



A monitoring and threat detection system using stream processing as a virtual function for Big Data

Martin Esteban Andreoni Lopez

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LA SORBONNE UNIVERSITÉ**

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Martin Esteban ANDREONI LOPEZ

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Menaces utilisant le Traitement de flux comme
une fonction virtuelle pour le Big Data**

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A MONITORING AND THREAT DETECTION SYSTEM USING STREAM PROCESSING AS A VIRTUAL FUNCTION FOR BIG DATA

Martin Esteban Andreoni Lopez

Tese de Doutorado apresentada ao Programa de Pós-graduação em Engenharia Elétrica, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutor em Engenharia Elétrica.

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Rio de Janeiro
Junho de 2018

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PROCESSING AS A VIRTUAL FUNCTION FOR BIG DATA

Martin Esteban Andreoni Lopez

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A MONITORING AND THREAT DETECTION SYSTEM USING STREAM PROCESSING AS A VIRTUAL FUNCTION FOR BIG DATA

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June/2018

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Guy Pujolle

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The late detection of security threats causes a significant increase in the risk of irreparable damages, disabling any defense attempt. As a consequence, fast real-time threat detection is mandatory for security administration. In addition, Network Function Virtualization (NFV) provides new opportunities for efficient and low-cost security solutions. We propose a fast and efficient threat detection system based on stream processing and machine learning algorithms. The main contributions of this work are i) a novel monitoring threat detection system based on streaming processing; ii) two datasets, first a dataset of synthetic security data containing both legitimate and malicious traffic, and the second, a week of real traffic of a telecommunications operator in Rio de Janeiro, Brazil; iii) a data pre-processing algorithm, a normalizing algorithm and an algorithm for fast feature selection based on the correlation between variables; iv) a virtualized network function in an Open source Platform for providing a real-time threat detection service; v) near-optimal placement of sensors through a proposed heuristic for strategically positioning sensors in the network infrastructure, with a minimum number of sensors; and finally vi) a greedy algorithm that allocates on demand a sequence of virtual network functions.

Resumo da Tese apresentada à COPPE/UFRJ como parte dos requisitos necessários para a obtenção do grau de Doutor em Ciências (D.Sc.)

Martin Esteban Andreoni Lopez

Junho/2018

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A detecção tardia de ameaças de segurança causa um significativo aumento no risco de danos irreparáveis, impossibilitando qualquer tentativa de defesa. Como consequência, a detecção rápida de ameaças em tempo real é essencial para a administração de segurança. Além disso, uma função virtual de rede Network Function Virtualization (NFV) oferece novas oportunidades para soluções de segurança eficientes e de baixo custo. Propomos um sistema de detecção de ameaças rápido e eficiente, baseado em algoritmos de processamento de fluxo e de aprendizado de máquina. As principais contribuições deste trabalho são: i) um novo sistema de monitoramento e detecção de ameaças baseado no processamento de fluxo; ii) dois conjuntos de dados, primeiro um conjunto de dados sintético de segurança contendo tráfego suspeito e malicioso, e o segundo, uma semana de tráfego real de um operador de telecomunicações no Rio de Janeiro, Brasil; iii) um algoritmo de pré-processamento de dados composto por um algoritmo de normalização e um algoritmo para seleção rápida de características com base na correlação entre variáveis; iv) uma função de rede virtualizada em uma plataforma de código aberto para fornecer um serviço de detecção de ameaças em tempo real; v) colocação quase perfeita de sensores através de uma heurística proposta para posicionamento estratégico de sensores na infraestrutura de rede, com um número mínimo de sensores; e finalmente vi) um algoritmo guloso que aloca sob demanda uma sequência de funções de rede virtual.

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Chapter 1

Introduction

In order to maintain the stability, reliability, and security of computer networks, it is fundamental to monitor the traffic to understand the type, volume, and intrinsic features of each flow that compose the whole traffic. Therefore, efficient network monitoring allows the administrator to achieve a better understanding of the network [1]. Network monitoring may vary from a simple long-term collection of link utilization statistics, to a complex upper-layer protocol traffic analysis to achieve network intrusion detection, network performance tuning, and protocol debugging. Current network monitoring tools, such as Tcpcmdump¹, Wireshark, NetFlow, Bro [2], are inadequate for current speed and management needs of large network domains. In addition, many of these current tools generate a massive collection of files that needs post-processing by another kind of tools.

In network monitoring data arrives in the form of streams from different sources. Monitoring data arise from several heterogeneous distributed sources, such as network packets or multiple kinds of logging systems [3]. These stream applications are characterized by an unbounded sequence of events, or tuples, that arrive continuously [4]. One of the main problems of this type of applications is the big amount of data generated. Even moderate speed networks generate huge amounts of data. For example, monitoring a single gigabit Ethernet link running at 50% utilization generates a terabyte of data in a couple of hours. The advent of the Internet of things (IoT) increases the need of real-time monitoring. The estimate number of sensors networked by 2025 is around 80 billion [5].

This scenario displays a high monitoring and protection complexity, with several challenges in security and data privacy. The billions of devices generate a big amount of data streams, which needs to be managed, processed, transferred, and stored in a secure real-time way. Besides, the big data characteristics of velocity, volume, and variety increase the number of vulnerabilities.

¹Tcpcmdump packet analyzer www.tcpcmdump.org

Consequently, detection time is essential to maintain security in communication systems [6]. If detection takes too long, irreparable damages will occur. Denial of Service (DoS) [7] attacks, for example, need to be mitigated as fast as possible in order to maintain a proper Quality of Service (QoS). The effective threat detection demands monitoring, processing, and management of data, in order to extract useful information from network traffic [1]. Current security systems, such as Security Information and Event Management (SIEM), designed to gather data and analyze it in a single point, are not effective, since 85% of network intrusions are detected weeks after they had happened [5]. Moreover, data leaking detection time is 206 days. Therefore, the long threat detection time makes unfeasible any kind of defense.

The impact of Distributed Denial of Service (DDoS) attacks is increasing, reaching attack rates of the order of 1 Tb/s [8]. The popularization of the attacks is so popular that it is possible to buy an hour of a DDoS attack for \$10 per hour on the deep web [9]. The attacks were no longer merely motivated by economic ends and became politically motivated [8]. Currently attacks aim to manipulate election results, such as the suspicion of Russian manipulation over the United States elections in 2016 [10].

One way to attain data processing optimization is to employ machine learning methods. These methods are well suited for big data, since with more samples to train, methods tend to have higher effectiveness [11]. However, with big data machine learning methods tend to perform high latency due to computation consumption. This high latency is a drawback for machine learning methods that must analyze data as fast as possible in order to have fast responses. Features Selection is one way to resolve this problem, reducing the number of features to smaller subset of the original. The main method to analyze big data in a distribute fashion is the MapReduce [12] technique with Hadoop [13] open-source implementation. Nevertheless, the platforms based on this technique are inappropriate to process real-time streaming applications. Applications processed by Hadoop correspond to queries or transactions performed in a static database without real-time requirements, data elements are synchronized to obtain an exact answer. Real-time monitoring applications require distributed stream processing that substantially differs from current conventional applications processed by distributed platforms. Network Monitoring normally requires to analysis multiple external stream sources, generating alerts in abnormal condition. The real-time feature is intrinsic to stream processing applications and a big number of alerts is normally expected. The stream data are unbounded and arrive asynchronously. Besides, the stream analysis requires historical data rather rather than just the latest arrived data. In cases of high incoming rates is common to filter the most

important data discarding others and, therefore, approximate solutions are required, such as sampling methods. Hence, to meet these applications requirements, distributed processing models have been proposed and received attention from researchers.

Real time analytic are essential for Future Internet and Smart Cities [14, 15]. Moreover, real-time stream processing enable the immediate analysis of different kinds of data and, consequently, they empower threat detection. Real-time distributed stream processing models can benefit traffic monitoring applications for cyber security threats detection [16]. Sensor monitoring in the Internet of Things (IoT), network traffic analysis, cloud management [17], smart grids [18] and security threats detection are applications that generate large amount of data to be processed in real time. In these critical application data need to be processed in real time in order to detect security threats.

To meet these needs, Distributed Stream Processing Systems (DSPS) have been proposed to perform distributed processing with minimal latency. Besides, open-source general-purpose stream processing platforms are now available, meeting the need of processing data continuously. These open-source platforms are able to define custom stream processing applications for specific cases. These general-purpose platforms offer an Application Programming Interface (API), fault tolerance, and scalability for stream processing.

Current enterprise networks rely on middleboxes. Middleboxes are intermediary devices that aims to improve network performance. Example of network middleboxes are firewalls that establishes a barrier for network attacks; load-balancers which improve performance distributing workload over network nodes; or proxies that reduce bandwidth consume [19]. Middleboxes are usually dedicated hardware nodes, which perform a specific network function. Hence, middlebox platforms come with high Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) [20]. In this way, the Network Function Virtualization (NFV) comes to leverage standard virtualization technology into the network core, and to consolidate network equipment into commodity server hardware [21]. In NFV, the network functions are deployed into virtualized environment and, thus, called Virtual Network Functions (VNF).

We aim to use NFV technology and its cluster infrastructure to combine virtualization, cloud computing and distributed stream processing to monitor network traffic. The objective is to provide an accurate, scalable, and real-time threat detection facility capable to attend usage peaks. The traffic monitoring and threat detection as a virtualized network function presents two main advantages: capacity self-adaptation to different traffic network load and high localization flexibility to place or move network sensors reducing latency.

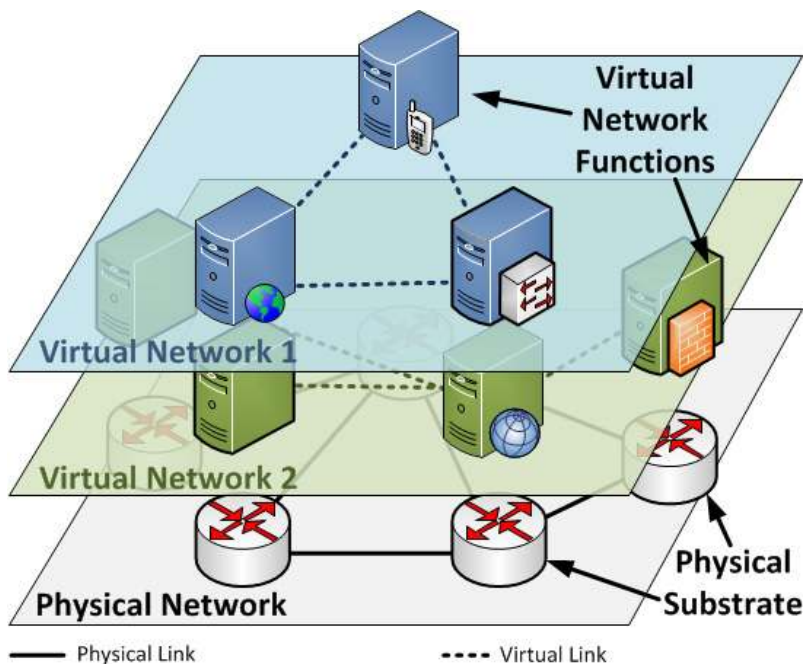


Figure 1.1: Example of virtual network functions. Two separated plans of virtual network functions decoupled from the underlying physical substrate.

When considering the deployment of middleboxes as Virtual Network Functions, a key challenge is the Service Function Chaining (SFC) [22]. The SFC problem stands for the requirement of traffic to pass through multiple middleboxes for packet processing in a previously defined order. It becomes harder when considering the NFV environment, because allocating virtual network function over the physical nodes have to consider the packet-processing chaining order among all VNFs in the traffic path, as shown in Figure 1.1. Therefore, two main constraints for VNF chaining are to reduce the delay introduced by placing the VNFs on the network topology, and to allocate VNFs on physical nodes that can provide enough resources to run the hosted functions.

Chaining virtual network functions is essentially an optimization problem that recalls the facility location problem [22]. Previous works propose linear programming models to search for a solution for VNF chaining, considering resource allocation and the routing between virtual instances [22–24]. Other works propose to outsource network functions to the cloud [19, 25], but do not specify an algorithm for placing VNFs on the network. Moreover, there are also works that place specific-purpose VNFs on the network, such as traffic sensors or network controllers [26, 27]. Our proposal uses a greedy algorithm to place general-purpose VNFs over a network topology and compares different heuristics. Our scheme estimates the resources at each physical node on the network and, then, places the VNFs according to the available resources of the physical nodes and the requested resources for the VNF.

1.1 Objectives

The goal of this manuscript is to present the research work and the obtained results achieved so far. The main idea is to show the state of art and the developed research work. The research topics assessed are Stream Processing, Real-Time Threat Detection System, Dataset and Future Selection, Virtual Network Function, and Virtual Network Function Chaining. We briefly describe research topics.

Stream Processing

We analyze and compare two native distributed real time native stream processing systems, the Apache Storm [28] and the Apache Flink [29], and one micro-batch system, the Apache Spark Streaming [30]. The architecture of each analyzed system is discussed in depth and a conceptual comparison is presented showing the differences between these open-source platforms. Furthermore, we evaluate the data processing performance and the behavior of systems when a worker node fails.

Real-Time Threat Detection System

We propose and implement an accurate real-time threat detection system, the CATRACA² tool [31]. The integrated system allows big data analysis in a stream processing manner. The proposed system uses machine learning for both attack classification and threat detection. Moreover, the system has a friendly graphical interface that provides a real-time visualization of the parameters and the attacks that occur in the network.

DataSet and Future Selection

We created two datasets, first a synthetic security dataset to perform traffic classification, second real traffic from a network operator in Rio de Janeiro, Brazil. Furthermore, we present a fast and unsupervised pre-processing algorithm for traffic classification. Our algorithm performs feature reduction in an unsupervised way, without the knowledge of the classes, and normalize stream data. In addition, the algorithm selects the best features to classify normal traffic from Denial of Service and Probe threats. We compare our algorithm with conventional features selection methods such as ReliefF [32], Sequential Feature Selection (SFS) and Principal Component Analysis (PCA) [33], and we show a better fulfillment in accuracy as well as in performance.

Virtual Network Function

We evaluate our threat detection tool as a Virtual Network Function (VNF). Consequently, we propose a virtualized network function in the Open Source Platform for Network Functions Virtualization (OPNFV) that provides an accurate real-time threat detection service. For the best of our knowledge, this is the first threat detection function using stream processing implemented in the

²documentation available at <http://catraca.gta.ufrj.br/>

OPNFV platform. The provided service is able to scale the number of processing cores by adding virtual machines to the processing cluster that executes the detection in a parallel-distributed way, processing up to 15 Million samples per minute. Besides, the Network Virtualization Platform enables the easy deployment of traffic capture sensor elements that can be placed and moved to several points in the network, offering customization and adaptability to network monitoring. The results show the potential for scalability, as we increase the number of processing cores in the distributed cluster. Another important feature of our proposal is the migration of processing machines. The experiments show that our system can migrate the processing elements without stopping the threat detection. The live migration enables the organization of the physical machines in processing cluster, which results in several advantages, such as shutting down machines for maintenance or for reduction of energy consumption or allocating resources in a smart way to attend the demand.

Virtual Network Function Chaining

We propose a scheme for placing and chaining Virtual Network Functions over a network topology according to four different heuristics. The first heuristic places the VNF nodes into physical nodes that introduce the minimum delay between the traffic source and destination. The second heuristic searches for the best placement of VNF nodes considering the nodes that have the biggest amount of available resources and, thus, places the VNF over the node most available. This approach increases the number of accepted requests of VNFs in a network. The third heuristic places the VNF nodes according to the betweenness-centrality of the topology nodes. In the betweenness-centrality approach, the requests are primarily responded by allocating the most central nodes on the topology, which reduces the introduced delay. However, as the resources of the most central nodes are used, the following requests are allocated into peripheral network nodes, introducing a greater delay on the VNF chaining. The fourth heuristic weights the available resources and the introduced delay for each physical node. This approach allocates the VNFs on the nodes that present the greatest probability of supplying enough resources and the lower delay. We deploy a greedy algorithm for all three approaches and we simulate the allocation of VNFs over a real network topology. We have published as first author

- GTA-17-27 Andreoni Lopez, M., Sanz, I. J., Mattos, D. M. F., Duarte, O. C. M. B., Pujolle, G. - “CATRACA: uma Ferramenta para Classificação e Análise Tráfego Escalável Baseada em Processamento por Fluxo”, in XVII Simpósio Brasileiro de Segurança da Informação e de Sistemas Computacionais - SBSeg’2017 -**Best Tool Award** - Brasília, DF, Brazil, November 2017.

<http://www.gta.ufrj.br/ftp/gta/TechReports/ASM17.pdf>

- GTA-17-21 Andreoni Lopez, M., Silva Souza, R., Alvarenga, I. D., Rebello, G. A. F., Sanz, I. J., Lobato, A. P., Mattos, D. M. F., Duarte, O. C. M. B. and Pujolle, Guy - “Collecting and Characterizing a Real Broadband Access Network Traffic Dataset”, in 1st Cyber Security in Networking Conference (CSNet’17) - **Best Paper Award** - Rio de Janeiro, Brazil, October 2017.
<http://www.gta.ufrj.br/ftp/gta/TechReports/ASAR17.pdf>
- GTA-17-06 Andreoni Lopez, M., Silva, R. S., Alvarenga, I. D., Mattos, D. M. F., Duarte, O. C. M. B. - “Coleta e Caracterização de um Conjunto de Dados de Tráfego Real de Redes de Acesso em Banda Larga”, in XXII Workshop de Gerência e Operação de Redes e Serviços (WGRS’2017) - SBRC’2017, Belém- Pará, PA, Brazil, May 2017.
<http://www.gta.ufrj.br/ftp/gta/TechReports/ASA17.pdf>
- GTA-17-04 Andreoni Lopez, M., Lobato, A. G. P., Mattos, D. M. F., Alvarenga, I. D., Duarte, O. C. M. B., Pujolle, G. - “Um Algoritmo Não Supervisionado e Rápido para Seleção de Características em Classificação de Tráfego”, in XXXV Simpósio Brasileiro de Redes de Computadores e Sistemas Distribuídos - SBRC’2017, Belém- Pará, PA, Brazil, May 2017.
<http://www.gta.ufrj.br/ftp/gta/TechReports/ALM17.pdf>
- GTA-16-34 Andreoni Lopez, M., Lobato, A. G. P., Duarte, O. C. M. B., and Pujolle, G. - “Design and Performance Evaluation of a Virtualized Network Function for Real-Time Threat Detection using Stream Processing”, Fourth Conference On Mobile And Secure Services (MobiSecServ), Miami, MI, USA, February 2018.
<http://www.gta.ufrj.br/ftp/gta/TechReports/ALDP16.pdf>
- GTA-16-31 Andreoni Lopez, M., Mattos, D. M. F., and Duarte, O. C. M. B. - “Evaluating Allocation Heuristics for an Efficient Virtual Network Function Chaining”, in 7th International Conference Network of the Future IEEE - NoF’2016, Búzios-RJ, Brazil, November 2016.
<http://www.gta.ufrj.br/ftp/gta/TechReports/AMD16b.pdf>
- GTA-16-24 Andreoni Lopez, M., Lobato, A. G. P., and Duarte, O. C. M. B. - “A Performance Comparison of Open-Source Stream Processing Platforms”, in IEEE Global Communications Conference - GLOBECOM’2016, Washington, DC USA, December 2016.
<http://www.gta.ufrj.br/ftp/gta/TechReports/ALD16b.pdf>

- GTA-16-11 Andreoni Lopez, M., Lobato, A. G. P., and Duarte, O. C. M. B. - “Monitoramento de Tráfego e Detecção de Ameaças por Sistemas Distribuídos de Processamento de Fluxos: uma Análise de Desempenho”, in XXI Workshop de Gerência e Operação de Redes e Serviços (WGRS 2016) - SBRC’2016, Salvador-Bahia, BA, Brazil, May 2016.
<http://www.gta.ufrj.br/ftp/gta/TechReports/ALD16b.pdf>
- GTA-16-05 Andreoni Lopez, M., Mattos, D. M. F., and Duarte, O. C. M. B. - “An elastic intrusion detection system for software networks”, in Annals of Telecommunications, Springer, ISSN 0003-4347, DOI 10.1007/s12243-016-0506-y, 2016.
<http://www.gta.ufrj.br/ftp/gta/TechReports/AMD16.pdf>

We also have published as co-author

- GTA-18-08 Sanz, I. J., Andreoni Lopez, M., Rebello, G. A. F. and Duarte, O. C. M. B.- “Um Sistema de Detecção de Ameaças Distribuídos de Rede baseado em Aprendizagem por Grafo”, in XXXVI Simpósio Brasileiro de Redes de Computadores e Sistemas Distribuídos - SBRC’2018. Campos de Jordão, SP, Brazil, May 2018
- GTA-18-02 Lobato, A. G. P., Andreoni Lopez, M., Sanz, I. J., Cardenas, A. A., Duarte, O. C. M. B. and Pujolle, Guy- “An Adaptive Real-Time Architecture for Zero-Day Threat Detection”, to be published in IEEE International Conference on Communications - ICC 2018, May 2018.
<http://www.gta.ufrj.br/ftp/gta/TechReports/LASC18.pdf>
- GTA-17-22 Sanz, I. J., Andreoni Lopez, M., Mattos, D. M. F., and Duarte, O. C. M. B. - “A Cooperation-Aware Virtual Network Function for Proactive Detection of Distributed Port Scanning”, in 1st Cyber Security in Networking Conference (CSNet’17), Rio de Janeiro, Brazil, October 2017.
<http://www.gta.ufrj.br/ftp/gta/TechReports/SAMD17.pdf>
- GTA-17-16 Lobato, A. P., Andreoni Lopez, M. E., Rebello, G. A. F., and Duarte, O. C. M. B. - “Um Sistema Adaptativo de Detecção e Reação a Ameaças”, to be published in Anais do XVII Simpósio Brasileiro em Segurança da Informação e de Sistemas Computacionais - SBSeg’17, Brasília, DF, Brazil, November 2017.
<http://www.gta.ufrj.br/ftp/gta/TechReports/LLD17.pdf>
- GTA-17-15 Sanz, I. J., Alvarenga, I. D., Andreoni Lopez, M. E., Mauricio, L. A. F., Mattos, D. M. F., Rubistein, M. G. and Duarte, O. C. M. B. - “Uma

Avaliação de Desempenho de Segurança Definida por Software através de Cadeias de Funções de Rede”, to be published in Anais do XVII Simpósio Brasileiro em Segurança da Informação e de Sistemas Computacionais - SBSeg’17, Brasilia, DF, Brazil, November 2017.

<http://www.gta.ufrj.br/ftp/gta/TechReports/SAA17.pdf>

- GTA-16-08 Lobato, A. G. P., Andreoni Lopez, M. and Duarte, O. C. M. B. - “An Accurate Threat Detection System through Real-Time Stream Processing”, Technical Report, Electrical Engineering Program, COPPE/UFRJ, April 2016.

<http://www.gta.ufrj.br/ftp/gta/TechReports/LAD16.pdf>

- GTA-16-10 Lobato, A. G. P., Andreoni Lopez, M. and Duarte, O. C. M. B. - “Um Sistema Acurado de Detecção de Ameaças em Tempo Real por Processamento de Fluxos”, in XXXIV Simpósio Brasileiro de Redes de Computadores e Sistemas Distribuídos - SBRC’2016, Salvador- Bahia, BA, Brazil, May 2016.

<http://www.gta.ufrj.br/ftp/gta/TechReports/LAD16b.pdf>

1.2 Text Organization

The rest of the paper is organized in six chapters. Chapter 3 discuss related work. Then, we introduce the concept of Stream processing, we compare stream processing platforms in Chapter 4 and we present the CATRACA tool for network monitoring and real-time threat detection system. In Chapter 5, we introduce the security dataset and the network operator dataset, we also discuss the feature selection methods proposing a new future selection algorithm. In addition, we propose an algorithm for stream data normalization. Chapter 6 presents the Virtual Network Function for threat classification and an algorithm for VNF chaining. Finally, Chapter 7 concludes the work and discuss the future work.

Chapter 2

Conclusion

This work proposed a fast and efficient network monitoring and threat detection system. We used a combination of machine learning and stream processing for real time threat detection. A new generation of tool is needed in order to real-time monitor and secure computer network. We described and compared the three-major open source distributed stream processing systems: Apache Storm, Apache Flink, and Apache Spark Streaming. We performed throughput analysis, allocating more processing cores to achieve higher processing rates, Apache Storm was able to process up to 15 Million samples per minute. Also, we performed fault tolerance test to compare these three most popular open-source Distribute Stream Processors (DSP). In this case, we show that Spark streaming, using micro-batch processing model, can recover the failure without losing any messages. Spark Streaming stores the full processing state of the micro-batches and distributes the interrupted processing homogeneously among other worker nodes.

In order to increase the analysis speed and improve the efficiency of big data analysis, it is mandatory to implement pre-processing methods. This work presented and compared different methods for dimensionality reduction and Feature selection. Furthermore, we proposed a new fast-unsupervised algorithm for pre-process stream data. The algorithm includes feature selection and data normalization. Our feature selection algorithm calculates the correlation of the features in a network traffic data and selects the best features in an unsupervised way. We selected the features with the higher absolute correlation in comparison with the others. This procedure tends to gather the features with most of the information of the dataset in a new set of features. The reduced new set of features is used, thus, to train the machine learning methods that classify and characterize the network traffic. Our algorithm was up to 10 times faster than literature algorithms for feature selection. We evaluated the feature selection algorithm in two different datasets achieving good performance. Moreover, our pre-processing algorithm is able to detect concept-drift in streaming data. We showed that our

normalizer adapts the data to a normal distribution reducing the error of machine learning classifiers. To evaluate the proposed algorithms, we implement eight machine learning algorithms, decision tree, neural networks, k-nearest neighbors, support vector machine with linear and RBF kernel, Gaussian Naive Bayes and Stochastic Gradient Descent. We evaluated their performance under six metrics, accuracy, precision, sensitivity, F-1 score, classification and training time. We created two datasets publicly available. First a synthetic security dataset obtaining real network traffic along with network threats composed of 24 features. The dataset contains more than 16 different types of attacks, as well as normal network traffic. The second dataset is composed by more than ten days of real traffic from a real telecommunication operator network (NetOp) located in the city of Rio de Janeiro, Brazil. The dataset represents the use of the fixed-line access service of 373 home users. The analysis of the data allows identifying that the main services accessed are those of DNS and web services. We use this information to create more than 5 TB of data combined in 45 flows features.

Network Function Virtualization (NFV) is a promising technique that enables to decouple the network function from its physical realization by virtualizing the network equipment. Thus, network functions are deployed within virtual environment and, thus, called Virtual Network Functions (VNF). Therefore, we deploy our threat detection system as a virtualized network function. The threat detection function is implemented in the Open-source Platform for Network Function Virtualization (OPNFV) and shows high performance and live migration features. The results shown that the implemented function prototype presents a high throughput and a low latency.

Combining stream processing, machine learning and feature selection we created the CATRACA tool. The proposed tool is executed in an OPNFV environment allowing the system to perform migration as closets as possible to the source attack. Moreover, the tool combines batch and stream processing in a big data architecture that allows to performs threat analysis on incoming traffic in real time on a historical database. Our tool displays the knowledge extracted from the enriched data through a graphical user interface for visualizing different analyzes and the geographical location of the source and destination of the threats in real time. CATRACA code is publicly available.

Finally, we proposed a method for the strategic location of traffic capture sensors. For this, a mathematical modeling was developed, obtaining a heuristic that takes into account the minimum number of sensors reached the maximum coverage of the network. The evaluation of the heuristic was analyzed in two different real topologies. The results show that with a high network coverage the proposed system has a great gain in relation to random choice. In addition, we model and

discuss the VNF sensor placement as an *NP*-hard problem. Our heuristic reduces the number of sensor and maximizes the network coverage.

We propose a VNF chaining scheme, in which a greedy algorithm places the VNFs on the network according to four different criteria. Our simulation and results show that using a heuristic for placing VNFs on nodes with the biggest amount of available resources increases the acceptance rate of VNF requests. Our simulation and results show that using a heuristic for placing VNFs on nodes with the biggest amount of available resources increases the acceptance rate of VNF requests by 53%. Moreover, we also show that using a heuristic for introducing minimum delay on the path, we are able to reduce the average packet-processing delay by 52%.

2.1 Future Work

New methods of anomaly detection and traffic classification need to be experimented in CATRACA to avoid the use of the batch layer. Algorithms such as deep learning or Hoeffding Trees should be implemented in the tool. Due to the distributed nature of our monitoring and threat detection tool, we need to implement an algorithm for event correlation. A future work foresees to detect intrusion symptoms by collecting diverse information at several architectural levels, from raw packet until system logs, using distributed security probes, as well as performing complex event analysis based on a complex event processin

Chapter 3

Related Work

This chapter discusses the state of art and presents the related work of the topics addressed in this work. We divide this chapter in four main topics. Section 3.1 describes the related work concerning Stream Processing Platforms. Section 3.2 addresses Real-time threat detection. Virtual Network Functions are presented in Section 3.3 and service chaining is introduced in Section 3.4.

3.1 Stream Processing Platforms Comparison

Distributed real-time stream processing systems is a recent topic that is gaining a lot of attention from researchers. Hence, performance evaluations and comparisons between stream processing systems are fairly unexplored in the scientific literature. Hesse and Lorenz compare the Apache Storm, Flink, Spark Streaming, and Samza platforms [34]. The comparison is restricted to description of the architecture and its main elements. Gradvohl *et. al* analyze and compare Millwheel, S4, Spark Streaming, and Storm systems, focusing on the fault tolerance aspect in processing systems [35]. Actually, these two above cited paper are restricted to conceptual discussions without experimental performance evaluation. Landset *et. al* perform a summary of the tools used for process big data [36], which shows the architecture of the stream processing systems. However, the major focus is in batch processing tools, which use the techniques of MapReduce. Roberto Colucci *et. al* show the practical feasibility and good performance of distributed stream processing systems for monitoring Signaling System number 7 (SS7) in a Global System for Mobile communications (GSM) machine-to-machine (M2M) application [37]. They analyze and compare the performance of two stream processing systems: Storm and Quasit, a prototype of University of Bologna. The main result is to prove Storm practicability to process in real time a large amount of data from a mobile application.

Nabi *et. al* compare Apache Storm with IBM InfoSphere Streams platform in an

e-mail message processing application [38]. The results show a better performance of InfoSphere compared to Apache Storm in relation to throughput and CPU utilization. However, InfoSphere is an IBM proprietary system and the source code is unavailable. Lu *et. al* propose a benchmark [39] creating a first step in the experimental comparison of stream processing platforms. They measure the latency and throughput of Apache Spark and Apache Storm. The paper does not provide results in relation to Apache Flink and the behavior of the systems under failure.

Dayarathna e Suzumura [40] compare the throughput, CPU and memory consumption, and network usage for the stream processing systems S, S4, and the Event Stream Processor Esper. These systems differ in their architecture. The S system follows the manager/workers model, S4 has a decentralized symmetric actor model, and finally Esper is software running on the top of Stream Processor. Although the analysis using benchmarks is interesting, almost all evaluated systems are already discontinued or not currently have significant popularity. Unlike the most of above-mentioned papers, we focus on open-source stream processing systems that are current available such as Apache Storm, Flink, and Spark Streaming [41, 42]. We aim at describing the architectural differences of these systems and providing experimental performance results focusing on the throughput and parallelism in a threat detection application on a dataset created by the authors.

3.2 Real-Time Threat Detection

Some proposals use Apache Storm stream processing tool to perform real-time anomaly detection. Du *et al.* use the Flume and Storm tool for traffic monitoring to detect anomalies. The proposal is to make the detection through the k-NN algorithm [43]. The article presents some performance results, but it lacks evaluation of the accuracy of detection and the tool only receive data from a centralized node, ignoring data from distributed sources. The work of Zhao *et al.* uses the Kafka and Storm, as well as the previous work, for the detection of network anomalies [44], characterizing flows in the NetFlow format. He *et al.* propose a combination of the distributed processing platforms Hadoop and Storm, in real time, for the detection of anomalies. In this proposal, a variant of the k-NN algorithm is used as the anomaly detection algorithm [45]. The results show a good performance in real time, however without using any process of reaction and prevention of the threats. Mylavarapu *et al.* propose to use Storm as a stream processing platform for intrusion detection [46].

Dos Santos *et al.* uses a combination of Snort IDS and OpenFlow to create

Of-IDPS. Snort IDS is used as a detection tool, while OpenFlow actions perform the mitigation or prevention of detected attacks [47]. An evolution of of-IDPS was proposed to develop an Autonomous Computation (AC) system to automatically create security rules in Software Defined Network (SDN) switches [6]. Rules are created applying a machine learning algorithm to Snort IDS alerts and OpenFlow logs. The machine learning method used in this work is the FP-Growth to find frequent item sets, also called association rules. Schuartz *et al.* propose a distributed system for threat detection in Big Data traffic [48]. Apache Storm and Weka machine learning tool are used to analyze KDD-99 dataset. The system is based in lambda big data architecture that combines batch and stream processing. Stream processing platforms have been used for security initiatives. Apache Metron¹ is a security analysis framework based on big data processing. Metron architecture consists of acquisition, consumption, distributed processing, enrichment, storage and visualization of the data layers. The key idea of this framework is to allow the correlation of security events from different sources. To this end, the framework employs distributed data sources such as sensors in the network, action logs of active network security elements and telemetry sources. The framework also relies on a historical foundation of network threats from Cisco. Apache Spot² is a project similar to Apache Metron still in incubation. Apache Spot uses telemetry and machine learning techniques for packet analysis to detect threats. The creators say that the big difference with Apache Metron is the ability to use common open data models for networking. Stream4Flow³ uses Apache Spark with the ElasticStack stack for network monitoring. The prototype serves as a visualization of network parameters. Stream4Flow [49], however, has no intelligence to perform anomaly detection. Hogzilla⁴ is an intrusion detection system (IDS) with support for Snort, SFlows, GrayLog, Apache Spark, HBase and libnDPI, which provides network anomaly detection. Hogzilla also allows to realize the visualization of the traffic of the network.

The proposed CATRACA tool, like Metron, aims to monitor large volumes of data using flow processing. The CATRACA tool is implemented as a virtualized network function (VNF) in the Open Platform for Network Function Virtualization (OPNFV) environment. CATRACA focuses on real-time packet capture, feature selection and machine learning. CATRACA can be combined with a mechanism of action for immediate blocking of malicious flows. Thus, the CATRACA tool acts as a virtualized network intrusion detection and prevention function that reports flow summaries and can be linked to other network virtualized functions [50] as

¹<http://metron.apache.org/> accessed April 2018

²<http://spot.incubator.apache.org>, accessed April 2018

³<https://github.com/CSIRT-MU/Stream4Flow>, accessed April 2018

⁴<http://ids-hogzilla.org/> accessed April 2018

defined in the network function chain patterns (Service Function Chaining - SFC) and network service headers (Network Service Header - NSH).

