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SURVEY

A Systematic Literature Review of Offensive and Defensive Security Solutions With Software Defined Network

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ABSTRACT Software Defined Networking (SDN) is one of the most significant innovations in telecommunication systems in the past two decades. From the very beginning, the scientific community understood the importance of investigating the possible usages of SDN as a means to increase network security, but also their potential to be exploited as an attack device. For this reason, there has been a massive production of research works, which, however, do not form a well-defined corpus. The literature is spread over many venues and composed of contributions with very different flavors. Though some review works already exist, in this work we conduct a systematic literature review of the field, gathering 466 relevant publications—the largest curated dataset on the topic to the best of our knowledge. In our work, the dataset undergoes a twofold analysis: (a) quantitative, through publication metadata, which allows us to chart publication outlets, approaches, and tackled issues; (b) qualitative, through 14 research questions that provide an aggregated overview of the literature contributions to the key issues, also to spot gaps left open. From these analyses, we derive a call for action to address the main open challenges.

INDEX TERMS Attack, defense, mitigation, security, SDN, threat.

I. INTRODUCTION

The level of complexity of modern communications, as well as their key role in our daily life, calls for outstanding levels of performance, reliability, and security. The TCP/IP protocol suite provided the basic technology for the widespread development of the Internet. Still, it was not designed to cope with the huge variety of use cases of today. The consequence was inevitably the ''ossification'' of the Internet, which has been overcome with the introduction of a number of additional devices performing several ancillary functions, the so-called middleboxes. The explosion of the number of middleboxes hinders effective management, smooth scalability, as well as controllable security of the network.

The Software Defined Networking (SDN) principle emerged with the goal to overcome these problems. It allows full decoupling between the network control and data planes, to allow full flexibility in functional evolution and guarantee scalability. Moreover, it allows network reconfiguration and adaptation to different application scenarios and operating conditions, within a time scale unforeseeable with legacy technologies. The SDN operates according to the model of a control plane implemented with *controllers* that communicate with *switches* implementing the data plane and are physically responsible for forwarding messages along the network. The communication between control and data planes can be implemented in various ways; nowadays, the de-facto standard is Openflow [15], and an SDN-enabled switch has one or more flow tables, configured by the SDN controller via the OpenFlow API. In normal operations, a flow table contains rules that match a given packet header with common networking actions such as prioritization, queuing, packet switching, etc. Besides the split between control and data planes, SDN brings forward two additional significant innovations, that are:

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- a flow may typically be identified by a subset of the packet header field that may belong to different protocol layers (for instance IP source and destination and some combination of TCP/UDP ports);
- forwarding rules may change over time as the controller dynamically makes new decisions on how to route individual flows, possibly reacting to some sort of network behavior.

The SDN approach attracted a lot of interest from both the academic and industrial communities in the last two decades [25]. The ability of this type of architecture to easily adapt to a particular scenario has made SDN a widely used technology to model complex network attack detection and mitigation solutions, but also, albeit less frequently, to orchestrate effective attack campaigns. The goal of this manuscript is to extensively analyze the state of the art regarding SDN security-related research from both defensive and offensive security points of view. We used the methodology of systematic literature review in order to obtain an overview of the main research trends. By studying a large number of papers that treat this topic, we identified the most relevant SDN usage scenarios, considering the common practice, implementation standards, or threat modeling methods. Furthermore, we tried to identify the correlations between SDN security and other developing technologies, such as Network Function Virtualization (NFV) and Machine Learning (ML).

This work is structured as follows:

- After this introduction, Section II lists the related works for the SDN security field and the state of the art in terms of systematic literature review.
- Section III describes the preliminary phase of the work, which is data collection. It describes the source querying and the publication gathering process, as well as the selection criteria.
- Section IV enunciates the research questions, which is the starting point for the qualitative analysis of the selected publications.
- Section V presents the results of the literature revision, providing both qualitative and quantitative information, giving priority to the qualitative ones which are the main goal of this work.
- In Section VI-B, the correlations between articles' keywords found in the abstracts and the correlations between research questions are presented, to highlight the main connected topics.
- Final remarks are presented in Section VII, with a particular focus on the open challenges we found to be relevant during the writing of this literature review.
- The last Section VIII provides overall observations and final conclusions.

II. RELATED WORK

There are some works that provide classic survey/review of offensive and defensive security applications of SDN. The main difference with the present work is that they either do not use a systematic approach or are not as general and comprehensive.

In fact, many reviews focus vertically on DDoS attack detection or mitigation, not considering other types of attacks or threats. Relevant works include:

Authors in [18] reviewed around 70 DDoS detection and mitigation mechanisms in SDN networks and discussed challenges to developing defense mechanisms for DDoS attacks. As far as we know this is the published work that is closest to this manuscript since the majority of the current literature (as it will be pointed out in section V-B2) focuses on DDoS detection. This is the only systematic review that is partially close to our proposed work.

In [2] otherwise authors proposed a survey about DoS and DDoS mitigation techniques in SDN. This work categorizes DoS in SDN into two groups: DoS attacks in SDN and SDN-based solutions to tackle DoS attacks in the networks.

In [9] authors presented a survey about DDoS attacks in SDN and Cloud Computing architectures. In section IV, the authors outline the tools mostly used in SDN and Cloud Computing. We believe that an important driving factor in SDN research is the presence of a few largely used technologies.

In [12] a literature review is presented, regarding various DDoS defense mechanisms to protect against attacks at every level in the SDN. Furthermore, a taxonomy of DDoS defense mechanisms is presented, based on attack targets.

Although these works proved to be well received and have been the inspiration for our review, we argue that they lack a more in-depth horizontal analysis of all possible SDN threats and attacks.

For this reason, we considered also some related work that tried to have a wider analysis of the security threats on SDN.

In [7] authors listed vulnerabilities and information security threats in SDN. This survey first divides threats into the control plane, data plane, and host/channel vulnerabilities and then proceeds to list information security issues and possible countermeasures to guarantee confidentiality, authenticity, integrity, consistency, and availability.

In [ds169] authors otherwise tackled the problem of SDN security issues classification according to the STRIDE threat model categories.

In [ds81] authors described a set of threats and vulnerabilities in SDNs derived by intrinsic problems of the paradigm or misconfigurations.

