if the connection is not used after a certain period

It is essential to know that when monitoring a TCP connection, we should theoretically see either one RST packet or two FIN packets passing through, but not more than one RST or one FIN. Among all the features used for today's datasets, this is one of the few that contains an absolute value that, if exceeded, indicates a malfunction during the dataset creation.

This behavior of RST and FIN flags provides a unique feature in network datasets. Unlike many other features with varying thresholds or patterns, the count of RST or FIN flags per connection has a clear, absolute limit. Exceeding this limit (more than one RST or more than two FIN packets per connection) strongly suggests either:

* An anomaly in the network behavior
* An error in the dataset creation process

For data scientists working with network traffic datasets, understanding these TCP flag behaviors can be crucial for:

* Data cleaning and preprocessing
* Feature engineering
* Anomaly detection
* Understanding the underlying network processes represented in the data

# **Related work**

We selected six papers that use HIKARI-2021; these are the only six papers available as we are writing. The two most cited papers that use CIC-IDS 2017 and use Shap, the remaining are the five most cited papers about CIC-IDS 2017. Other than HIKARI-2021 and CIC-IDS 2017, some papers contain other datasets. In *Table 3.1*, we used some of the criteria mentioned in (Catillo et al., 2023) about the ML implications; it is a list of common issues related to ML models for IDS. We excluded the data partitioning issues since we are not building a neural network with memory or solving any other problem where the chronological order of the data is relevant. We also excluded the lack of transferability since we need better datasets to make a model that can be deployed in the real world. Moreover, we added explainability criteria for the papers that used a post hoc explainability algorithm. No one matches the updated dataset criteria; in the case of HIKARI-2021, the authors released a new data capture to improve the problem of an imbalanced dataset, but it has yet to be adopted. In the case of CIC-IDS 2017, we consider the updated version NFS-2023-TE, which is the latest of a series of refinements of CIC-IDS 2017. The dataset was published during the writing of this document, so it has yet to be adopted. All attacks refer to the fact that some papers do not use all the dataset categories; in this case, we usually expect the performance metrics to be higher. Attack-revealing features and ease of detection: In the case of HIKARI 2021, we found two papers that include the index generated by pandas as a feature that can help some models detect attacks. Since the attacks have been performed in a specific time range, with the index, a decision tree can detect that between specific ranges that are mostly attacks. While in NFS-2023-TE, there is a feature called protocol, since all the attacks have been performed over TCP, a model will be biased thinking that all the UDP connections are not attacks, but attacks over UDP exist. Unmotivated complexity refers to the fact that some papers propose a complex deep learning (DL) algorithm without making a comparison with simpler models. In the case of an IDS, lower inference time and computationally cheap models are advantages, so when a complex model is proposed, it should be compared to a simpler one, for example, a random forest (RF). A comparison with previous work is usually insufficient since we noticed that something different in data preparation or other metrics are used, making the comparison useless. Moreover, some work does a comparison without fine-tuning the classic ML model, making the comparison unfair. The latest is source code; this is the most important since if something is not mentioned or unclear on the paper, it can be found in the source code. Moreover, if needed, all the other mentioned aspects can be fixed. For example, metrics can be added if a paper does not use an F1 score with the source code.