3.3 Virtual Network Function

Machine learning is used for attack detection in virtualized environments [51, 52]. Azmandian *et al.* present an application based on machine learning to automatically detect malicious attacks on typical server workloads running on virtual machines. The key idea is to obtain the feature selection by Sequential Floating Forward Selection (SFFS) algorithm, also known as Floating Forward Search, and, then, classify the attacks with the K-Nearest Neighbor (KNN) and the Local Outlier Factor (LOF) machine learning algorithms. The system runs in one physical machine under VirtualBox environment. Li *et al.* present cloudmon [52], a Network Intrusion Detection System Virtual Appliance (NIDS-VA), or virtualized NIDS. Cloudmon enables dynamic resource provisioning and live placement for NIDS-VAs in Infrastructure as a Service (IaaS) cloud environments. The work uses Snort IDS and Xen hypervisor for virtual machine deployment. Moreover, Cloudmon uses fuzzy model and global resource scheduling to avoid idle resources in a cloud environment. The proposal employs the conventional Snort IDS, based on signature method, to detect misuse and focuses on the resource allocation. BroFlow covers the detection and mitigation of Denial of Service (DoS) attacks. Sensors run in virtual machine under Xen hypervisor, and, thus, include a mechanism for optimal sensor distribution in the network [16]. An attack mitigation solution, based on Software Defined Networking, complements the proposal, focusing on DoS attacks detection based on an anomaly algorithm implemented in the Bro IDS.

CATRACA is proposed as a virtualized network function on Open Source Platform for Network Function Virtualization (OPNFV) that provides a threat detection facility. The function employs open source tools to detect threats in real time using flow processing and machine learning techniques.

The problem of specific sensor placement is studied by Chen *et al.*. The authors propose a technique based on Genetic Algorithms (GA) [53] for sensor placement. The proposed algorithm has as heuristic the minimization in the sensor number and the maximization of the detection rate. Bouet *et al.* also use GA as optimization technique for the deployment of Deep Packet Inspection (DPI) virtual sensors [54]. Bouet proposal minimize the sensor number and the load analyzed by each sensor, however, this proposal based on GA requires high processing time to obtain the results without warranting the solution convergence [55]. We model and propose an heuristic for optimization in VNF sensor placement, reducing the

number of sensor and maximizing the network coverage [56, 57].

3.4 Service Chaining

Virtual Network Function chaining is currently a trend topic in research. Several researches deal with the optimization problem to place a set of VNFs [22–24].

Addis *et al.* propose a mixed integer linear programming formulation to solve the VNF placement optimization from the Internet Service Providers (ISPs) point of view [23]. In a similar way, Bari *et. al* use a Integer Linear Programming in order to optimize the cost of deploying a new VNF, the energy cost for running a VNF, and the cost of forwarding traffic to and from a VNF [22]. A Pareto optimization is used for placing chained VNFs in an operator’s network with multiple sites, based on requirements of the tenants and of the operator [24].

Other works propose the optimization placement of specific VNF [16, 27, 58]. A virtual Deep Packet Inspection (vDPI) placement is proposed by Bouet *et. al.* to minimize the cost that the operator faces [58]. In a previous work [16], we proposed the placement of an Intrusion Detection and Prevention System (IDPS) by a heuristic that maximize the traffic passing through each node. In another previous work [27], we proposed a heuristic to optimize the placement of distributed network controllers in a Software Defined Network environment.

Nevertheless, none of these works considers the trade-off of the costumers’ requests and infrastructure provider availability.

Estimating resource usage for optimizing allocation has been proposed in many other contexts. Sandpiper [59] is a resource management tool for datacenters. It focuses on managing the allocation of virtual machines over a physical infrastructure. Other proposal that estimates the resource usage for allocating virtual machines in a datacenter is Voltaic [60]. Voltaic is a management system focused on cloud computing which aims to ensure compliance with service level agreements (SLAs) and optimize the use of computing resources.

In Section 6.3, we propose four heuristics in order to minimize the delay between source and destination nodes for the best customer Quality of Experience (QoE). Another heuristic is proposed to minimize the resource usage on the network nodes to increase Infrastructure Provider (IP) benefits. Finally, a heuristic for using the most central nodes first to improve customer QoE and IP benefit. We compare the four proposed heuristics with a greedy algorithm and we tested over a real Service Provider topology [61].

Chapter 4

Threat Detection using Stream Processing

In this chapter, we present a threat detection prototype using stream processing. First, we present the main data processing techniques. Then, we introduce the stream processing paradigm. Next, we describe and compare the main Open-Source stream processing platforms in order to select the most suitable for our Network Analytics tool. Finally, we present the CATRACA tool, a network monitoring and threat detection tool using stream processing and machine learning techniques.

4.1 Methods of Data Processing

Stream processing makes it possible to extract values on moving, as batch processing does for static data. The purpose of stream processing is to enable real-time, or near-real-time, decision making by providing the ability to inspect, correlate, and analyze stream data as data flows through the processing system. Examples of scenarios that require stream processing are: traffic monitoring applications for computer network security; social networking applications such as Twitter or Facebook; financial analysis applications that monitor stock data flows reported on stock exchanges; detection of credit card fraud; inventory control; military applications that monitor sensor readings used by soldiers, such as blood pressure, heart rate, and position; manufacturing processes; energy management; among others. Many scenarios require processing capabilities of millions or hundreds of millions of events per second, making traditional system such as Data Base Management System (DBMS) inappropriate to analyze stream data [62]. Data Base Management Systems store and index data records before making them available to the query activity, which makes them unsuitable for real-time

applications or responses in the sub-second order [63]. Static databases were not designed for fast and continuous data loading. Therefore, they do not directly support the continuous processing that is typical of data stream applications. Also, traditional databases assume that the process is strictly stationary, differing from almost all real-world applications, in which the output could gradually change over time. Security Threats in TCP/IP networks are a typical example of moving data, in which the output changes over time.

Data processing is divided in three main processing approaches: batch, micro-batch, and stream. The analysis of large sets of static data, which are collected over previous periods, is done with batch processing. A famous technique that use batch processing is the MapReduce [12], with the popular open-source implementation Hadoop [13]. In this scheme, data is collected, stored in files, and, then, processed, ignoring the timely nature of the data production. However, this technique presents large latency, with responses greater than 30 seconds, while several applications require real-time processing, with responses in microsecond order [64]. Despite, this technique can perform near real-time processing by doing micro-batch processing. Micro-batch treats the stream as a sequence of smaller data blocks. For minor intervals, the input is grouped into data blocks and delivered to the batch system to be processed. On the other hand, the third approach, stream processing, analyzes massive sequences of unlimited data that are continuously generated [65].

Stream Processing differ from the conventional batch model in: i) the data elements in the stream arrive online; ii) the system has no control over the order in which the data elements arrive to be processed; iii) stream data are potentially unlimited in size; iv) once an element of a data stream has been processed, it is discarded or archived and cannot be retrieved easily, unless it is explicitly stored in memory, which is usually small relative to the size of the data streams. Further, latency of stream processing is better than micro-batch, since messages are processed immediately after arrival. Stream processing performs better for real time; however, fault tolerance is costlier, considering that it must be performed for each processed message.

Table 4.1 summarizes the main differences between static batch processing and moving data stream processing.

Both these paradigms, batch and stream processing, are combined in the lambda architecture to analyze big data in a real-time manner [66]. Lambda architecture uses a stream fast path for timely approximate results, and a batch offline path for late accurate results. In the lambda architecture, stream data can be used to update batch processing parameters of an off-line training for a real-time threat detection. The lambda architecture combines traditional batch processing over a

Table 4.1: Feature comparison summary between batch processing and flow processing.

	Batch	Stream
Num. times it can process data	Multiple times	once
Processing Time	Unlimited	Restricted
Memory usage	Unlimited	Restricted
Result type	Accurate	Approximate
Processing topology	Centralization. / Distrib.	Distributed
Fault Tolerance	High	Moderate

historical database with real-time stream processing analysis.

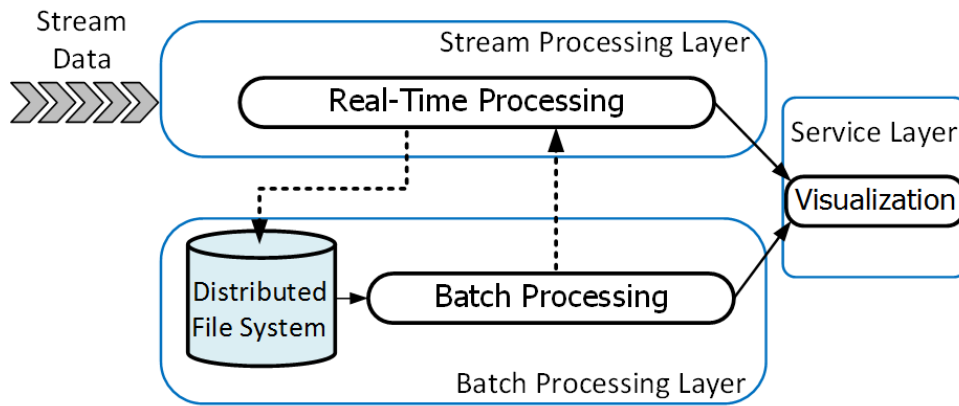


Figure 4.1: The three-layered lambda architecture, which combines stream with batch processing: stream processing, batch processing, and service layers.

As shown in Figure 4.1, the lambda architecture has three layers: the stream processing layer, the batch-processing layer, and the service layer. The stream processing layer deals with the incoming data in real-time. The batch-processing layer analyzes a huge amount of stored data in a distributed way through techniques such as map-reduce. Finally, the service layer combines the obtained information of the two previous layers to provide an output composed by analytic data to the user. Therefore, the lambda architecture goal is to analyze, accurately and in real-time, stream data, even with an ever-changing incoming rate to obtain results in real-time based on historical data.

4.2 The Stream Processing

The data flow processing is modeled through a Directed Acyclic Graph (DAG). The graph is composed by source data node which continuously emit samples, and interconnected processing nodes. A data stream ψ is an unbounded set of data, $\psi = \{D_t | t > 0\}$ where a point D_t is a set of attributes with a time stamp. Formally,

one data point is $D_t = (\mathbf{V}, \tau_t)$, where \mathbf{V} is a n-tuple, in which each value corresponds to an attribute, and τ_t is the time stamp for the t -th sample. Sources nodes emit tuples or messages that are received by Processing Elements (PE). Each PE receives data on its input queues, performs computation using local state and, finally, produces an output to its output queue. Figure 4.2 shows the conceptual stream processing system architecture.

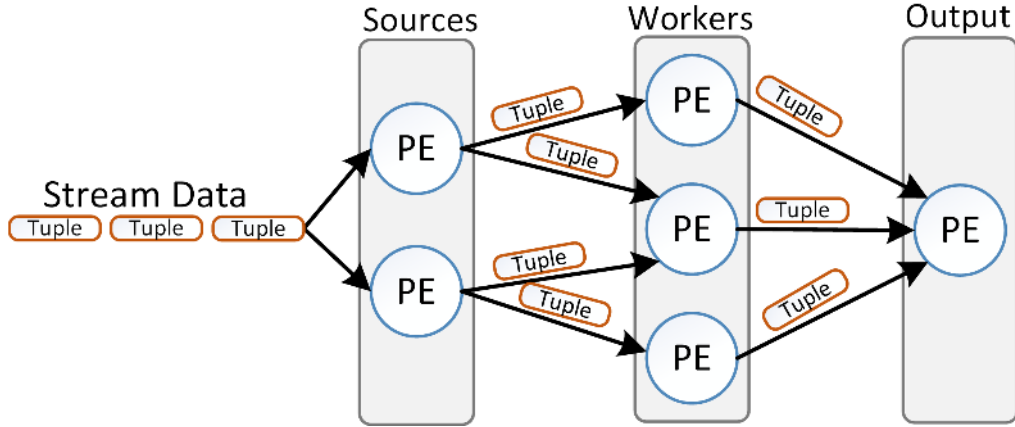


Figure 4.2: stream processing architecture. Processors Elements (PE) interconnected creating a directed acyclic graph. The data stream is received by the PE sources, they are immediately processed by workers and finally are aggregated at output.

A number of requirements must be met on distributed stream processing platforms, Stonebraker *et al.* highlight the most important [4]. The ability to process data online without the need to store it for operations is critical to maintaining low latency, since storage operations such as writing and reading on disk add unacceptable processing delays. In addition, ideally the processing system be active, depending only in own policies to operate on the data without relying on external instructions. Due to the large volume, data must be partitioned to treat them in parallel. High availability and fault recovery are also critical in flow processing systems. In low latency applications, recovery must be fast and efficient, providing processing guarantees. Thus, stream processing platforms must provide resiliency mechanisms against imperfections or failures, such as delays, data loss or out-of-order samples, which are common in distributed stream processing in computational clusters. Besides, processing systems must have a highly optimized execution mechanism to provide real-time response for applications with high data rates. Therefore, the ability to process millions of messages per second with low latency, within microseconds, is essential. To achieve this performance, platforms must minimize the communication overhead between distributed processes. Active backup, passive backup, and upstream backup algorithms are used by Distributed Stream Processors (DSP) to provide data processing guarantees upon

failures. Furthermore, platforms must store data efficiently, access and modify status information, and combine them with data streams in real time. This combination allows the adjustment and verification of algorithms for better performance.

4.3 Stream Processing Platforms

Stream processing platforms have been researched since the 90s, presenting an evolution in three generations. First-generation platforms were based on database systems that evaluate rules expressed as condition-action pairs when new events arrive. These systems were limited in functionality and also were not designed for large volumes of stream data. Examples of this generation systems include Starburst [67], Postgres [68] and NiagaraCQ [69]. The company Apama¹, founded in 1999, was the first real-time, event-driven analysis application company focused on Business. The technology provided by the Apama platform allowed to monitor events, analyze them and perform actions in milliseconds.

Second-generation systems focus on extending the Structured Query Language (SQL) to process stream data by exploring the similarities between a stream and an online query. In May 2003, at Stanford University, the STanford stREam data Manager (STREAM) [70] project was created. The STREAM project is considered to be one of the first general-purpose Data Stream Management Systems (DSMS). The STREAM project prompted the foundation in 2003 of Coral8². In 2007, Coral8 launched a commercial platform, based on Microsoft technologies, capable of processing and analyzing thousands of SQL requests per second. The Aurora [62] project was launched in 2002 in a collaboration with Brandeis University, Brown University and MIT. The main drawback of Aurora is that the project was designed as a single, centralized flow processing mechanism. A new distributed version was released in 2003, called Aurora*. One last version was officially released under the name Borealis [63], with some other improvements, such as fault tolerance. The Medusa [71] project used the Borealis distribution to create a federated flow processing system. Borealis and Medusa became obsolete in 2008. The Aurora/Borealis projects boosted in 2003 the founding of the company StreamBase System³, which commercially launched the StreamBase platform for Complex Event Processing (CEP) for decision-making purposes. The University of

¹The first real-time event analysis company, Apama Stream Analytics, was sold in 2005 to Progress Software Cooperation for \$ 25 million. https://www.softwareag.com/corporate/products/apama_webmethods/analytics/default.html Accessed April 2018.

²Sold to Aleri in 2009.

³Sold to TIBCO Software in 2013.

Berkeley, in 2003, creates a language for continuously executing SQL queries based on the Postgres database system called TelegraphCQ [72]. Based on the TelegraphCQ, the Truviso⁴ was created in 2009, and in 2012 Truviso was acquired by Cisco. In 2006, Cornell University created Cayuga [73], a state-of-the-art publish/subscribe system, which developed a simple query language to perform processing over data that scales both with arrival rate of events as well as number of queries. Cayuga was replaced by Cougar⁵ and is still an active search. Third-generation systems have emerged to address the need for Internet companies to process large volumes of data produced at high speed. The main focus of this generation is the scalable distributed processing of data in computational clusters. Google revolutionizes distributed processing by proposing the MapReduce [12] programming model for scalable parallel processing of large volumes of data in clusters. The key idea to spread-process-combine is used to scalably perform different tasks in parallel on commodity servers in a cluster. The Hadoop [13] platform is the Open Source implementation of MapReduce to perform analytics on big data. However, due to the high latency that MapReduce produces, some projects have been proposed to perform real-time data stream analysis. The Spark project replaces Hadoop's MapReduce to perform memory operations that Hadoop performs on data retrieved from the disk. The open source platforms Storm and Flink are proposed for stream processing. The Spark platform proposes an extension for stream processing in micro-batches, the Spark streaming. Next, Apache Storm, Apache Flink and Apache Spark streaming are described as third-generation open source scalable platforms.

4.3.1 Apache Storm

Apache Storm⁶ [28] is a real-time stream processor, written in Java and Clojure. Stream data abstraction is called tuples, composed by the data and an identifier. In Storm, applications consist of topologies forming a directed acyclic graph composed of inputs nodes, called Spouts, and processing nodes, called Bolts, and edges represent data stream. Spouts are responsible for abstracting incoming data into tuples that flow through the graph. Each Bolt execute a user-defined function considered as atomic. A topology works as a data graph in which nodes process the data as the data stream advance in the graph. A topology is analog to a MapReduce Job in Hadoop. Both Bolts and Spouts are parallelizable and can be

⁴Truviso Analytic <http://jtonedm.com/2009/03/03/first-look-truviso/> Accessed April 2018

⁵Cougar processing <http://www.cs.cornell.edu/database/cougar/> Accessed April 2018

⁶Nathan Marz, PhD from Stanford University, working on BackType, develops Storm in 2011, a framework for distributed stream processing, to handle in real time the large number of messages (tweets) received by Twitter company. The BackType company is acquired by Twitter and Storm becomes open source, migrating to the Apache Foundation in 2013.

defined with a degree of parallelism that indicates the number of competing tasks present on each node. An example of a topology with two Spouts and three Bolts is shown in Figure 4.4. The grouping type used defines the link between two nodes in the processing graph. The grouping type allow the designer to set how the data should flow in topology.

Storm has eight data grouping types that represent how data is sent to the next graph-processing node, and their parallel instances, which perform the same processing logic. The main grouping types are: *shuffle*, *field*, and *all* grouping. In *shuffle* grouping, the stream is randomly sent across the Bolt instances. In *field* grouping, each Bolt instance is responsible for all samples with the same key specified in the tuple. Thus, a Bolt will be responsible for all samples of a certain type and be able to concentrate the information regarding such group. Finally, in *all* grouping, samples are sent to all parallel instances.

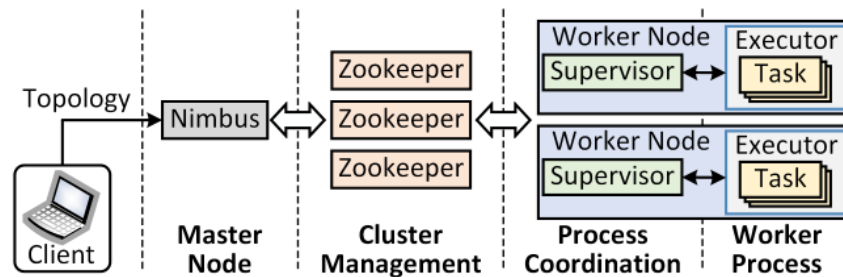


Figure 4.3: Storm architecture. Nimbus receives topologies and communicates to Supervisors that coordinate process in workers. All the coordination between Nimbus and Supervisors is made by *Zookeeper* who store the cluster state.

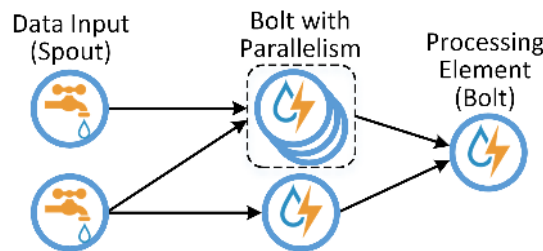


Figure 4.4: Storm topology with element processors *Spouts* and *Bolts*. *Spouts* are inputs nodes while *Bolts* are nodes that produce a processing in the tuples.

Figure 4.3 shows the coordination processes in a Storm cluster. The manager node, Nimbus, receives a user-defined topology. In addition, Nimbus coordinates each process considering the topology specification, i.e., coordinates Spouts and Bolts instantiation and their parallel instances. The Zookeeper is responsible for managing the worker nodes and for storing state of all elements of the system. At each worker node, a supervisor monitors the performers, which are processes responsible for performing one or more tasks. Supervisors report the status and

availability of the executors through a periodic heartbeat mechanism, allowing Nimbus to identify system failures. Executors failures are handled by the supervisors themselves, who restart the corresponding processes on the worker node. A supervisor failure is handled by the Nimbus, which can relocate all tasks from the failing supervisor to another worker node. If Nimbus fails, the system is still capable of running all outstanding topologies, but the user is not able to submit new topologies. After recovery, the Nimbus and the supervisors can resume the last state stored in the Zookeeper.

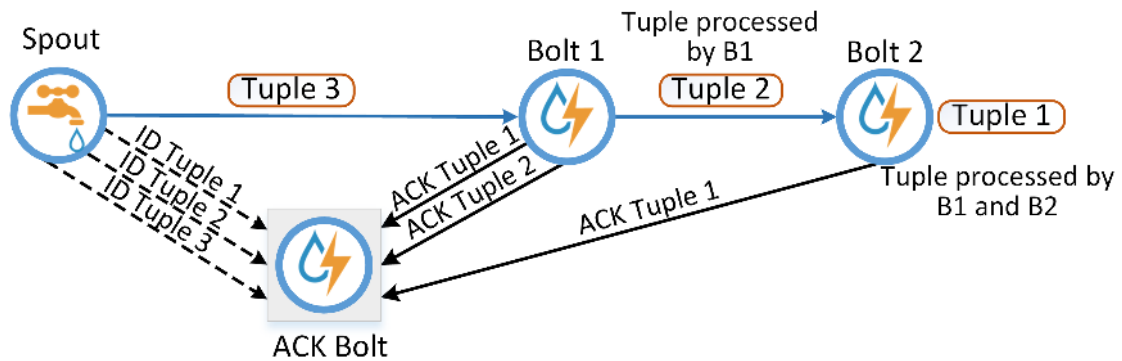


Figure 4.5: At-least-once delivery semantic used in Apache Storm. Every time a tuple is emitted by a spout, a record is saved in the acknowledge bolt. After the tuple leaves the topology, the ack bolt acknowledge all operators.

Apache Storm uses storage and acknowledgment (ACK) mechanisms to ensure tuples are processed even after a failure. For this, all tuples are identified by the spouts and their identifiers are sent to a special Bolt, which stores the state of each tuple. An example of topology with Acker Bolt is shown in Figure 4.5. For each processed tuple, a Bolt should send a positive acknowledgment (ACK) to the Acker Bolt. If all the tuples receive an ACK for each Bolt, the acknowledgment Bolt ignores the IDs and informs the Spout that the processing has been successful. Otherwise, the acknowledgment Bolt asks the Spout to resubmit all tuples and the system goes back to the point of failure. Non-receipt of an ACK is recognized by the expiration of a timer timeout defined in the acknowledgment Bolt. This ensures message delivery semantics “at least once”, where each tuple is processed one or more times in the case of reprocessing. It is still possible to disable Acker Bolt for applications that do not require processing guarantees.

4.3.2 Apache Flink

The Apache Flink⁷ [74] is a hybrid processing platform that supports stream and batch processing. The core of Flink is stream processing, making batch processing a special case. The analytical tasks of Flink are abstracted in Directed Acyclic Graphs (GAD) formed by four components: sources; operators; exit taps; and records that run through the graph. The abstraction of the topology is performed through programming in Java or Scala. As in Storm, the task division is based on a master-worker model. Figure 4.6 shows the Apache Flink architecture. The Flink master node is called the job manager and interacts with client applications with responsibilities similar to the Storm master node (Nimbus). The job manager receives client applications, organizes the tasks and sends them to the workers nodes, which are called task manager. In addition, the work manager maintains the status of all executions and each worker. The states of workers are informed through a periodic heartbeat signal mechanism. The task manager has a function similar to the worker node in the Storm. Task managers perform tasks assigned by the job manager and exchange information with other task managers when needed. Each task manager provides slots of processing to the computational cluster, which are used to execute tasks in parallel.

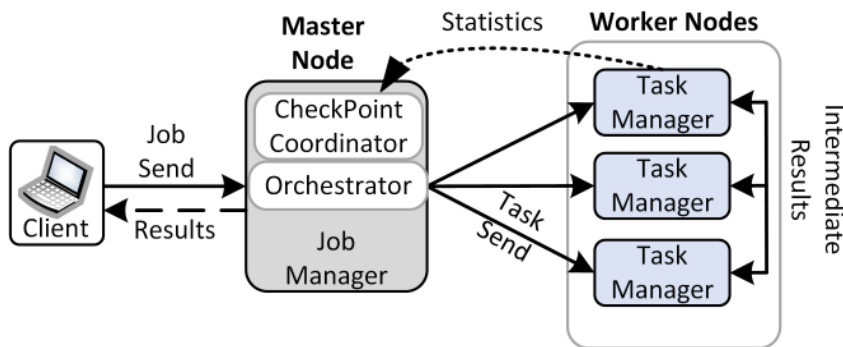


Figure 4.6: Architecture of Flink system. The Job manager receives jobs from clients, divides the jobs into tasks, and sends the tasks to the workers. Workers communicate statistics and results.

The abstraction of the data stream in Flink is called `DataStream` and is defined as a sequence of partially ordered records. Partly because there is no guarantee of order if an operator element receives more than one data stream as input.

`DataStreams` are similar to Storm tuples and receive stream data from external sources, such as message queues, sockets, and so on. `DataStream` programming supports several native functions for operating data streams, such as *map*, *filtering*, *reduction*, *join*, which are applied incrementally to each entry, generating a new

⁷Flink was born in 2010 from a European research project called “Stratosphere: Information Management in the Cloud” developed in collaboration with the Technical University of Berlin, Humboldt-Universität zu Berlin and Hasso-Plattner-Institut Potsdam. In 2014, Stratosphere re-names the project to Flink and opens its code at the Apache Foundation.

DataStream. Each of these operations can be parallelized by configuring a parallelism parameter. Thus, parallel instances of the operations are assigned to the available processing slots of the task managers to simultaneously handle DataStream partitions. This method allows distributed execution of operations on data stream.

Figure 4.7 shows the checkpoint recovery method used by Apache Flink. Flink has a reliable delivery semantics of *exactly-once* messages. This semantics is based on the fault tolerance scheme with checkpoints, or checkpoints barriers, so that the system can return on failure. Barriers work as control registers and are regularly injected into the data stream by the source elements to flow through the graph along with the sample records. When a barrier passes through an operator element, it performs a snapshot of the state of the system. The snapshot consists of storing the state of the operator, for example the contents of a sliding window or a custom structure of data, and its position in the data stream. After an alignment phase between operators to make sure the barrier has crossed all the operators that handle that stream, operators write the snapshot in a durable file system, such as HDFS. In case of software, node or network failure, Flink interrupts the DataStream. The system immediately reset the operators and restarts from the last successful snapshot capture. As in Storm, Flink fault tolerance is guaranteed based on the premise that the system is preceded by a persistent forwarding message system, such as Apache Kafka. In the special case of batch processing, there is no fault tolerance scheme, and if a fault occurs, the entire operation must be restarted from scratch.

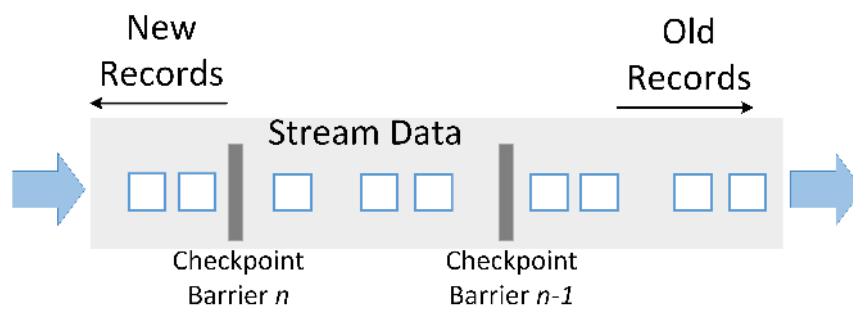


Figure 4.7: Barriers are injected in source elements and flow through the graph together with the samples, flow downstream and trigger state snapshots when they pass through operators. When an operator receives a barrier from every incoming stream, it checkpoints its state to durable storage.

4.3.3 Apache Spark Streaming

Spark is a project initiated by UC Berkeley and is a platform for distributed data processing, written in Java and Scala. Spark has different libraries running on the top of the Spark Engine, including Spark Streaming [30] for stream processing.

Apache Spark is a parallel engine, which executes the MapReduce technique.

Apache Spark is optimized to execute MapReduce jobs into the main memory, improving performance while compared with Hadoop [30].

The stream abstraction is called Discrete Stream (D-Stream) defined as a set of short, stateless, deterministic tasks. In Spark, stream computation is treated as a series of deterministic batch computations on minor intervals. Similar to MapReduce, a job in Spark is defined as a parallel computation that consists of multiple tasks, and a task is a unit of work that is sent to the Task Manager. As Figure 4.8 shows, when a stream enters Spark, it divides data into micro-batches, which are the input data of the Distributed Resilient Dataset (RDD), the main class in Spark Engine, stored in memory. A DStream is a potentially infinite sequence of Resilient Distributed Dataset (RDD). Then the Spark Engine executes by generating jobs to process the micro-batches. RDD are the basic elements in the Spark Engine and are partitioned across all the nodes in the cluster. RDD are by definition immutable, when an operation, called transformation, such as `map()`, `join()`, `filter()` is applied it creates a new RDD. When a transformation is applied to the RDD, Spark does not execute it immediately, instead it creates a lineage that keeps track of what all transformations has to be applied on that RDD, including from where it has to read the data. All transformation are computed when an action such as `save()/display()` is called in the driver program. Linage allows Spark to recover the last operation performed in case of failure.

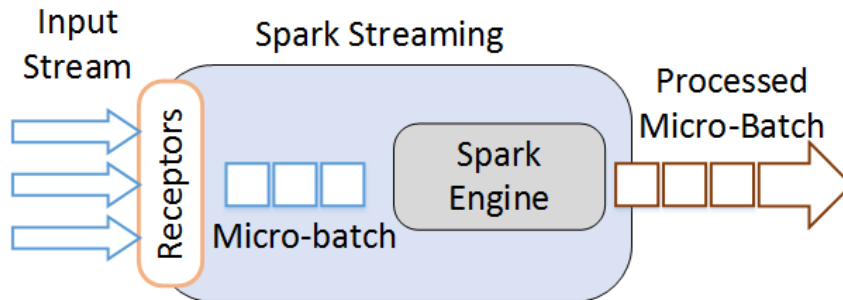


Figure 4.8: Micro-batch processing used in Spark stream. The input streams are received by receptors and it transforms in micro-batch that are executed in a traditional Map-Reduce Spark Engine.

Figure 4.9 shows the layout of a Spark cluster. Applications or jobs within the Spark run as independent processes in the cluster which is coordinated by the master or Driver Program, responsible for scheduling tasks and creating the Spark

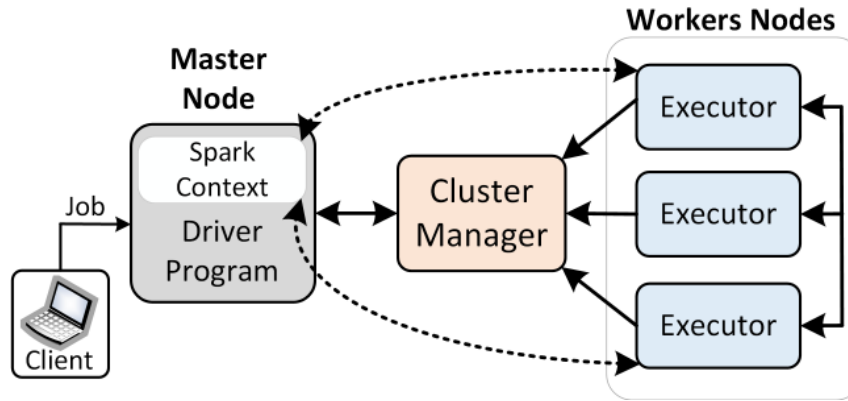


Figure 4.9: Cluster architecture of Spark stream system. Composed by a driver program, cluster manager and worker nodes that execute the task.

Context. The **Spark Context** connects to various types of cluster managers, such as the Spark StandAlone, Mesos or Hadoop YARN (*Yet Another Resource Negotiator*). These cluster managers are responsible for resource allocation between applications. Once connected, Spark executes task within the task managers, which perform processing and data storage, equivalent to Storm workers, and results are then communicated to the **Spark Context**. The mechanism described in Storm, in which each worker process runs within a topology, can be applied to Spark, where applications or jobs are equivalent to topologies. A disadvantage of this concept in Spark is the messages exchange between different programs, which is only done indirectly such as writing data to a file, worsen the latency that could be around seconds in applications of several operations.

Because Spark operates on data stored in volatile memory, there is a need to provide fault tolerance for data while it is being processed, not just after saving to disk as done on Hadoop. Spark has “*exactly-once*” message delivery semantics. The idea is to process a task on several distinct working nodes and, in the event of a failure, the processing of the micro-batch can be redistributed and recalculated. The state of the RDDs is periodically replicated to other working nodes. Tasks are then discretized into smaller tasks performed on any node, without affecting execution. Thus, failing tasks can be thrown in parallel, evenly distributing the task, without affecting performance. This procedure is called parallel recovery. The semantics of “*exactly-once*” reduce the overhead compared to *upstream backup*, where all tuples must be positively recognized, as in the Storm. However, micro-batch processing has disadvantages. The configuration and distribution of each micro-batch may take longer than the arrival rate of the native stream. Consequently, micro-batches are stored in a processing queue affecting latency.

Fault Tolerance Schemes on Distributed Processing Platforms

A robust fault tolerance scheme is essential for distributed processing platforms running on cluster, which are sensitive to node failures in network and software. It should be noted that a datacenter has a structure in computational clusters, in which nodes are low-cost commercial off-the-shelf (COTS) servers. In batch processing systems, latency is acceptable and as a result, the system does not need to recover quickly from a failure. However, in real-time systems since the data is not stored, failures can mean data loss. Therefore, fast and efficient recovery is important to avoid loss of information [75].

The most common form of failure recovery is storage and forwarding, also known as *upstream backup*. Considering a processing topology, the algorithm uses the parent nodes to act as backups, storing and temporarily preserving the tuples in their output queues until their downstream neighbors process them and send positive acknowledgment (ACK). Every tuple must be individually positively recognized with an ACK. If any of these downstream neighbors fails, an ACK will not be sent, and by timer overflow, the parent node reproduces the tuples on another node. Another form of positive recognition is by group tuples. Simply identify a missing tuple that the entire group of tuples is reproduced.

A disadvantage of this approach is the long recovery time since the system must wait until the protected node takes over. To address this problem, in [65] the *parallel recovery* algorithm is proposed. In this algorithm, the system periodically checks the states replicating asynchronously to other nodes. When a node fails, the system detects the missing partitions and launches tasks to retrieve them from the last checkpoint. Many tasks can be launched at the same time to calculate different partitions on different nodes. Thus, *parallel recovery* is faster than the *upstream backup*.

Another solution is proposed in [29] based on the *Asynchronous Barrier Snapshot* (ABS) algorithm. The main idea is to mark the overall state of a distributed system. In ABS algorithm, a snapshot is the overall state of the rendering distributed system represented as a graph. A snapshot capture all the information necessary to restart the calculation of that particular execution state. A barrier separates the record set in two sides. From one side, records that accompanies the current snapshot, and from the other side the records that are inserted into the next snapshot. Barriers do not interrupt data flow. Several different snapshot barriers may be in the stream at the same time, which means that multiple snapshots may occur simultaneously. When a source receives a barrier, the source takes a snapshot from its current state and then transmits the barrier to all outputs. When a non-source task receives a barrier from one of its inputs, it blocks

that input until it receives a barrier of all inputs. When the barriers were received from all entries, the task takes a snapshot from its current state and transmits the barrier to its outputs. The task then unlocks its input channels to continue its computation. Thus, disaster recovery reverts all states of the operator to their states taken from the last successful snapshot and restarts the inbound streams from the last barrier for which there is a snapshot.