In [27] authors presented a survey on cyber-defense measures developed using SDN. This survey includes malware and social engineering as attack vectors. In this survey, the interesting topic is social engineering, which declined in the flavor of phishing.

There are also surveys that analyze the security of the control plane, in terms of infrastructure configuration which is something that we also evaluated in our work; e.g.:

In [1] a survey that analyzes the decentralization of different SDN controllers is proposed. Other than this, the manuscript goes through a number of different parameters which comprise security.

In [ds138] otherwise an analysis of the main threats and vulnerabilities of SDN controlled IoT environment, at the control plane, is performed.

Also, the scientific community proposes works that aim to review existing SDN-based solutions to detect and react to attacks with state-of-the-art paradigms such as NFV and ML.

In [11] for example authors presented a survey that analyzes strategies to monitor, protect and react to IoT threats. The authors believe that security solutions that combine SDN and NFV are not often considered in the literature but there are several advantages (in terms of scalability, on-demand network programmability, energy efficiency, and mobility support) to revert this trend.

In [21] finally a review is shown evaluating techniques of Machine Learning/deep learning used to develop SDN-based NIDS models. The authors believe that with the help of ML/DL, SDN-based NIDS can be used in critical infrastructures.

Although literature that tackles certain specific topics of SDN is rich and established, we argue that there is no **comprehensive** and **systematic** literature review on offensive and defensive cybersecurity solutions based on SDN.

The related works that we discussed did not use a systematic approach or did not include the different aspects of cybersecurity. We believe that the maturity of the SDN paradigm makes it relevant and strongly justifies a systematic analysis of the literature.

However, to our knowledge, a systematic literature review about SDN Security solutions both from an offensive or defensive point-of-view has not been realized yet.

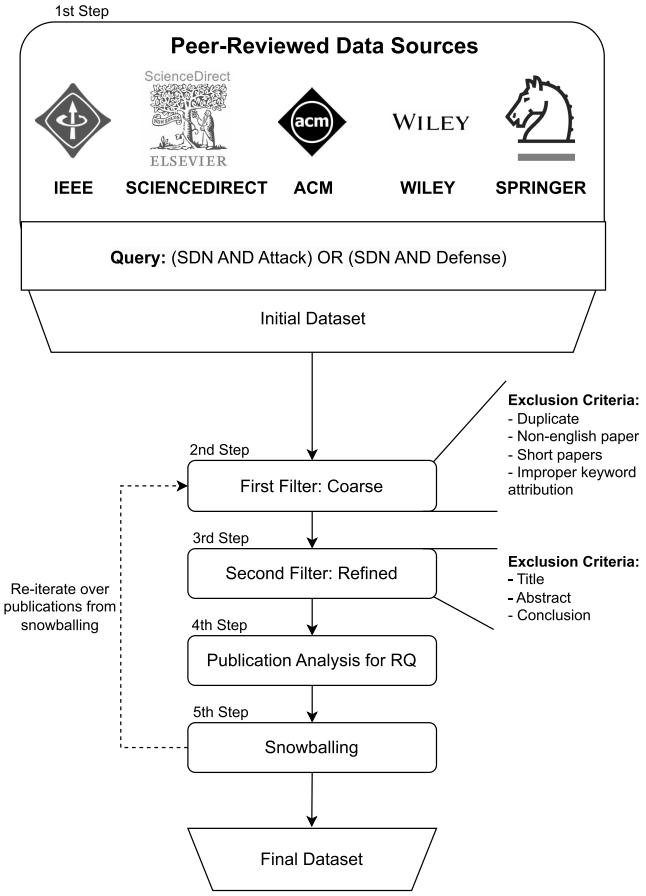


FIGURE 1. Schema of the method followed to gather the dataset for this survey.

III. REVIEW METHOD

In this section, we describe the methodology of our systematic review. Following the guidelines by [19], and as depicted in Fig. 1, we started by searching and retrieving the literature for relevant publications from several data sources by using the same keyword query. We then performed a manual revision process of the automatically selected publications to exclude those that fall out of the scope of this study. The resulting dataset consists of 466 publications. We analyzed these publications to collect statistical and objective answers to our research questions, which are detailed in Section IV.[1]

A. SELECTION QUERY AND COLLECTION OF PUBLICATIONS

In the literature, we can find many security aspects related to SDN. In several cases, these aspects are also part of wider application contexts such as Blockchain and Edge Computing. For this reason, the use of the query "sdn AND security" produced more than ten thousand papers, an amount that would make it a daunting task to find any meaningful insight.

We, therefore, opted for a more restrictive query:

"(sdn AND attack) OR (sdn AND defense)".

[1]The list of the publications and their bibliography information is publicly available at https://doi.org/10.5281/zenodo.6959369

In this work we focus on papers that propose specific solutions, entailing the usage of SDN for offensive or defensive purposes. Accordingly, we looked at how SDN can be used to create infrastructure to perform attacks or to create or host defense mechanisms.

Given the potential unmanageable size of the data set, an additional pre-selection criterion we adopted was to consider white literature only: in terms of quantity, it represents a very meaningful sample of the research produced during the considered time frame, and in terms of quality, it allowed us to rely on peer-reviewed papers only. Thanks to the more uniform organization of white literature, we are also more confident in the level of consistency of our choice and application of the selection criteria. This is not to say that grey literature is not worth investigating. Blog posts, personal websites, technical reports, white papers, etc., are often the preferred venues for practitioners to share ideas. However, as also pointed out in [20], "it is very difficult to uniquely measure the quality of grey literature when conducting a systematic, controllable, and replicable secondary study" and we are not aware of a standard method for the evaluation of grey literature.

It was also decided to limit the search to papers published from 2015 onwards. We have therefore collected 3494 papers, coming from 5 distinct sources:

TABLE 1. Related work classification based on the topic.