Table 3.1 - Related works \* shap was used but for feature selection \*\* they use all the features, but they group them (Panigrahi & Borah, 2018)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Paper | *Avoid attack-revealing features and ease of detection* | *Avoid unmotivated complexity* | *Use of the evaluation metrics* | *Source code* | *Explainability* | *Updated dataset* | *All attacks* | *Dataset used* |
| (Kwon et al., 2023) | Yes | Yes | Yes | No | No | No | Yes | Hikari-2021 |
| (Noori et al., 2023) | Yes | Yes | Yes | No | No | No | No | Hikari-2021 |
| (Louk & Tama, 2023) | - | No | Yes | No | No | No | No | Hikari-2021 |
| (Rajak et al., 2022) | - | No | Yes | No | No | No | Yes | Hikari-2021 |
| (Fernandes & Lopes, 2022) | No | Yes | Yes | No | No | No | Yes | Hikari-2021 |
| (Fernandes et al., 2023) | No | Yes | Yes | No | No | No | Yes | Hikari-2021 |
| (Chauhan & Shah Heydari, 2020) | Yes | No | Yes | No | No \* | No | Yes | CIC-IDS 2017 |
| (Sarhan et al., 2022) | Yes | Yes | Yes | No | Yes | No | Yes | CIC-IDS 2017 |
| (Zavrak & Iskefiyeli, 2020) | Yes | Yes | No | No | No | No | Yes | CIC-IDS 2017 |
| (Kurniabudi et al., 2020) | Yes | Yes | No | No | No | No | Yes\*\* | CIC-IDS 2017 |
| (Yulianto et al., 2019) | Yes | Yes | Yes | No | No | No | No | CIC-IDS 2017 |
| (Maseer et al., 2021) | Yes | Yes | Yes | No | No | No | Yes\*\* | CIC-IDS 2017 |
| (J. Liu et al., 2021) | Yes | Yes | No | No | No | No | Yes | CIC-IDS 2017 |
| This work | Yes | Yes | Yes | Yes | Yes | Yes | Yes |  |

# **Methodology**

## **Dataset choice**

In February 2024, the three datasets with the most citations in Google Scholars were CIC-IDS 2017 (Sharafaldin et al., 2018) with 3149 citations, NLS-KDD (Tavallaee et al., 2009) with 5131 citations, and UNSW-NB15 (Moustafa & Slay, 2015) with 2740 citations, these two are improvements based on the raw data of KDD Cup ’99 (Lee et al., 1999). We focus on two datasets derived from CIC-IDS 2017, illustrating why it may no longer be the best option.

By making CIC-IDS 2017, the authors have achieved for the first time the goal of covering all the 11 criteria given by (Gharib et al., 2016) by using CICFlowMeter (Lashkari et al., 2017). However, the analysis of the pcap files by (Engelen et al., 2021) and (L. Liu et al., 2022) revealed over 5% corruption in dataset labeling and non-compliance of CICFlowMeter with TCP connection closure standards (Brownlee et al., 1999). This led to the creation of WTMC-2021 and a patched version of CICFlowMeter. One year later, WTMC-2021 improved with the name of CRiSIS-2022 (Lanvin et al., 2023) by adding the attack port scan that was not labeled and sorting and removing the duplicates in the pcap file, again thanks to a new patch of CICFlowmeter. In 2023 (Pekar & Jozsa, 2024)noticed that even after the patching, CICFlowMeter was not closing the connection after a FIN or RST packet and was also making some missing or negative values, so they decided to make NFS-2023-TE by using NFStream (Aouini & Pekar, 2022). NFS-2023-TE creates a new flow at first FIN or RST flag like most of the flow analyzers do (Hofstede et al., 2014), while NFS-2023-nTE creates a new flow after a timeout like WTMC-2021 and CRiSIS-2022 do, this second dataset has been made only for the sake of comparison with its predecessor.

Things may change, however, since the authors of CICFlowMeter said in an email exchange that they are making a new tool written in Python with more than 50 new features for 130 features.

Hikari 2021 (Ferriyan et al., 2021) is a dataset inspired by CIC-IDS 2017 but includes seven new requirements; they also provide the pcap files, a csv file, and a pkl of the dataset. They offered 84 traffic features and two target features, one multi-categorical and the other one binary; among the 84 traffic features, most of them were inspired by the ones of CIC-IDS 2017. In this dataset, the authors have focused only on web attacks since 80% of the attacks nowadays are done on the application layer. So, they have performed three different attacks, but on the dataset, a fourth one is present since while they were analyzing the background traffic, they found a crypto miner attack. The raw data were extracted using tcpdump, while the labeling and analysis of the background traffic were done with Zeek, which also added some features that are not present in CIC-IDS 2017. These features are the IP address, source and destination ports, and uid. Since the paper's release, the dataset has received an update that improves the dataset by increasing the size of the minority classes.