The delivery assurance semantics that a system offers to process a sample can be divided into three types: “Exactly once”, “at least once”, and “at most once”. The simplest semantics is “at most once”, also known as “may be once” where there is no error recovery, that is, the samples are processed or lost. When a failure occurs, data can be routed to another processing element without losing information. The “at most once” semantic should be use in applications where the occasional loss of a message does not leave a system in an inconsistent state. In the semantics “exactly once” positive recognitions are individual by tuple. Also, in the “exactly once”, the system guarantees that a source that crashes will eventually restart. The system must keeps track of calls on sinks that have crashed, and allows them to be later adopted by a new sink. In the semantics “at least once”, also known as “once or more”, the error correction is done together for a group of samples, so if an error occurs with any of the samples, the entire group is reprocessed and therefore it is possible that some samples are processed one more time. In “at least once” semantic, the source continues to send tuples to the sink until it gets an acknowledgement. If one or more acknowledgements are lost, the server may execute the call multiple times. The semantics “at least once” is less costly than “exactly once”, which requires individual confirmation for each processed tuple. Table 4.2 presents a summary of features underlined in the comparison of the stream processing systems. The programming model can be classified as compositional and declarative. The compositional approach provides basic building blocks, such as Spouts and Bolts on Storm and must be connected together in order to create a topology. On the other hand, operators in the declarative model are defined as higher-order functions, that allow writing functional code with abstract types and the system will automatically create the topology.

4.4 Performance Evaluation of the Platforms

This section evaluates the processing rate and behavior during the node failure of the three flow processing platforms presented: Apache Storm version 0.9.4, Apache Flink version 0.10.2 and Apache Spark stream version 1.6.1, with microbatch size set to 0.5 seconds. The evaluated application is a threat detection system with a neural network classifier programmed in Java. The experiments were performed in

Table 4.2: Overview of the comparison between Stream Processing Systems.

	Storm	Flink	Spark stream
Stream Abstraction	Tuple	DataStream	DStream
Build Language	Java/Closure	Java/Scala	Java/Scala
Messages Semantic	At least once	Exactly one	Exactly one
Failure-Tolerance Mechanism	Upstream Backup	Check-point	Parallel Recovery
API	Compositional	Declarative	Declarative
Failures Subsystem	Nimbus, Zookeeper	No	No

an environment with eight virtual machines running on a server with the Intel Xeon processor E5-2650 at 2.00 GHz and 64 GB of RAM. The experiment topology configuration is a master and seven working nodes for the three systems evaluated. The results are presented with a confidence interval of 95%.

Apache Kafka in version 0.8.2.1, which operates as a publish/subscribe service, was used to enter data at high rates in flow processing systems. In Kafka, the samples, or events, are called messages, name used from now on. Kafka abstracts the flow of messages into threads that act as buffers or queues, adjusting different rates of production and consumption. Therefore, producers record the data in topics and consumers read the data from those topics. The dataset used is a security dataset created by the authors [76], which was replicated to obtain enough data to evaluate the maximum processing the system can operate on.

4.4.1 Experiments Results

The first experiment evaluates the performance of platforms in terms of processing [77]. The full contain of the dataset is injected into the system and then it is replicated as many times as necessary to create a large volume of data. The experiment calculates the rate of consumption and processing of each platform. Also, the parallelism parameter was varied, which represents the total number of cores available for the cluster to process samples in parallel. Figure 4.10 shows the results of the experiment. Apache Storm has the highest throughput. For a single core, unparallelled, Storm already shows better performance with a flow rate of at least 50% higher when compared to Flink and Spark streaming. Flink has a linear growth, but with values always inferior to those of Apache Storm. The processing rate of Apache Spark streaming, when compared to Storm and Flink, is much

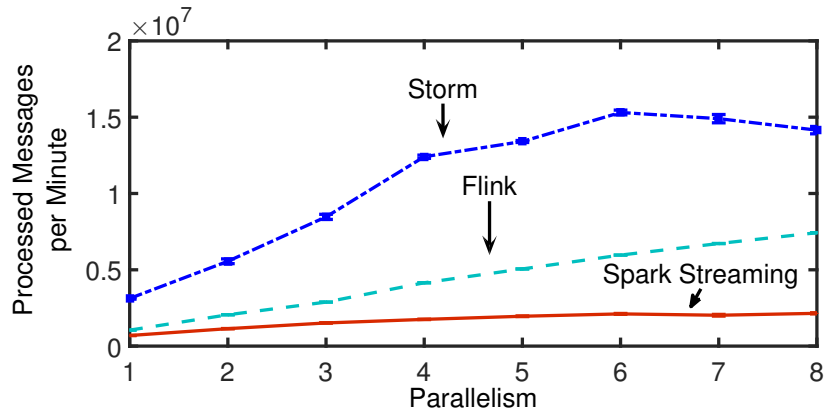


Figure 4.10: Throughput results of the platforms in terms of number of messages processed per minute as function of the task parallelism for Security Dataset.

lower and this is due to the use of microbatch. Each microbatch is pooled prior to processing, generating a delay in processing by samples. Apache Storm behavior is linear up to four-core parallelism. Then, the processing rate grows until the parallelism of six, in which the system saturates. This behavior was also observed in Apache Spark streaming with the same parallelism of six cores.

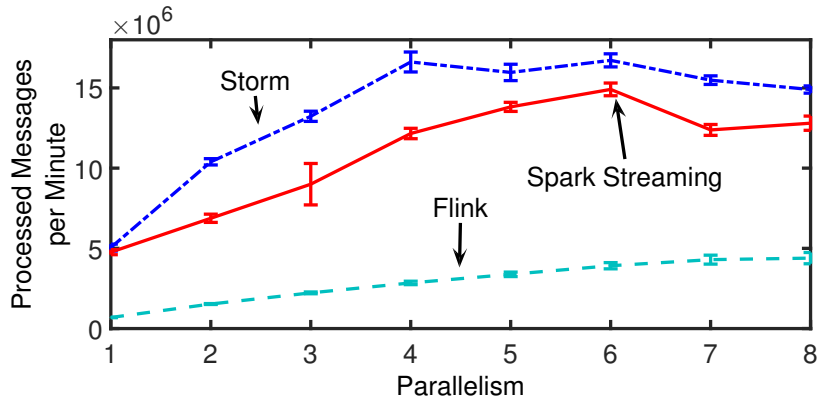


Figure 4.11: Throughput results of the platforms in terms of number of messages processed per minute as function of the task parallelism. Evaluation of the word-count performance in Twitter Dataset.

All three platforms offer the word-count application as examples of tutorials, so we show this result for an unbiased comparison that is not affected by code implementation on each platform. This experiment counts the number of times each word appears in a text, using a dataset containing more than 5,000,000 tweets [78]. Figure 4.11 shows the performance of the three systems in the wordcount program. This experiment shows a similar result to that shown previously. However, in this case Spark streaming outperform Apache Flink. The second experiment shows the system behavior when a node fails. Messages are sent at a constant rate to analyze the system behavior during the crash. The node

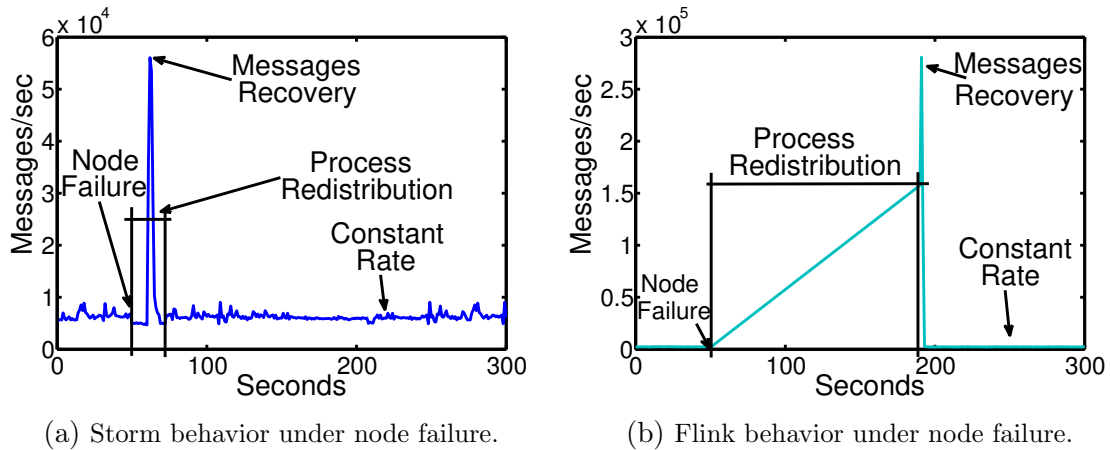


Figure 4.12: Storm and Flink behavior during a node failure. A failure is produced at 50 seconds. a) Storm and b) Flink system behavior after detecting the failure and consisting of process redistribution and message recovery procedures.

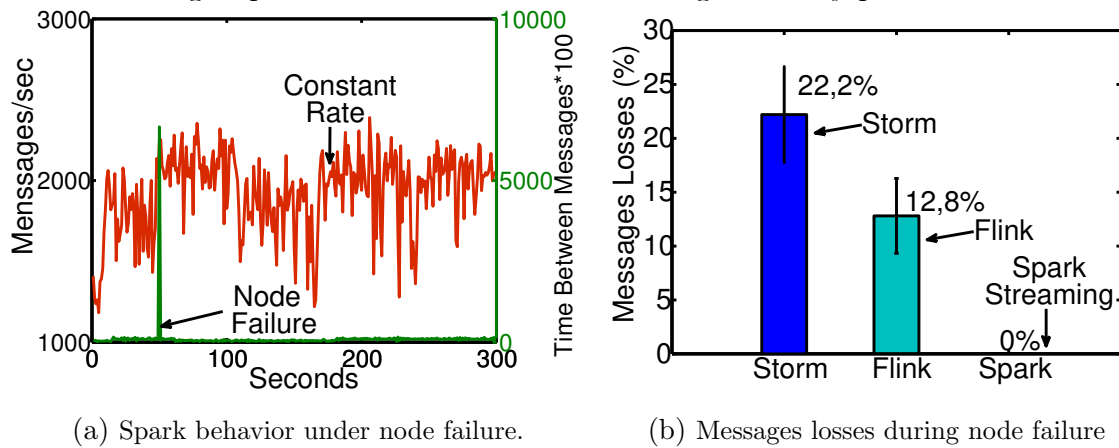


Figure 4.13: Spark stream behavior during a node failure and message losses comparison. a) The Spark system behavior under failure, indicating that it keeps stable and does not lose messages. b) Percentage of message losses.

failure is simulated by turning off a virtual machine. Figures 4.12, 4.13 show the behavior of the three systems before and after a worker node failure at 50 seconds. Apache Storm takes some time in the redistribution processes after the fault was detected. This time is due to communication with the Zookeeper. Zookeeper has an overview of the cluster and reports the state for Nimbus in Storm, which reallocates the processes on other nodes. Soon after this redistribution, the system retrieves Kafka messages at approximately 75 seconds. Although the system can quickly recover from node failure, during the process there is a significant message loss. A similar behavior is observed in Apache Flink. After detecting the failure at approximately 50 seconds, the system redistributes the processes for active nodes. Flink does this process internally without the help of any subsystem, unlike Apache Storm that uses Zookeeper.

Figure 4.12b shows that time period in which Flink redistributes processes is much

greater than the time spent in Apache Storm. However, message recovery is also higher, losing some messages during the process redistribution. Figure 4.13a shows Spark streaming behavior during a failure. When a failure occurs at approximately 50 seconds, the system behavior is basically the same as before. This is due to the use of tasks with micro-batch that are quickly distributed without affecting performance. Spark stream shows no message loss during fail. Thus, despite the low performance of Spark stream, it could be a good choice in applications where resilience and processing all messages are necessary.

Figure 4.13b shows the comparison of lost messages between Storm, Flink and Spark. The result shows that Spark had no loss during the fault. The measure shows the percentage of lost messages by systems, calculated by the difference of messages sent by Apache Kafka and messages analyzed by the systems. Thus, Apache Flink has a smaller loss of messages during a fault with about a 12.8% compared to 22.2% in Storm. We obtain the result with 95% confidence interval. We can conclude that if we want to prioritize throughput, Apache Storm is the best choice. On the other hand, if fault tolerance and “exactly once” message processing is required, Apache Spark must be employed.

4.5 The CATRACA Tool

CATRACA tool uses Network Function Virtualization (NFV) technology and its infrastructure to combine virtualization, cloud computing, and distributed stream processing to monitor network traffic and detect threats. The goal is to provide an accurate, scalable and real-time threat detection tool capable of meeting peaks of use, providing a high Quality of Service. Traffic monitoring and threat detection as a virtualized network function have two main advantages: the ability to self-adapt to different traffic volumes and the flexibility of installation and migration of sensors in the network to reduce the latency in monitoring [16]. Thus, the tool analyzes large volumes of data, the Machine Learning techniques classify the traffic into normal or threat, and, finally, the knowledge extracted from the flows is presented in a user interface.⁸

The prototype is divided in three main modules to perform real-time threat detection. The Capture Module, the Stream Processing Module and the Alarms Module compose our system to ensure security in several network components. Thus, several probes distributed in different network locations compose the Capture Module and, then, the data are grouped to be processed in a centralized point.

⁸The tool, as well as its documentation and complementary information can be accessed at <http://gta.ufrj.br/catraca>

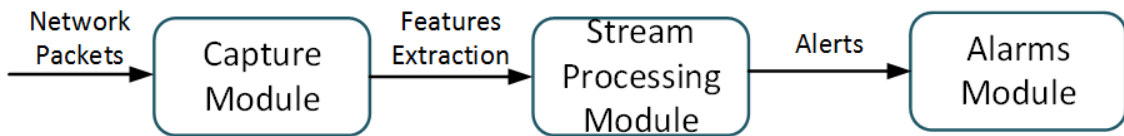


Figure 4.14: Diagram flow of stream processing analysis. Analyzing process composed by three modules. The packets enter to the capture module, where the features are extracted, then the features are processing in the Stream module and finally and alerts are send to the alert module.

4.5.1 CATRACA Architecture

The CATRACA architecture is composed of three layers: Visualization Layer, Processing Layer and Capture Layer, as shown in Figure 4.15.

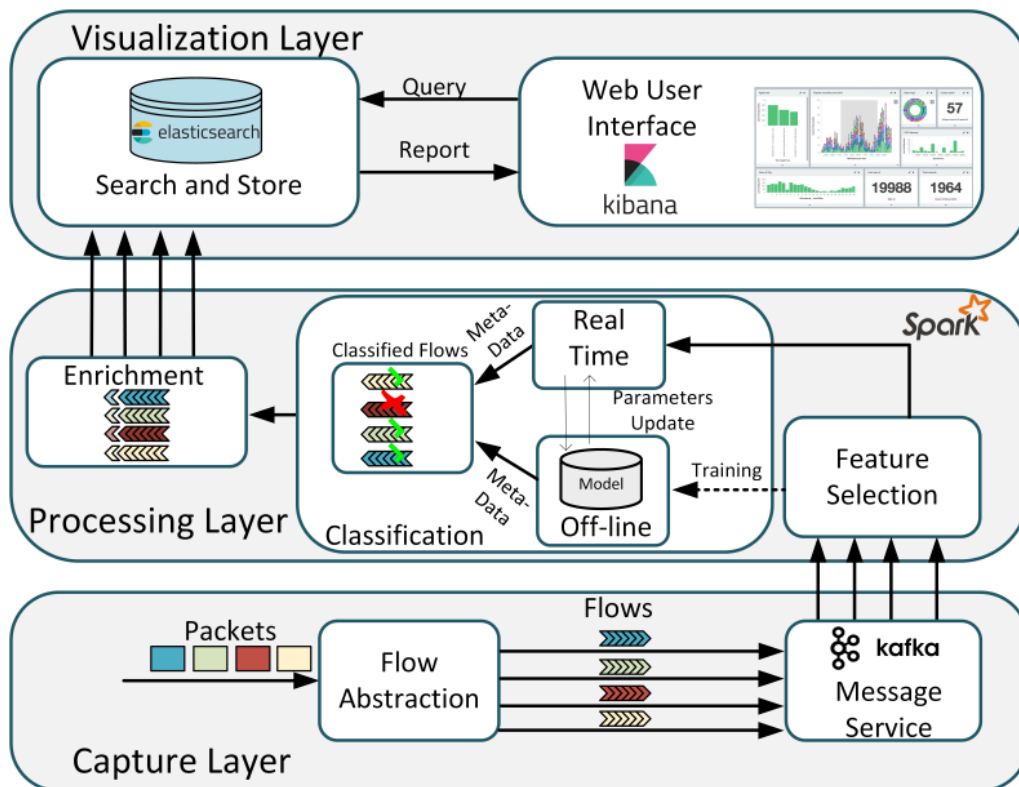


Figure 4.15: The layered architecture of the CATRACA tool: the capture layer, the processing layer, and the visualization layer.

The first layer, the capture layer, is responsible for capturing the packets. The packets are captured, through traffic mirroring, by the libpcap library. A python application based on flowtbag abstracts the packets into flows. A flow is defined as a sequence of packets with the same quintuple source IP, destination IP, source port, destination port, and protocol, during a time window. In all, 46 flow features are extracted and published in a producer/consumer service of Apache Kafka. This service operates as a low latency queue and data flow manipulation system,

where queue features are consumed by the processing layer.

The processing layer is instantiated in a dedicated cloud for classification and its core is the Apache Spark. The Spark framework has been chosen among the different flow-processing platforms because it presents the best fault tolerance performance [41], making CATRACA more robust in case of failure. Spark is implemented in a cluster following the master/slave model, where slaves have the capacity to expand and reduce resources, making the system scalable. Once the flow arrives in the processing layer, the feature selection algorithm [76] selects the most important characteristics for threat classification. In the processing step, the processed metadata is enriched through different information such as the geographical location of the analyzed IPs. Finally, the flows are classified as malicious or benign through machine learning (ML) algorithms based on decision trees.

Finally, the visualization layer is implemented using the Elastic Stack. The elastic stack allows custom event viewing in real time. Thus, the output of the processing layer is sent to the elasticsearch which provides a fast search and store service.

Elasticsearch communicates through queries with the user interface that runs in the Kibana environment in which represents the results to be viewed by the user.

The proposed Traffic Classification

The classification begins with the pre-processing in selection of the most important characteristics of the flows [76]. The tool can then operate in either real time or offline mode. The offline traffic classification consists of processing of the mini-batches Spark platform. In this mode, large volume datasets are loaded in a distributed file system, such as the Hadoop Distributed File System (HDFS). The data set is separated into a set of training and a test set at a ratio of 70 % to training and 30 % to the test. Thus, Spark performs processing by the technique map-reduce. A machine learning algorithm is trained to obtain the classification model.

The decision tree classification algorithm is implemented in the tool, due to its training speed allied to its high accuracy and precision [79]. The decision tree is a greedy algorithm that performs a recursive binary partitioning of the resource space. Each sheet is chosen by selecting the best separation from a set of possible divisions, to maximize the gain of information in a tree node. The division into each node of the tree is chosen from the $argmax_d GI(CD, d)$, where $GI(CD, d)$ is the information gain when a division d is applied to a set of CD data. The gain of information GI of the tool CATRACA is the impurity of Gini, $\sum_{i=1}^C f_i(1 - f_i)$, which indicates how separated the classes are, where f_i is the frequency of class i in a node and C is the number of classes. Once it is obtained, the template is

stored in the file system and loaded into be used in real-time traffic classification mode online. Thus, it is also possible to validate the model with the 30% training set obtained earlier.

The Table 4.3 shows the confusion matrix of the security dataset evaluation [79]. The confusion matrix clearly specifies the rate of false positives and other metrics of each class in the test data set. The rows represent the elements that actually belong to the real class and the columns the elements that were classified as belonging to the class. Therefore, the prominent diagonal elements of this array represent the number of elements that are correctly sorted. In addition, Table 4.3 shows metrics complementary to the confusion matrix. By observing the values of Accuracy and Precision it is possible to see the good performance of the decision tree algorithm in off-line classification. The table verified that the algorithm presented a high accuracy in almost all classes, with a low false positive rate. Another way to see the false positive rate is to observe the values that are outside the main diagonal.

Table 4.3: Confusion Matrix and Evaluation Metrics of Decision Tree for GTA/UFRJ Dataset.

	Normal	DoS	PortScan	Precision	Overall Accuracy
Normal	29126	1	0	99.97%	95.99%
DoS	60	5845	0	98.94%	
PortScan	8	1782	9434	84.05%	
Recall	99.76%	76.62%	100%		

Table 4.4: Confusion Matrix and Evaluation Metrics of Decision Tree for NetOp Dataset.

	Normal	Threat	Precision	Overall Accuracy
Normal	3713600	30140	99.19%	98.74%
Threat	22350	416100	94.90%	
Recall	99.40%	93.24%		

After obtaining the classification model from the historical base, one can evaluate the accuracy of the tool with data arriving in real time. The operation of the CATRACA tool in real time uses the stream module of the Spark platform. Thus, abstracted packets in streams, captured on different virtual machines in the cloud, are processed as they reach the Spark platform. When a stream arrives at the detection tool, it is summarized in characteristics using the selection algorithm [76], in order to reduce processing time. Thus, the vector of selected characteristics is evaluated in the model obtained in the off-line processing. After extracting the analytical data from the flows, the results are stored in a database for further analysis. The stored data has the information collected during the

detection of threats and can be reprocessed offline to calculate the parameters to be used in the real-time model. To make the system more accurate, there is a feedback, since the calculated offline parameters with historical data set the processing model for real-time threat detection.

Real-Time Visualization of Enriched Data

The visualization of the enriched data occurs through a simple and friendly web interface to allow the user to monitor the different parameters of the network in real time. The open source viewer Kibana, a component of the Elastic stack, was used for the development of the web interface, as it allows the visualization of the data in a simple and fast way allied to the performance of processing of queries with large volumes of data with low latency.

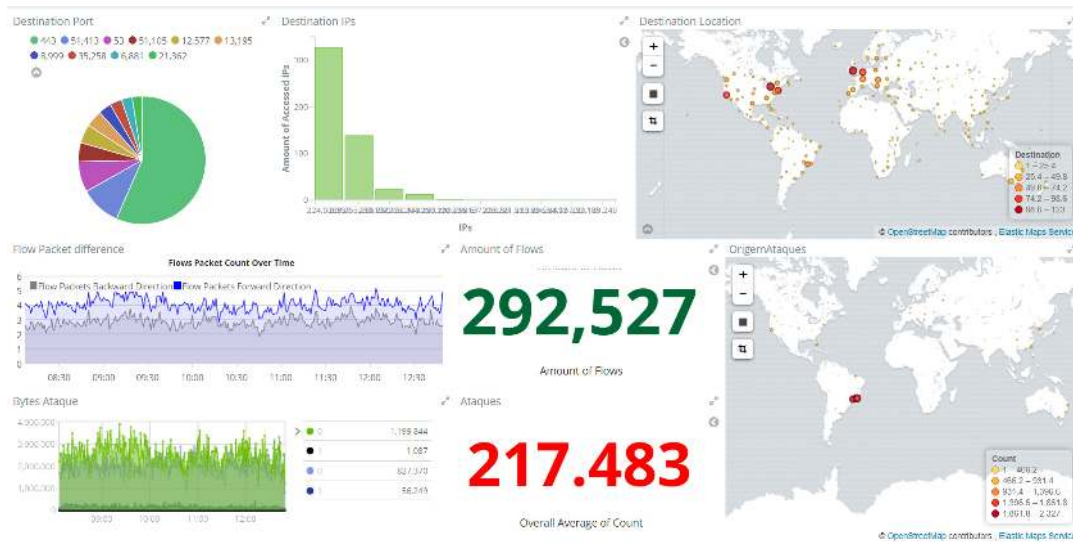


Figure 4.16: Dashboard panel view of CATRACA.

Figure 4.16 shows some of the different scenarios that can be viewed in the control panel, such as the most accessed destination/source ports, the most commonly used destination IP addresses, the average size of the flows in the round-trip directions, the number of analyzed flows, among others. It is worth emphasizing the visualization of the attacks in progress through a map that portrays the origin, the destination and the number of occurrences. This is possible due to the enrichment of the data through the correlation with geolocation metadata in the processing module. Thus, both data and threats are viewed in real time. In addition, all data is stored in time stamp, allowing the processing of the data through time series.

Chapter 5

Dataset and Feature Selection

This chapter presents and analyzes two datasets. First a security dataset that we have created in the laboratory GTA/UFRJ. Second more than ten days, in two different periods of real traffic for a network operator in Rio de Janeiro, Brazil. Then, we introduce the concepts of Feature Selection and Dimensionality Reduction, and, finally, we propose a new algorithm for feature selection.

5.1 Security Dataset Creation

In order to evaluate the defense mechanisms against network attacks, the first challenge is to obtain a suitable dataset for the evaluations. The availability of datasets in the literature is limited as there is concern about privacy and the fear of leakage of sensitive information contained in packet payload [80]. One of the main datasets available is the **DARPA** [81], consisting of raw TCP/IP traffic and UNIX operating system data of a simulated network obtained over seven weeks of collection totaling 9.87 GB of data. Because DARPA 98 consists of raw files, it is necessary to extract the features of these files to use them in machine learning algorithms. A greater amount of background traffic and different types of attacks were added to build the DARPA 99. The first two weeks were attack free, so it is suitable for training anomaly detection algorithms. In the next five weeks several simulated attacks were used against the base. New attacks were introduced in DARPA 99 [82], mainly attacks on different operating systems like SunOS, Solaris, Linux, and Windows NT.

Most research uses a mixture of the two datasets referring to the DARPA dataset. The KDD99 dataset, in turn, was created from the files of the DARPA 98 set for an intrusion detection competition in the year 1999 [83] and consists of samples defined by 41 features and an output class. The dataset is composed of two weeks of attacks. The classes are divided into five categories that contain 24 types of training attacks and 14 types of attacks in the training set, totaling 38 attacks.

The training set consists of 494,021 flows and the test set 311,029 flows. Classes include Denial of Service (DoS), Probe, Root2Local (R2L), User2Root (U2R), and Normal Traffic. One of the problems of KDD99 is imbalance. Approximately 80% of the samples are considered attacks, which differs widely from reality. The dataset contains few types of U2R and R2L attacks and many of these attacks are duplicates. By duplicating samples, classifiers become biased to denial of service (DoS) attacks and to normal traffic, which are the most abundant in KDD99. The NSL-KDD is a modification of the original KDD-99 set and has the same 41 features and the same five categories as the KDD 99. The improvements of the NSL-KDD over KDD 99 are the elimination of redundant and duplicate samples to avoid a biased classification and overfitting, and a better cross-class balancing to avoid random selection. Despite the reduction in size, the NSL-KDD maintains the proportions between classes as in KDD 99, with 125,973 training samples and 22,544 test samples. However, DARPA, KDD, as well as NLS-KDD are criticized because their traffics are synthetic and therefore do not faithfully represent real computer network scenarios [84]. These datasets contain redundant data, which affect the performance of classification algorithms. Another important critic is datasets outdated, since they have been simulated for over 15 years [85] and many applications, as well as attacks, have since appeared.

Since the creation of KDD99, other datasets have been published and made available introducing advantages and disadvantages. In this way, there is no dataset that suits all cases and the choice of which one to use depends on the scenario and the application. Some examples of dataset often found in the literature are a simulation traffic of a real scenario, the **UNB ISCX IDS 2012** [86] dataset, a simulated botnet traffic from **CTU-13** [87] dataset, traffic of a real DDoS attack in **CAIDA DDoS¹** dataset, real traffic of a backbone between US and Japan in **MAWI** [88], real honeypots traffic in **Kyoto** [89], and current traffic from LBNL² edge routers.

A contribution of this work is the creation of two dataset with synthetic and real network traffic to evaluate network security tools. Firstly, we elaborate a dataset through the packet capture in computers from our lab, GTA at Federal University of Rio de Janeiro. Then we analyze real network traffic captured for more than ten days of a real network operator in Rio de Janeiro, Brazil.

¹The Cooperative Analysis for Internet Data Analysis, <http://www.caida.org> accessed April 2018

²Lawrence Berkeley National Laboratory - LBNL/ICSI Enterprise Tracing Project, <http://www.icir.org/enterprise-tracing/download.html> accessed April 2018

GTA/UFRJ dataset

The traffic contains both normal traffic and real network threats. After the packets are capture, data is gathered from packet header and grouped in a time window, generating flow data. We define a flow as a sequence of packets from the same IP source to the same IP destination.

Each flow has 24 features, generated by TCP/IP header data such as TCP, UDP and ICMP packet rate, number of source and destination ports, number of each TCP flag, among others. Table 5.1 shows the full list of features. The analysis of packet header information detects two threat classes: Denial of Service (DoS) attacks and Probe. Therefore, we elaborate the dataset with several attacks from both these classes. Altogether, the dataset contains seven types of DoS and nine types of Probe. The DoS attacks are *ICMP flood*, *land*, *nestea*, *smurf*, *SYN flood*, *teardrop*, and *UDP flood*. The different types of probe in the dataset are *TCP SYN scan*, *TCP connect scan*, *SCTP INIT scan*, *Null scan*, *FIN scan*, *Xmas scan*, *TCP ACK scan*, *TCP Window scan*, and *TCP Maimon scan*. We perform the threats using tools from the *Kali Linux* distribution, which aims to test computer system security. These attacks were labeled in the dataset by origin and destination IP filters, separating the traffic belonging the attack machines from the rest.

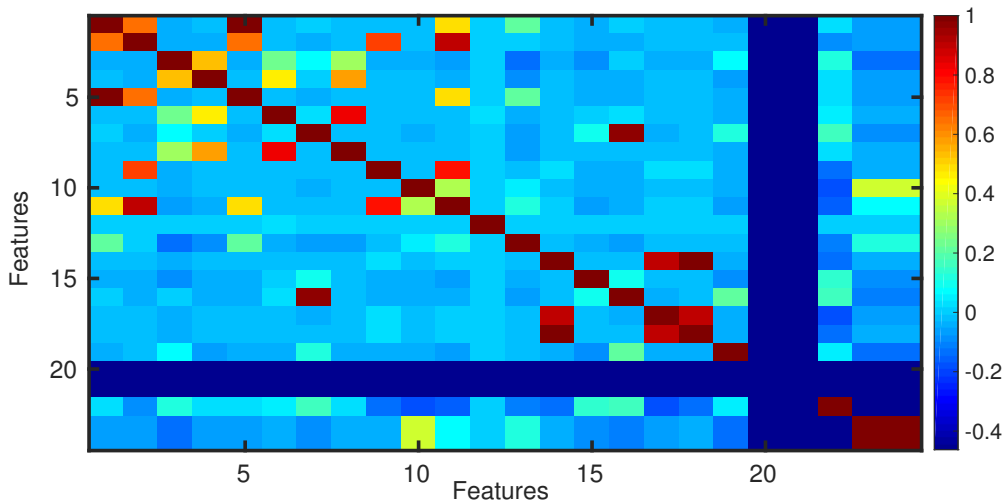


Figure 5.1: Correlation matrix of the 24 features available in the dataset. The dark red points indicate the maximum correlation and the blue points indicate the minimal correlation.

In Figure 5.1, we plot the correlation between the 24 features in our created dataset. This matrix calculates the Pearson correlation, also known as Pearson product-moment correlation coefficient (PPMCC). Pearson correlation is a measure of the linear dependence between two variables X and Y. Values in PPMCC vary from +1 to -1, where one is total positive linear correlation, zero is

Table 5.1: The 24 features obtained for each flow from TCP/IP headers.

Number	Abbreviation	Feature
1	qtd_pkt_tcp	Amount of TCP Packets
2	qtd_src_port	Amount of Source Ports
3	qtd_dst_port	Amount of Destination Ports
4	qtd_fin_flag	Amount of FIN Flags
5	qtd_syn_flag	Amount of SYN Flags
6	qtd_psh_flag	Amount of PSH Flags
7	qtd_ack_flag	Amount of ACK Flags
8	qtd_urg_flag	Amount of URG Flags
9	qtd_pkt_udp	Amount of UDP Packets
10	qtd_pkt_icmp	Amount of ICMP Packets
11	qtd_pkt_ip	Amount of IP Packets
12	qtd_tos	Amount of IP Service Type
13	ttl_m	Average TTL
14	header_len_m	Average Header Size
15	packet_len_m	Average Packet Size
16	qtd_do_not_frag	Amount of “Do Not Frag” Flags
17	qtd_more_frag	Amount of “More Frag” Flags
18	fragment_offset_m	Average Fragment Offset
19	qtd_rst_flag	Amount of RST Flags
20	qtd_ece_flag	Amount of ECE Flags
21	qtd_cwr_flag	Amount of CWR Flags
22	offset_m	Average Offset
23	qtd_t_icmp	Amount of ICMP Types
24	qtd_cdg_icmp	Amount of ICMP Codes

no linear correlation. In the figure, total correlation is represented by the dark red color and the no linear correlation is represented by dark blue color. Features 21 and 22 indicate the “Amount of ECE Flags” and the “Amount of CWR Flags,” respectively. The Explicit Congestion Notification (ECN) Echo (ECE) and the Congestion Window Reduced (CWR) flags are used to warn senders of congestion in the network thereby avoiding packet drops and retransmissions. In the correlation matrix, these two features are represented in a dark blue color, indicating the lowest possible correlation. In the case of our dataset, these two variables are empty. This is due to the fact that we create our dataset in a simple network that is free of congestion. On the other hand, features 23, “Amount of ICMP Types” and 24 “Amount of ICMP Codes”, are represented with a dark red. This mean, that the two features are highly correlated, as a consequence, only one feature is sufficient to describe the data. In the case of this dataset, the ICMP type always coincides with the ICMP codes.

Altogether, around 95 GB of packet capture data were collected, resulting in

214,200 flows composing normal and malicious traffic³. To evaluate the machine learning algorithms, we perform holdout validation. In Holdout validation, the data is split into two different datasets labeled as a training and a testing dataset. Holdout validation is the simplest method and show good performance [90]. This method results in statistics that are determined with new data, not analyzed in the training phase, as usually employed in scientific works of the area. For the anomaly detection, the training is performed with 70% of legitimate flow data to determine normal behavior. The other 30% are used to determine false-positive rate and the attack data are used to calculate the attack-detection rate. Figure 5.2 show the relation of classes used in the dataset. The Normal class is around 70% of the dataset with 106955 samples. The Denial of Service (DoS) class is 10% of the total dataset with 16741 samples, and, finally, Probe class represents almost the 20% of the dataset with 30491 samples.

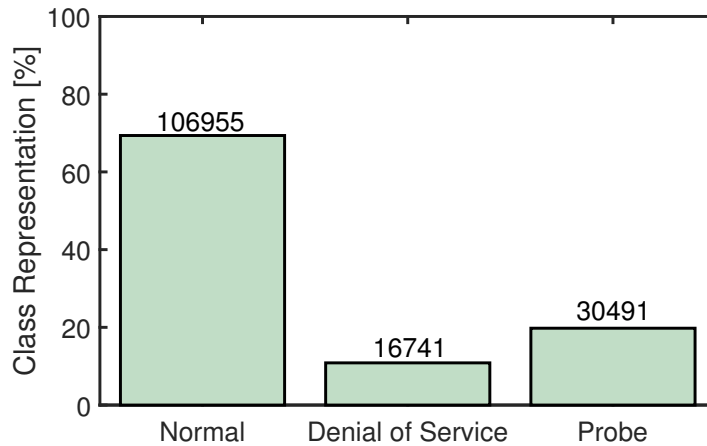


Figure 5.2: Classes Distribution in the Dataset. The main class is the Normal with almost 70% of the dataset, DoS is around 10% and Probe correspond to 20% of the Dataset.