Category	Description	Articles
SDN	Review or Survey about SDN Security vulnerabilities and defence mechanisms	[bb7], [ds169], [bb27], [ds81], [bb21]
SDN + Other Topic	Review or Survey about SDN and another topic combined	[bb1] (SDN and controller decentralization) [ds138] (SDN Security and IoT) [bb11] (SDN Security and NFV)
DDoS	DDoS attacks and defence mechanisms against SDN architectures	[bb2], [bb12], [bb12], [bb9]

- ACM (https://dl.acm.org/), 776 paper;
- IEEE Explore (https://ieeexplore.ieee.org/), 940 paper;
- Science Direct (https://www.sciencedirect.com/), 1143 paper;
- Wiley (https://onlinelibrary.wiley.com/), 192 paper;
- Springer (https://link.springer.com//), 443 paper.

The publications were collected up to December 2021, using the academic subscriptions provided by the University affiliation of the authors.

B. PUBLICATION TRIAGE

The publications obtained from the process described above were further reviewed in two steps, each consisting of different exclusion criteria. During the first step, for each paper, we checked the presence and frequency of the search keywords *SDN, Attack* and *Defense* in the text. We discarded the papers characterized by a small and irrelevant use of the above keywords, i.e. those with less than 4 occurrences of the term *SDN* or both of the terms *Attack-Defense*. We have also removed the papers in which the terms are mentioned exclusively in the bibliography and those where the keywords are interpreted in a different way than intended.

We then discarded publications not written in English and those consisting of less than 4 pages. Lastly, we proceeded to eliminate any duplicate papers, received from more than one data source.

In the second step, we performed an analysis of the title, the abstract, and the conclusions of each publication and we discarded the papers where the SDN or the Security topic was just orthogonal to the main paper goal.

Summarizing, we performed a paper filtering operation based on the following exclusion criteria (**E**i):

- E1: The paper includes parts about SDN, although this is not the central topic;
- E2: The security of SDN, in terms of attacks or defense measures, is not a topic of the paper, or it is not the main one;
- E3: In the body of the paper there are less than 4 occurrences of search keywords *Attack* and *Defense*;
- E4: The concatenated text of the title, abstract, and conclusions does not present any of the search keywords.

At the end of this process, we then obtained a final dataset of 466 papers, distributed across the following publishers:

- ACM (Digital Library – https://dl.acm.org/), 96 papers;
- IEEE (IEEExplore – https://ieeexplore.ieee.org/), 190 papers;
- Elsevier (Science Direct – https://www.sciencedirect.com/), 68 papers;
- Wiley (Online Library – https://onlinelibrary.wiley.com/), 40 papers;
- Springer (Online Library –link.springer.com/), 72 paper.

IV. RESEARCH QUESTIONS

In this section, we present the research questions that guided our systematic review.

Usually, the research questions for systematic literature reviews are fairly broad and not more than six. In our study, we chose to adopt more questions (14) but mostly dichotomous (i.e., with yes-or-no answers), with the goal of favoring precision and objectiveness.

To define the questions and seek guidance in categorizing the relevant security issues for SDN and Security, we took inspiration from the related work presented II, as well as from the state of the art in standards and methodologies such as [23]. We grouped the research questions into 4 groups (**G**i):

- G1: Threat Model. Questions on how to classify and identify threats.
- G2: Security approach. Questions about the security approach adopted, for example, whether threat prevention, identification, or mitigation mechanisms are used.
- G3: Infrastructure. Questions on the infrastructure study subject.
- G4: Primary goal. Questions on the main purpose of the paper being studied.

A. FIRST GROUP: THREAT MODEL

Mapping the usage of threat models is important to see gaps when a security the violation must be handled, or if known models are outdated and need to be adjusted. The usage of a formal threat model has proven to be extremely useful in the identification of attack types and their strategic countermeasures [6].

Several threat models exist in the literature. The most famous one is STRIDE [13] named after the Spoofing, Tampering, Repudiation, Information Disclosure, Denial of Service, and Elevation of privilege security threats. Other threat models however exist, such as PASTA [24] or OWASP [16].

In our review and with this first group of questions, we aimed to understand whether a publication fol-

lowed a known model, strategy, or guideline. Alternatively, we wanted to know if new security models were proposed. This group is composed of the following questions:

- Q1: Does the paper consider STRIDE aspects?
- Q2: Even without explicitly mentioning STRIDE, does it involve at least one of its features such as:
  - Spoofing
  - Tampering
  - Authentication and Authorization
  - Repudiation
  - Information disclosure (privacy breach or data leak)
  - Denial of service
  - Elevation of privilege
- Q3: If considered, does the paper propose/discuss a concrete implementation/solution developed by the same author or just one taken from the literature?
- Q4: Does the paper consider, propose or follow another relevant threat model rather than STRIDE or some proposed by the same authors? (e.g. PASTA., or any other threat modeling by design approach)
- Q5: Does the paper mention policies/workflows/guidelines to handle violations?

B. SECOND GROUP: GENERAL APPROACH

Securing a network of computers is a complex process that has numerous aspects to take into consideration. The second group of questions aims to provide a more detailed picture of the implemented functionalities and approaches adopted in the literature concerning this study.

This group is composed of the following questions:

- Q6: Is the paper mentioning IDS functionalities?
- Q7: Is the paper mentioning IPS functionalities?
- Q8: Is the paper mentioning Threat Intelligence?
- Q9: Is the paper mentioning Exfiltration Leaks?
- Q10: Does the paper approach/address insider threats?

C. THIRD GROUP: INFRASTRUCTURE

The SDN approach provides *by design* extensive integration with complementary architectures, such as NFV, which allow the entire network to be virtualized, providing centralized control and orchestration capabilities; there is also the possibility, during the implementation phase of the network, to make use of existing software components. This fourth group's questions aim to obtain a detailed classification of the infrastructures proposed in the selected papers.

This group is composed of the following questions:

- Q11: Does the paper use NFV management/orchestration?
- Q12: Does the paper mention known technologies such as:
  - Onos
  - Ryu
  - Open Source Mano
  - Mininet
  - P4 language
- Q13: Does the paper mention/use Machine Learning techniques?

Insights

Insights: In the following subsections, we highlight in boxes (like this one) the main insights that emerge from our analysis. From each insight, an open challenge ensues, which we summarize in a bold typeface at the start of its description. We will use these challenges in Section V to structure our discussion about useful future directions for research on SDN security.

D. FOURTH GROUP: MOTIVATION

Finally, the fourth group focuses on the purpose of the publications under review, examining whether there are research trends in a specific context or relative to a specific category of attacks.