We decided to build our models using NFS-2023-TE and HIKARI-2021, which, as far as we know, are the two most updated generic datasets. (Catillo et al., 2023) list some typical dataset issues in *Table 4.1*, we will see if NFS-2023-TE and HIKARI-2021 have improved compared to CIC-IDS 2017 mentioned in the paper.

Table 4.1- Typical dataset issues

|  |  |  |
| --- | --- | --- |
| Issue | HIKARI-2021 | NFS-2023-TE |
| *Simplification of the data collection environment* | Not addressed | Not addressed |
| *Contemporaneity and effectiveness of the attack* | Hikari 2021 focuses only on encrypted traffic at the application layer, saying that 80% of attacks are done at this level. As far as we know, this is the most updated dataset available; this would be a good option until a new one emerges. | The data used was generated seven years ago. Moreover, some attacks in the dataset have been proven ineffective nowadays. In (Catillo et al., 2021) they |
| *Representativeness of the normal baselines* | Not addressed | Not addressed |
| *Bugs of the feature extractor and incorrect ﬂow records* | Hikari 2021 does not provide any source code and mentions that the labeling was made with Zeek alongside an undefined Python tool, so we analyzed the dataset before using it. This part will be discussed later. However, in an email exchange with the authors, they said the source code would be released. | To avoid this problem, NFS-2023-TE was made with NFStream, which was chosen since it is an open-source tool with a broad user base, and the labeling process has been documented and released alongside the Python code used. |
| *Data Labeling (Was the traffic analyzed or labeled based on IP, port, and timestamp?)* | The background data were analyzed with Zeek, which led to the discovery of an attack. HIKARI 2021 does not provide the timestamp, and part of the payload is encrypted to ensure privacy; it is not possible to prove if there is any flaw in the labeling. | NFS-2023-TE should deliver on this point since it has been made on top of the refinement that has improved the original issues of the labeling part. |
| *Class imbalance* | Probing is around 2,9 times bigger than Bruteforce, which has 7988 samples. This difference is considerably smaller than NFS-2023-TE, making over-sampling possible if needed. | PortScan is around 14574 times bigger than Hearthbleed, with only 11 samples. With such a small sample, it is impossible to make a good model. |

* 1. **Explainability algorithms**

Shap (Lundberg & Lee, 2017) is a Python library that uses a game theoretic approach by computing an approximation of the Shapley values to create post hoc explanations for any machine learning models. With this work, among other explainers, they introduced Kernel Shap, a model-agnostic explainer adapted from Lime (Ribeiro et al., 2016), and Deep Shap, a model-specific explainer for neural networks that has adapted the algorithm of Deep Lift (Shrikumar et al., 2017).

Lately, two other papers (Lundberg et al., 2018, 2020) introduced Tree Shap, a model-specific explainer for trees and ensembles of trees, which is so fast compared to Deep Shap and Kernel Shap that, in most cases, can explain the entire training set in a few seconds. However, the library Fast Tree Shap (Yang, 2021) introduced an optimized version of the Tree Shap algorithm, which is faster in single-core but can overcome the original algorithm's single-core limitation, allowing even faster parallel execution. Since Fast Tree Shap has all the characteristics of Tree Shap, when we talk about Tree Shap, we will refer to both Tree Shap and Fast Tree Shap algorithms.

Tree Shap explainers and Linear Shap can provide true-to-the-model explanations (H. Chen et al., 2020) instead of other explainers that are true to the data. By breaking the dependence between features by following the rules of causal inference (Janzing, 2019), true-to-the-model explanations assign a value different from zero to a feature only if the model uses it. In the case of a true-to-the-data explanation, if two features correlate 100%, the same importance will be assigned to them even if one is not used.

Even though Tree Shap is a fast post hoc explainer, a glass box model like the Explainable Boosting Machine (EBM) (Lou et al., 2013) does not require any post hoc explanation. Being a GA2M model, it promises to be accurate as a state-of-the-art black box model without sacrificing explainability.