Network Operator Dataset

We collected real and anonymized data from a major telecommunications operator⁴. The dataset is created by capturing 9 TB of access data of 373 residential broadband users in the city of Rio de Janeiro, Brazil. Capture is performed from 16th of February until 3rd of March of 2017. The dataset contains legitimate traffic, attacks and other security threats. An Intrusion Detection System (IDS) inspects the traffic and then summarizes a set of flow features associated with either an IDS alert or a legitimate traffic class.

³Data can be consulted through email contact with authors.

⁴Anonymized data can be consulted through email contact with authors.

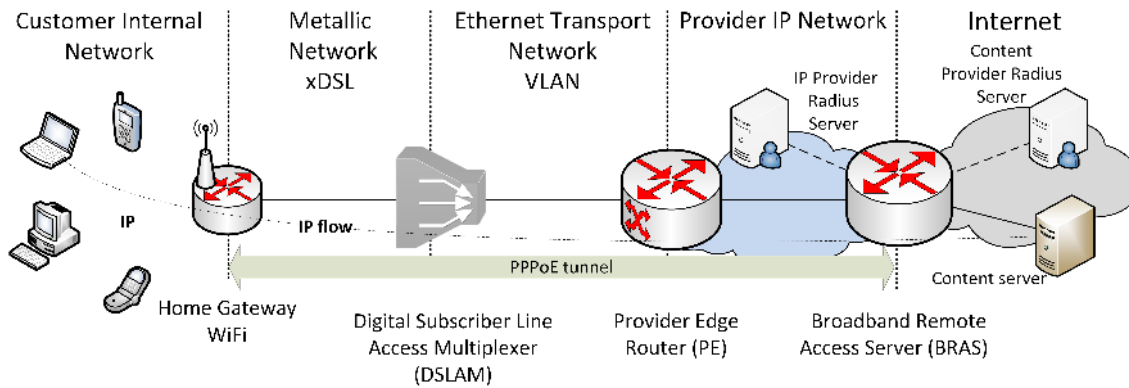


Figure 5.3: Typical topology of broadband access network. The connection between the Home Gateway and the Internet is authenticated and registered by the Radius server. The traffic is encapsulated in Point-to-Point Protocol over Ethernet (PPPoE) sessions between the user's home and the Broadband Remote Access Server (BRAS). Traffic inspection and collection occurs after BRAS.

Figure 5.3 shows a typical access topology for the broadband service composed of a Customer Premises Equipment (CPE) connected to a Digital Subscriber Line Asymmetric Multiplexer (DSLAM), a transport network, such as Multiprotocol Label Switching (MPLS) network, and a section aggregator Broadband Remote Access Server (BRAS) that authenticates the session of the users through a RADIUS server, also responsible for auditing the network usage. Thus, in an access network for fixed broadband users, the inspection is performed only after the aggregation of the traffic, since there are no nodes that allow the inspection of the data in the users' premises or in the perimeter closest to the users.

The analyzed traffic is composed of the aggregated traffic coming from the high capillarity, last mile, of different users with a wide variety of service profiles accessed by each user and generating a large data volume.

The analyzed dataset was created from the capture of raw packets containing real Internet Protocol (IP) traffic information of the residential users. Traffic was collected and recorded uninterruptedly for one week in through the `tcpdump`⁵ software. The processes of collecting and writing file were packet unfiltered, therefore, all packets on the network were raw and recorded directly in the dataset. The physical collection structure has been configured by mirroring the aggregate traffic of one DSLAM to another port of the transport network metro Ethernet switch. The mirroring of the DSLAM port on the switch allows all traffic originated or destined to the DSLAM to be cloned to a computer running an Ubuntu Linux operating system.

To ensure high-speed storage and to allow easy data transport, the dataset was written to an external hard drive with a USB 3.0 interface. Figure 5.4 shows the

⁵Available at <http://www.tcpdump.org>.

basic topology and the assembled structure for data collection. It is worth to mention that analyzing all traffic from operator is out of scope, thus data consumption samples satisfy the needs for the proposed characterization.

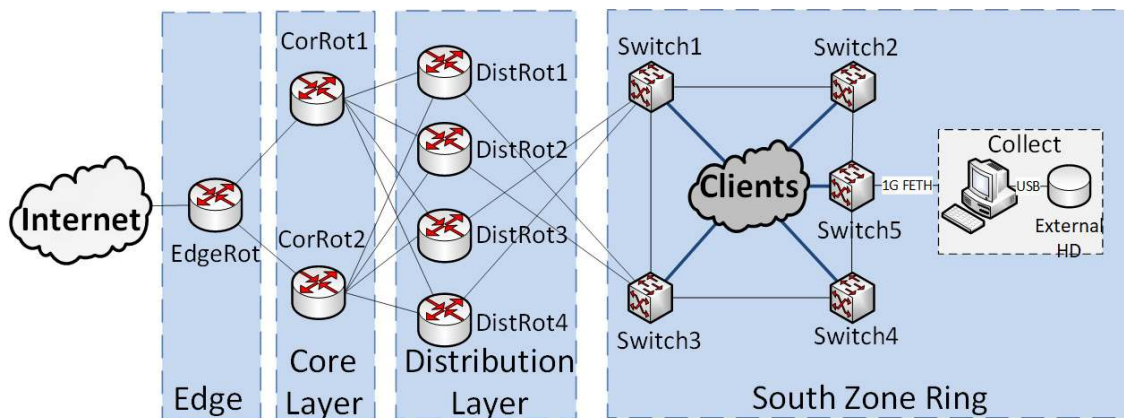


Figure 5.4: Topology of the data collection structure of the main DSLAM port with 373 broadband clients.

The data capture procedure ensures no loss in port mirroring at 1 Gb/s. Thus, 100% of the traffic generated by the 373 customers was collected and recorded in the dataset, totaling 5 TB of information. Although the average available speed at each port of the DSLAM is approximately 12 Mb/s, generating a hypothetical aggregate traffic of more than 4 Gb/s, it was verified that during the entire capture process, aggregate real traffic did not exceed 800 Mb/s. Aggregate traffic is composed by round-trip, uplink and downlink traffic. It is worth noting that all the captured traffic comes from fixed broadband sessions.

The Data Analysis

The analysis of captured data from the telecommunications operator’s network was divided into three stages. The first stage handles the raw data capture files through a network intrusion detection system (IDS) and then generates a summary of the data in the form of flows. We use the flow definition based on RFC 7011 [91]. A flow is defined as the set of packets collect during a window time in a monitoring point sharing common features. These features include information of the packets header and statistics employed in the packet, We abstract the flow in 43 features. The first stage is shown in Figure 5.5. Data analysis was based on the features extraction of flows represented by the captured packets, as well as the verification of possible alerts through an IDS. Since the packets comes from residential clients with Asymmetric Digital Subscriber Line (ADSL) access, the captured traffic is encapsulated in Point-to-Point Protocol over Ethernet (PPPoE) sessions which

make the analysis of packets harder for some IDS that do not perform the inspection of this type of protocol, such as Snort [92]. Therefore, to perform traffic classification on different types of alerts, the Suricata IDS⁶, Version 3.2, was used with its most recent signature database.

The classification between normal traffic and alert was performed based on Suricata signatures since there was no previous knowledge about threat information. Because the data is real and hence untagged, it is impossible to ensure that all flows are legitimate or, even after IDS classification, that all alert flows are indeed malicious.

Parallel to packets classification by the IDS, the captured packets were decapsulated from the PPPoE session using the tool `stripe`⁷ and were summarized in flows through the `flowtbag`⁸ tool. In addition, a Python application was developed to process the output of the Suricata IDS, and the summarized flow features in order to correlate which flow was reported as an alert by the IDS.

Thus, it was possible to obtain a flow dataset with the respective class labels. As we remove source and destination IP addresses features from the dataset to ensure the data anonymization, the dataset presents 43 features of each flow plus the class to which each flow belongs. The output class, feature 44, is given by the type of alert generated by the IDS or 0 in the case of a normal flow.

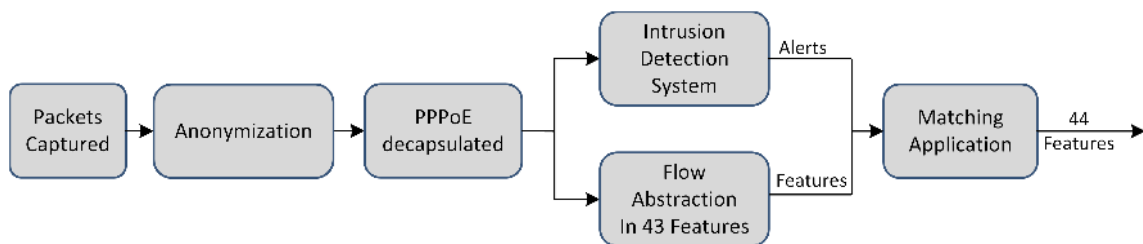


Figure 5.5: NetOp dataset processing steps. Packets are first anonymized, then PPPoE encapsulation is removed. An Intrusion Detection System (IDS) is used to classify alerts, in parallel, packets are abstracted in 43 flow features. Finally, an application is used to match traffic flows with IDS alerts, generating a flow with 44 features corresponding to 1 if alert and 0 to normal traffic.

Figure 5.6 shows the number of threats and normal flow in each day of the dataset in 2017. We can see that almost all days contains around 30% of alerts. Only day 17/2 contains less number of alerts. The maximum alerts number was during the Saturday 25/2 with 1.8 Million alerts.

Figure 5.7 shows the source and destination ports of the flows. The figure focuses on the 1024 first ports (from 0 to 1023), as they are the operating-system restricted ports. Usually, these ports are used by daemons that execute services with system

⁶Available at <https://suricata-ids.org>.

⁷Available at <https://github.com/theclam/stripe>.

⁸Available at <https://github.com/DanielArndt/flowtbag>.

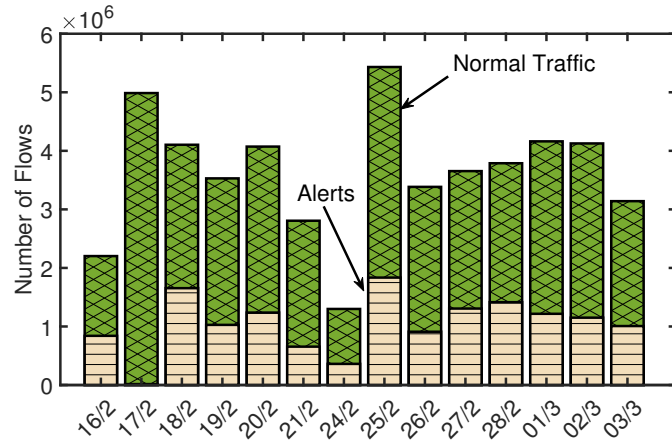


Figure 5.6: Number of Alerts and Normal Traffic flows in Network Operator dataset.

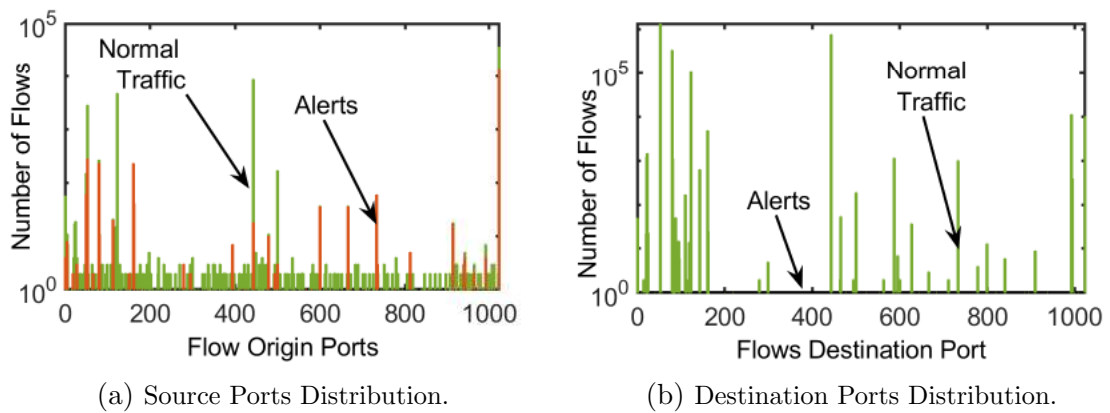


Figure 5.7: Ports used in flows. Comparison of the use of the lowest 1024 ports (restricted ports) in the evaluated flows. Because they are home users, the largest number of flows originating from these ports are flows that generate alerts.

administrator privileges. Our flow definition assumes that the source port initiates the TCP connection. Because the dataset portrays home users, it is expected that most connections will be destined to restricted and dynamics ports. Thus, it is remarked that the number of alerts coming from connections that the destination port is in the range of restricted ports is relatively low to the total number of connections on these ports, Figure 5.7b. When considering the flows, in which the source port is in the range of restricted ports, almost all flows are labeled as alert by the IDS, shown in Figure 5.7a. Another important fact is that most of the analyzed flows reflect the use of the DNS service (UDP 53) and HTTPS and HTTP services (TCP 443 and 80). The prevalence of HTTPS services over HTTP reflects the shift that major Internet content providers, such as Google and Facebook, have done to use encrypted service by default to ensure users' privacy and security. The relation between the most accessed services and flow duration is shown in Figures 5.8a and 5.8b. The duration of analyzed flows is mostly less than 40 ms, characterizing the use of DNS, HTTP and HTTPS services. Regarding the protocols used, the prevalence of UDP flows is evident and refers to DNS queries.

It is worth mentioning that the number of alerts generated by UDP flows is more than 10 times greater than the number of alerts generated by TCP flows. Another important point is that the number of flows that generate alerts is approximately 26% of total flows.

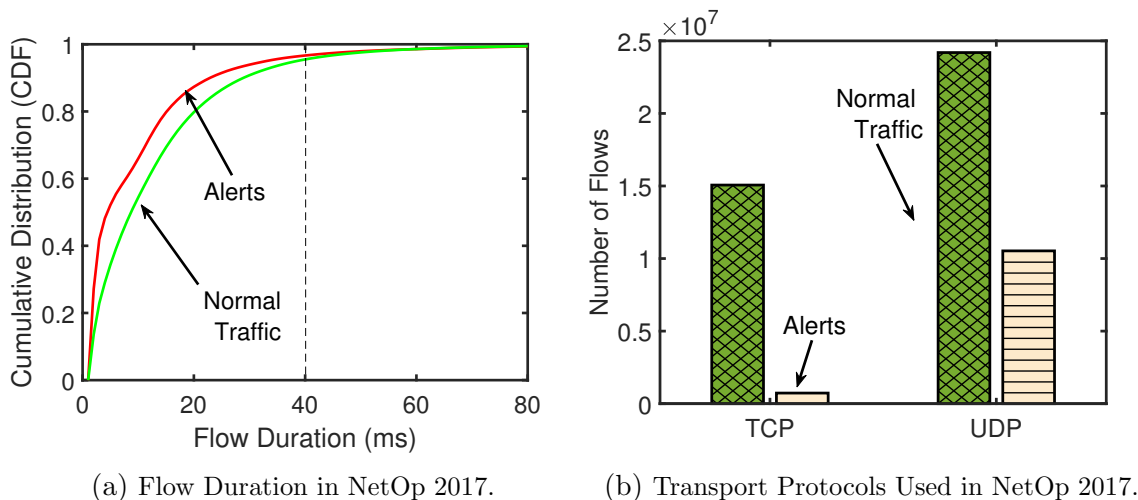


Figure 5.8: Cumulative Probability Density Function (CDF) for the distribution of the duration of flows in milliseconds and number of flows per transport protocols. A) The flows that generate alerts are shorter in duration than the average flow. B) The legitimate flows with UDP are numerous due to DNS (port 53 UDP). The number of alerts in UDP is more than 10 times greater than in TCP flows.

Figure 5.9 shows the characterization of the number of packets per flow in uplink and bytes per packet in downlink direction. In uplink direction, Figure 5.9a, 80% of alerts starts with 20 packets or less while normal traffic starts with almost 80 packets. This behavior is typical from probe or scans attacks that send small amount of packet to discover target vulnerabilities. In Figure 5.9b alerts and normal traffic show a similar pattern of 11% of flows, however, alerts use more than 100 Bytes in more than 30% of flows.

Considering the amount of data transferred in each flow, Figure 5.10 compares the round-trip flows in relation to volume in bytes. The disparity of the traffic volume in both directions of the communication is evident. While in one way 95% of traffic has a maximum volume of 100 B, in the other way, the same traffic share presents up more than 500 B. This result demonstrates that the residential broadband user profile is a content consumer. Another interesting point is that the flows that generate alerts have a similar traffic volume profile in both directions. Asymmetric traffic is more typical of the legitimate users.

Figure 5.11 shows the behavior of the sub-flows generated in each connection. A sub-flow is considered a flow in one direction. Both Figures 5.11a, 5.11b, sub-flows size in uplink and downlink, shows a very similar behavior. More than 20% of Normal traffic flows, reach 900 B, but this value is reached in almost 60% of the flows. Values of sub-flows are almost ten times bigger than values represented in

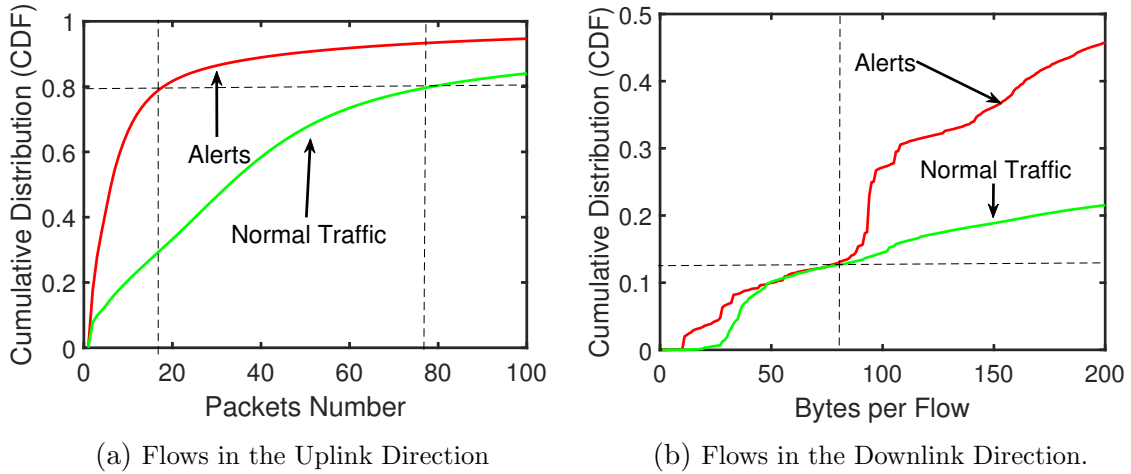


Figure 5.9: Cumulative Probability Density (CDF) function for the distribution of the number of packets per flow. Flows that generate alerts tend to have fewer packets.

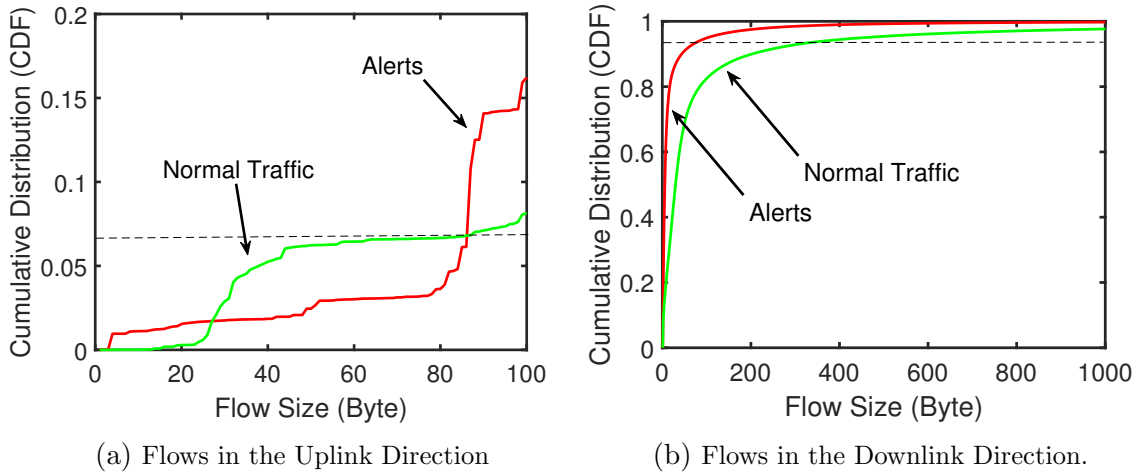


Figure 5.10: Cumulative Probability Density (CDF) function for volume distribution in bytes by flow. Flows that generated alerts tend to have smaller volumes in transferred bytes.

Figures 5.10 where Bytes flows size are shown. This is because the flows are mostly of short duration, evidenced in Figure 5.8a, and thus do not generate sub-flows. Data analysis showed that the flows do not pass to the idle state. Another important feature is the total amount of data in the packet headers. Figure 5.12 shows that in both flows directions, alert and total traffic have the same behavior. In particular, there is symmetry in the round-trip traffic in terms of the volume of data in the headers. It highlights that malicious traffic do not rely on the usage of header options. Also, in both senses, uplink and downlink show a similar behavior. Until 90 Bytes per header alerts and normal traffic are similar, however, with 900 Bytes are represented by almost 30% of normal traffic and close to 60% of alerts flows.

At the end of the knowledge extraction phase, the profile of the alerts generated by

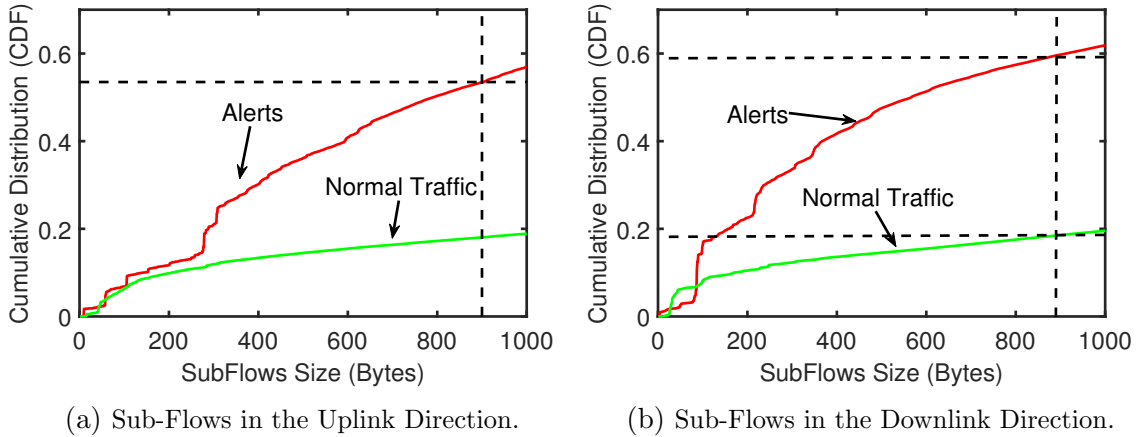


Figure 5.11: Cumulative Probability Density (CDF) function for volume distribution in bytes by sub-flow in each flow. Flows that generate alerts tend to have smaller volumes in bytes that are transferred in sub-flows

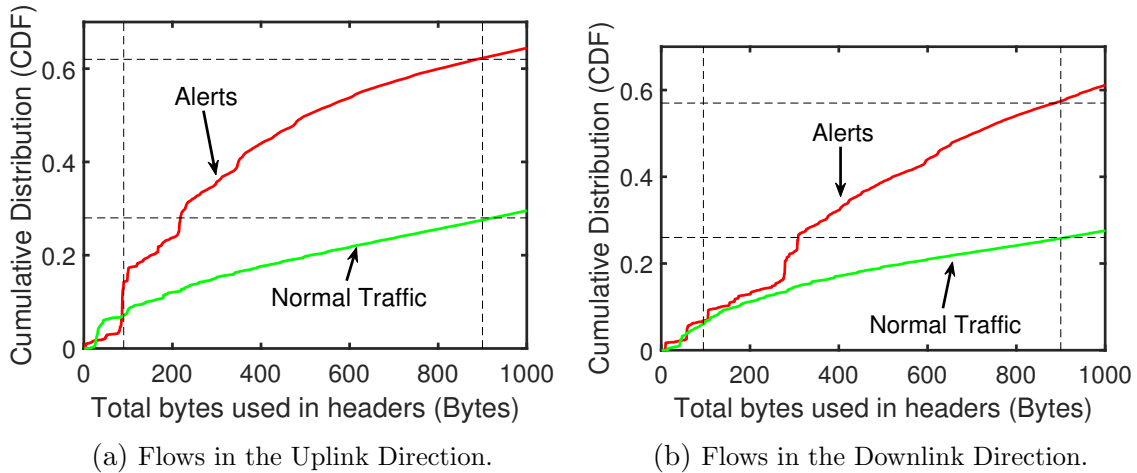


Figure 5.12: Cumulative Probability Density Function (CDF) for volume distribution in bytes of the data trafficked in headers. The behavior of traffic that generates alerts is very similar to total traffic.

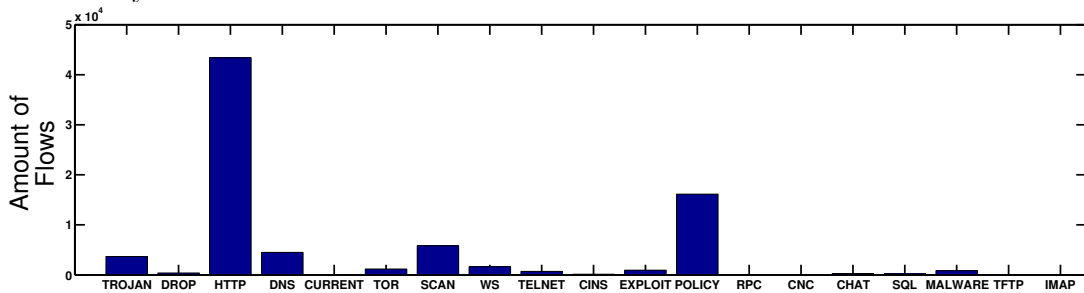


Figure 5.13: Distribution of the main types of alerts in the analyzed traffic.

IDS were analyzed. Figure 5.13 shows which are the main classes of alerts triggered by the IDS. Alerts for attacks against HTTP are the most frequent. This class of alerts includes SQL injection attacks through HTTP calls and XSS attacks (cross-site scripting). Home users can execute these attacks, as they use the parameters of HTTP calls to insert some malicious code into the servers and,

therefore, are not filtered by access rules. Other important alerts are port scanning, vulnerability scanning, and execution of malicious applications (trojan and malware). The scans are generally intended to identify open ports and vulnerabilities in user premises such as the home gateway. Alerts for trojan and malware identify activities typical of known malicious applications that aim to create and exploit vulnerabilities in the devices of the home users. The other alerts refer to mechanisms of information theft and to Byzantine-attack signatures on common protocols, such as IMAP and Telnet⁹.

5.2 Feature Selection and Dimensionality Reduction

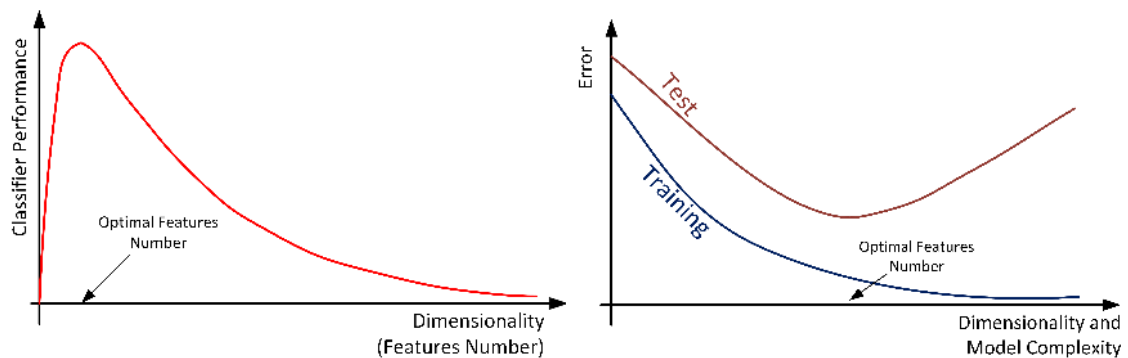
An information can be represented or classified by its features or attributes. The number of features or attributes used to represent information varies greatly. A relevant problem is that increasing the number of attributes does not always improve the accuracy of the information classification. This problem is known as the “curse of dimensionality” [93] which states that there are an optimal number of features that can be selected in relation to the size of the sample to maximize the performance of the classifier.

Figure 5.14a shows that when dimensionality increases, the performance of the classifier increases until the optimal number of features is reached. From this optimal value, the performance falls. Therefore, from the optimal value of feature number, increasing dimensionality without increasing the number of training samples results in a decrease in classifier performance. Figure 5.14b shows the performance degradation of the algorithms. The increase in dimensionality is directly proportional to the complexity of the model, obtaining an error rate in the low training. However, these models present the overfitting problem during the training step, in which the data perform poorly in the test step. Figure 5.14c shows that the number of dots increases exponentially with increasing dimensionality. In spaces with many dimensions, the points become sparse and not very similar, with points very distant from each other and approximately equidistant, which leads to a classifier prone to errors. In addition, other problems arise when using a high number of dimensions with machine learning algorithms. Some traditional distance metrics, such as Euclidean distance, are no longer meaningful in high dimensions, requiring the use of other types of metrics, such as the cosine distance, which have a higher computational cost.

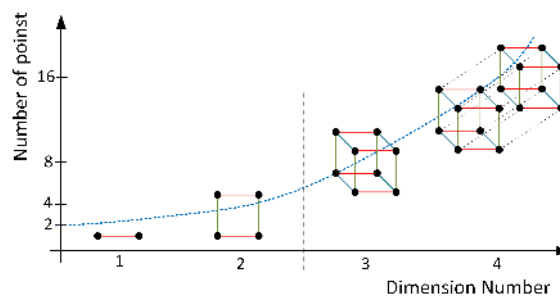
Therefore, it is common to reduce the number of features or dimensionality prior

⁹Mainly used for remote configuration of network equipment.

to the application of a machine learning algorithm.



(a) Performance of the classifier with increasing dimensionality. (b) Overfitting effect on training data, which reduces test performance.



(c) Exponential growth of the number of points with an increase in dimensionality.

Figure 5.14: The “curse of dimensionality” problem. This problem asserts that there are an optimum number of features that can be selected in relation to the size of the sample to maximize the performance of the classifier.

Feature selection or dimensionality reduction techniques are used to further the learning performance. Feature selection maintains the most relevant features of the original dataset, creating a smaller subset of the features. On the other hand, the dimensionality reduction takes advantage of the redundancy of the input data, calculating a smaller set of new dimensions or synthetic features. The new synthetic features are a linear or non-linear combination of the input features. The main idea of the methods is to remove all redundant information, keeping only the necessary information, which is sufficient to represent the original information. The purpose of both feature selection and dimensionality reduction is to produce a minimum set of features so that the new subset maintains the most similar performance of the generating set. Therefore, feature selection and dimensionality reduction improve classification performance by providing faster and therefore economically viable classifiers. The feature selection has an additional property, because it allows a better understanding of the process that generates the data. In the dimensionality reduction the selected features are synthetic and composed of a combination of the original features, which makes it difficult to understand the

process.

The dimensionality reduction can also be seen as the process of deriving a set of degrees of freedom, which are used to reproduce most of the variability of a dataset [94]. Ideally, the reduced representation must have a dimensionality that corresponds to the intrinsic dimensionality of the data. The intrinsic dimensionality of the data is the minimum number of dimensions required to meet the observed properties of the data. Generally, in dimensionality reduction a new feature space is created through some kind of transformation of the original feature space.

Thus, in the reduction of dimensionality, given the random variable of n -dimensions $\mathbf{x} = (x_1, x_2, \dots, x_n)$, it is possible to find a lower dimensional representation of it, $\mathbf{s} = (s_1, s_2, \dots, s_k)$ with $k \leq n$. Many algorithms with different approaches have been developed to reduce dimensionality that can be classified into two groups: linear and non-linear. The linear reduction of dimensionality is a linear projection, in which n -dimensional data are reduced in k -dimensional data using k linear combinations of n variables. Two important examples of linear dimension reduction algorithms are Principal Component Analysis (PCA) and Independent Component Analysis (ICA).

The objective of the PCA is to find an orthogonal linear transformation that maximizes the feature variance. The first PCA base vector, called the main direction, describes better the variability of the data. The second vector is the second-best description and must be orthogonal to the first and so on in order of importance. On the other hand, the goal of ICA is to find a linear transformation in which the base vectors are statistically independent and not Gaussian, that is, the mutual information between two variables of the new vector space is equal to zero. In signal processing, ICA is used to separate two mixed signals. A common example is the cocktail party [95], in which the objective is to listen one-person speech in a noisy room. Unlike PCA, the base vectors in ICA are neither orthogonal nor ranked in order, all vectors are equally important. PCA is normally used when we want to find a reduced representation of the data. On the other hand, the ICA is normally used to obtain features extraction, identifying and selecting the features that best suit the application.

Figure 5.15 shows the eigenvalues associated to the synthetic dataset (GTA/UFRJ). The first fourth components calculated by the PCA linear transformation represent 80% of the total variance. Therefore, these fourth components are selected and the others, that represents less than 20% of the total data variance, are discarded, improving the processing time, which is critical in real-time applications.

In cases where high-dimensional data have a non-linear nature, linear algorithms

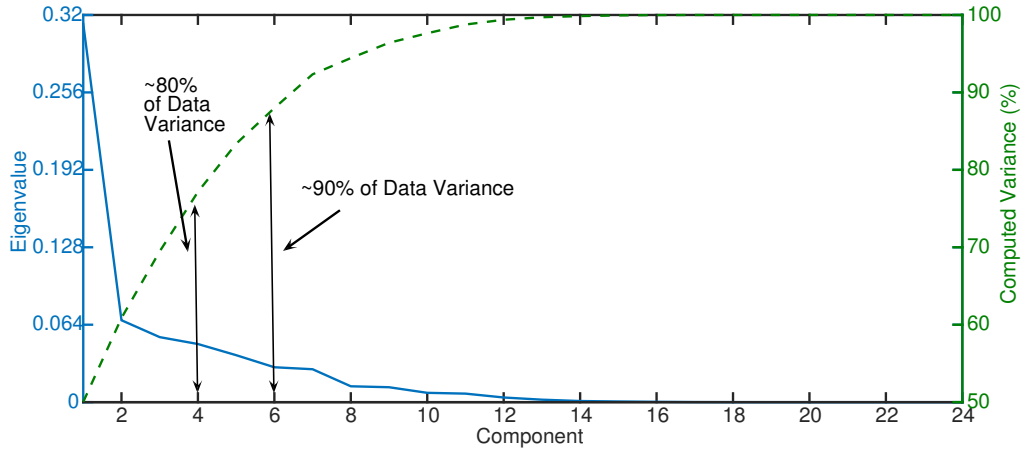


Figure 5.15: Eigenvalue for each of the 24 flow features in GTA/UFRJ dataset. The eigenvalue associated to each of the transformed features is proportional to the data variance. 80% and 90% of the total data variance is represented between the fourth and the sixth highest principal components.

do not perform well. This means that the relationship between classes is not described in a linear subspace, as shown in Figure 5.16a. For these cases, it is possible to use the PCA technique with kernels functions. A Kernel function transforms the input vectors of the original space into a larger dimensional space, in which the problem becomes linearly separable [33].