This group is composed only of one question, aimed to look if the paper studies a specific attack type:

- Q14: Is it a paper focused on a specific attack?

The motivation for defining this last question comes from the fact that, based on our experience, we expected a predominance of jobs dedicated to denial of service. Consequently, the question aimed to select the paper where there is a clear attack type studied, and then we used such information to categorize also the attacks. These results are reported in detail in section V-B1.

V. REVIEW RESULTS

In this section, we present the results of the literature review. We start by presenting quantitative results from the metadata of the publications in the dataset. This is useful to map the trends of the research over time as well as the current shape of the field, in terms of the number of contributions, type (proceedings, articles), communities, and keywords. This is followed by a qualitative analysis which aims at providing a detailed insight into existing research patterns, gaps, and uncovered areas of the field.

A. METADATA ANALYSIS

We start our quantitative analysis by presenting in Fig. 2 the time distribution of the selected publications. As expected, the interest in the topic has been increasing constantly in the considered time frame, as proven by the trend of the number of publications since 2015.

1) PUBLICATION OUTLETS

For the quantitative analysis, we considered the metadata of the selected papers, thus performing a preliminary classification. In Fig.2 the temporal distribution of the publications is shown: as we argued, there is an increasing trend in the number of papers over the years; this is certainly a consequence of the growing interest in SDN security both from the

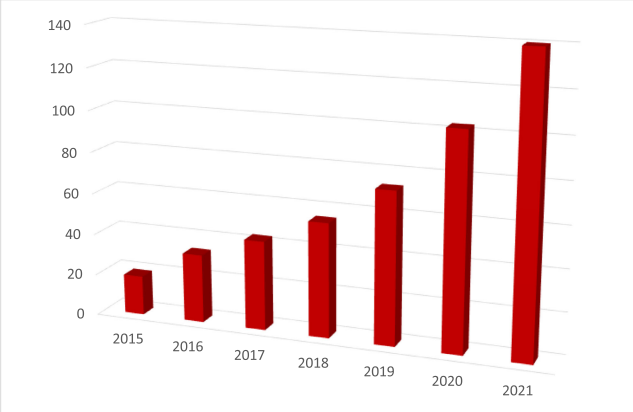


FIGURE 2. Paper distribution by year.

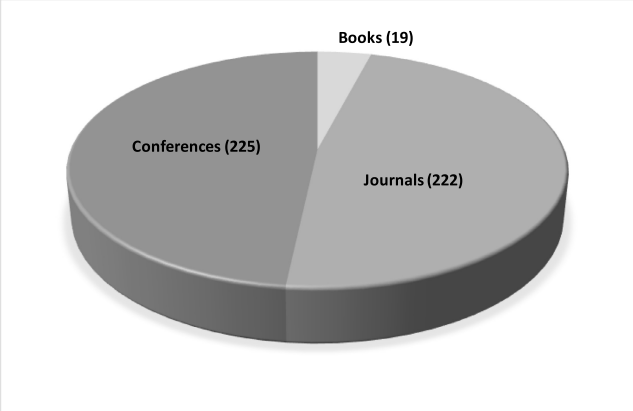


FIGURE 3. Paper distribution by type of publication.

academic and industrial worlds [ds303], [ds416]. A classification by publication category follows, in Fig. 3. As expected in the final data set we found also several reviews and surveys, 44 papers precisely, that satisfied our requirements described in III.

We continued with a classification by publication site, depicted in Fig. 4. The names of the conferences and journals are shown in the graph with their official acronym, if available. With reference to the conferences, it can be derived that there is a relatively uniform distribution among the various publication sites; this is not so true for journals, where there is a predominance of CN and IEEE Access, followed by NCA and IJCS with lower frequency (see App. VIII-B for the acronyms).

B. QUALITATIVE RESULTS

In this section, we make considerations derived by reading the selected papers and evaluating them in the light of the research questions, presented in Section IV.

1) THREAT MODEL

From the combined result of questions Q1 and Q4, we can derive that the papers that use threat models are 17% of the total. Among these, only 7 adopt the standard STRIDE model. In addition, there are 12 papers that, even if they do not use it, mention STRIDE in relation to existing literature.

STRIDE is used on surveys that aim to carry out wide-ranging studies on the safety of SDN; these papers do not focus on a single attack, rather aiming to classify and evaluate sets of attack [ds15], [ds34], [ds383]. In 3 papers, STRIDE is mentioned in connection with monitoring and measurement tools [ds76], [ds92], [ds141]. An important thing worthy of notice is that most of these papers that explicitly use STRIDE are 2015 and 2016 papers, which indicates that, however still considered, threat analysis is moving to a new evolution of Threat models, especially for SDN environment.

Without explicitly mentioning the STRIDE threat model, there are 302 publications - 64% of the total - that satisfy question Q2 and therefore deal with these aspects. A graphical representation of the distribution of the attacks considered in the papers is provided in Fig. 5. As can be easily seen from the graph, the papers tend to deal with Denial of Service attacks and their related aspects; the remaining attacks, namely Spoofing, Tampering, Repudiation, Information Disclosure, Authentication, and Authorization, are widely present in the literature, albeit to a lesser extent. Finally, only 7 papers deal with aspects related to the Elevation of Privilege, one of which [ds15], however, uses the STRIDE threat model.