* 1. **ML model choice**

In the survey (Zhang et al., 2022), the authors highlight some limitations of explainable AI for cyber security, a big subject that includes IDS. We will focus on how two future improvements highlighted in this survey. The first is a high-quality dataset, which has been covered in this work. The second future improvement mentioned is the trade-off between explainability and performance. Decision tree (DT) was one of the chosen models that, with the addition of tree shap, helped to understand the model itself and how these datasets are made. Then we have boosted models paired with tree shap; the ability of tree shap to provide a true-to-the-model explanation with the incredible performance of these models has driven this choice. Boosted models can handle imbalanced data very well; in the case of NFS-2023-TE, this is a requirement given the small size of some categories. We have chosen Random Forest (Breiman, 2001), LightGBT (Ke et al., 2017), XGBoost (T. Chen & Guestrin, 2016), CatBoost (Dorogush et al., 2017) and EBM.

* 1. **Preprocessing**

To achieve better results, we opted to under-sampling all the datasets. For HIKARI-2021, all the classes were sampled to have 7988 samples for each class; moreover, we merged Bening and background traffic. This number has been chosen since the smaller class is that big. Meanwhile, for NFS-2O23-TE, under-sampling was performed to have 738 samples for each class except for smaller classes. In this case, we decided to test different numbers of samples, and this was the one performing the best. This is a significant limitation of this study, but the alternative of removing some attacks is not that better. With only 11 samples in the smallest class, over-sampling was not considered to avoid overfitting the synthetic data.

We used 80% of the stratified data for the training split to keep the same ratio between classes. Moreover, we performed 5-fold cross-validation.

* 1. **Evaluation metrics**

We used two metrics available in sklearn called F1 macro and F1 weighted.

Where N is the number of classes, i is a class, and wi is the weight of a class in the entire dataset. We can notice that in the case of a balanced dataset, there is no difference between the two equations; that is the case for HIKARI 2021 after the under-sampling.

# ***Results***

* 1. ***Data set analysis***

While in NFS-2023-TE, we did not find any flaw in the dataset, in HIKARI 2021, we noticed that the flag count for FIN and RST is higher than how it is supposed to be, having a maximum of 140 FIN packages and 110 RST packages. Moreover, the most extended flow lasted 17942 seconds, about 4.9 hours. Since the capturing sessions of HIKARI 2021 lasted 3 to 5 hours, the tool did not have a timeout, nor was it closing the connection at the first RST or FIN flag. Likely, the tool was always ignoring any timeout, RST, or FIN packet since if we filter for all the connections that lasted less than 181 seconds, with less than 2 RST and 3 FIN packets, we obtain only 104 samples for bruteforce and 59 for bruteforce-XML. For instance, NFS-2023-TE closes a connection after 120 seconds, and CICFlowMeter was supposed to close a connection after the 2 FIN packets. This evidence led to a possible conclusion that the flows within the range we selected were those with a unique IP and port combination during the capture. If two or more connections open with the same combination during the capture, they show these unexpected statistics.

Since there is no documentation about the labeling and the authors still need to release the timestamps, we cannot make it suitable for real-world usage. Instead, we decided to show how explainability can be used to expose the simplified test bed.

We also analyzed the Pcap files using the same tools as the CRiSIS 2022 reordercap and editcap with a window of 500 microseconds. We found that 0,03% of the packages were duplicated, and 0,23% were out of order. The authors confirmed that issue and did not perform preprocessing before making the dataset.

* 1. **Model performance**

The following training, classification, and explanation times have been measured on a Dell XPS 13 9315 with a 12th gen i7-1250u and 16gb of ddr5 ram running Fedora 39 with Linux 6.8. For the environment information, there is a YAML file on the GitHub repository with all the versions of the packages in the conda environment. It is crucial to notice that Sklearnex and daal4py have been used to improve inference time, and all the models have been set to use all the cores available.