Figure 5.16 shows a comparison of linear and non-linear reduction methods. The original dataset, shown in Figure 5.16a, is a case of two concentric circles, each circle is a class. The goal is to reduce a 2-dimensions (\mathbb{R}^2) space into a 1-dimension space (\mathbb{R}^1). After applying a linear reduction, Figure 5.16b, the Principal Components cannot achieve a subspace where the classes are linearly separated into space (\mathbb{R}^1). This is because the two concentric circles are two separable nonlinear classes. After applying a non-linear method, such as a Gaussian Kernel PCA, shown in Figure 5.16c, the method gets a subspace where the classes have separated properly.

There are two approaches to class separation in data that cannot be separated linearly, as shown in Figure 5.16a. The first mapping the data into a larger space, in which the classes can be separated linearly by straight lines as shown in Figure 5.17b. The example of Figure 5.17 is a binary example, in the plane of \mathbb{R}^1 there is no linear hyperplane that is able to separate the two classes.

If the problem is taken to a plane with a higher dimensionality, $\mathbb{R}^1 \rightarrow \mathbb{R}^2$, it is possible to find a hyperplane, dash line in Figure 5.17b that separates classes. The dataset can be mapped into a space of a larger dimension, $\mathbb{R}^1 \rightarrow \mathbb{R}^2$, and thereby enable a linear hyperplane to separate classes, as shown in Figure 5.17b.

This hyperplane, when brought down to a smaller dimension, corresponds to a

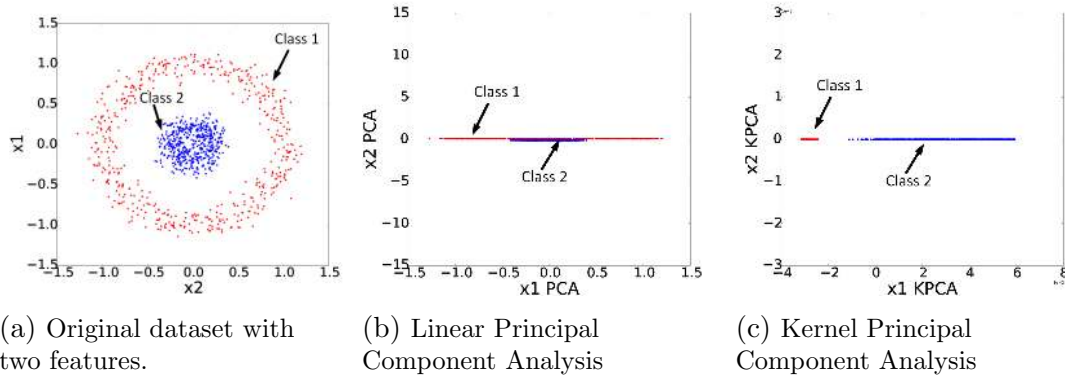


Figure 5.16: Example of non-linear class separation. a) two classes in a concentric circle manifold; b) The linear PCA is not able to separate properly the two classes; c) A better result is achieved when used the Kernel PCA.

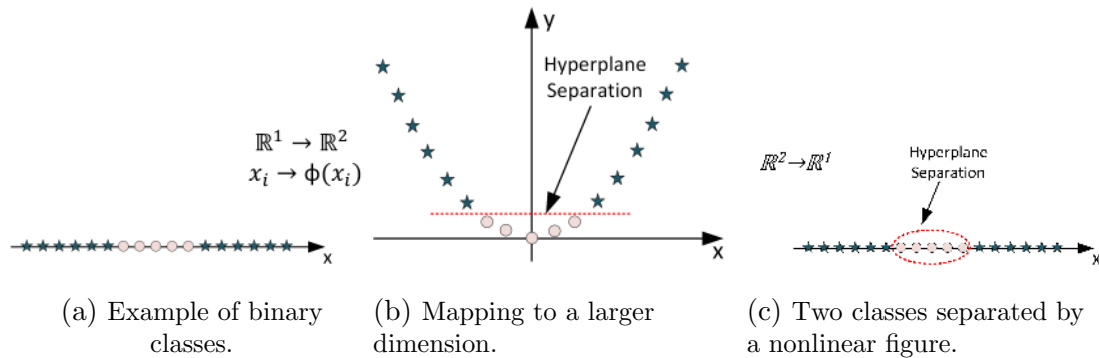


Figure 5.17: Strategies for separating non-linear data distribution classes: a) original dataset of two classes with non-linear distribution; b) data mapping with increase of size that allows the separation with linear algorithms, such as PCA; c) use of nonlinear hyperplane, as in the PCA nonlinear kernel algorithm.

nonlinear figure as shown in Figure 5.17c $\mathbb{R}^2 \rightarrow \mathbb{R}^1$. However, when mapping to larger dimensions, the “curse of dimensionality” explained above is incurred, which generates a high computational cost. To solve this problem the “kernel trick” is applied. A kernel function is a similarity function that corresponds to the dot product in an expanded vector space. The idea is to find a nonlinear function in which dimension mapping is not necessary and computation is independent of the number of features. The idea is to find a nonlinear function in which dimension mapping is unnecessary and computation is independent of the number of features. If there exists a nonlinear transformation $\Phi(x)$ from the original D -dimensional feature space to an M -dimensional feature space, where $M \gg D$. Then each data point x_i is projected to a point $\Phi(x_i)$. If the $K()$ matrix containing the scalar products among all pairs of data points is now calculated as $K(x_i, x_j) = \Phi(x_i)^T \Phi(x_j)$. Then each data point x_i is projected to a point $\Phi(x_i)$. The most commonly used kernels are the polynomial, Gaussian and tangent nucleus (hyperbolic tangent). If a used kernel is linear, we can see the standard

PCA as a case of the Kernel PCA.

5.2.1 Feature Selection

The feature selection produces a subset of the original features, which are the best representatives of the data. As opposed to dimensionality reduction there is no loss of meaning. Feature selection techniques can be divided into three types of algorithms [96]: wrappers, filter and embedded.

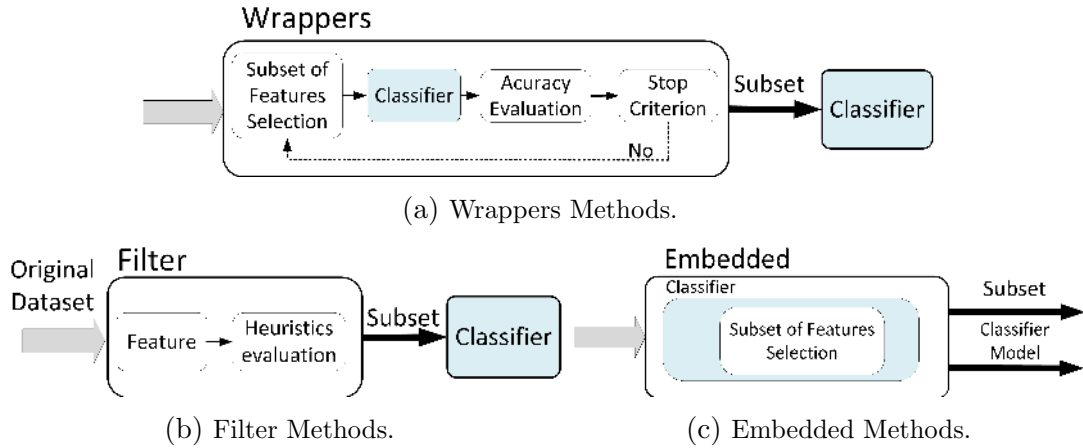


Figure 5.18: Feature Selection Methods. a) Wrappers methods use a classifier to evaluate the subset of features. b) Filter methods use heuristics to evaluate a feature or a subset. c) The embedded methods use a specific classification algorithm to make the selection naturally.

The wrappers algorithms, as shown in Figure 5.18a, use machine learning techniques such as Support Vector Machine (SVM), decision tree, among others, to measure the quality of features subsets without incorporating knowledge about the specific structure of the classification function. Thus, the method will evaluate subsets based on the accuracy of the classifier. The evaluation is repeated for each subset until it finds a set that performs well. In high dimensional dataset this search is a NP-hard problem. Wrappers methods tend to be more accurate than the filter methods, at a higher computational cost [97]. One popular Wrapper algorithm is the Sequential Forward Selection (SFS). Starting with an empty set S and the full set of all features X , the SFS algorithm makes a bottom-up search and gradually add features selected by an evaluation function to S , that minimizes the mean square error (MSE). At each iteration, the feature to be included in S is selected among the remaining available features of X . One problem of this method is that SFS is prone to select redundant features. Once a feature is selected, it cannot be chosen at a later stage.

Embedded methods are a sub-class of wrappers methods. In this case, the subset of features is obtained as well as the model where they were selected. Embedded

methods perform the feature selection process during the learning phase of a classifier. These methods select features based on criteria generated during the learning process of a specific classifier. In contrast to wrappers methods, embedded methods do not separate learning from feature selection. As in wrappers methods, embedded methods use the accuracy of a classifier to evaluate the relevance of the feature. However, embedded methods need to modify the classification algorithm in the learning process. The SVM-RFE feature selection method was proposed in the elimination of recursive features in the selection of genes for cancer classification [98]. The algorithm selects the features according to a classification problem based on the training of a linear vector support machine (SVM). The features with the lowest ranking are removed according to a w criterion, sequentially backward. The criterion w is the value of the hyperplane decision in the SVM.

To reduce the high computational cost of evaluating the various subsets of classifier-based features, the filter methods were implemented. Filter methods are called open-loop methods because they have no interaction with the classifier. Instead of classifiers the method uses heuristics to evaluate the relevance of the feature in the dataset [99]. As its name implies, the feature that does not exceed the heuristic criterion is filtered. Gaining information, distance, consistency and similarity between features as well as statistical measures are some of the most used heuristics in filter evaluation. Since the selection process is done in a step prior to classification, only after the best features are found, classification algorithms can use them. While this method is fast to select features, having no interaction with the classifier subset of feature may imply lower accuracy. One of the most popular filter methods is Relief, in which the feature score is calculated as the difference between the distance of the closest sample from the same class and the closest sample of the different class. The main disadvantage of this method is that data classes must be labeled in advance. Relief is limited to problems with only two classes, but ReliefF [32] is an enhancement to the Relief method that handles multiple classes using the nearest k -neighbors technique. ReliefF is a supervised method in which classes labeling must be known prior to application of the method. In applications such as network monitoring and threat detection, network flows reach unclassified classifiers. Therefore, unsupervised algorithms must be applied.

5.2.2 Correlation Based Feature Selection

We present the Correlation Based Feature Selection, a simple unsupervised filter method for feature selection. Our algorithm is inspired in the Correlation Features

Selection (CFS) [100]. Hall uses the idea of punctuating the variables through the correlation between the variables and the output class. The CFS algorithm calculates the correlation between the variable and the class to get the importance of each feature. Thus, the CFS is dependent on output class information *a priori*, so it is a supervised algorithm. The information dependence on the output class is a limitation in applicability, such as the classification of network traffic, since there is no *a priori* knowledge between the network traffic flow and the corresponding class.

Our algorithm is based in the correlation between features. The Pearson correlation of two variables is a measure of their linear dependence. Pearson coefficient value is between $-1 \leq \rho \leq 1$, where 1 means that the two variables are directly correlated, linear relationship, and -1 in the case of inverse linear relationship, also called anticorrelation.

The Pearson Coefficient ρ , can be calculated in terms of mean μ and standard deviation σ ,

$$\rho(A, B) = \frac{1}{N-1} \sum_{i=1}^N \left(\frac{A_i - \mu_A}{\sigma_A} \right) \left(\frac{B_i - \mu_B}{\sigma_B} \right), \quad (5.1)$$

or in terms the of covariance

$$\rho(A, B) = \frac{cov(A, B)}{\sigma_A \sigma_B}, \quad (5.2)$$

then we calculate the weight vector,

$$\mathbf{w}_i = \frac{\sigma^2}{\sum_{j=0}^{j=N} |A_{ij}|}. \quad (5.3)$$

Firstly, we need to obtain the correlation matrix, calculated with Equation 5.2, line 1 algorithm 1. The correlation matrix is the pairwise covariance calculations between all pairs of features. Then, using the Equation 5.3 we can establish a weight w that is a measure of the importance of the feature. In order to calculate w , we sum the absolute values of the correlation features, lines 5-6 algorithm 1. This sum in absolute value is due to the fact that the Pearson coefficient, ρ , may assume negative values. Then we calculate the variance \hat{V} of each feature that privilege the feature that has greater variance and lower covariance, line 8 algorithm 1. The idea is to establish which feature represent the most information, giving the correlation between two features. Furthermore, the weight values give us an indication of the amount of information the feature has independently of the others. The weight w has values between $0 \leq N$, where N is the number of features, and 0 means that a feature is totally independent of the other. The

higher the w value is, the higher is the correlation with other features, thus the lesser is the aggregated information by this feature.

Algorithm 1: Correlation Based Feature Selection

Input : X : Matrix of Features
Output: \mathbf{r} : Vector of Ranked Features, \mathbf{w} : Vector of weights

```

1  $A = Corr(X)$  /* Correlation Matrix */
2 for  $0 \leq i < len(A)$  do
3    $W_i = 0$ 
4   for  $0 \leq j < len(A_i)$  do
5      $k_i = abs(A_{ij})$  /* Absolute Values */
6      $aux_i += k_i$  /* Sample Addition */
7   end
8    $\mathbf{w}_i = \hat{V}(A_i)/aux_i$  /* Calculate Weights */
9 end
10  $\mathbf{r} = sort(\mathbf{w}, reverse = True)$ 

```

5.2.3 Case of Use: Traffic Classification

In order to evaluate the proposed algorithm, we perform traffic classification to detect threats. We chose this application, because it is very time sensitive and our algorithm can significantly reduce the processing time, enabling prompt defense mechanisms. We implemented traffic classification using machine learning algorithms on our synthetic dataset GTA/UFRJ. Threat detection system must allow real-time detection and the elimination of intervention from security experts to classify threats and configure the system. Human intervention is a major source of errors and an important factor that slows down threat detection. Then automatic threat classification is fundamental for network security.

Decision Tree (DT) with C4.5 algorithm, Artificial Neural Networks (ANN), and Support Vector Machine (SVM), are the classification algorithms implemented to evaluate the algorithm. We selected these algorithms because they are among the most used for network security [101]. In all methods, we used holdout validation, splitting dataset in 70% for training set and test with the remaining 30%. During the training phase, we perform tenfold cross validation to avoid overfitting. In cross validation, parts of the dataset are divided and not used in model parameters estimation. They are further used to check whether the model is general enough to adapt to new data, avoiding overfitting to training data.

In **decision tree**, leaves represent the final class and branches represent conditions based on the value of one of the input features. During the training part, the C4.5 algorithm determines a tree-like classification structure. The real-time

implementation of the decision tree consists in if-then-else rules that generate the tree-like structure previously calculated. The results are presented in the Section 5.2.4, along with the ones from the other algorithms.

The **Artificial Neural Networks** (ANN) are based on the human brain, in which each neuron performs a small part of the processing, transferring the result to the next neuron. In artificial neural networks, the output represents a degree of membership for each class, and the highest degree is selected. The weight vectors Θ are calculated during the training. These vectors determine the weight of each neuron connection. In the training, there are input and output sample spaces and the errors, caused by each parameter. Errors are minimized through the back-propagation algorithm.

In order to determine to which class a sample belongs each neural network layer computes the following equations:

$$z_{(i+1)} = \Theta_{(i)}a_{(i)} \quad (5.4) \quad a_{(i+1)} = g(z_{(i+1)}) \quad (5.5) \quad g(z) = \frac{1}{1 + e^{-z}} \quad (5.6)$$

where $a_{(i)}$ is the vector that determines the output of layer i , $\Theta_{(i)}$ is the weight vector that leads layer i to layer $i + 1$, and $a_{(i+1)}$ is the output of layer $i + 1$. The function $g(z)$ is the *Sigmoid* function that plays an important role in the classification. For high values of z , $g(z)$ returns one and for low values $g(z)$ returns zero. Therefore, the output layer gives the degree of membership of each class, between zero and one, classifying the sample as the highest one.

The **Support Vector Machine** (SVM) is a binary classifier, based on the concept of a decision plane that defines the decision thresholds. SVM algorithm classifies through the construction of a hyper-plane in a multidimensional space that split different classes. An iterative algorithm minimizes an error function, finding the best hyper-plane separation. A kernel function defines this hyper-plane. This way, SVM finds the hyper-plane of maximum margin, that is, the hyper-plane with the biggest distance possible to both classes.

The real-time detection is performed by the classification to each one of the classes: normal and non-normal; DoS and non-DoS; and probe and non-probe. Once SVM calculates the output, the chosen class is the one with the highest score. The classifier score of a sample x is the distance from x to the decision boundaries, that goes from $-\infty$ to $+\infty$. The classifier score is given by:

$$f(x) = \sum_{j=1}^n \alpha_j y_j G(x_j, x) + b, \quad (5.7)$$

where $(\alpha_1, \dots, \alpha_n, b)$ are the estimated parameters of SVM, and $G(x_j, x)$ is the used kernel. In this work, the kernel is linear, that is, $G(x_j, x) = x'_j x$, which

presents a good performance with the minimum quantity of input parameters.

5.2.4 Classification Results

We compare our feature selection algorithm with the methods presented in Section 5.2. We try a lineal Principal Component Analysis (PCA), The ReliefF algorithm, the Sequential Forward Selection (SFS), and the Support Vector Machine Recursive Feature Elimination (SVM-RFE). For all methods, we analyze their version with four and six features. In order to make a fair comparison, we tested all the algorithms with the classification methods presented before. We use a decision tree with the CART algorithm with minimum 4096 leaves, a binary support vector machine (SVM) with linear kernel, and finally a neural network with one hidden layer with 10 neurons. Figure 5.19 presents information gain (IG) sum of the selected feature for each evaluated algorithm. Information gain measures the amount of information, in bits, that a feature possesses in relation to the class prediction, if the only information available is the presence of the given feature and the corresponding class distribution. Thus, it is computed as the difference of target class entropy and the conditional entropy of target class given the feature value as known. When employing six features, the results show that our algorithm has information retention capability between SFS and ReliefF, and greater than SVM-RFE. The information retention capability of PCA, is greater than feature selection methods, as each feature is a linear combination of the original features and is computed to retain most of dataset variance.

Figure 5.20 shows the performance accuracy of the three classifiers algorithms Decision Tree, Neural Network and Support Vector Machine (SVM). In the first group, the decision tree best results is shown by our proposal with six features in 97.4%. The following result is PCA with four and six features in 96% and 97.2%. The Sequential Forward Selection (SFS) presents the same result with four and six features with 95.5%. The ReliefF algorithm has the same results in both four and six features is 91.2%. Finally, the lowest result is show by SVM-RFE algorithm with four and six features.

The second classifier, the neural network, the best result is shown by the PCA with six features in 97.6% of accuracy, however the PCA with four features present a very low performance with 85.5%. ReliefF presents the same results for both features in 90.2%. Our proposal shows a result with 83.9% and 85.0% for four and six features. On the other hand, the SFS presents the worst results of all classifiers, 78.4% with four features and 79.2% with six features. One impressive result is the SVM-RFE, with four features presents a very low result of 73.6% that is one of the worst for all classifiers, however, with six features present almost the

same best second result with 90.1%.

In the Support Vector Machine (SVM) classifier, the PCA presents a similar behavior compared with the neural networks. For six features presents the highest accuracy of all classifiers with 98.3%, but just 87.8% for four features. ReliefF again presents the same result for both cases in 91.4%. Our proposal has 84% for four features and 85% for six features. SFS present the same result for both features in 79.5%. The lowest accuracy of this classifier is the SVM-RFE with 73.6% for both cases.

The Sensitivity metric shows the rate of correctly classified samples. It is a good a metric to evaluate the success of a classifier, when using a dataset in which a class has much more samples than others. In our problem, we use sensitivity as metric to evaluate our detection success. For this, we consider the detection problem as a binary classification, i.e., we consider two classes: a normal and an abnormal traffic. In this way, the Denial of Service (DoS) and Scan threat classes were joined into a common attack class. Similar to Accuracy representation in Figure 5.20, Figure 5.21 represents the sensitivity of the classifiers applying the different methods of feature selection. In the first group, the classification with Decision Three, PCA shows the best sensitivity with 99% of correct classification, our algorithm achieves a performance with almost 95% of sensitivity, with four and six features. Neural Networks, represented in the second group, has the best sensitivity with PCA using six features with 97.7%, then our results show a good performance with both four and six features in 89%. In this group the worst sensitivity of all

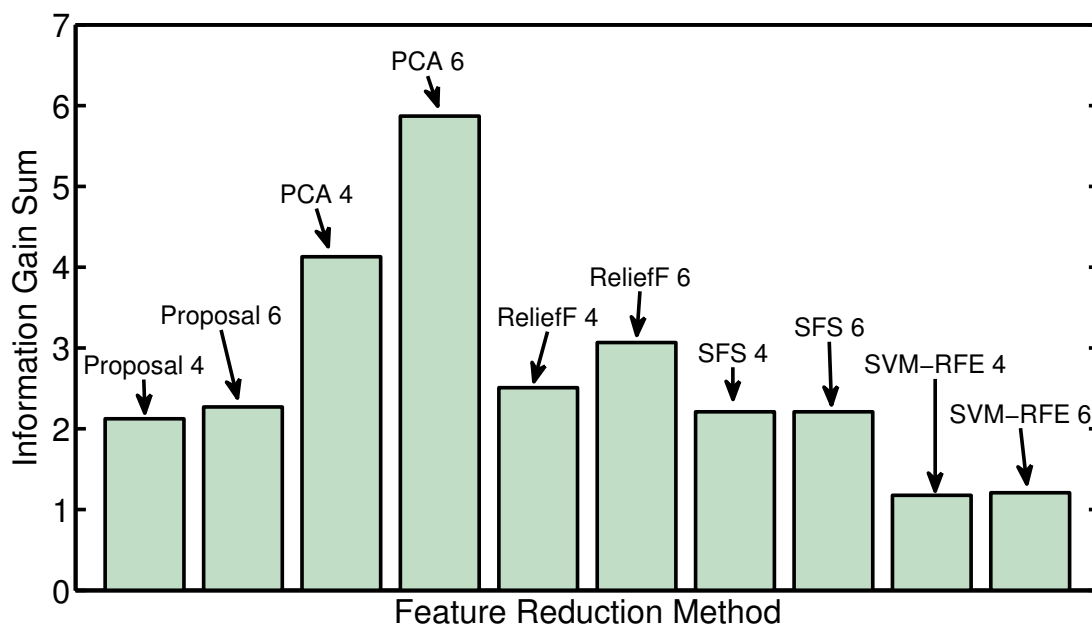


Figure 5.19: Information gain sum for feature selection algorithms. The selected features by our algorithm keeps an information retention capability between SFS and ReliefF.

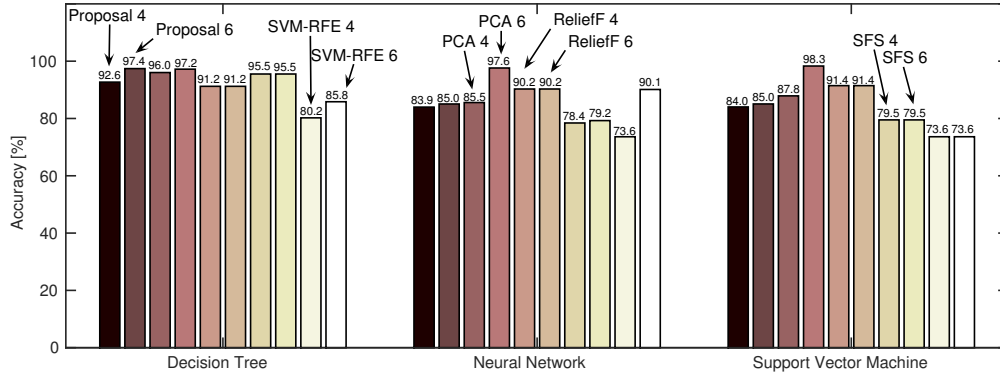


Figure 5.20: Accuracy comparison of features selection methods. Our Proposal, Linear PCA, ReliefF, SFS and SVM-RFE compared in decision tree, SVM, and neural network algorithms.

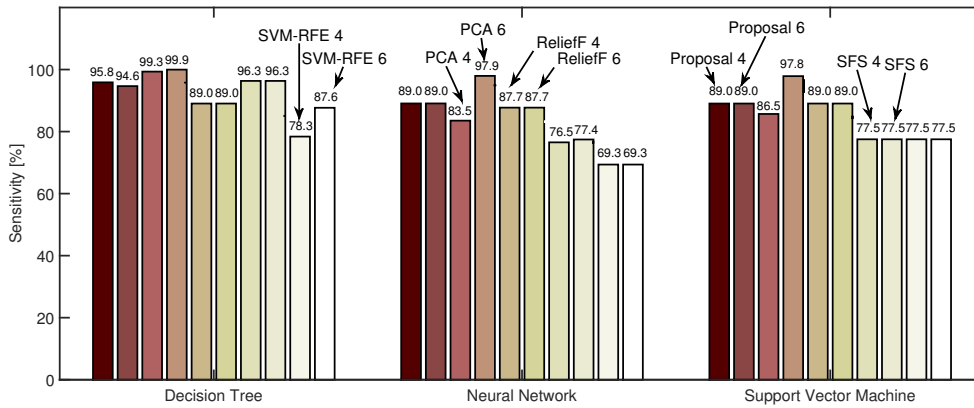


Figure 5.21: Sensitivity of detection in decision tree, SVM, and neural network algorithms for feature selection methods.

classifiers is reached by the SVM-RFE with four and six features in 69.3%. Finally, the last group shows the Sensitivity for Support Vector Machine (SVM) classifier. Again, showing a similar behavior as the previous group PCA with six features shows the best sensitivity with 97.8%. Then, the second-best result is reached by our algorithm, as well as with ReliefF, with 89% of sensitivity with both features. It is worthy to note that our algorithm presents a stable behavior in Accuracy as well as in Sensitivity. We highlight that our algorithm performs nearly equal to PCA. PCA creates artificial features that are a composition of all real features, while our algorithm just selects some features from the complete set of features. In this way, our algorithm was the best feature-selection method that was evaluated, and it also introduce less computing overload when compared with PCA.

Finally in Table 5.2 we present the features selected by each method of features selection. We exclude the PCA because its output are new synthetic features. All methods show six features according with its importance. It is possible to see none of the methods selects the same features. Nevertheless, ReliefF and SFS selects as

Table 5.2: Features Selection Comparison for the three Feature Selection Methods.

	Proposal	ReliefF	SFS	SVM-REF
Number of Feature	12,15,19, 13,10,7	2,11,9, 19,22,3	15,11,8, 5,20,21	14,12,13, 24,23,22
Name of Features	qtd_tos, packet_len_m, qtd_rst_flag, ttl_m, qtd_pkt_icmp, qtd_ack_flag	qtd_src_port, qtd_pkt_ip, qtd_pkt_udp, qtd_rst_flag offset_m, qtd_dst_port	packet_len_m, qtd_pkt_ip, qtd_urg_flags, qtd_syn_flag, qtd_ece_flag, qtd_cwr_flag	header_len_m qtd_tos ttl_m qtd_cdg_icmp qtd_t_icmp offset_m

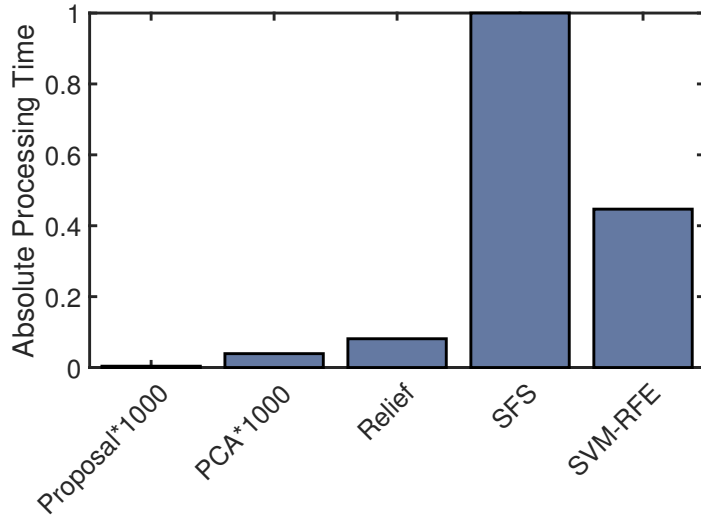


Figure 5.22: Performance of features selection algorithms according to processing time. The proposal and the PCA show the best processing time.

the second-best feature number 11, “*qtd_pkt_ip*”. One surprised result from the SFS is the election of the features 20 and 21, “*qtd_ece_flag* and *qtd_cwr_flag*”. In the correlation matrix of our dataset presented in Section 5.1, we discussed in that these two features do not add any information because they are empty variables. We realized that one of the main features is number 15 “*pkt_len_m*”. In this dataset, the average packet length is fundamental to classify attacks. One possible reason is than during the creation of the dataset the Denial of Services (DoS) and Probe attacks were performed for an automated tool. Mainly this automated tool produces attacks without altering the length of the packet.

In Figure 5.22 we show a comparison in processing time of all implemented algorithms for feature selection. All measures are in absolute value. Our proposal and PCA are multiplied by 1000 in order to display the values. We consider absolute value as the relation between the worst processed time and the processing time of each algorithm. The value of 1 represent the worst result, achieved by SFS show the worst performance. The SFS algorithm performs multiple iteration in

order to minimize the mean square error (MSE). Consequently, all these iterations increase the processing time. Our proposal shows the best processing time together with PCA, because both implementations perform a matrix multiplication, and matrix multiplication is a simple computation function. The measurements are performed in Intel Xeon processors with clock frequency of 2.6 GHz and 256 GB of RAM.

The next experiment is to evaluate our proposal in different dataset. We use the NSL-KDD dataset. The NSL-KDD is composed of 42 features with four classes, DoS, Probe, U2R, R2L. To evaluate this dataset, we have increase the number of classifiers. Besides SVM, Neural Network and Decision Tree, we add K -Nearest Neighbors, Random Forest, Support Vector Machine (SVM) with Radial Basis Function (RBF) kernel, Gaussian Naive Bayes, and Stochastic Gradient Descendant. Adding these algorithms, we cover the full range of the most important algorithms for supervised machine learning.

The **Random Forests** (RF) algorithm is a way to avoid class overfitting from a simple decision tree. Random Forest constructs several decision trees that are trained in different parts of the same dataset. This process decreases variance of classification and improves the performance regarding the classification of a single tree. The prediction of the class in the RF classifier consists of applying the sample as input to all the trees, obtaining the classification of each one of them and using a voting system to decide the resulting class. The construction of each tree must obey the following rules: for each node d , select k features of total m features, such that $k \ll m$. To calculate the best binary division of the k features for the node d , using an objective function; repeat the previous steps until each tree reaches l number of nodes or until its maximum extension.

Bayesian algorithm (**Naive Bayes** - NB) starts from the strong premise of independence between the features to simplify the prediction of the classification. This mean that each feature does not influence the value of the others features. From this premise, the method calculates the textit a priori probabilities of each characteristic, or a set of them, for a given class. In the input of a new sample, the algorithm calculates for each characteristic what is the probability of belonging to one of the classes. The output of all probabilities of each feature will result in a posterior probability of this sampling belonging to each of the classes. The algorithm then returns the classification that contains the highest estimated probability. According to the Bayes' theorem, we have that the probability posteriori is given by

$$P(C|X) = \frac{P(X|C) * P(C)}{P(X)} = \frac{\prod_{i=1}^m p(x_i|C) * P(C)}{P(X)}, \quad (5.8)$$

where X is the unknown sample and C is the class to be parsed. Therefore, the posteriori probability is given by the product of the conditional probability of X in C with the a priori probability of the C class in the sampling, divided by a constant term of standardization of the attributes $P(X)$ for each sample. The objective is to maximize the numerator to find the class that best fits the set of features of the unknown sample. The NB algorithm can be implemented in several ways. For a set of continuous feature values, it is assumed that the features follow the normal distribution and therefore the **Gaussian Naive Bayes**(GNB) is used. In this case, the individual probability of each feature, considering v the value of the feature x of the input sample, is given by

$$P(x = v|C) = \frac{1}{\sqrt{2\pi\sigma_C^2}} e^{-\frac{(v - \mu_C)^2}{2\sigma_C^2}}, \quad (5.9)$$

where μ_C is the mean and σ_C^2 is the variance of the values of x with respect to class C . Other approaches include Multinomial Naive Bayes (MNB), used for discrete data, and Bernoulli Naive Bayes (BNB), in the case of binary variables. The **k-Nearest Neighbors** - (k-NN) algorithm is a non-parametric classifier. k-NN assumes no simple probability distributions on the data, and is easy to implement. The class definition of an unknown sample is based on the k-neighbors classes closest to the sample. The value k is a positive integer and usually small. If $k = 1$, then the sample class is assigned to the class of its nearest neighbor. If $k > 1$, the sample class is obtained by starting a resultant function, such as a simple voting or weighted voting, of the k-neighbors classes. The neighborhood definition is based on a measure of similarity between samples in the feature space. Euclidean distance is commonly used in the threat detection literature, however, other distances have good results and the best choice for similarity measure will depend on the type of dataset used [102]. The Euclidean distance of two samples \mathbf{p} and \mathbf{q} in the space of n features is given by

$$d(\mathbf{p}, \mathbf{q}) = \sqrt{\sum_i^n (p_i - q_i)^2}. \quad (5.10)$$

Although simple, the k-NN algorithm has a high computational complexity, since for each new sample it is necessary to calculate its distance with all other samples. Therefore, the k-NN algorithm is not suitable for large datasets.

In **Stochastic Gradient Descent** (SGD) algorithm a gradient is approximated by a single sample. In a binary classification problem it is possible to use the

Sigmoid Function, expressed by

$$h_{\theta}(x) = \frac{1}{1 + e^{-\theta^T x}}, \quad (5.11)$$

to perform logistic regression. In the Sigmoid function, low product values of the parameters θ^T times the sample feature vector x return zero, whereas high values return one. When a new sample $x_{(i)}$ arrives, the SGD evaluates the Sigmoid function and returns one for $h_{\theta}(x_{(i)})$ greater than 0.5 and zero otherwise. This decision presents an associated cost, based on the real class of the sample $y_{(i)}$. The cost function is defined in Equation 5.12. This function is convex and the goal of SGD algorithm is to find its minimum, expressed by

$$J_{(i)}(\theta) = y_{(i)} \log(h_{\theta}(x_{(i)})) + (1 - y_{(i)}) \log(1 - h_{\theta}(x_{(i)})). \quad (5.12)$$

On each new sample, the algorithm takes a step toward the cost function minimum based on the gradient of the cost function.

Validation in NSL-KDD dataset

In this experiment we vary the number of feature selected to evaluate the impact in the accuracy. We analyze the performance with no feature selection (No FS), and then we reduce features from 10% to 90%. All the experiments were performed using a K -fold validation. The K -fold cross-validation performs K training iterations in the fractions of the data and, at each iteration, in the $K - 1$ fractions of the remaining data, performs the test in a mutually exclusive way. We use $K = 10$ that is the amount commonly used. Figure 5.23 shows the effect of feature selection. No Feature Selection performs good for almost all algorithms, however reducing the number of features in 10% improve accuracy in all algorithms but in Random Forest. In contrast, a bigger reduction of feature deteriorates the accuracy of the classifiers.