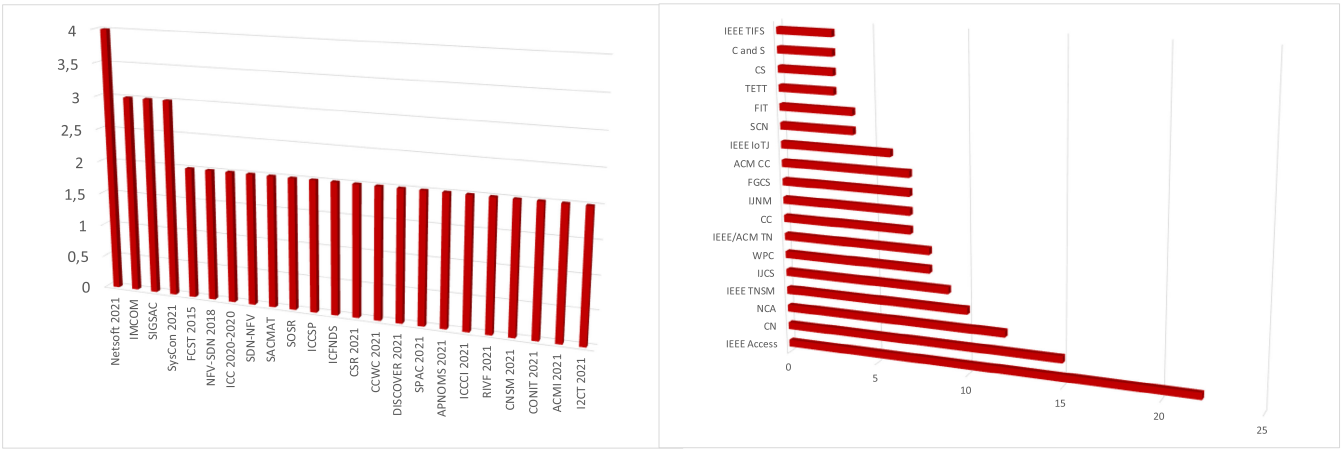
Apparently, the PASTA threat model is never mentioned, let alone adopted. It is therefore possible to state that the most widespread trend is the use of custom threat models, formulated *ex novo*, except in rare cases [ds260], [ds336], [ds404], [ds419]. The custom threat models are mostly aimed at mitigating specific attacks - of a very heterogeneous nature - and are totally tied to that specific threat, making it impossible to generalize them.

Furthermore, threat models are used extensively in connection with DoS/DDoS attacks. These classes of attacks are made up of numerous execution modes, each exploiting a particular vulnerability; the threat models formulated for DoS/DDoS cover in detail a single attack scenario. We argue that there is a lack of a common structure in the threat models, which can form a basis for developing specific models for the different DoS/DDoS attacks.

In conclusion, the analysis did not reveal the predominance of any standard formalism for threat models; this is certainly due to the complexity of the SDN architecture and to a large extent the trend to use SDN in relation to Denial of Service attacks (see Section V-B4).

Insights

Fragmentation of outlets: There are no reference venues for the area of SDN security. This makes it difficult for researchers and practitioners to keep up with the state of the art, as well as to find dedicated conventions where they can discuss this topic with the rest of the community. This is particularly evident with conferences, while we can identify 4 to 5 journals that collect most of the references.



(a) Conferences (b) Journals

FIGURE 4. Paper distribution according to publications site (the acronyms refers to major journal and conferences and are explained in the Appendix).

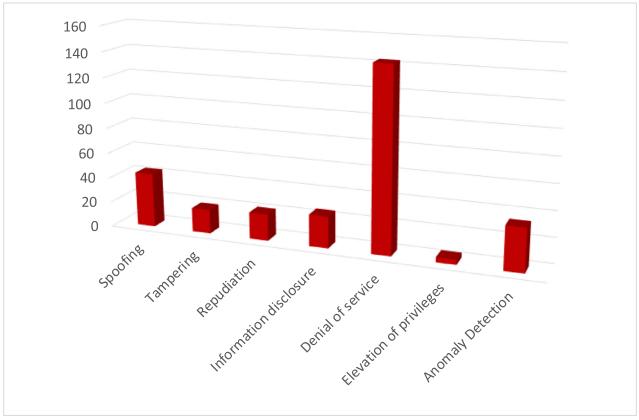


FIGURE 5. Paper classification based on attack type.

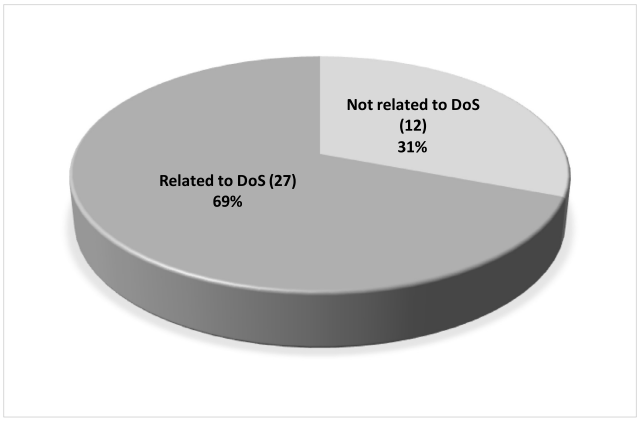


FIGURE 6. IDS/IPS distribution according to the denial of service attacks.

2) SECURITY STRATEGY/APPROACH

From questions Q6 and Q7 we can see that 37 papers mention SDN solutions that rely on IDS functionality, thus accounting for 8% of the total of the articles. Furthermore, 17 papers that mention IPS, 4% of the total. Overall, 54 articles talk about IDS or IPS (Q6 OR Q7).

As in the previous section, there are many differences in the implementation, the proposed architectures, and on the objective of the work. An overview of the collected data can be found below:

- Several papers, such as [ds22], [ds61], [ds234], [ds367] propose IDS functionalities implemented at the SDN controller level, in a case in particular [ds398], deployed in the cloud. Furthermore, others propose controller-level implementations of Ryu (sometimes in connection with the Snort software) [ds50], [ds109], [ds389]. Generally, there is a close and growing relationship between intrusion detection and the use of Machine Learning techniques such as [ds178];
- The works [ds246], [ds260], [ds313], [ds442] implement at application level some sort of IDS/IPS service;
- [ds392] features an IDS architecture integrated into an OpenFlow switch, resulting in an Anomaly Detection Rate of 91.98% and a false positive detection rate of 0.55%, considering multiple attacks;
- [ds6], [ds25], [ds195] instead propose more complex systems, structured and implemented on multiple levels of the SDN;
- [ds136] and [ds346] just propose the study of sampling methods for IDS;
- [ds388] implement a Collaborative IDS, external to an SDN network, based on Snort for intrusion detection and on blockchain to protect the transmitted data, capable of detecting different types of attacks and with particular pay attention to the insider threats to which the collaborative model is exposed. Blockchain-based verification for IDS seems to be a new growing trend in the fields, with interesting applications shown in [ds211], [ds239].