Table 5.1 - NFS-2023-TE and NFS-2023-nTe parameters

|  |  |  |
| --- | --- | --- |
| mode | parameter | value |
| Random forest | n\_estimators | 10 |
| max\_depth | 14 |
| max\_features | None |
| bootstrap | False |
| catboost | iterations | 40 |
| depth | 11 |
| learning\_rate | 0.4 |
| loss\_function | MultiClass |
| ebm | learning\_rate | 1 |
| lightgbm | objective | MultiClass |
| num\_class | 15 |
| learning\_rate | 0.01 |
| num\_iterations | 250 |
| max\_depth | 4 |
| num\_leaves | 6 |
| xgboost | n\_estimators | 60 |
| max\_depth | 10 |
| objective | multi:softprob |
| learning\_rate | 0.3 |
| Dt | max\_depth | 14 |

The parameter tuning of *Table 5.1* was done following the suggestions of the documentation for each library and by looking at what was working for the other models. We used the metrics f1 macro of sklearn to evaluate the results, and when different parameters were giving similar results, a shorter training time was used to lead the decision.

Table 5.2 - NFS-2023-TE training times



*Table 5.2* shows the training time, explanation time, and the sum of both in ms for each model tested with 6087 samples. Fast tree shap is set to choose the best algorithm for the explanation automatically. These times have some variance but show the order of magnitude necessary to run each model. We can notice that even if EBM is the slowest during training, it can be faster than lightgbm and xgboost if we consider the explanation time. The random forest is close to the decision tree thanks to using only ten trees, which is considerably less than the GAM models. Another thing to consider is that even if Catboost uses fewer trees than the lightgbm and xgboost, it is slower to train.

Table 5.3- NFS-2023-TE – average F1 score of 5-fold



In *Table 5.3*, we compare the prediction time in μs for 1522 samples; in this case, we have used the magic function %timeit of ipython to compute the mean of different runs. Doing the mean is essential because it is statistically more significant. With such a smaller duration, a warmup of the function is necessary to reduce the computation time. Without the warmup run, the classification time of the decision tree was 3 ms because, at the first run, the computer loaded the prediction function into memory, which took more time than the prediction itself.

Looking at the EBM, we notice that it is the best with F1 macro but the worst with F1 weighted. Comparing these results with the decision tree shows that the decision tree has a problem with Hearthbleed and Web Attack - SQL Injection, which misclassifies two samples for the first and 4 with the latter. In comparison, the EBM misclassifies 111 samples in the DoS Slowhttptest. These results expose the need for a balanced dataset; we can argue that EBM is the best one because it can handle each attack well, but on the other hand, building a model over 11 samples will lead to something that will not work in the real world.

Moreover, we need to consider the prediction time; by looking at the F1 results, lightgbm is probably the winner by being the second-best in both macro and weighted scores but the worst in prediction time. Lightgbm is twice as slow as the random forest, which scores nearly the same in the F1 metrics, making the random forest the best alternative overall. The classification time is so important because, in case of a DoS attack that opens and closes the connection at a fast enough speed, the model needs to keep up with each new flow generated; otherwise, the NIDS will run out of service. Another reason why this classification time is necessary is that it can make a difference between enabling or not the use on the edge and lead to less expensive devices when the GPU is not required for running an NIDS.

Table 5.4 - HIKARI 2021 parameters

|  |  |  |
| --- | --- | --- |
| model | parameter | value |
| cat | iterations | 10 |
| depth | 8 |
| learning\_rate | 0.6 |
| loss\_function | MultiClass |
| dt | max\_depth | 8 |
| ebm | default |  |
| lightgbm | objective | MultiClass |
| num\_leaves | 16 |
| n\_estimators | 5 |
| max\_depth | 6 |
| rf | n\_estimators | 5 |
| max\_depth | 10 |
| max\_features | None |
| bootstrap | False |
| xgb | n\_estimators | 3 |
| max\_depth | 8 |
| learning\_rate | 1 |
| objective | multi:softprob |

*Table 5.4* shows how the parameters for HIKARI-2021 lead to less complex models except for the ebm. One of the reasons is that this dataset is balanced after the under-sampling.

Table 5.5- HIKARI-2021 training times



Therefore, *Table 5.5* shows lower training times for the 31952 training samples compared to NFS-2023-TE. EBM is the only model that has increased the training time because, contrary to the other models, it was impossible to build a smaller model with fine-tuning.