We also measure others metrics such as Precision, Sensitivity, F1 - Score, training and classification time. We compare the effect of 10% reduction in all these metrics. Figure 5.24 shows accuracy, precision, sensitivity and F1 - score for dataset with no feature selection, Figure 5.24a, and with 10% of reduction, Figure 5.24b. For KNN, SVM with Radial Basis Function (RBF) kernel, and Gaussian Naive Bayes metrics remain the same. For the Neural Network MLP and for SVM with linear kernel an improvement between 2-3% in all metrics is reached with a 10% of features reduction. Random Forest present the worst performance when features are reduced, all metrics worsen their values between 8-9%.

Stochastic Gradient Descendant (SGD) also suffer a small reduction of 1% in their

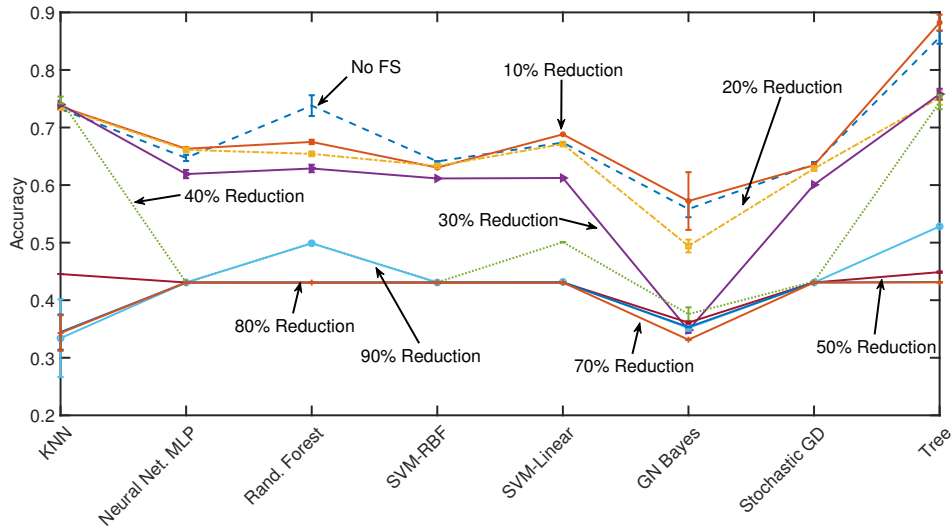


Figure 5.23: Evaluation of Feature Selection varying the selected features in NSL-KDD dataset.

metrics. Decision tree are the most benefited improving between 3-4% their metrics.

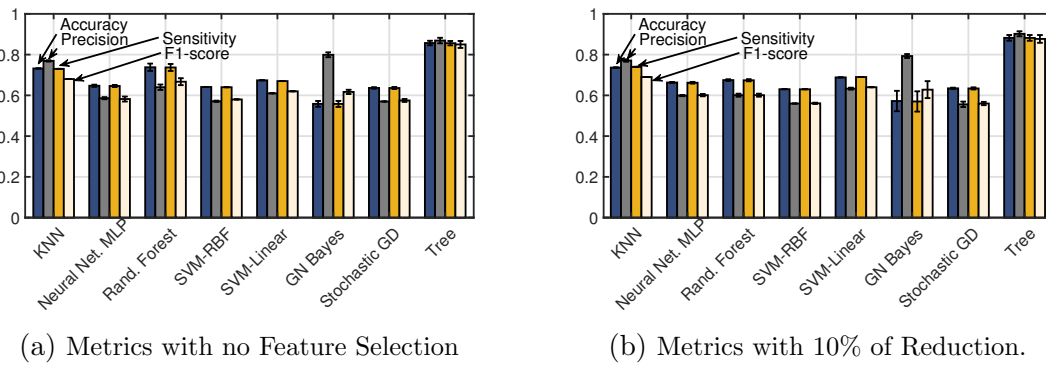


Figure 5.24: Accuracy, precision, sensitivity and F1-Score for NSL-KDD. a) Metrics with no future selection. b) Metrics reducing only 10% of the initial features.

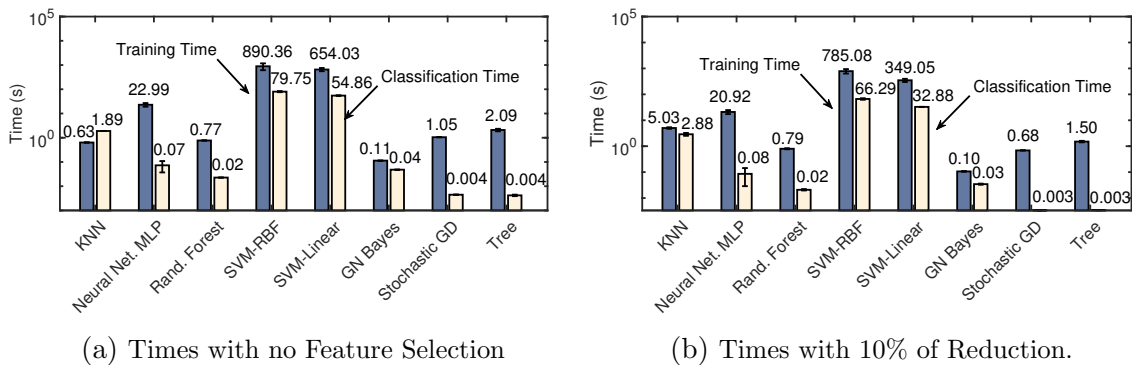


Figure 5.25: Classification and training NSL-KDD. a) Times with no future selection. b) Times reducing only 10% of the initial features.

Figure 5.25 analyze training and classification time for all classifiers. Figure 5.25a

shows training and classification time with no features selection, while Figure 5.25b shows results with 10% of features reduced. KNN algorithm augmented considerably its training time, passing from 0.63 seconds to 5.03 seconds, while classification time also suffer an increase passing from 1.89 to 2.88 seconds. Neural Network reduced training time in 9% from 22.99 to 20.92 seconds, classification time got 0.01 seconds of increase. Random Forest was increased in 0.02 seconds in training time and classification time remain the same, these values are negligible because of the error of the cross validation. SVM-RBF and SVM with linear kernel are the most benefited from features reduction. SVM-RBF reduces 11% the training time while 16% the classification time. SVM-Linear reduces 46% classification time from 654 seconds to 349 seconds and 40% training time from 54.86 to 32.88 seconds. Feature reduction in Gaussian Naive Bayes, Stochastic Gradient Descendant and Decision Tree impact strongly in training time with a reduction of approximately 30%, while classification time was reduced one-time unit in three algorithms.

5.2.5 Preprocessing Stream Data

Data preprocessing is the most time-consuming task in machine learning [103]. As we explained in Section 5.2, feature selection is mandatory for machine learning. However, all Feature Selection algorithms assume that data arrive pre-processed. Normalization, also known as feature scaling, is an important method for proper use of classification algorithms. If the features in the dataset has different scales, it impacts on the performance of the classification algorithm. Ensuring normalized feature values, normally between $\{-1, 1\}$; implicitly weights all features equally in their representation. In classifier algorithms that calculate distance between two points, a weighted feature effect is appreciated. If one of the feature has a bigger range of values, the distance calculation will be highly influenced by this feature. Therefore, the range of all features should be normalized so that each feature contributes approximately proportionately to the final distance.

In addition, many pre-processing algorithms consider that data is statically available before the beginning of the learning process [104]. However, in real-world application, data is not presented before learning process. As a consequence, it is necessary to use online pre-processing methods.

Current state of art has proposal several algorithms in online feature selection. Perkins and Theiler Grafting algorithm based on a stage wise gradient descent approach. Gradient Feature Testing (grafting) [105] treats feature selection as an integral part of learning a predictor. The objective function is a binomial negative log-likelihood loss. Grafting operates in an incremental iterative fashion, gradually

building up a feature set while training a predictor model using gradient descent. In each iteration, a fast gradient-based heuristic is used to identify a feature that is most likely to improve the existing model. While Grafting algorithm is able to handle streaming features, it needs to select in advance the value of a regularization parameter λ to determine which feature is most likely to be selected for the model at each iteration. Choosing a suitable regularization parameter inevitably requires information about the global feature set. Therefore, Grafting is ineffective in dealing with streaming features with an unknown feature size.

The Alpha-investing method [106] considers that new features arrive in a stream manner generated sequentially for a predictive model. The main advantage of Alpha-investing is the possibility to handle candidate feature sets of unknown or even infinite sizes. Every time a feature arrives, alpha-investing use a linear regression to dynamically reduce the threshold of error to be included in the model. As a drawback, alpha-investing only consider the addition of new features without evaluating the redundancy after the feature is added.

Wu *et al.* presented the Online Streaming Feature Selection (OSFS) algorithm and its faster version, the Fast-OSFS algorithm to avoid the redundancy of added features [107]. The OSFS algorithm uses a Markov blanket of a feature to determine the relevance of the feature in relation with their neighbors. The Markov blanket for a node A in a Bayesian network is the set of nodes A composed of A 's parents, its children, and its children's other parents. In a Markov random field, the Markov blanket of a node is its set of neighboring nodes. A Markov blanket may also be denoted by $MB(A)$. However, facing the scalability and online processing challenges in big data analytics, the computational cost inherent in those three algorithms may still be prohibitive when the dimensionality is extremely high in the scale of millions or more.

Smart Preprocessing for Streaming Data (SPSD) is an approach that use min-max normalization of numerical features [108]. The authors use two metrics to avoid unnecessary renormalization, SPSD only renormalizes when change amount exceed some threshold value of the metrics. Data streaming is grouped in equal size chunk where all operations are produced. The first data chunk is used to take the references min-max values and to send the normalized data for model training. The metric 1 represents the amount of sample falling outside the min-max reference values, the metric 2 is the relation between new samples values in each dimension and the referenced min-max value for that dimension.

Incremental Discretization Algorithm (IDA) uses a quantile approach to discretize data streaming [109]. The algorithm discretizes data stream in m equal frequency bins. A sliding window version of the algorithm is proposed to follow the evolution of the data stream. To follow the distribution drift, the algorithm maintains the

data into bins with fixed quantiles of the distribution, rather than fixed absolute values.

We propose an unsupervised preprocessing method. Our method include normalization, and feature selection all together. The proposal is parametric-less. Our algorithm follows an active approach for concept drift detection. The active approach monitors the concept, the label, to determine when a drift occur before take any action. Passive approach, in contrast, updates the model every time new data arrives wasting more resources. We adapted the Feature Selection algorithm presented in Section 5.2.2 to calculate correlation between features in a sliding window. Also, a normalization algorithm is proposed to handle stream data.

Normalization Process

In our normalization algorithm 2, a histogram of a feature f_i is represented as a vector b_1, b_2, \dots, b_n , such that b_k represents the number of samples that falls within the bin. For each feature of the dataset, we create an histogram. The main idea behind the algorithm is to approximate the histograms to a normal distribution as shown in Figure 5.26.

In practice, it is not possible to know in advance the *min* and *max* for an attribute. As a consequence, we use a sliding window approach, where the dataset X are the s last seen samples. For every sliding window we obtain the *min* and *max* values of each feature. Then, data values are grouped in a set b of intervals called bins. The idea is to divide the feature f_i in a histogram composed by bins b_1, b_2, \dots, b_m , where $m = \sqrt{n} + 1$, being n the number of features, as shown in line 3 in algorithm 2.

A bin in the histogram represents a range of values, and the height of the bar represents the frequency of values in that bin. Each bin is consist of thresholds k , for example the feature f_i is grouped in $b_1 = [min_i, k_1)$, $b_2 = [k_1, k_2)$, \dots , $b_m = [k_m - 1, max_i]$. The step between threshold k is called pivot and it is determined as $(max_i - min_i)/m$, as it is show in algorithm 3. However, if the *min, max* values of the previous sliding window are smaller/bigger than *min, max* of the current window, that is, $min_{i-1} < min_i$ or $max_{i-1} > max_i$, new bins are created until the new values of min/max are reached. With the creation of new bins, the proposal is able to detect changes in the concept drift but it cannot follow the change in the distribution.

The frequency of each bin is obtained by comparing the sample x_i against the thresholds k of the bins, line 4 algorithm 4. If the value of the sample x_i is in-between the thresholds of the bin_j , then the frequency f_{q_j} of the bin_j is increased by one. Moreover, we calculate the relative frequency of each bin as the relation between the bin frequency and the total number of samples, $fr_j = f_{q_j}/N$.

Algorithm 2: Stream Normalization Algorithm

Input : X : Sliding window of Features, w : Window Number**Output:** H : Normalized Features, f_r : relative frequency

```
1 if  $w == 1$  then
2   for feature  $f$  in  $X$  do
3      $b_n = \sqrt{n} + 1$ ; /*  $n$ : number of features */
4      $H = \text{CreateHistogram}(X, b_n)$ ;
5   end
6   else if  $w > 1$  then
7     for sample  $s$  in  $f$  do
8        $[H, f_r] = \text{UpdateHistogram}(X, b)$ ;
9     end
```

Algorithm 3: CreateHistogram() Function

Input : X : Sliding window of Features, b_n : number of bins**Output:** H : Histogram

```
1  $[max, min] = \text{CalculateMaxMin}$ ;
2  $k = (max - min) / (b_n)$ ; /*  $k$ : threshold */
3 for bin  $b$  in  $b_n$  do
4    $b = [min_i, k]$ ;
5    $k += min$ ;
6 end
```

Algorithm 4: UpdateHistogram() Function

Input : X : Sliding window of Features, b_n : number of bins**Output:** H : Histogram, f_r : relative frequency

```
1 for sample  $s$  in  $X$  do
2   for  $b$  in bin do
3     if  $s$  in  $b$  then
4        $b+ = 1$ ; /* getting frequency */
5     else if then
6       add bin to b until s in b
7     end
8      $f_r = \text{Calculate using Equation 5.13}$ ;
9      $H = \text{map } f_r \text{ to NormalDistribution}$ ;
10 end
```

Finally, the relative frequency values f_r are mapped into a normal distribution by:

$$Z > P \left(x = \sum_0^m f_{r_j} \right). \quad (5.13)$$

with Equation 5.13 is it possible to see that all values are now mapped into a normal probability distribution with $\mu = 0$ and $\sigma = 1$, line 8 in algorithm 4. As a

consequence, all samples are normalized between $-1 \leq x_i \leq 1$.

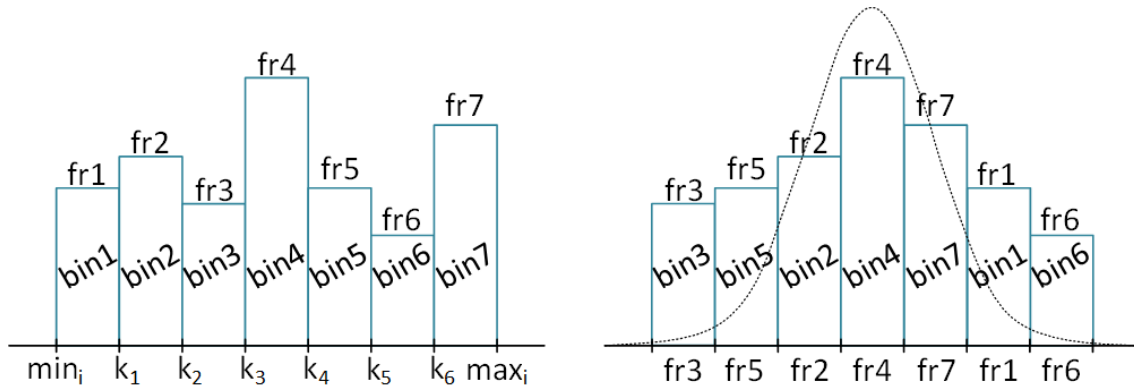


Figure 5.26: Representation of the feature divided in histogram. Each feature is divided in bins that represent the relative frequency of the samples comprised between the thresholds k . The second step of the algorithm approximate the histogram to a normal distribution.

If we consider the process that generate the stream is non-stationary it implies a possible concept drift. Haim and Tov affirm that histogram must be dynamics when dealing with streaming data [110]. That means that intervals do not have fixed value and the bins adapts to concept drift. However, if the bins remain static it reflects the evolution of the change during time [109]. In our application, feature normalization for network monitoring, we follow the former approach. Maintaining fixed intervals allow us to see how a feature evolutes over time. In addition, as our histogram algorithm creates new bins when a value does not enter in any of the current intervals, it gives us the possibility to detect outliers. If a bin contains a value of 1 for several periods of time, we consider an outlier. In streaming data, maintain all the samples x_i is computationally inefficient and in case of unlimited data it will never fit in the memory. Our algorithm efficiently keeps only the frequency of each bins making.

Shapiro–Wilk test was used to verify that our proposal follows a normal distribution after normalization. Table 5.3 show Shapiro-Wilk test, we considered α -level = 5%. We evaluate the hypothesis that our proposal normalization method follows a normal distribution. When check the results the proposal method has a p -value of $0.24 > 0.05$, and W is closer to one, $W=0.93$, then we assume that samples are not significantly different than a normal population. In the case of Smart Preprocessing for Streaming Data (SPSD),Max-Min normalization, p -value is smaller than the α -level, and W indicates that it is far from 1. As a consequence, we refuse the hypothesis assuming than sample data are significantly different than a normal population. Figure 5.27 shows a graphical interpretation of the Shapiro–Wilk test, it represent a sample after being normalized. We can see that our proposal follows the normal distribution, the blue points follow the dash

line, while the max-min approach follows a right skewed distribution.

Table 5.3: Hypothesis comparison for a normal distribution approach. In Shapiro-Wilk test p -value is $0.24 > 0.05$, and W is closer to one, $W=0.93$, confirming that values follows a normal distribution.

	Shapiro-Wilk	
	Mean W	Mean p
proposal	0.93	0.24
max-min	0.65	9.28e-07

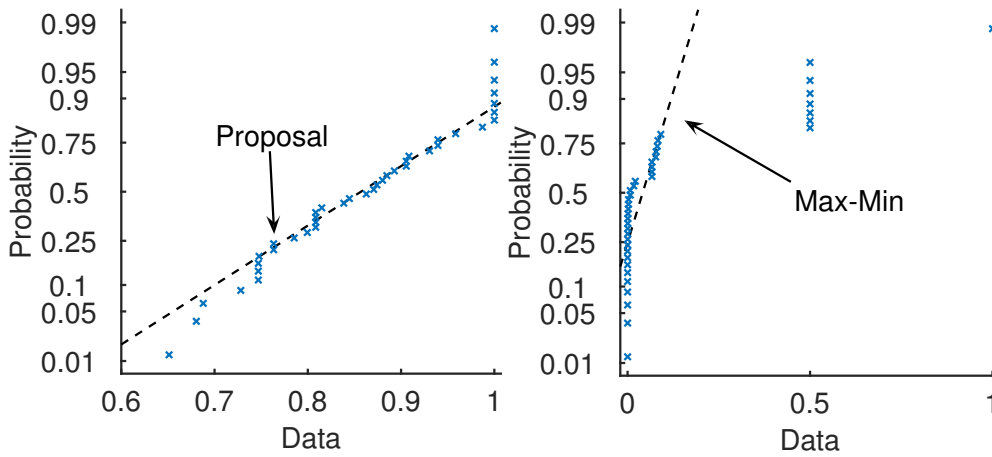


Figure 5.27: Representation of the Shapiro-Wilk comparing the proposed normalization algorithm with a max-min stream normalization.

The most complex function in the normalization process is to update the bins. If the reference values max, min of the windows changed, the bins update functions takes $\mathcal{O}(n)$ time. The creation of the histogram is only done in the first window and takes constant time. The histogram update uses a binary search to fill the bin value $\mathcal{O}(\log n)$ times.

Many open-source software exist to abstract packets into flow features such as tcptrace¹⁰, flowtbag¹¹, Traffic Identification Engine (TIE)¹², flowcalc¹³, Audit Record Generation and Utilization System (ARGUS)¹⁴, among others. We choose flowtbag because it abstracts more packets features than others. Flowtbag get 40 features: (5) flow tuple information (IP/Ports/protocol), (4) packets/byte in forward/backward direction, (8) packets statistics forward/backward direction, (8) time between packets forward/backward direction, (4) flow time statistics, (4)

¹⁰Tcptrace <http://www.tcptrace.org>

¹¹flowtbag: <https://github.com/DanielArndt/flowtbag>

¹²Traffic Identification Engine <http://tie.comics.unina.it/doku.php>

¹³flowcalc <http://mutrics.iitis.pl/flowcalc>

¹⁴ARGUS <http://www.qosient.com/argus/>

subflow packets/bytes forward/backward direction, (4) TCP flags, (2) Bytes used in headers, (1) type of service.

We group features into eight groups. Flow tuple information is removed because our algorithm works with numerical features. Table 5.4 describes the groups. We established the window size in 1000 samples. Figure 5.28 show accuracy for each seven algorithms for classification. In Decision Tree all groups show a similar behavior and have a very high accuracy rate. In Gaussian Naive Bayes and in SVM with linear kernel, group 3 Time Between Packets and Group 5 SubFlow information, represent the lowest accuracy. However, for the rest of the groups, also reach very high accuracy. In K -Nearest Neighbors shows a special case, besides group 2, which is the highest accuracy, all the other groups show a different behavior. In Neural Networks Groups 2 and 3, Packet Statistics and Time between Packets, are the highest accuracy the rest of the groups maintain in 50%. Random Forest show a similar behavior than Decision Tree with high accuracy in all their groups, nevertheless, the group 5 SubFlow information is the lowest. Stochastic Descendant Gradient show the highest accuracy in group 2,6 and 7. We conclude that group 2, Packet Statistics, is the most influent in the accuracy calculation for all the classifiers.

Table 5.4: Features Groups

Group	Description	Number of Features
G1	Packet Volume	4
G2	Packet Statistics	8
G3	Time Between Packets	8
G4	Flow Time Statistics	9
G5	SubFlow Information	4
G6	TCP Flags	4
G7	Bytes in headers + ToS	3

To evaluate our model under concept-drift, we use the flow diagram of the Figure 5.29. We force traditional learning methods to become adaptive learners in order to detect the concept drift. Adaptive learners can dynamically adapt to new training data when learned concept is contradict. Once a concept drift is detected, a new model is created.

We validate the proposal with the Network operator dataset (NetOp). The dataset is labeled in threats and normal traffic, a binary classification problem. We divide the dataset in training set and test set, in a relation of 70% for training and 30% for test. We consider the training set as static, in which T consecutive sample windows have been presented for training. We have used the Synthetic Minority class Oversampling TEchnique (SMOTE) [111] approach to oversampling the minority class, only in the training set, initial window. When a number of samples

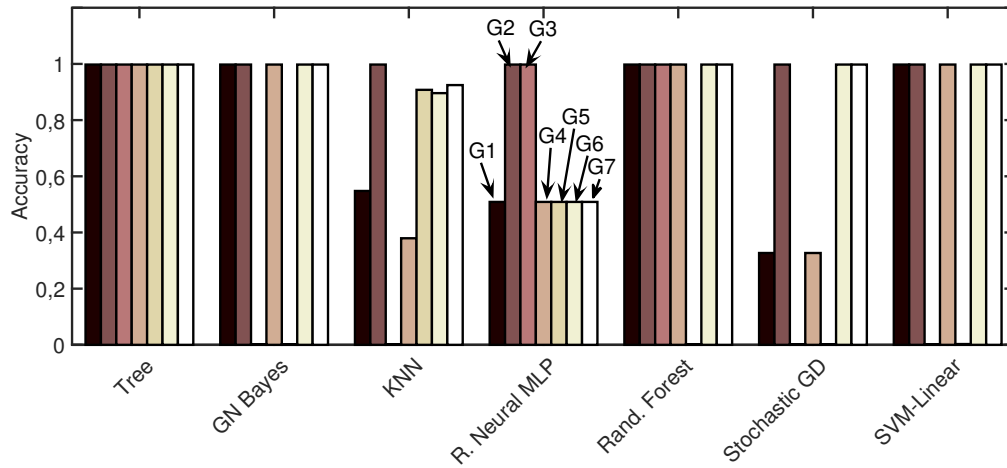


Figure 5.28: Evaluation of group features with different machine learning algorithms.

in a class is predominant in the dataset is called class imbalance. Class imbalance is typical in our application when attacks are rare events in relation to normal traffic. The test set is streaming data arriving with the same frequency. Data is grouped in a sliding window of N samples.

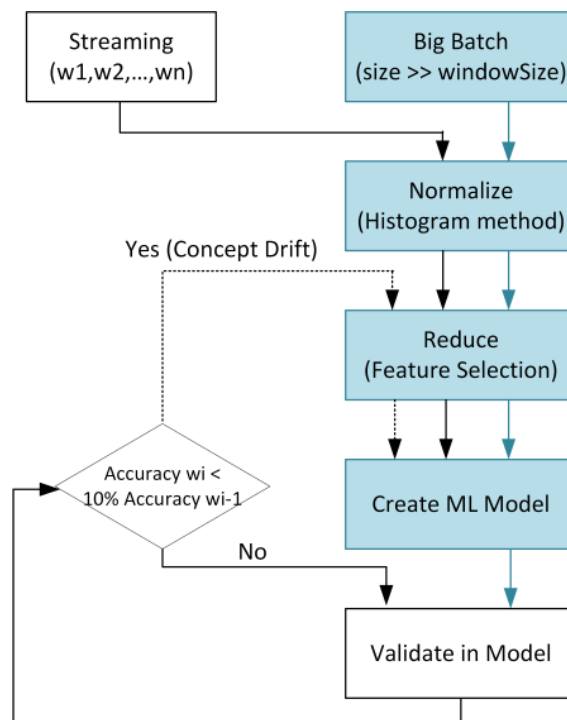


Figure 5.29: Flow diagram used for proposal evaluation

Figure 5.30 show the accuracy when we analyze one day from NetOp dataset, day 25, which was the day that presents the bigger number of threats. In this experiment, we want to see the impact of the concept-drift in the final accuracy. We train different statics algorithm with 30% of the dataset. We use as window size 1000 samples. The decision tree has the worst accuracy when compared with

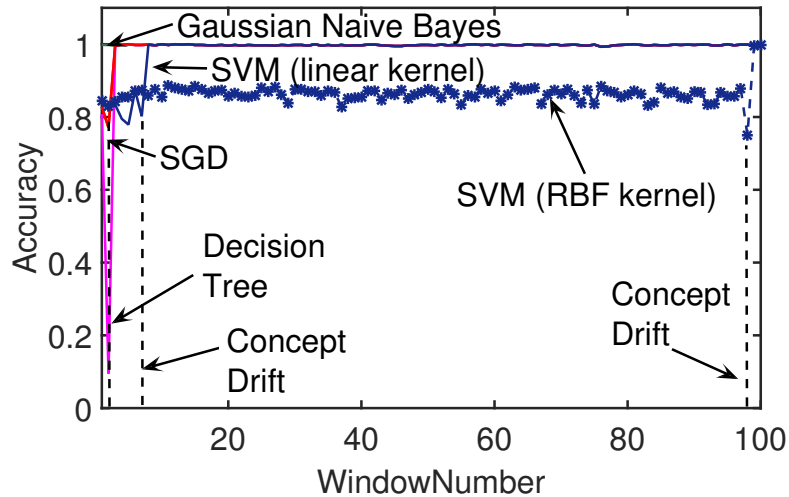


Figure 5.30: Concept Drift detection. Evaluation of pre-processing methods for concept drift detection. Our proposal was able to detect early concept drift in SGD, Decision Tree and in SVM with linear kernel. Gaussian Naive Bayes shows a very high performance with no concept-drift.

other algorithms. Decision tree shows a low accuracy in the first windows. This behavior means that the model created in during the training step does not fully represent the model of the entire dataset. Stochastic Gradient Descendant show a similar behavior of decision tree having a concept drift in the second window. The SVM with linear presents a concept drift in the seventh window. SVM-RBF shows a lower accuracy during all experiment but a concept drift at the last window. Finally, due to the implementation of the Gaussian Naive Bayes it follows the same probability distribution as our normalization method, as consequence does not present any concept drift.

This chapter present two security datasets. The first dataset was created at laboratory GTA/UFRJ and presents three classes, DoS, Probe and Normal, composed by 25 features. The second dataset was more than ten days of real traffic for a network operator in Brazil. NetOp dataset is divided in two classes, normal traffic and alerts and it is composed of 45 features. Also, we present an unsupervised pre-processing algorithm. The evaluation of the algorithms shows a good behavior in batch mode and in stream mode, being able to reach a good performance in batch mode and capable of detecting concept drift in stream mode.

Chapter 6

The Virtual Network Function

This chapter introduces the concept of Network Function Virtualization and the Open Network Function Virtualization Platform (OPNFV). We present our proposed threat detection system as a Virtual Network running on OPNFV that will provide flexibility, agility, and cost reduction to monitor network traffic. Moreover, we propose a heuristic for virtual sensor placement. Finally, we propose a greedy based algorithm for service chaining.

6.1 The Network Function Virtualization

Network Function Virtualization (NFV) technology intends to offer software virtualized network services using costumer on the shelf (COTS) hardware in order to lower Operating Expenditures (OPEX) and Capital Expenditures (CAPEX) costs, and greatly reducing the time to the market (TTM) of innovations [112]. The key idea is to offer communication, processing, and storing services for big data [113]. Thus, Virtual Network Functions (VNF) are implemented in software running on different physical servers, usually on a cluster environment. Therefore, network services such as firewall and threat detection can be executed as a set of VNF allowing a bigger flexibility, scalability, and easier deployment when compared to traditional services. The main goal of the NFV technology is to optimize network services. This concept is complemented with the idea of Software Defined Networking (SDN) that provides a greater programmability for network management due to its global network view in the network controller. Specially, SDN acts in the control and in the implementation of packet forwarding and processing, while NFV acts in the provision of network services, such as firewall, Intrusion Detection System (IDS), Network Address Translation (NAT), or even higher layer services, such as Web servers, email servers, among others. Instead of using expensive proprietary network equipment, a strong tendency is rising to provide services with open-source trusted platforms that integrate the

processing, storing, and communication of data. This means that the main concept of NFV is to decouple the Network Functions (NFs) from the physical infrastructure on which they run [114]. Trying to accelerate the implantation of Virtualized Network Functions, the Linux Foundation develops a collaborative project called Open source Platform for Network Functions Virtualization (OPNFV)¹. The main idea behind OPNFV is to use open-source software to provide a platform compatible with the European Telecommunications Standards Institute (ETSI) standards.

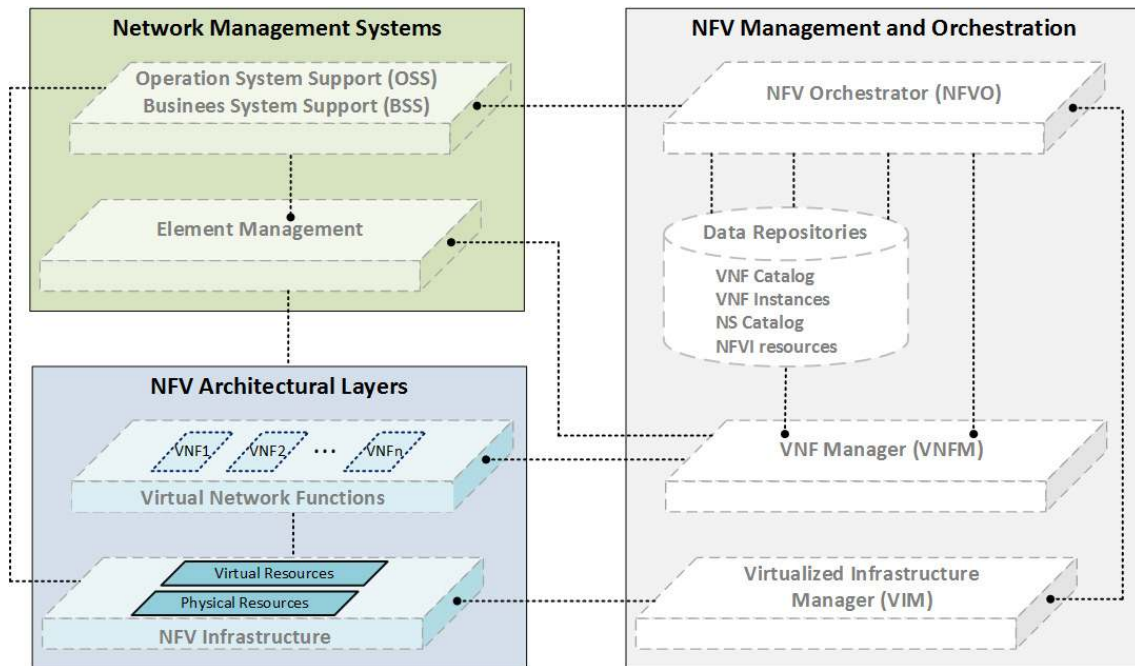


Figure 6.1: ETSI NFV MANO framework, composed by three main components, Network Management System, NFV Architectural Layers, and NFV Management and Orchestration.

Figure 6.1 presents the MANO framework. According with the ETSI definition the MANO framework [115] consist of three functional blocks: The Virtualized Infrastructure manager (VIM), which is responsible for manage and control the physical and virtual infrastructure in a single domain. One NFV architecture could contain more than one VIM specialized to manage one or more certain type of NFVI resource such as compute, store, among others. Second is the Virtual Network Function Manager (VNFM), that is responsible for the management of the life cycle of one or more VNFs. Finally, the Network Function Virtualized Orchestration (NFVO) combines one or more functions to create the end-to-end service. The NFVO could be divided into resource orchestration and service orchestration. Resource orchestration ensure there are adequate compute, storage, and network resources available to provide a network service. This orchestrator

¹The Open source Platform for Network Functions Virtualization <https://www.opnfv.org/>

can work with the VIM or directly with the NFVI, and it has the ability to coordinate, authorize, release, and engage NFVI resources independently of any specific VIM. It also provides governance of VNF instances sharing resources of the NFVI. On the other hand, the Service Orchestration is responsible for the creation of end-to-end services composed by different VNFs, also known as service chaining, and to manage the network topology for the different instances. Furthermore, the MANO contains data repositories that keep different type of information. The first is the Network Service (NS) catalog, which contains templates for services in terms of VNFs can be deployed and implemented, as well as their connectivity in the virtual links. This catalog can contain additional information such as NFV instances lifetime. Another catalog is the NFVI resources, that contains the information about available/allocated resources in the NFVI.

6.1.1 The Open source Platform for Network Function Virtualization (OPNFV)

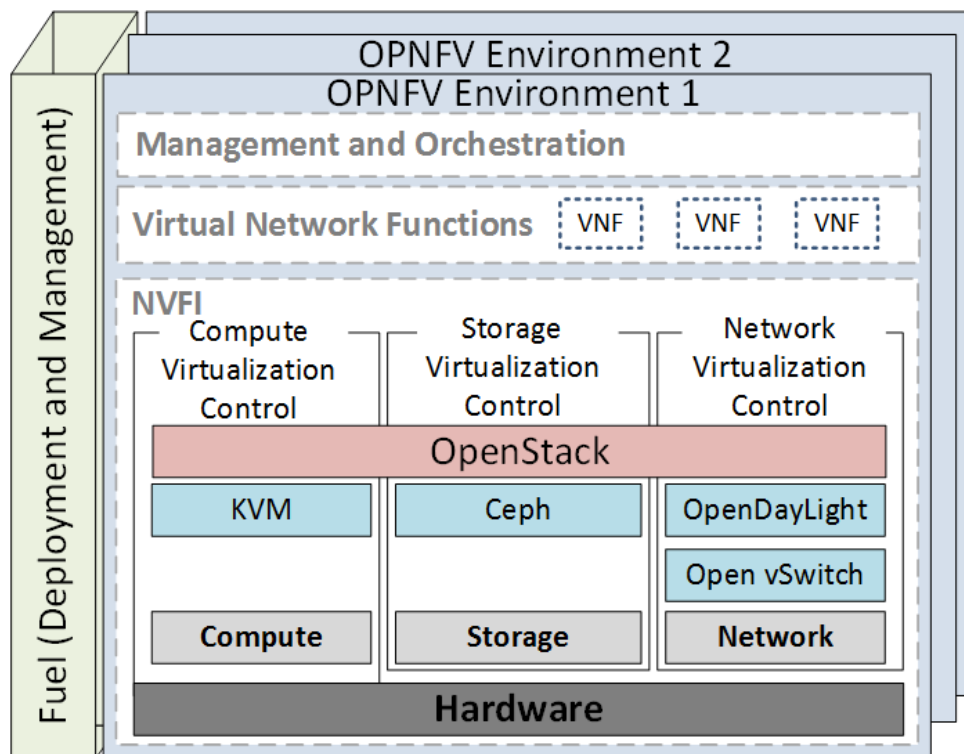


Figure 6.2: The OPNFV architecture: Network Virtual Function Infrastructure (NFVI), Virtual Network Functions (VNFs), and Management and Orchestration. The deployment and management of the OPNFV environments is coordinated by Fuel.