Insights

Dedicated attack trees and threat models: While there are attacks that specifically choose SDN for both the offensive and defensive approach, such as those that leverage the scalability of SDN architectures to cause a denial of service, there are no dedicated threat models to help developers become aware of those particular threats.

Insights

Global view/control: The centralized nature of the SDN controller introduces the need for technologies that provide global yet decentralized observability and control, i.e., tools that aid in the enforcement of security policies over a whole architecture without single points of failure.
Reaction & recovery techniques: while we found solutions to prevent and detect attacks, there are only a few proposals of SDN-based active defense systems that could react to and recover from them.
Comprehensive technological references: SDN use diverse sets of technology stacks, each characterized by peculiar exploits. To secure such architectures effectively, system administrators need dedicated technological references to avoid known threats.

It should also be noted - as shown in Fig. 6 - that more than half of the papers that satisfy Q6 or Q7 are strictly related to the defense of Denial of Service attacks, further confirming the predominance of the latter area in the literature. There is hardly any mention of Threat Intelligence (Q8, 3 paper); Exfiltration Leak (Q9) and Insider Threat (Q10) are dealt with to a greater, but still limited extent, for a total of 25 papers.

3) INFRASTRUCTURE

The adoption of the NFV paradigm is a natural complement to SDN that allows obtaining a completely virtualized network architecture and facilitates the monitoring and management of the network. There is a medium-low presence (of about 12%) of works that exploit NFV (Q11) in the dataset. The trend is therefore to consider the SDN architecture standalone, considering only threats and security vulnerabilities that concern SDN *per se*. However, some papers present software implementations on NFV, which demonstrate how network orchestration can assist the security of SDN. For example, [ds277] exploits NFV to implement a *Data Plane* monitoring system based on Machine Learning techniques to detect botnet attacks. Reference [ds155] presents a *closed-loop* system, where NFV monitors traffic to detect DDoS attacks and alerts the SDN controllers whenever an attack is spotted, in order to adopt mitigation measures. In [ds194] otherwise, authors proposed a monitoring and security framework for multi-access edge computing infrastructure based

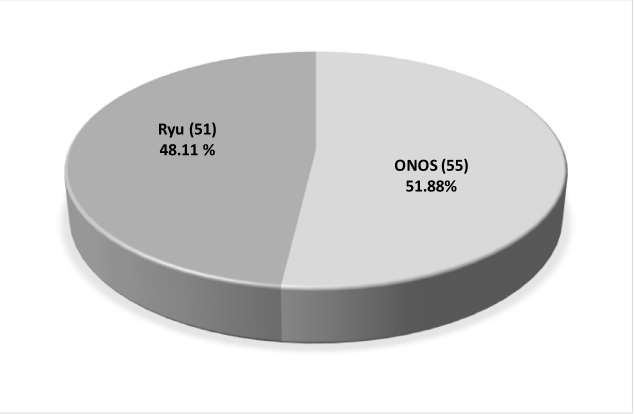


FIGURE 7. ONOS and Ryu mentions.

on the deployment of NFV over an SDN architecture. NFV certainly takes on more relevance when it is used in more structured areas, such as Cloud computing or 5G. In fact, the following contributions can be highlighted:

- [ds438] proposes a security framework for 5G, based on SDN/NFV;
- [ds121] implements two VNFs and an SDN application, in order to detect and mitigate botnet attacks in 5G;
- [ds6] presents an IDS/IPS, based on SDN/NFV and designed for the protection of 5G networks.
- [ds456] presents a service function chain deployment in cloud-fog computing networks

We then tried to understand if there are common ways of orchestrating or managing NFV architectures, for instance, adopting the ETSI NFV-MANO approach, and maybe exploiting the open-source implementation Open Source Mano (OSM) made available by ETSI. Following a targeted check, in connection with question Q12, it appears that in the analyzed papers there is no mention, let alone of the adoption, of OSM. Our feeling is that the management and orchestration of the virtualized network infrastructure are not considered relevant in the literature we have analyzed.

In this group of questions, we also evaluated the number of publications that mention or are based on known open-source implementations of SDN-related building blocks, such as Mininet for network emulation or Onos and Ryu as controller implementations. A medium-high number of publications - 180, equal to the 38% of the total - mention at least one of these technologies.

Onos and Ryu are widely mentioned in relation to IDS/IPS or simple threat detection mechanisms (see section V-B2). In Fig. 7 we show the distribution of the mention of Onos and Ryu in the papers that satisfy Q12. Regarding this, we highlight a survey that aims at fully analyzing the security of SDN controllers comparing the main open-source implementations.[2] In this work, 9 principles are suggested and

[2]OpenDaylight (Lithium), ONOS (Junco), Ryu (3.5), Floodlight (1.2), OpenContrail (R4.0).

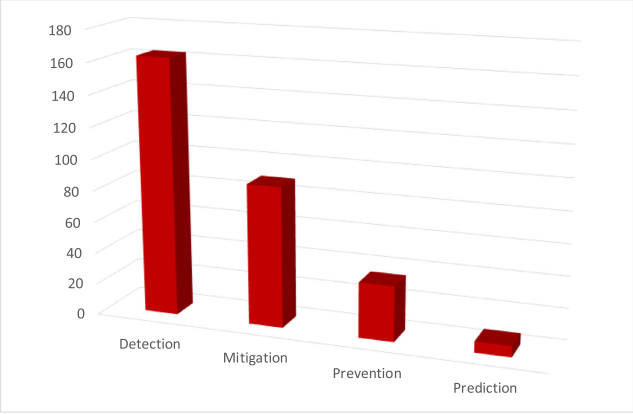


FIGURE 8. Machine learning usage in DoS detection and mitigation.

explained as a methodology to safeguard an SDN controller [ds383].

Dixit et al. [ds101] identify vulnerabilities in infrastructures that use NMDA[3] and show their impact and risk on the availability, integrity, and confidentiality of an SDN network.

The P4 language usage is very scarce in the literature considered. Noteworthy contributions are [ds440] that proposes,[4] a new architecture for packet parsing, integrated into SDN switches and strongly based on the P4 language specification and on the security *by design* offered by Blockchain, and [ds466] where authors propose a packet forwarding control mechanism based on P4 for software-defined networking.