Table 5.6 - HIKARI-2021 F1 score and times



*Table 5.6* shows how the model performs nearly the same regarding the F1 score, while the faster model was the decision tree, making it the best model for HIKARI-2021.

* 1. ***Model explanations***

We decided to compare the explanations of the decision tree with the one of the catboost since they decided to give different features importance. Moreover, we printed the decision tree to analyze why tree shap gave more importance to some features.

Figure 5‑1 - NFS-2023-TE - decision tree feature importance with shap of bot class

A graph with red and black text

Description automatically generated

*Figure 5‑1* shows the feature importance of a decision tree for the class bot of NFS-2023-TE. The model has misclassified only 1 sample out of 737 using only a small subset of the available features. The same pattern of using a few features applies to the other attacks. The only exception is benign traffic, which requires more features to be detected. The benign class assigns positive importance to more features because most of the split leads to either attack or benign traffic.

Figure 5‑2 - HIKARI-2021 - decision tree feature importance with shap of bruteforce-XML class

Immagine che contiene testo, schermata, numero, linea

Descrizione generata automaticamente

In *Figure 5‑2*, we can see that the decision tree gives almost all the importance to one feature; with only the first two nodes, the decision tree can classify bruteforce-XML with a gini coefficient of 0.041. This means that 6388 of the 6526 were correctly classified.

Table 5.7 - fwd\_pkts\_payload.max quintiles

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **category** | **min** | **25%** | **50%** | **75%** | **max** |
| **Background** | 0 | 0 | 40 | 127 | 15741 |
| **Benign** | 0 | 0 | 36 | 426 | 3456 |
| **Bruteforce** | 0 | 357 | 373 | 425 | 786 |
| **Bruteforce-XML** | 0 | 746 | 747 | 748 | 925 |
| **Probing** | 517 | 517 | 517 | 517 | 517 |
| **XMRIGCC CryptoMiner** | 40 | 40 | 50 | 50 | 232 |

*Table 5.7* shows the quintile grouped by category for the first feature shown in *Figure 5‑2*, knowing that the tree’s root node selects all the samples less or equal to 737 and that the false branch filters all the samples less or equal to 761.5 made clear why this feature is the most important in detecting a bruteforce-XML attack. The problem is that this quintile distribution of this feature is not valid in the real world. Moreover, changing the payload size can fool a model built with these data.

Figure 5‑3- HIKARI-2021 - decision tree feature importance with shap of XMRIGCC CryptoMiner

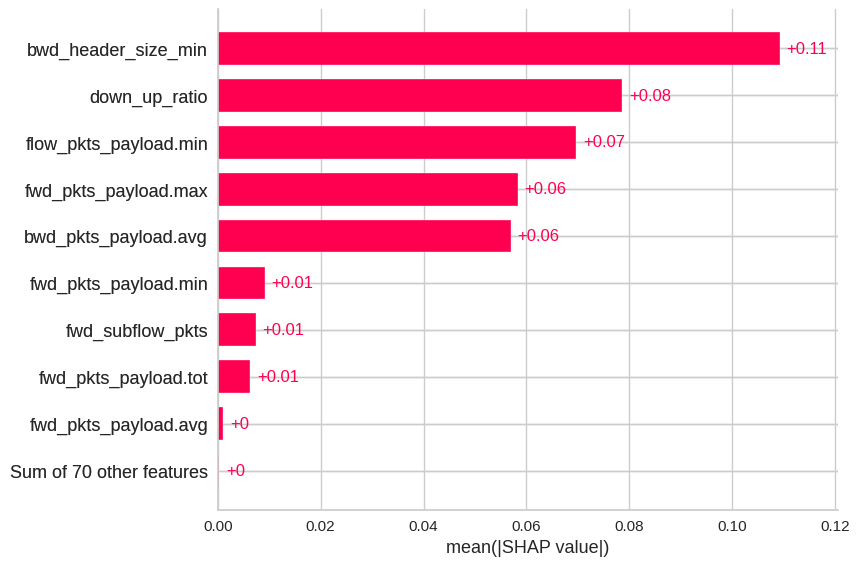


Table 5.8 - Down\_up\_ration mean and std

|  |  |  |
| --- | --- | --- |
| **category** | **mean** | **std** |
| **Background** | 0.810244 | 0.721923 |
| **Benign** | 2.015250 | 32.321667 |
| **Bruteforce** | 8.794107 | 89.440773 |
| **Bruteforce-XML** | 20.071672 | 128.065872 |
| **Probing** | 1.298040 | 0.119266 |
| **XMRIGCC CryptoMiner** | 0.000000 | 0.000000 |