Figure 6.2 shows the architecture of the Open source Platform for Network Function Virtualization (OPNFV). As it can be seen, OPNFV implement only the NFV Architectural Layer component from the ETSI NFV MANO framework. Fuel

deploys and manages the OPNFV environment. Three main modules compose this environment, the Network Function Virtual Infrastructure (NFVI), the Virtual Network Functions (VNFs) and the Management and Orchestration (MANO). MANO provides the functionality required for the provisioning of VNFs, and related operations such as the configuration of VNFs and the infrastructure on which these functions run.

When the ETSI MANO concept is mapping into the OPNFV platform, the NFVI contains the compute, storage and network module. The compute module administrates the virtual machines through the KVM hypervisor. The Storage module uses the Ceph tool that is a distributed object store and file system. The network module uses the Software Defined Networking (SDN) paradigm through the OpenDayLight controller that manages the Open vSwitches virtual switches. Network services are deployed in middleboxes or network appliances called virtualized network functions (VNF). VNFs consist of one or more virtual machines that run specific network functions such as firewall, IDS, NAT, among others. The Virtual Network Functions (VNFs) can be combined together, chaining in deliver full-scale networking communication services [116]. We implemented our proposed Threat Detection System as a virtual network function (VNF). Finally, the Management and Orchestration layer provides the logic and functionality required for the provision of resources, configuring the VNFs and the infrastructure.

6.1.2 Threat-Detection Prototype Performance Evaluation

CATRACA [31] configuration is shown in Figure 6.3 as a virtual network function. To evaluate the performance of the prototype, we analyze latency requirements and speedup factor for real-time stream processing. We perform the experiments in the OPNFV Brahma Putra 3.0 environment and we use a module developed by the Sahara project to provide an Apache Spark cluster. Our OPNFV environment is composed by 96 GB of RAM, 700 TB of storage and 128 cores of Intel Xeon processors with clock frequency of 2.6 GHz. We calculate all the results with 95% of confidence interval.

CATRACA first uses a machine learning model trained offline. A decision tree algorithm is trained offline from dataset within a combination of normal traffic and threats stored in a historical database. We distribute sensors machine to capture traffic over the network. Sensor machine are simple devices that mirror captured traffic to the spark cloud, specially to Kafka. Kafka abstracts message stream into topics that act as buffers or queues, adjusting different production to consumption rates. To avoid latency overhead, sensor machine must be as much simple as possible. Finally, the offline model is loaded in the spark cloud, and the master

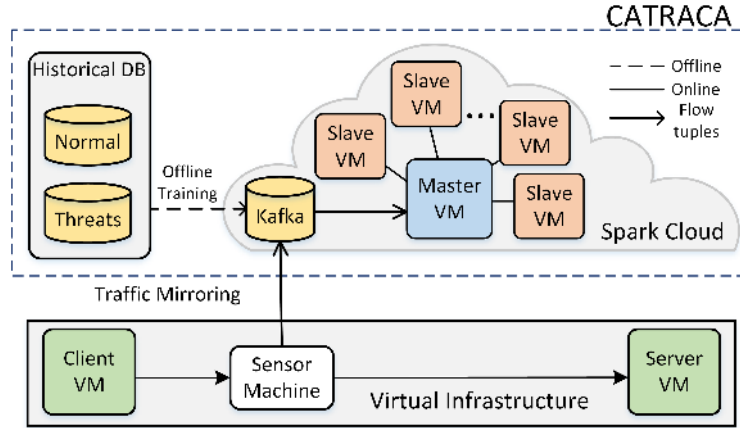


Figure 6.3: Messages processed per second (left axis) and speedup factor (right axis) in function of the task parallelism for the Apache Spark Streaming Engine.

VM will apply the model to classify network traffic in real time.

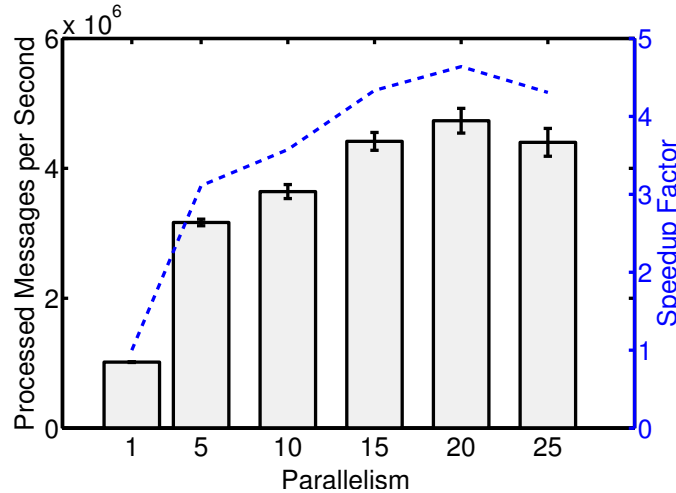


Figure 6.4: Messages processed per second (left axis) and speedup factor (right axis) in function of the task parallelism for the Apache Spark Streaming Engine.

The first experiment measures the performance of CATRACA in terms of processing throughput and latency. The dataset is fully injected into the system and also replicated as many times as necessary to obtain a huge amount of data to submit into our system. The experiment calculates the consumption of messages by our stream processing engine and its processing rate. We also vary the parallelism parameter, which represents the total number of cores available for the cluster to process samples in parallel. Each slave VM is configured with only one core, and we create as many Virtual Machines as possible. Figure 6.4 shows the results of the experiment. The left y axis shows the system throughput given by the number of messages processed per second, and the right y axis indicates the speedup factor. The speedup factor is calculated as follow: $S_{latency} = \frac{La1}{La2}$; Where $La1$ is the latency of the system when parallelism is equal to one, and $La2$ is the

latency of the system with the variation of the parallelism parameter. In other words, it represents the decrease factor in latency or the speed up factor.

The proposed Virtual Network Function is able to improve the processing capacity up to twenty cores in parallel. The system shows an improvement for latency as well as for throughput. Considering throughput, the system is able to handle more than five million of messages per second. Moreover, the speed factor reaches around 4.65 for a parallelism of twenty cores. This value indicates that the system can parallelize and improve the speed of almost five times with twenty virtual machines running one core each.

The second experiment aims to show the operation efficiency of the implemented function under live migration. The live migration offers a great flexibility for the user and it is possible thanks to the virtualization, achieved through the OPNFV platform. In our proposed threat-detection virtualized network function, live migration provides several advantages. A security advantage is the possibility to place and rearrange dynamically sensor machines to better protect the network and reduce the threat detection time. We can place a sensor machines where ingress more attack traffic or near a sensitive server to be protected. A general advantage concerning the processing cluster is the ability to migrate machines, allowing a smart distribution among the physical servers and enabling the optimization of the number of running servers, avoiding the waste of resources.

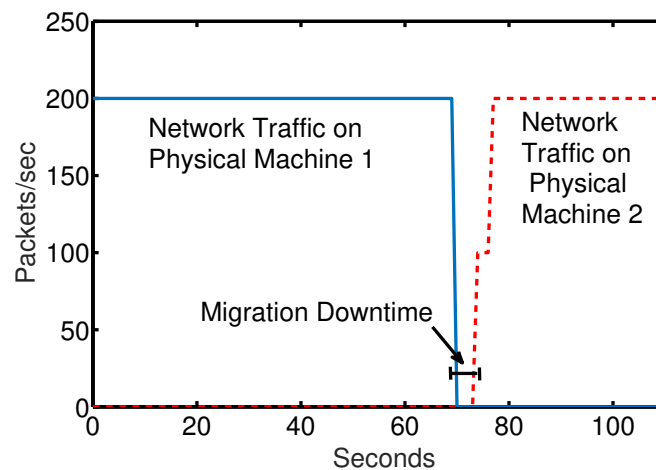


Figure 6.5: A Virtual Machine migration from the Physical Machine 1 to Physical Machine 2. The constant flow rate applied to the virtual machine at Physical Machine 1, after 60 seconds approximately of migration, goes to Physical Machine 2.

Figure 6.5 shows the behavior of a network flow under live migration. In this experiment we send a constant-rate flow of 200 packets per second from one virtual machine to another. Both virtual machines are hosted in the same physical machine. Then, approximately at 60 seconds, the migration process is started, in

order to migrate the virtual machine that receive the flow to another physical server. The Figure 6.5 show the low migration downtime, making the flow unaffected under the migration. therefore, the migration feature allows our threat detection application to set monitoring sensors as close to the client as possible, avoiding latency problems.

6.2 Modeling and Optimization Strategy for VNF Sensor Location

Our system has the capability to distribute sensors along the whole network. Nevertheless, because of cost or performance reasons, we can establish a reduced number of sensors instead of placing sensors in every switch. Hence, then sensor placement results into an optimization problem. This section models formally the problem of the sensor network placement. A heuristic is proposed to minimize the sensors number and maximize the network coverage reached for each sensor. We assume that each node owns enough processing power to analyze all incoming network traffic, as it is for example, in a datacenter.

Let G be a finite connected graph $G = (V; E)$, where V is the non-empty set of all available nodes in the network and E is the set of non-directed edges of G . Let $v \in V$ be a vertex, and $s \in S \subseteq V$, where S is the subset of nodes which are implemented as a threat detection sensor. We use x^v as the variable that determines if vertex v holds a sensor s

$$x^v = \begin{cases} 1, & \text{if } v \in S \\ 0, & \text{otherwise} \end{cases} \quad (6.1)$$

Each vertex sends a traffic unit to each other vertices. Therefore, the total amount of traffic T in the network equals $T = \frac{|V|(|V|-1)}{2}$. The traffic from the source i to destination j uses a single path, and we represent whether vertex v is in the path of i, j traffic by $t_{ij}^v = 1$, otherwise $t_{ij}^v = 0$. Thus, the total amount of traffic passing through vertex v is $t^v = \sum_{i \neq j} t_{ij}^v$. We also define an auxiliary variable $y_{i,j}$ to determine whether there is a sensor in the path from the source i to destination j . The variable $y_{i,j}$ is given by

$$y_{i,j} = \begin{cases} 1, & \exists v \in V \mid x^v \wedge t_{i,j}^v \\ 0, & \text{otherwise} \end{cases} \quad (6.2)$$

Thus, the total amount of traffic analyzed by the sensors is

$$T_x = \sum_{i \neq j \in V} y_{i,j}, \quad (6.3)$$

The objective function $F(x)$ represents the global cost to minimize composed by two objective functions: the number of sensors in the network and the total network traffic coverage that is analyzed by all sensors. Then, we want to minimize the global cost

$$\min F(x) = F_{sensor}(x) - F_{traf}(x), \quad (6.4)$$

where $F_{sensor}(x)$ is the relation between the sensor nodes and the total of vertices in the network, expressed by

$$F_{sensor}(x) = \frac{1}{|V|} \sum_{v \in V} x^v, \quad (6.5)$$

and $F_{traf}(x)$ is the traffic percentage in relation to the total amount of network traffic that each sensor node analyzes, given by

$$F_{traf}(x) = \frac{T_x}{T} = \frac{1}{T} \sum_{i \neq j \in V} y_{ij} \quad (6.6)$$

such that $0 \leq F_{sensor}(x) \leq 1$ e $0 < F_{traf}(x) \leq 1$. Besides, $\sum_{v \in V} x^v \leq |V|$, and $x^v \in [0, 1]$. This problem can be reduced to a Set Covering Problem (SCP), a nondeterministic polynomial time NP-hard problem. To solve this problem, we use a greedy algorithm, which sorts the vertex list according to t^v , the amount of traffic that pass through the vertices. Thus, the algorithm chooses first central nodes that concentrate the largest amount of the traffic. We use as metric the amount of traffic $H(x) = T_x/T$ covered by the current sensors. Hence, after the selection of a sensor node, it is verified if the solution $H(x)$ reaches a target amount of traffic and stops. Otherwise, the algorithm selects another node. The process is repeated until the sensor set covers the target amount of traffic, or when it is not possible to add more sensors. Greedy algorithms make locally optimal choices that eventually reaches a global optimal. Nevertheless, the computational cost execution is low comparing with other solutions.

We also used the Simulated Annealing (SA) optimization method, which guarantees convergence to a global minimal in an undetermined time. Every iteration selects a number of sensors and their positions at random and generate a new candidate solution that could be accepted in case it has a lower objective function $F(x)$ than the previous iteration. If the solution is worse than the previous one, SA accepts the new solutions by a decreasing probability according to iteration. Thus, the solution may be accepted even if the objective function is higher to the previous one. This behavior is necessary to avoid the solution convergence to a local minimal. The perturbation used to select the number of

sensors and the positions follow a Cauchy distribution. Hence, we use the greedy to obtain the fastest result and the Simulated Annealing to evaluate how far from the minimal the result is.

6.2.1 Optimal VNF Sensor Placement

To evaluate the proposed heuristic we use a real topology from *topology zoo*². The analyzed topology is the Brazilian Internet backbone network, *Rede Nacional de Ensino e Pesquisa* (RNP), that has 31 vertex with 34 edges distributed geographically in the Brazilian states. The real topology can be seen in Figure 6.6.



Figure 6.6: The Brazilian *Rede Nacional de Ensino e Pesquisa* (RNP) real topology, with 31 vertex and 34 edges.

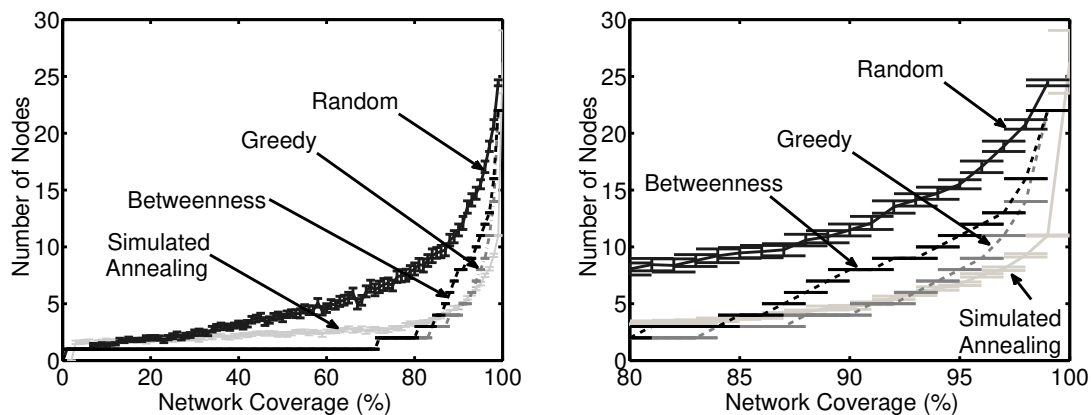
We have evaluated our metric with two meta-heuristic solutions, greedy and simulated annealing, and with a random choice. In addition, it is implemented the choice by the betweenness centrality. Betweenness centrality is shown in Equation 6.7, where σ_{ij} is the total number of shortest paths from node i to node j and $\sigma_{ij}(v)$ is the number of those paths that pass through v . The betweenness centrality expresses the influence that a specific node could have on other nodes in the network [117]. The betweenness centrality consider all the nodes and paths in the network, while our proposal is relative to each node.

$$g(v) = \sum_{i \neq v \neq j} \frac{\sigma_{ij}(v)}{\sigma_{ij}} \quad (6.7)$$

Figure 6.7a shows in percentage the covered traffic in relation with the number of VNF sensors used. The system determines the best position that each node should be located warranting the maximal network coverage. With low network coverage

²www.topology-zoo.org

the behavior of all approaches are similar. The random choice shows the worst behavior followed by the simulated annealing. Then, the simulated annealing improved its results over the random choice. The betweenness and the greedy proposal present an exact result until approximately 80%. Figure 6.7b shows in higher detail the results. The random choice is still being the worst approach followed by the betweenness. Both approaches with our heuristic show the best efficiency for high values of network coverage, minimizing the number of sensors nodes used. The simulated annealing presents better behavior despite of its high computational cost. With 95% of network coverage the random solution uses 15 nodes and the greedy and simulated annealing reduce it by two times using 7 nodes. Moreover, with 99%, the simulated annealing improves the result by more than two times when compared with the random choice, placing 11 nodes instead of 21 nodes required by the random choice.



(a) Heuristic evaluation in a topology of 31 nodes.

(b) Network coverage vs. Number of sensors in a zoomed region.

Figure 6.7: Efficiency results of different placement methods in function of the number of sensor nodes required to cover all network traffic.

6.3 The Virtual Network Function Chaining Problem

Service chaining simply consists of a set of network services interconnected through the network infrastructure to support an application requested for the customer. Traditionally, Service Function Chaining (SFC) were built in the early years of high-performance computing being rigid and static installed at fixed locations in the core or at the edge of the carrier network [118]. The SFC is enhanced with the advent of NFV that enables operators to configure network services dynamically in software without having to make changes to the network at

the hardware level. Therefore, virtualized NFs (VNFs) can be placed when and where needed. This implies an optimization problem that uses VNFs or services as a graph to address the requirement for a better utilization of resources, for latency decreases and for network optimization [23]. Typically, network flows go through several network functions as shown in Figure 6.8. When a NF or a set of NFs are specified the flows traverse these NFs in a specific order so that the required functions are applied to the flows. Usually, the NFs demand certain dependency among them that should be chaining to the traffic in a network in a specific order. Depending on the way each network function is set in the chain, it impacts in network traffic, application performance, and latency.

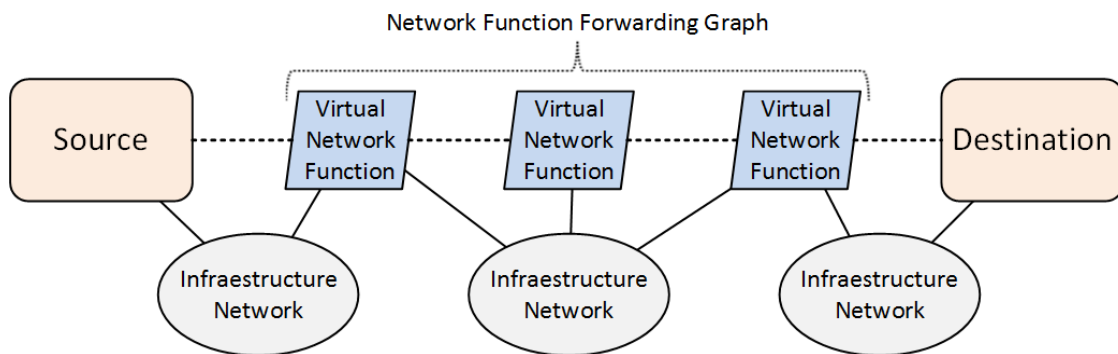


Figure 6.8: Example of Network Function forwarding graph. Three Virtualized Network Functions (VNF) are chained from the source to the destination to establish a service. The virtual network functions are executed over the physical network infrastructure.

The VNF chaining problem consists, thus, of two sub-problems. The first sub-problem is the placement problem, in which the VNF instances are allocated onto physical nodes. This problem consists into finding a physical node that has enough resources to host the VNF, serving it with the requested resources. The second sub-problem consists into a routing challenge, because mapping a set of VNFs over a physical topology should consider the iteration among all VNFs. The routing problem should ensure that the traffic between VNFs would always suffer a limited delay, and the network path presents enough bandwidth. If any of these constraints are not satisfied by the chaining scheme, the VNF request may not be accepted. Therefore, deciding for accepting VNF requests is also part of the VNF chaining problem.

6.3.1 The Proposed VNF Chaining Scheme

Our proposal considers a scenario in which the requests for a new Virtual Network Function arrive to a network manager, who has to allocate them into the available nodes. We consider as a request a sorted list of VNFs that describes the order in

which traffic has to be processed. Therefore, the allocation of the request on the network has to consider the order of the VNFs as well as the source and the destination of the traffic handled by the set of VNFs in the request. We also consider that, when allocating a VNF over a physical node, the physical node has to provide enough resources to answer the needs of all hosted VNFs. Our proposed scheme is composed of two main phases. The first phase is to estimate the resources available on the physical nodes and the resources requested by the VNFs. The second phase is to run a greedy algorithm that takes as input the VNF requests as they arrive, and then it places each VNF on a physical node that have enough resources. Our greedy algorithm considers four different heuristics to place the VNFs on the network.

Estimating the available resources on physical and virtual nodes is challenging because there are three main resources which should be considered: CPU, memory, and network. In order to summarize all resources into one single variable, we consider the `Volume` metric introduced by Wood *et al.* [59]. We consider that the `volume` of a physical server is 1, and the `volume` of each VNF is given by

$$Volume_{VNF} = \frac{1}{1 - cpu} * \frac{1}{1 - mem} * \frac{1}{1 - net}, \quad (6.8)$$

where `cpu` stands for the normalized CPU usage of the VNF, `mem` for memory, and `net` for network. Thus, for each VNF the `volume` metric is the ratio of the resources on physical node that the VNF is requesting. The VNF `volume` ranges from 0 to 1, where 1 means that a VNF is requesting an entirely available physical node to be installed.

Following, on the second phase, we run a greedy algorithm that allocates a VNF request as it arrives. Our algorithm adopts one of the four heuristics:

- **minimum latency**, in which the algorithm chooses the node that introduces a minimum delay to the path, in comparison to the previous selected nodes to host the other VNFs, or the source of the traffic;
- **maximum usage of resources**, in which the algorithm chooses the node that has the biggest amount of available resources to host a VNF, without considering the routing constrains between the already placed VNFs;
- **most central nodes**, in which the algorithm chooses to place the VNF into the most central node, i.e. the node that presents the greatest betweenness-centrality value, and has enough resources to host the VNF;
- **weighted latency and resource**, in which the probability of choosing each a node for hosting a VNF is weighted based on the latency that it introduces

to the path and the available resources that it has. The weight of the node i is given by

$$w_i = \left(1 - \frac{lat_i}{\max_{j \in N}(lat_j)}\right) \times \left(\frac{rec_i}{\max_{j \in N}(rec_j)}\right),$$

where lat_i stand for the latency introduced by node i , rec_i is the available resources in node i , and N is the set of all nodes in the network. The greedy algorithm searches for hosting VNFs on the nodes that have the biggest w_i value first.

Our proposal works as follows. First, the network manager receives a sorted list with the requested VNFs, the source and the destination of the traffic, and the requested resources of each VNF. Then, our algorithm selects the first VNF on the request and search for a node in which the requested resources meet the available resources on the physical node. To verify if the physical node has enough resources, the algorithm compares the VNF `volume` with the available `volume` of the physical node. If the available `volume` is greater than the requested, the VNF is installed on this candidate physical node. Otherwise, the algorithm selects the next physical node till finding an available node. If there is no available physical node that meets the requested VNF `volume`, the VNF request is entirely rejected and no VNF is allocated. After mapping all VNFs over the physical nodes, the VNFs are installed and the `volume` of each physical node that receives a VNF is decremented by the `volume` of the VNF that it hosts. It is worth noting that a VNF request should be entirely accepted or rejected. If the algorithm realizes that there is not enough resource in any node in the network to complete the VNF request allocation, the request is completely rejected and no node is allocated on the network. We adopt the all or nothing approach, because a partially allocated VNF request does not implement all packet-processing functions that it supposed to deploy, thus it is not a feasible solution.

6.4 The Evaluation of the Proposal

We evaluate the proposed greedy algorithm through simulation. We implemented a simulator³, written in Python language, in which the VNF requests arrive at each simulation step. At a simulation step, the proposed scheme evaluates the used resources of each physical node on the network topology and generates the available *volume* metric for each physical node. Then, our scheme gets the next

³available at <https://github.com/tinchoa/VNFsimulator>

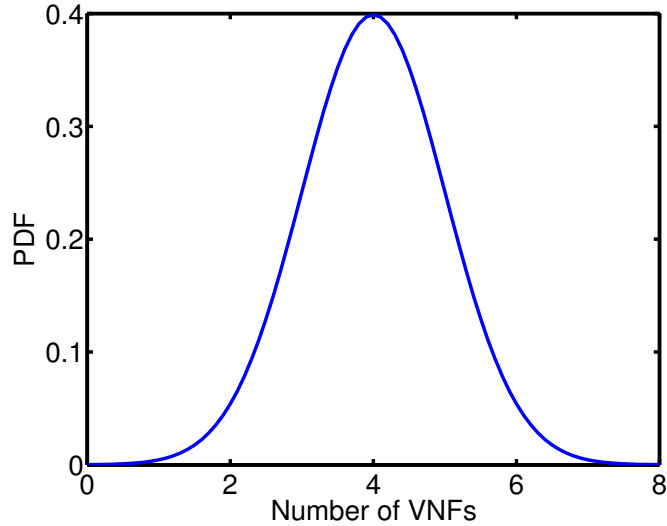


Figure 6.9: Probability density function of the number of VNFs in a request. The modeled number of VNFs in each request follows a normal distribution, with mean equals to 4, and standard deviation equals to 1 ($\mu = 4$ and $\sigma = 1$).

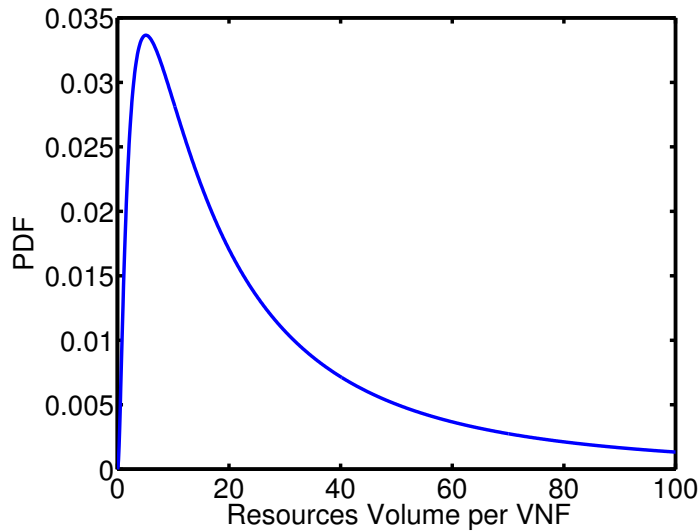


Figure 6.10: Probability density function of the volume of resources used by each VNF. The modeled resource consumption of each VNF follows a lognormal distribution, with mean equals to 3, and standard deviation equals to 1.17 ($\mu = 3$ and $\sigma = 1.17$). The lognormal distribution is truncated at 100, which represents the maximum volume usage ($volume = 1$).

request and allocates the VNFs on the network according to one of the proposed heuristics.

We establish the proposal evaluation in two steps. The first step is to simulate the customer Virtual Network Functions (VNFs) requests. The requests are generated based on a normal distribution with $\mu = 4$ and $\sigma = 1$, as it is shown in Figure 6.9. In this way, the customer requests are generated randomly associating different number of VNF for each request. We model the number of VNFs in each request

based on the studies realized by Sekar *et al.* [20]. We consider that a Virtual Machine (VM) deploys each VNF. Then, we simulate the resource consumption of each VNF. We model the resource consumption based in a lognormal distribution, with $\mu = 3$ and $\sigma = 1.17$, as it is shown in Figure 6.10. The resource consumption of each VNF is modeled as a truncated lognormal distribution because it should reflect the behavior of the middleboxes, in which it usually uses a small amount of resources. The distribution is truncated at 100, because it is the maximum *volume* that a VNF can assume ($volume_{VNF} = 1$). As result, we obtain the costumer VNF request with different resource *volume* and a selected order of chaining. We highlight that the resources of the all VNFs over a single physical host is never higher than 100%. An example of a VNF costumer request is $[VNF_1 = 15\%, VNF_2 = 26\%, VNF_3 = 45\%]; src, dst$, where the number of VNF are randomly chosen, and the *src* and *dst* are the source and destination of each chaining request. The source and the destination are uniformly chosen on the network topology. Our model does not consider that VNFs quit the network after being allocated.

The second step of the proposal evaluation asserts the optimization heuristics. Our experiments evaluate the placement heuristics against the RNP (Rede Nacional de Pesquisa) topology. Using a greedy algorithm, we place the VNF in different nodes and we evaluate the amount of VNF requested for each heuristic. We consider only the propagation delay between the nodes to estimate the latency between the nodes. The propagation delay is estimated according to the distance between nodes. We consider the propagation speed of 2×10^8 *m/s*, which is commonly used in other works [119]. The distance between each node is calculated based on the geographic location of each node.

The results in Figure 6.11 show that the maximum resource allocation heuristic is the one that accepts more requests around 53% more request than the betweenness-centrality heuristic. The betweenness-centrality heuristic is the simplest to calculate, as it only depends on the topology characteristics. Nevertheless, it is the one that rejects the greatest number of requests. In addition, the latency heuristic presents a better performance when compared with the betweenness-centrality, however, this heuristic shows the worst complexity when executed. It is worth noting that, although the maximum resource allocation heuristic optimizes the acceptance rate of VNFs on the network, it does not consider the routing constraints between VNFs. In this way, it increases the delay introduced by the deployment of network functions as VNFs because the packets may pass through distant nodes in order to follow the entire packet-processing path.

We also compare the dispersion of the latency distribution of the allocated VNFs

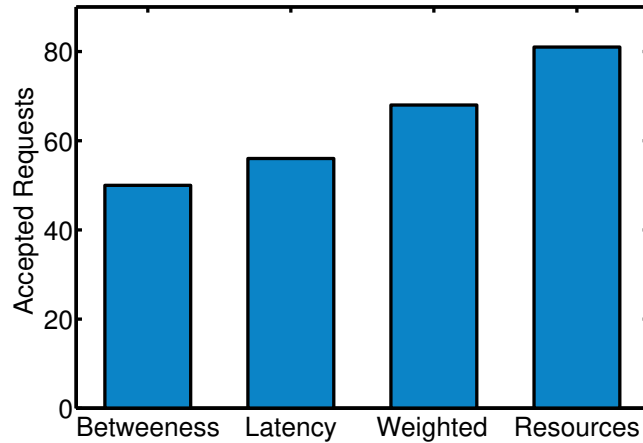
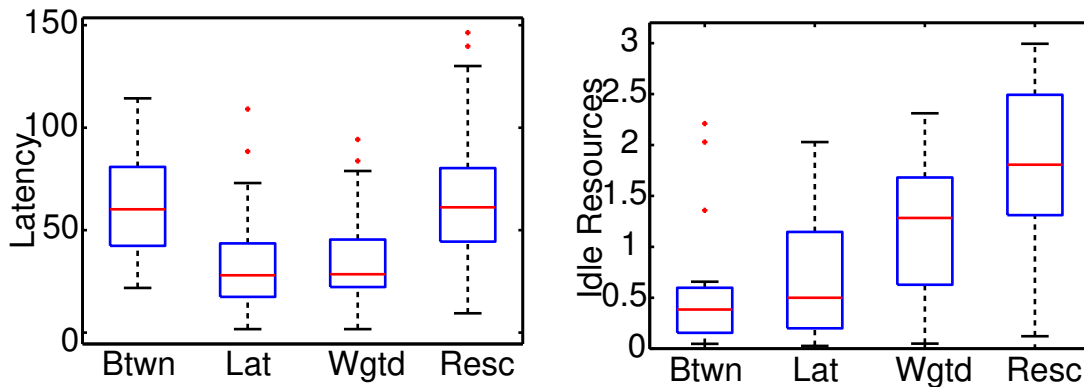


Figure 6.11: Number of accepted requests for each proposed heuristics. The maximum resource allocation heuristic is the one that accepts more requests. The betweenness-centrality heuristic is the simplest to calculate, as it only depends on the topology characteristics, but it is the one that rejects the greatest number of requests.



(a) Dispersion of the latency distribution into the allocated VNFs.

(b) Dispersion of the remaining idle resource distribution after allocating all VNFs.

Figure 6.12: **Btwn** stands for the betweenness-centrality; **Lat**, for latency; **Wgtd**, for weighted latency and resource; **Resc**, for maximum resource. a) The minimum latency heuristics introduces the lower average delay on the packet-processing path. The maximum resource usage heuristic is the one that presents the greatest dispersion into the latency distribution thanks of ignoring the latency concerns when placing the VNFs. b) The Maximum Resource heuristic presents the most distributed remaining resources.

for each heuristic. As shown in Figure 6.12a, the minimum latency heuristics introduces the lowest average delay on the packet-processing path. The maximum resource usage heuristic is the one that presents the greatest dispersion into the latency distribution thanks of ignoring the latency concerns when placing the VNFs. This result shows that the Latency heuristic reduces 52% the average delay when compared with the betweenness-centrality heuristic. Moreover, the latency

heuristic also achieves the greatest number of accepted VNF requests, which have the minimum latency, even when compared with maximum resource allocation that achieves to allocate more requests than all others. Figure 6.12a also reveals that the latency is limited in all heuristics and, even in the highest delay scenario, it is still limited to 150 ms. Figure 6.12b shows the remaining resources after all VNF allocation. Although the maximum resource heuristic instantiates more VNFs, it presents the biggest amount of idle resources. Nevertheless, it is also the most distributed idle resource pattern, which implies a load distribution between all physical nodes.

Comparing Figures 6.11 and 6.12a, we emphasize that the greater dispersion of the latency achieved by the maximum resource allocation heuristic is a reflect of the greater number of accepted requests, when compared with the minimum latency heuristic. It is worth noting that all heuristics are compliant with the resource constraints. Therefore, choosing among the four heuristics, when designing a NFV environment, should consider the goals of the network manager. In case of the main goal is to maximize the number of accepted VNFs, the results show that we should select the maximum resource allocation heuristic, in order to presents good results of latency between nodes. Nevertheless, if the main goal is to achieve the maximum performance of VNFs, the minimum latency heuristics is best choice. Intermediary solutions are the weighted latency and resource solution, which keep the bounded latency, and it increases up to 22% the acceptance rate when compared to the Latency heuristic.