Finally, the use of the Mininet network simulator is very widespread: 160 papers out of the 180 that satisfy Q12 mention this software. Mininet seems to be very effective and widely used for simulation and evaluation purposes of the research carried out.

About one-third of the considered papers adopt or mention Machine Learning techniques and algorithms (Q13). There is a strong correlation between Machine Learning and IDS/IPS systems, as seen in sect. V-B2. While not implementing real IDS/IPS, there is a large number of papers dealing with the detection and mitigation of attacks, mainly Denial of Service. Here too there is an evident influence of the Machine Learning world. Further considerations in this regard are provided in the next section.

Insights

SDN solutions are built around commercial technologies: Commercial controllers such as Onos and Ryu are widely used. NFV is mostly used as a supporting technology to the SDN while Mininet is by far the most used software to simulate the use cases. Most of the papers considered adopting a traditional SDN approach to the infrastructure since the P4 language is usually not the first option.

[3]Network Management Datastore Architecture.
[4]Blockchain-enabled Packet Parser.

4) MAIN GOAL

In this subsection, we continue discussing the information obtained regarding the general main purpose that can be inferred from the dataset. By briefly examining the data, it is clear that the absolute majority of the works aim to protect against Denial Of Service attacks (Derived from Q14). In fact, 186 papers - 39% of the total - propose strategies to detect, mitigate, prevent, or predict the attacks in question. Furthermore, as anticipated in Section V-B1, we can count a total of 231 papers (50%), if we also consider papers that do not deal exclusively with DoS. Fig. 8 shows the distribution of contributions by defense method implemented: we find the highest frequency in detection and mitigation strategies, often implemented jointly. There are also contributions related to methods of prevention and prediction, albeit to a lesser extent; these usually have to do with the implementation of real IPS: for example, in [ds109] an IPS that includes a Honeynet is proposed, in [ds398] otherwisethe IPS is an NFV that can be deployed into the cloud. SDN has in fact been also used to perform deep packet inspections, as proposed in [14].

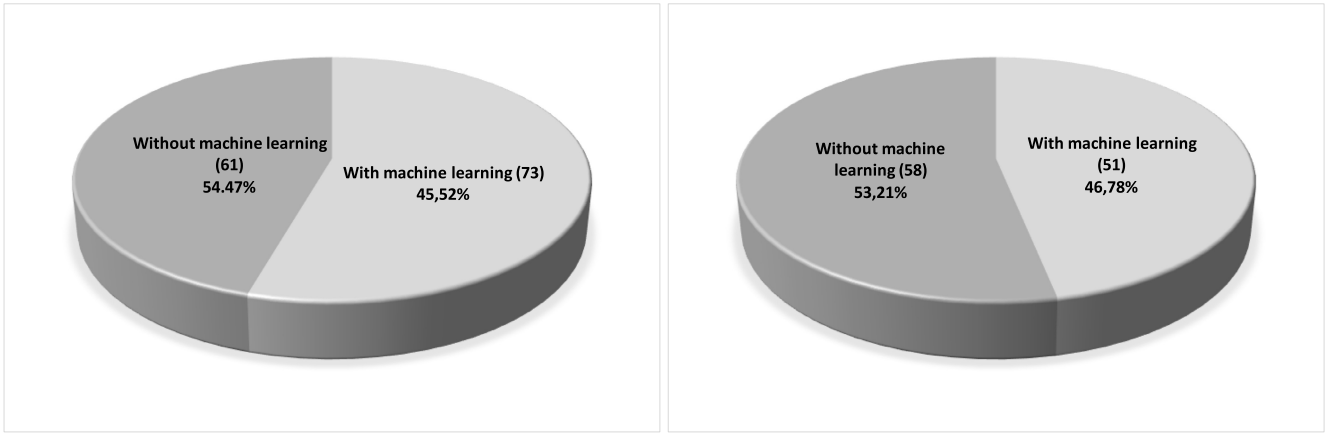
Recalling the detection and mitigation methods, in Fig. 9 it is possible to see how both are strongly linked to algorithms or Machine Learning techniques; therefore, a good rate of effectiveness is shown in the use of Machine Learning to tackle DoS.

With regard to industrial network environments, there is a low number of contributions (derived from Q14). However, some of the 8 papers that meet these requirements are noteworthy. For example, [ds283] proposes a reactive security mechanism based on SDN/NFV to monitor industrial networks, in which there is also a honeynet. Similarly, [ds315] aims to protect ICS by providing policies for monitoring, detecting, and re-configuring networks via SDN/NFV.

Regarding the mitigation of non-DoS attacks (derived from Q14), there are some articles - in total 15 - dealing with port scanning and spoofing (IP/ARP). These attacks are mostly mentioned in conjunction with DoS, in the context of the IDS/IPS systems described above.

There are also a small number of articles dealing with particular attacks, not related to DoS, to which SDN is vulnerable. The most interesting are:

- In [ds428] the network isolation attack is discussed, which allows an attacker to access user network privileges without being aware of this. An implementation based on ONOS is proposed, in order to prevent this attack and other spoofing attacks;
- Zhao et al. [ds459] highlight the problems deriving from the link discovery process of SDN networks, proposing a new operational scheme. The experimental evaluation shows that this scheme is able to solve link fabrication problems;
- [ds151] extends the study of the aforementioned problem, discussing topology poisoning attacks by proposing a topology verification scheme to prevent host hijacking and link fabrication attacks.



(a) Detection (b) Mitigation

FIGURE 9. Machine Learning usage distribution for DoS Detection and Mitigation.

- [ds42] deals with DDoS but the solution, in this case, is to protect the SDN controller itself.

Insights

Denial of Service-oriented research: The most common objectives of the papers are mitigation, detection, and prediction of Denial of Service attacks. The papers usually do not deal with industrial topics or attacks different from DoS.

5) MACHINE LEARNING USAGE

A well-defined trend in the dataset is the use of Machine Learning techniques within SDN solutions. The first works appear as early as 2015 but over time the use of ML algorithms to support SDN security analysis has become an increasingly common solution. We also find this trend in our dataset where 163 papers (about 34% of the total) consider Machine Learning techniques and algorithms. The techniques used are different, ranging from Random Forest classification to the most common Bayesian statistics up to reinforcement learning techniques. One pattern, however, is quite clear and sharp. Most of the papers use Machine Learning on DoS attacks. Since it was impractical to describe all 163 papers, we have prepared Table 2, which groups them by category and type of Machine Learning technique, describing those that we consider relevant.