*Figure 5‑3* shows the importance of the features of XMRIGCC CryptoMiner with the decision tree. Again, only a few selected features have been used; the most important is bwd\_header\_size\_min which for this attack is always zero then we have down\_up\_ratio. Table 5.8 shows that the crypto miner is the only one with always 0 for this feature, making it easy to understand why it is essential for this class. Down\_up\_ratio is also the most critical feature for probing, where we can see that the mean value is around 1.3, with a low standard deviation compared to the other attacks. This is the second most important feature for classifying background, but in this case, we do not have any hypothesis as to why.

Figure 5‑4 - NFS-2023-TE - catboost impact on the model output of DDoS with shap sorted by highest magnitude of impact

Immagine che contiene testo, schermata, numero, Carattere

Descrizione generata automaticamente

*Figure 5‑4* is the explanation of the catboost algorithm where we can see that the feature with the highest magnitude of all is bidirectional\_fin\_packets, which shows up for Bot, DDoS, DoS Slowhttptest, DoS Slowloris, Heartbleed, Infiltration, and Web Attack – XSS as one of the two most important feature in average or the one with the highest magnitude of impact. By analyzing this feature, we can notice that Bot and Web Attack -XSS always have 1 FIN packet, while DDoS averages 99% of the samples with 1 FIN packet. This characteristic makes the difference in the other attacks cited at the 85th percentile of the distribution showing 0 FIN packets. To understand why we have a lot of 0 we analyzed the duration and for Infiltration and Heartbleed, most of the connection gets closed because of the timeout, while for DoS Slowhttptest and DoS Slowloris, it is hard to tell since they did not reach the timeout either they send an RST packet.

All these analyses conclude that using a more complex model than a decision tree or a random forest is difficult to justify for these datasets. However, this does not mean that the decision tree is ready for deployment in the real world. The reason behind this algorithm's success is the oversimplified test bed.

# **Conclusion**

We first saw that CICIDS-2017 is nowadays one of the most popular datasets cited in Google Scholar, and then we saw how new proposals such as NFS-2023-TE and HIKARI-2021 aim to improve the work done with CIC-IDS 2017. In particular, NFS-2023-TE uses the same raw data as CICIDS-2017, while HIKARI-2021 proposes a new, updated test bed.

Then, we analyzed the flaws in the current literature and the dataset in use, which led to the proposal of a new methodology, with the addition of the explainability part, as seen in other work.

HIKARI-2021 has been analyzed using the criteria proposed by NFS-2023-TE, which led to the discovery of some flaws in the raw data and the dataset generation.

Finally, the analysis of the results shows how comparing simpler models such as the decision tree is necessary to have a benchmark for more complex models. Moreover, we have shown how explainable AI algorithms such as Shap need to be used to help build better models and to increase the accountability of the proposed models. Thanks to the explanations, we discovered something about the dataset, which has helped us avoid mistakes during the work. More than once, features that were not supposed to be in the training set were identified thanks to Shap.

Future improvements must be made to build a model that can be transferred to the real world. Since datasets are far from ready, building complex models using these data does not add any real contribution. This work has added two contributions. We have performed the first analysis of HIKARI-2021, exposing significant issues, and we provided some examples of how tree shap can be used to understand models and datasets better. New studies need to focus on implementing new methodologies, analyzing existing datasets to find areas of improvement, and building these new datasets. Even if the HIKARI-2021 test bed was simplified, making a refinement like NFS-2023-TE for CIC-IDS 2017 is a step in the right direction.

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# **Appendix A**

Source code available at: <https://github.com/ludotosk/tesi>

A picture containing text, screenshot, font, design

Description automatically generated