In this chapter we analyze our Virtual Network Function performance. First we describe the Network Function Virtualization and the Open Network Function Virtualization Platform (OPNFV) and the benefits it brings to CATRACA. Then we propose a heuristic for virtual sensor placement maximizing the traffic analyzed with the minimum number of sensors in the network. Finally, we propose a greedy based algorithm for service chaining. We evaluated four heuristics. Our simulation and results show that using a heuristic for placing VNFs on nodes with the biggest amount of available resources increases the acceptance rate of VNF requests by 53%

Chapter 7

Conclusion

This work proposed a fast and efficient network monitoring and threat detection system. We used a combination of machine learning and stream processing for real time threat detection. A new generation of tool is needed in order to real-time monitor and secure computer network. We described and compared the three-major open source distributed stream processing systems: Apache Storm, Apache Flink, and Apache Spark Streaming. We performed throughput analysis, allocating more processing cores to achieve higher processing rates, Apache Storm was able to process up to 15 Million samples per minute. Also, we performed fault tolerance test to compare these three most popular open-source Distribute Stream Processors (DSP). In this case, we showed that Spark streaming, using micro-batch processing model, can recover the failure without losing any messages. Spark Streaming stores the full processing state of the micro-batches and distributes the interrupted processing homogeneously among other worker nodes. In order to increase the analysis speed and improve the efficiency of big data analysis, it is mandatory to implement pre-processing methods. This work presented and compared different methods for dimensionality reduction and Feature selection. Furthermore, we proposed a new fast-unsupervised algorithm for pre-process stream data. The algorithm includes feature selection and data normalization. Our feature selection algorithm calculates the correlation of the features in a network traffic data and selects the best features in an unsupervised way. We selected the features with the higher absolute correlation in comparison with the others methods. This procedure tends to gather the features with most of the information of the dataset in a new set of reduced features. The reduced new set of features is used, thus, to train the machine learning methods that classify and characterize the network traffic. Our algorithm was up to 10 times faster than literature algorithms for feature selection. We evaluated the feature selection algorithm in two different datasets achieving good performance. Moreover, our pre-processing algorithm is able to detect concept-drift in stream data. We showed

that our normalizer adapts the data to a normal distribution reducing the error of machine learning classifiers. To evaluate the proposed algorithms, we implement eight machine learning algorithms, decision tree, neural networks, k-nearest neighbors, support vector machine with linear and Radial Basis Function (RBF) kernel, Gaussian Naive Bayes and Stochastic Gradient Descendant. We evaluated machine learning algorithm performance under six metrics, accuracy, precision, sensitivity, F-1 score, classification and training time.

We created two datasets publicly available. First a synthetic security dataset obtaining real network traffic along with network threats composed of 24 features. The GTA/UFRJ dataset contains more than 16 different types of attacks, as well as normal network traffic. The second dataset, NetOp, is composed by more than ten days of real traffic from a real telecommunication operator network located in the city of Rio de Janeiro, Brazil. The dataset represents the use of the fixed-line access service of 373 home users. The analysis of the data allows identifying that the main services accessed are those of DNS and web services. We use this information to create more than 5 TB of data combined in 45 flows features. Each flow is classified as normal traffic or alert from a previous Intrusion Detection System.

Network Function Virtualization (NFV) is a promising technique that enables to decouple the network function from its physical realization by virtualizing the network equipment. Thus, network functions are deployed within virtual environment and, thus, called Virtual Network Functions (VNF). Therefore, we deploy our threat detection system as a virtualized network function. The threat detection function is implemented in the Open-source Platform for Network Function Virtualization (OPNFV) and shows high high throughput and a low latency and live migration features.

Combining stream processing, machine learning and feature selection we created the CATRACA tool. The proposed tool is executed in an OPNFV environment allowing the system to perform migration as closets as possible to the source attack. Moreover, the tool combines batch and stream processing in a big data architecture that allows to performs threat analysis on incoming traffic in real time on a historical database. Our tool displays the knowledge extracted from the enriched data through a graphical user interface for visualizing different analyzes and the geographical location of the source and destination of the threats in real time. CATRACA code is publicly available.

Finally, we proposed a method for the strategic location of traffic capture sensors. For this, a mathematical modeling was developed, obtaining a heuristic that considers the minimum number of sensors reached the maximum coverage of the network. The evaluation of the heuristic was analyzed in two different real

topologies. The results show that with a high network coverage the proposed system has a great gain in relation to random choice. In addition, we modeled and discussed the VNF sensor placement as an NP -hard problem. Our heuristic reduces the number of sensor and maximizes the network coverage.

We proposed a VNF chaining scheme, in which a greedy algorithm places the VNFs on the network according to four different criteria. Our simulation and results showed that using a heuristic for placing VNFs on nodes with the biggest amount of available resources increases the acceptance rate of VNF requests by 53%. Moreover, we also showed that using a heuristic for introducing minimum delay on the path, we are able to reduce the average packet-processing delay by 52%.

7.1 Future Work

New methods of anomaly detection and traffic classification need to be experimented in CATRACA to avoid the use of the batch layer. Algorithms such as deep learning or Hoeffding Trees should be implemented in the tool. Due to the distributed nature of our monitoring and threat detection tool, we need to implement an algorithm for event correlation. A future work foresees to detect intrusion symptoms by collecting diverse information at several architectural levels, from raw packet until system logs, using distributed security probes, as well as performing complex event analysis based on a complex event processing engine

Bibliography

- [1] HU, P., LI, H., FU, H., et al. “Dynamic defense strategy against advanced persistent threat with insiders”. In: *2015 IEEE Conference on Computer Communications (INFOCOM)*, pp. 747–755. IEEE, 4 2015. ISBN: 978-1-4799-8381-0. doi: 10.1109/INFOCOM.2015.7218444.
- [2] PAXSON, V. “Bro: a system for detecting network intruders in real-time”, *Computer Networks*, v. 31, n. 23-24, pp. 2435–2463, 12 1999. ISSN: 13891286. doi: 10.1016/S1389-1286(99)00112-7.
- [3] BAR, A., FINAMORE, A., CASAS, P., et al. “Large-scale network traffic monitoring with DBStream, a system for rolling big data analysis”. In: *2014 IEEE International Conference on Big Data (Big Data)*, pp. 165–170. IEEE, 10 2014. ISBN: 978-1-4799-5666-1. doi: 10.1109/BigData.2014.7004227.
- [4] STONEBRAKER, M., ÇETINTEMEL, U., ZDONIK, S. “The 8 requirements of real-time stream processing”, *ACM SIGMOD Record*, v. 34, n. 4, pp. 42–47, 12 2005. ISSN: 01635808. doi: 10.1145/1107499.1107504.
- [5] CLAY, P. “A modern threat response framework”, *Network Security*, v. 2015, n. 4, pp. 5–10, 2015.
- [6] DOS SANTOS, L. A. F., CAMPIOLO, R., MONTEVERDE, W. A., et al. “Abordagem autônômica para mitigar ciberataques em LANs”, *Simpósio Brasileiro de Redes de Computadores e Sistemas Distribuídos - SBRC 2016*, 2016.
- [7] NASSERALA, A., MORAES, I. M. “Analyzing the producer-consumer collusion attack in Content-Centric Networks”. In: *2016 13th IEEE Annual Consumer Communications & Networking Conference (CCNC)*, pp. 849–852. IEEE, 2016.
- [8] CHANDRASEKAR, K., CLEARY, G., COX, O., et al. “Internet Security Threat Report-Symantec Corporation,V22”. Accessed April 2018, 2017.

Available in: <<https://www.symantec.com/content/dam/symantec/docs/reports/istr-22-2017-en.pdf>>.

- [9] ARMOR. “The Black Market Report 2018-03”. Accessed April 2018, 2018. Available in: <<https://www.armor.com/app/uploads/2018/03/2018-Q1-Reports-BlackMarket-DIGITAL.pdf>>.
- [10] ICA, I. C. A. *Assessing Russian Activities and Intentions in Recent US Elections 2017-01D*. Technical report, Office of the director of national Intelligence, 2017. Available in: <https://www.dni.gov/files/documents/ICA_2017_01.pdf>.
- [11] MAYHEW, M., ATIGHETCHI, M., ADLER, A., et al. “Use of machine learning in big data analytics for insider threat detection”. In: *IEEE Military Communications Conference, MILCOM*, pp. 915–922, 10 2015.
- [12] JIANG, W., RAVI, V. T., AGRAWAL, G. “A Map-Reduce system with an alternate API for multi-core environments”. In: *Proceedings of the 10th IEEE/ACM International Conference on Cluster, Cloud and Grid Computing*, pp. 84–93. IEEE Computer Society, 2010.
- [13] KALA KARUN, A., CHITHARANJAN, K. “A review on Hadoop—HDFS infrastructure extensions”. In: *IEEE Conference on Information & Communication Technologies (ICT)*, pp. 132–137. IEEE, 2013.
- [14] BATISTA, D. M., GOLDMAN, A., HIRATA, R., et al. “InterSCity: Addressing Future Internet research challenges for Smart Cities”. In: *2016 7th International Conference on the Network of the Future (NOF)*, pp. 1–6. IEEE, 11 2016. ISBN: 978-1-5090-4671-3. doi: 10.1109/NOF.2016.7810114.
- [15] CRUZ, P., COUTO, R. S., COSTA, L. H. M. “An algorithm for sink positioning in bus-assisted smart city sensing”, *Future Generation Computer Systems*, 10 2017. ISSN: 0167739X. doi: 10.1016/j.future.2017.09.018.
- [16] ANDREONI LOPEZ, M., FERRAZANI MATTOS, D., DUARTE, O. C. M. B. “An elastic intrusion detection system for software networks”, *Annales des Telecommunications/Annals of Telecommunications*, v. 71, n. 11-12, pp. 595–605, 12 2016. ISSN: 0003-4347. doi: 10.1007/s12243-016-0506-y.

- [17] DAB, B., FAJJARI, I., AITSAADI, N., et al. “VNR-GA: Elastic virtual network reconfiguration algorithm based on Genetic metaheuristic”. In: *IEEE GLOBECOM*, pp. 2300–2306, 12 2013.
- [18] GUIMARÃES, P. H. V., MURILLO P., A. F., ANDREONI LOPEZ, M. E., et al. “Comunicação em Redes Elétricas Inteligentes: eficiência, confiabilidade, segurança e escalabilidade”. In: *SBRC 2013 - Minicursos*, pp. 101–164, 5 2013.
- [19] SHERRY, J., HASAN, S., SCOTT, C., et al. “Making Middleboxes Someone else’s Problem: Network Processing As a Cloud Service”, *SIGCOMM Comput. Commun. Rev.*, v. 42, n. 4, pp. 13–24, 8 2012. ISSN: 0146-4833.
- [20] SEKAR, V., EGI, N., RATNASAMY, S., et al. “Design and Implementation of a Consolidated Middlebox Architecture”. In: *9th Symposium on Networked Systems Design and Implementation (NSDI)*, pp. 323–336, San Jose, CA, 2012. USENIX. ISBN: 978-931971-92-8.
- [21] JEON, H., LEE, B. “Network service chaining challenges for VNF outsourcing in network function virtualization”. In: *International Conference on Information and Communication Technology Convergence (ICTC)*, pp. 819–821, 10 2015.
- [22] BARI, M. F., CHOWDHURY, S. R., AHMED, R., et al. “On orchestrating virtual network functions”. In: *11th International Conference on Network and Service Management (CNSM)*, pp. 50–56, 11 2015.
- [23] ADDIS, B., BELABED, D., BOUET, M., et al. “Virtual network functions placement and routing optimization”. In: *IEEE 4th International Conference on Cloud Networking (CloudNet)*, pp. 171–177, 10 2015.
- [24] MEHRAGHDAM, S., KELLER, M., KARL, H. “Specifying and Placing Chains of Virtual Network Functions”. In: *IEEE 3rd International Conference on Cloud Networking (CloudNet)*, pp. 7–13, 10 2014.
- [25] LAUFER, R., GALLO, M., PERINO, D., et al. “CliMB: Enabling Network Function Composition with Click Middleboxes”. In: *Proceedings of the 2016 Workshop on Hot Topics in Middleboxes and Network Function Virtualization, HotMiddlebox ’16*, pp. 50–55, New York, NY, USA, 2016. ACM. ISBN: 978-1-4503-4424-1.
- [26] ANDREONI LOPEZ, M., DUARTE, O. C. M. B. “Providing elasticity to intrusion detection systems in virtualized Software Defined Networks”.

In: *2015 IEEE International Conference on Communications (ICC)*, v. 2015-Septe, pp. 7120–7125, London, United Kingdom, 6 2015. IEEE. ISBN: 978-1-4673-6432-4. doi: 10.1109/ICC.2015.7249462.

- [27] MATTOS, D. M. F., DUARTE, O. C. M. B., PUJOLLE, G. “A Resilient Distributed Controller for Software Defined Networking”. In: *IEEE ICC 2016 - Next Generation Networking and Internet Symposium (ICC'16 - NGN)*, Kuala Lumpur, Malaysia, 5 2016.
- [28] TOSHNIWAL, A., TANEJA, S., SHUKLA, A., et al. “Storm@Twitter”. In: *ACM SIGMOD International Conference on Management of Data*, pp. 147–156. ACM, 2014.
- [29] CARBONE, P., FÓRA, G., EWEN, S., et al. “Lightweight Asynchronous Snapshots for Distributed Dataflows”, *Computing Research Repository (CoRR)*, v. abs/1506.0, 2015.
- [30] FRANKLIN, M. “The Berkeley Data Analytics Stack: Present and future”. In: *IEEE International Conference on Big Data*, pp. 2–3. IEEE, 2013.
- [31] ANDREONI LOPEZ, M., SANZ, I. J., FERRAZANI MATTOS, D. M., et al. “CATRACA: uma Ferramenta para Classificação e Análise Tráfego Escalável Baseada em Processamento por Fluxo”. In: *Salão de Ferramentas do XVII Simpósio Brasileiro de Segurança da Informação e de Sistemas Computacionais - SBSeg'2017*, pp. 788–795, 2017.
- [32] ROBNIK-ŠIKONJA, M., KONONENKO, I. “Theoretical and Empirical Analysis of Relief and RRelief”, *Machine Learning*, v. 53, n. 1/2, pp. 23–69, 2003. ISSN: 08856125. doi: 10.1023/A:1025667309714.
- [33] SCHÖLKOPF, B., SMOLA, A. J., MÜLLER, K.-R. “Kernel principal component analysis”. In: *Advances in kernel methods*, pp. 327–352. MIT Press, 1999.
- [34] HESSE, G., LORENZ, M. “Conceptual Survey on Data Stream Processing Systems”. In: *IEEE 21st International Conference on Parallel and Distributed Systems*, pp. 797–802, 2015.
- [35] GRADVOHL, A. L. S., SENGER, H., ARANTES, L., et al. “Comparing distributed online stream processing systems considering fault tolerance issues”, *Journal of Emerging Technologies in Web Intelligence*, v. 6, n. 2, pp. 174–179, 2014.

- [36] LANDSET, S., KHOSHGOFTAAR, T. M., RICHTER, A. N., et al. “A survey of open source tools for machine learning with big data in the Hadoop ecosystem”, *Journal of Big Data*, v. 2, n. 1, pp. 1–36, 2015.
- [37] COLUCCIO, R., GHIDINI, G., REALE, A., et al. “Online stream processing of machine-to-machine communications traffic: A platform comparison”. In: *IEEE Symposium on Computers and Communication (ISCC)*, pp. 1–7, 6 2014. doi: 10.1109/ISCC.2014.6912528.
- [38] NABI, Z., BOUILLET, E., BAINBRIDGE, A., et al. “Of Streams and Storms”, *IBM White Paper*, 2014.
- [39] LU, R., WU, G., XIE, B., et al. “Stream Bench: Towards Benchmarking Modern Distributed Stream Computing Frameworks”. In: *IEEE/ACM 7th International Conference on Utility and Cloud Computing*, pp. 69–78, 2014.
- [40] DAYARATHNA, M., SUZUMURA, T. “A performance analysis of System S, S4, and Esper via two level benchmarking”. In: *Quantitative Evaluation of Systems*, Springer, pp. 225–240, 2013.
- [41] ANDREONI LOPEZ, M., LOBATO, A. G. P., DUARTE, O. C. M. B. “A Performance Comparison of Open-Source Stream Processing Platforms”. In: *IEEE GLOBECOM*, pp. 1–6, Washington, USA, 12 2016. IEEE. ISBN: 9781509013289. doi: 10.1109/GLOCOM.2016.7841533.
- [42] ANDREONI LOPEZ, M., LOBATO, A. G. P., DUARTE, O. C. M. B. “Monitoramento de Tráfego e Detecção de Ameaças por Sistemas Distribuídos de Processamento de Fluxos: uma Análise de Desempenho”, *XXI Workshop de Gerência e Operação de Redes e Serviços (WGRS) do SBRC’2016*, pp. 103–116, 2016.
- [43] DU, Y., LIU, J., LIU, F., et al. “A real-time anomalies detection system based on streaming technology”. In: *Sixth International Conference on Intelligent Human-Machine Systems and Cybernetics (IHMSC)*, v. 2, pp. 275–279. IEEE, 2014.
- [44] ZHAO, S., CHANDRASHEKAR, M., LEE, Y., et al. “Real-time network anomaly detection system using machine learning”. In: *11th International Conference on the Design of Reliable Communication Networks (DRCN)*, pp. 267–270. IEEE, 2015.

- [45] HE, G., TAN, C., YU, D., et al. “A real-time network traffic anomaly detection system based on storm”. In: *Proceedings - 2015 7th International Conference on Intelligent Human-Machine Systems and Cybernetics, IHMSC 2015*, v. 1, pp. 153–156, 2015. ISBN: 9781479986460. doi: 10.1109/IHMSC.2015.152.
- [46] MYLAVARAPU, G., THOMAS, J., TK, A. K. “Real-Time Hybrid Intrusion Detection System Using Apache Storm”. In: *17th International Conference on High Performance Computing and Communications*, pp. 1436–1441. IEEE, 8 2015. ISBN: 978-1-4799-8937-9. doi: 10.1109/HPCC-CSS-ICISS.2015.241.
- [47] SANTOS, L. A. F., CAMPIOLO, R., BATISTA, D. M. “Uma Arquitetura Autônoma para Detecção e Reação a Ameaças de Segurança em Redes de Computadores”. In: *III WoSiDA'14*, pp. 1–4, 2014.
- [48] SCHUARTZ, F. C., MUNARETTO, A., FONSECA, M. “Sistema Distribuído para Detecção de Ameaças em Tempo Real Utilizando Big Data”. In: *XXXV Simpósio Brasileiro de Telecomunicações e Processamento de Sinais (SBrT)*, 2017.
- [49] JIRSIK, T., CERMAK, M., TOVARNAK, D., et al. “Toward Stream-Based IP Flow Analysis”, *IEEE Communications Magazine*, v. 55, n. 7, pp. 70–76, 2017. ISSN: 0163-6804. doi: 10.1109/MCOM.2017.1600972.
- [50] SANZ, I. J., ALVARENGA, I. D., ANDREONI LOPEZ, M., et al. “Uma Avaliação de Desempenho de Segurança Definida por Software através de Cadeias de Funções de Rede”. In: *XVII Simpósio Brasileiro em Segurança da Informação e de Sistemas Computacionais - SBSeg 2017*, 2017.
- [51] AZMANDIAN, F., KAEELI, D. R., DY, J. G., et al. “Securing virtual execution environments through machine learning-based intrusion detection”. In: *25th International Workshop on Machine Learning for Signal Processing (MLSP)*, pp. 1–6, 2015.
- [52] LI, B., LI, J., LIU, L. “CloudMon: a resource-efficient IaaS cloud monitoring system based on networked intrusion detection system virtual appliances”, *Concurrency and Computation: Practice and Experience*, v. 27, n. 8, pp. 1861–1885, 2015.
- [53] CHEN, H., CLARK, J. A., TAPIADOR, J. E., et al. “A multi-objective optimisation approach to IDS sensor placement”. In: *Computational*

Intelligence in Security for Information Systems, Springer, pp. 101–108, 2009.

- [54] BOUET, M., LEGUAY, J., CONAN, V. “Cost-based placement of virtualized Deep Packet Inspection functions in SDN”. In: *IEEE Military Communications Conference, MILCOM*, pp. 992–997. IEEE, 2013.
- [55] FERRAZ, L. H. G., MATTOS, D. M. F., DUARTE, O. C. M. B. “A two-phase multipathing scheme based on genetic algorithm for data center networking”. In: *IEEE GLOBECOM 2014*, pp. 2270–2275, 12 2014.
- [56] ANDREONI LOPEZ, M., MATTOS, D. M. F., FERRAZ, L. H. G., et al. “Localização Eficiente de Sensores Colaborativos para Detecção e Prevenção de Intrusão em Ambientes Virtualizados”. In: *XX Workshop de Gerência e Operação de Redes e Serviços (WGRS 2015) do SBRC’2015*, 2015.
- [57] ANDREONI LOPEZ, M., PASTANA LOBATO, A. G., DUARTE, O. C. M. B., et al. *Design and Performance Evaluation of a Virtualized Network Function for Real-Time Threat Detection using Stream Processing*. Technical Report GTA-16-34, Grupo de Teleinformática e Automação (GTA), Universidade Federal do Rio de Janeiro (UFRJ), 2016.
- [58] BOUET, M., LEGUAY, J., COMBE, T., et al. “Cost-based placement of vDPI functions in NFV infrastructures”, *International Journal of Network Management*, v. 25, n. 6, pp. 490–506, 2015.
- [59] WOOD, T., SHENOY, P., VENKATARAMANI, A., et al. “Sandpiper: Black-box and gray-box resource management for virtual machines”, *Computer Networks*, v. 53, n. 17, pp. 2923–2938, 2009. ISSN: 1389-1286.
- [60] CARVALHO, H. E. T., DUARTE, O. C. M. B. “VOLTAIC: volume optimization layer to assign cloud resources”. In: *Proceedings of the 3rd International Conference on Information and Communication Systems, ICICS’12*, pp. 3:1–3:7, 2012. ISBN: 978-1-4503-1327-8.
- [61] ANDREONI LOPEZ, M., MATTOS, D. M. F. D., DUARTE, O. C. M. B. “Evaluating Allocation Heuristics for an Efficient Virtual Network Function Chaining”. In: *7th International Conference Network of the Future (NoF’16)*. IEEE, 2017. ISBN: 9781509046713. doi: 10.1109/NOF.2016.7810141.

- [62] CARNEY, D., ÇETINTEMEL, U., CHERNIACK, M., et al. “Monitoring Streams: A New Class of Data Management Applications”. In: *28th International Conference on Very Large Data Bases*, pp. 215–226, 2002.
- [63] ABADI, D. J., AHMAD, Y., BALAZINSKA, M., et al. “The Design of the Borealis Stream Processing Engine.” *Cidr*, pp. 277–289, 2005. doi: 10.1.1.118.7039.
- [64] RYCHLY, M., KODA, P., SMRZ, P. “Scheduling Decisions in Stream Processing on Heterogeneous Clusters”. In: *Eighth International Conference on Complex, Intelligent and Software Intensive Systems (CISIS)*, pp. 614–619, 7 2014.
- [65] ZAHARIA, M., DAS, T., LI, H., et al. “Discretized streams: Fault-tolerant streaming computation at scale”. In: *XXIV ACM Symposium on Operating Systems Principles*, pp. 423–438. ACM, 2013.
- [66] MARZ, N., WARREN, J. *Big Data: Principles and Best Practices of Scalable Realtime Data Systems*. 1st ed. Greenwich, CT, USA, Manning Publications Co., 2013.
- [67] WIDOM, J. “The Starburst rule system: Language design, implementation, and applications”, *IEEE Data Engineering Bulletin*, 1992.
- [68] STONEBRAKER, M., KEMNITZ, G. “The POSTGRES next generation database management system”, *Communications of the ACM*, v. 34, n. 10, pp. 78–92, 1991.
- [69] CHEN, J., DEWITT, D. J., TIAN, F., et al. “NiagaraCQ: A scalable continuous query system for internet databases”. In: *ACM SIGMOD Record*, v. 29, pp. 379–390. ACM, 2000.
- [70] ARASU, A., BABCOCK, B., BABU, S., et al. *STREAM: The Stanford Data Stream Management System*. Technical Report 2004-20, Stanford InfoLab, 2004.
- [71] BALAZINSKA, M., BALAKRISHNAN, H., STONEBRAKER, M. “Load management and high availability in the Medusa distributed stream processing system”. In: *Proceedings of the 2004 ACM SIGMOD international conference on Management of data - SIGMOD '04*, p. 929, New York, New York, USA, 2004. ACM Press. ISBN: 1581138598. doi: 10.1145/1007568.1007701.

- [72] CHANDRASEKARAN, S., COOPER, O., DESHPANDE, A., et al. “TelegraphCQ: continuous dataflow processing”. In: *Proceedings of the 2003 ACM SIGMOD international conference on Management of data*, p. 668. ACM, 2003.
- [73] DEMERS, A. J., GEHRKE, J., PANDA, B., et al. “Cayuga: A General Purpose Event Monitoring System.” In: *Proceedings of the Conference on Innovative Data Systems Research*, v. 7, pp. 412–422, 2007.
- [74] CARBONE, P., EWEN, S., HARIDI, S., et al. “Apache Flink: Unified Stream and Batch Processing in a Single Engine”, *Data Engineering*, pp. 28–38, 2015.
- [75] KAMBURUGAMUVE, S., FOX, G., LEAKE, D., et al. “Survey of distributed stream processing for large stream sources”. 2013.
- [76] ANDREONI LOPEZ, M., LOBATO, A. G. P., MATTOS, D. M. F., et al. “Um Algoritmo Não Supervisionado e Rápido para Seleção de Características em Classificação de Tráfego”. In: *XXXV SBRC'2017*, Belém- Pará, PA,, 2017.
- [77] ANDREONI LOPEZ, M., LOBATO, A. G. P., DUARTE, O. C. M. B., et al. “An evaluation of a virtual network function for real-time threat detection using stream processing”. In: *IEEE Fourth International Conference on Mobile and Secure Services (MobiSecServ)*, pp. 1–5, 2018. doi: 10.1109/MOBISECSERV.2018.8311440.
- [78] CHENG, Z., CAVERLEE, J., LEE, K. “You Are Where You Tweet: A Content-based Approach to Geo-locating Twitter Users”. In: *Proceedings of the 19th ACM International Conference on Information and Knowledge Management, CIKM '10*, pp. 759–768. ACM, 2010. ISBN: 978-1-4503-0099-5.
- [79] LOBATO, A. G. P., ANDREONI LOPEZ, M., DUARTE, O. C. M. B. “Um Sistema Acurado de Detecção de Ameaças em Tempo Real por Processamento de Fluxos”. In: *SBRC'2016*, pp. 572–585, Salvador, Bahia, 2016.
- [80] HEIDEMANN, J., PAPDOPOULOS, C. “Uses and challenges for network datasets”. In: *Conference For Homeland Security, 2009. CATCH'09. Cybersecurity Applications & Technology*, pp. 73–82. IEEE, 2009.

- [81] LIPPMANN, R. P., FRIED, D. J., GRAF, I., et al. “Evaluating intrusion detection systems: The 1998 DARPA off-line intrusion detection evaluation”. In: *Proceedings of DARPA Information Survivability Conference and Exposition. DISCEX'00.*, v. 2, pp. 12–26. IEEE, 2000.
- [82] HAINES, J. W., LIPPMANN, R. P., FRIED, D. J., et al. *1999 DARPA intrusion detection evaluation: Design and procedures*. Technical report, Massachusetts Inst Of Tech Lexington Lincoln Lab, 2001.
- [83] LEE, W., STOLFO, S. J., MOK, K. W. “Mining in a data-flow environment: Experience in network intrusion detection”. In: *Proceedings of the fifth ACM SIGKDD international conference on Knowledge discovery and data mining*, pp. 114–124. ACM, 1999.
- [84] TAVALLAEE, M., BAGHERI, E., LU, W., et al. “A detailed analysis of the KDD CUP 99 data set”. In: *Proceedings of the Second IEEE Symposium on Computational Intelligence for Security and Defence Applications*. IEEE, 2009.
- [85] SOMMER, R., PAXSON, V. “Outside the closed world: On using machine learning for network intrusion detection”. In: *IEEE Symposium on Security and Privacy (SP)*, pp. 305–316. IEEE, 2010.
- [86] SHIRAVI, A., SHIRAVI, H., TAVALLAEE, M., et al. “Toward developing a systematic approach to generate benchmark datasets for intrusion detection”, *Computers and Security*, v. 31, n. 3, pp. 357–374, 2012. ISSN: 0167-4048.
- [87] GARCIA, S., GRILL, M., STIBOREK, J., et al. “An empirical comparison of botnet detection methods”, *Computers & Security*, v. 45, pp. 100–123, 2014.
- [88] FONTUGNE, R., BORGNAT, P., ABRY, P., et al. “{MAWILab}: Combining Diverse Anomaly Detectors for Automated Anomaly Labeling and Performance Benchmarking”. In: *ACM CoNEXT '10*, Philadelphia, PA, 2010.
- [89] JUNGSUK, S., TAKAKURA, H., OKABE, Y. *Description of Kyoto university benchmark data*. Technical Report 01, Academic Center for Computing and Media Studies (ACCMS), Kyoto University, 2006.
- [90] TANTITHAMTHAVORN, C., MCINTOSH, S., HASSAN, A. E., et al. “An Empirical Comparison of Model Validation Techniques for Defect

Prediction Models”, *IEEE Transactions on Software Engineering*, v. 43, n. 1, pp. 1–18, 1 2017. ISSN: 0098-5589. doi: 10.1109/TSE.2016.2584050.

- [91] B. CLAISE, E., B. TRAMMELL, E., AITKEN, P. “Specification of the IP Flow Information Export (IPFIX) Protocol for the Exchange of Flow Information”. RFC 7011 (Informational), 2013.
- [92] ROESCH, M. “Snort-Lightweight Intrusion Detection for Networks”. In: *Proceedings of the 13th USENIX conference on System administration*, pp. 229–238. USENIX Association, 1999.
- [93] ZHAI, Y., ONG, Y.-S., TSANG, I. W. “The Emerging Big Dimensionality”, *Comp. Intell. Mag.*, v. 9, n. 3, pp. 14–26, 2014. ISSN: 1556-603X. doi: 10.1109/MCI.2014.2326099.
- [94] VAN DER MAATEN, L., POSTMA, E., DEN HERIK, J. “Dimensionality reduction: a comparative”, *Journal of Machine Learning Research*, v. 10, pp. 66–71, 2009.
- [95] AINHOREN, Y., ENGELBERG, S., FRIEDMAN, S. “The cocktail party problem”, *IEEE Instrumentation and Measurement Magazine*, 2008. ISSN: 10946969. doi: 10.1109/MIM.2008.4534378.
- [96] MLADENIĆ, D. “Feature Selection for Dimensionality Reduction”. In: Saunders, C., Grobelnik, M., Gunn, S., et al. (Eds.), *Subspace, Latent Structure and Feature Selection (SLSFS): Statistical and Optimization Perspectives Workshop.*, Springer Berlin Heidelberg, pp. 84–102, Bohinj, Slovenia, 2006. ISBN: 978-3-540-34138-3. doi: 10.1007/11752790-5.
- [97] ANG, J. C., MIRZAL, A., HARON, H., et al. “Supervised, Unsupervised, and Semi-Supervised Feature Selection: A Review on Gene Selection”, *IEEE/ACM Transactions on Computational Biology and Bioinformatics*, v. 13, n. 5, pp. 971–989, 9 2016. ISSN: 1545-5963. doi: 10.1109/TCBB.2015.2478454.
- [98] GUYON, I., WESTON, J., BARNHILL, S., et al. “Gene selection for cancer classification using support vector machines”, *Machine learning*, v. 46, n. 1-3, pp. 389–422, 2002.
- [99] CHANDRASHEKAR, G., SAHIN, F. “A survey on feature selection methods”, *Computers & Electrical Engineering*, v. 40, n. 1, pp. 16–28, 2014. ISSN: 0045-7906. doi: <http://dx.doi.org/10.1016/j.compeleceng.2013.11.024>.

- [100] HALL, M. A. *Correlation-based Feature Selection for Machine Learning*. Tese de Doutorado, The University of Waikato, 1999.
- [101] BUCZAK, A., GUVEN, E. “A Survey of Data Mining and Machine Learning Methods for Cyber Security Intrusion Detection”, *IEEE Communications Surveys Tutorials*, , n. 99, pp. 1–26, 2015.
- [102] PRASATH, V. B. S., ALFEILAT, H. A. A., LASASSMEH, O., et al. “Distance and Similarity Measures Effect on the Performance of K-Nearest Neighbor Classifier - A Review”, *CoRR*, v. abs/1708.0, 2017.
- [103] GARCÍA, S., LUENGO, J., HERRERA, F. “Tutorial on practical tips of the most influential data preprocessing algorithms in data mining”, *Knowledge-Based Systems*, v. 98, pp. 1–29, 4 2016. ISSN: 09507051. doi: 10.1016/j.knosys.2015.12.006.
- [104] RAMÍREZ-GALLEGO, S., KRAWCZYK, B., GARCÍA, S., et al. “A survey on data preprocessing for data stream mining: Current status and future directions”, *Neurocomputing*, 2017. ISSN: 18728286. doi: 10.1016/j.neucom.2017.01.078.
- [105] PERKINS, S., THEILER, J. “Online feature selection using grafting”. In: *Proceedings of the 20th International Conference on Machine Learning (ICML-03)*, pp. 592–599, 2003.
- [106] ZHOU, J., FOSTER, D. P., STINE, R. A., et al. “Streamwise feature selection”, *Journal of Machine Learning Research*, v. 7, n. Sep, pp. 1861–1885, 2006.
- [107] WU, X., YU, K., DING, W., et al. “Online feature selection with streaming features”, *IEEE transactions on pattern analysis and machine intelligence*, v. 35, n. 5, pp. 1178–1192, 2013.
- [108] HU, H., KANTARDZIC, M. “Smart preprocessing improves data stream mining”. In: *49th Hawaii International Conference on System Sciences (HICSS)*, pp. 1749–1757. IEEE, 2016.
- [109] WEBB, G. I. “Contrary to popular belief incremental discretization can be sound, computationally efficient and extremely useful for streaming data”. In: *IEEE International Conference on Data Mining (ICDM)*, pp. 1031–1036. IEEE, 2014.

- [110] BEN-HAIM, Y., TOM-TOV, E. “A streaming parallel decision tree algorithm”, *Journal of Machine Learning Research*, v. 11, n. Feb, pp. 849–872, 2010.
- [111] CHAWLA, N. V., BOWYER, K. W., HALL, L. O., et al. “SMOTE: synthetic minority over-sampling technique”, *Journal of artificial intelligence research*, v. 16, pp. 321–357, 2002.
- [112] YANG, W., FUNG, C. “A survey on security in network functions virtualization”. In: *IEEE NetSoft Conference and Workshops*, pp. 15–19. IEEE, 2016.
- [113] MIJUMBI, R., SERRAT, J., GORRICO, J.-L., et al. “Network Function Virtualization: State-of-the-Art and Research Challenges”, *IEEE Communications Surveys & Tutorials*, v. 18, n. 1, pp. 236–262, 2015.
- [114] MIJUMBI, R., SERRAT, J., GORRICO, J.-L., et al. “Management and orchestration challenges in network functions virtualization”, *IEEE Communications Magazine*, v. 54, n. 1, pp. 98–105, 1 2016. ISSN: 0163-6804. doi: 10.1109/MCOM.2016.7378433.
- [115] ETSI GS NFV-MAN. *Network Functions Virtualisation (NFV); Management and Orchestration*. Technical Report 001, European Telecommunications Standards Institute (ETSI), 12 2014.
- [116] BARI, M. F., CHOWDHURY, S. R., AHMED, R., et al. “Orchestrating Virtualized Network Functions”, *Transactions on Network and Service Management*, v. PP, n. 99, 5 2016.
- [117] MEDEIROS, D. S. V., CAMPISTA, M. E., MITTON, N., et al. “Weighted Betweenness for Multipath Networks”. In: *Global Information Infrastructure and Networking Symposium (GIIS)*, 2016.
- [118] QUINN, P., NADEAU, T. *Problem Statement for Service Function Chaining*. Technical Report RFC 7498, Active Internet-Draft, TETF Secretariat, 2015.
- [119] COUTO, D. R. S., SECCI, S., CAMPISTA, M. E. M., et al. “Reliability and Survivability Analysis of Data Center Network Topologies”, *Journal of Network and Systems Management*, v. 24, n. 2, pp. 346–392, 2016.