Most of the papers deal with classic DoS, more precisely DDoS. The main purpose of the majority of the works is, of course, to identify and mitigate an attack in progress. Most of these jobs, therefore, try to replace an IDS or create rules for the same IDS to which they link. In works such as [ds45], [ds365], [ds391] for example, authors evaluate several Support Vector Machines (SVM) techniques to detect abnormal behaviors and attacks as early as possible. An important research branch uses Machine Learning directly on the controller, to try to defend or mitigate the effects of a DoS attack. The centralized nature of SDN controllers, in particular, is a topic that this context has been widely discussed.

For example, in [ds253] the authors proposed a Supervised Learning Approach to Mitigate Host location Hijacking Attacks, implemented in the SDN controller. This plugin controller monitors the legitimacy of the hosts and identifies users impersonating the hosts in the data plane, and can be deployed in both centralized and decentralized SDN controller setups.

In [ds349] a new full architecture is otherwise proposed, spanning the stack from the data plane to the application level, able to both identify DoS attacks and trigger events to mitigate them at every level of the architecture.

A similar strategy has been used in [ds256], where the authors proposed a microservice-based controller architecture that is able to efficiently scale horizontally in case of a DoS attack.

In [ds3] otherwise, authors identify five control functions required by a realistic production network to accomplish essential network services, and then they analyze threats and defense mechanisms pertaining to these five functions when implemented by L2 networks. A new evaluation framework to objectively compare the security of both network paradigms is provided, using two threat models.

In [ds445] the DDoS detection is based on an entropy detection scheme, which is implemented in conjunction with its respective ISP domain. Another very interesting Machine Learning DDoS detection mechanism can be found in [ds250]. In this case, the authors exploit the features of a programmable data plane in P4 language. A very similar approach has been made in [ds38] where in this case authors proposed a ML classifiers for the mitigation phase, based on five threat vectors that represent compromised controllers.

There are also several works that aim at bringing ML capabilities inside the controller for specific DoS attack vectors. A good example is [ds181], where authors analyzed three supervised classifiers and four semi-supervised classifiers for

five types of saturation attacks (TCP-SYN, UDP, ICMP, IP-Spoofing, and TCP-SARFU) and their combinations, through a detection framework which uses controller monitoring data such as CPU utilization, channel bandwidth, and flow table utilization.

Another important trend that we have found is deep/reinforcement learning, which leverages one of the strengths of SDN. We noticed that this ML technique is widely adopted to identify anomaly behavior (especially DoS). The main reason for this choice is that it exploits the reconfiguration capabilities of the SDN architectures which allows real-time generation of aggregated data. Reinforcement learning exploits these features by feeding algorithms with new rewards.

For example in [ds189] authors propose a non-intrusive traffic sampling mechanism for multiple traffic analyzers on an SDN-capable network using a deep deterministic policy gradient, which is a representative deep reinforcement learning algorithm for continuous action control.

In [ds353] a framework is developed, with a deep learning Boltzmann machine-based flow analyzer to identify the anomalous switch requests. This framework is then integrated with a blockchain mechanism in which all the switches are registered, verified (using zero-knowledge proof), and, thereafter, validated in the blockchain using a voting-based consensus mechanism.

Previous works used Deep Learning in order to strengthen the mitigation mechanism for large-size attacks. But there are also several works that use Deep Learning to improve the detection phase. A good example is presented here in [ds407] where a DDoS attack detection method based on information entropy and deep learning is proposed. Primarily, suspicious traffic is inspected through information entropy detection by the controller. Then, fine-grained packet-based detection is executed by the convolutional neural network model to distinguish between normal traffic and attack traffic.

A recent alternative approach is presented in [ds105] where a new deep learning algorithm, denoted the Parallel Online Deep Learning algorithm, is defined in order to update weights on the fly according to both aforementioned constraints simultaneously. A weight defines the amount of data allowed which can be transmitted by a node and that is dynamically updated according to its contribution to the queuing capacity of the controller, and the number of flow rules in the switch. In [ds190] otherwise, authors proposed a feature dynamic deep learning approach for DDoS mitigation within the ISP domain

Deep Neural Networks are also used in conjunction with an IDS in an SDN network, such as in [ds387] where, for the purpose of effective attack detection in a test-bed, a flow-based anomaly detection is deployed with Deep Neural Networks to improve the signature-based IDS limitation with a higher detection rate and low false-positive triggers.

There are also several hybrid approaches that combine a Deep Learning algorithm in support of a well-known one for better long predictions. For example, in [ds227] a hybrid Cuda-enabled DL-driven architecture is proposed, which leverages the predictive power of Long short-term memory and Convolutional Neural Networks for efficient and timely detection of multi-vector threats and attacks.

Another interesting trend in Machine Learning is its vertical usage over a specific category of DoS, namely Low-rate DoS (LDoS) attacks. Machine Learning has been proven to be very effective for this kind of attack. A good example of this approach can be found in [ds462] where to improve the detection accuracy of the low-rate DDoS attack against the SDN data layer, a new method based on Factorization Machine is proposed. The features extracted from the flow rules are used to detect low-rate DDoS attacks, and the detection of low-rate DDoS attacks based on Machine Learning algorithms is implemented.

Similar work has been made in [ds312] where authors, taking advantage of flow based nature of SDN, proposed a Generalized Entropy (GE) based metric to detect the low rate DDoS attack to the control layer. In [ds372] otherwise, also the mitigation steps after detection are introduced, with a framework based on the histogram-based gradient boosting and finding peaks algorithm to detect LDoS attacks and mitigate their influence in the SDN in real-time. In [ds66] the machine learning algorithm is otherwise used to choose the target in the moving target defense scenarios. Considering a specific LDoS attack against port (Portscan), interesting work is [ds267], where a detection and mitigation system of DDoS and Portscan attacks in SDN environments (LSTM-FUZZY) is presented.

One of the most relevant trends for Machine Learning applied to the security of SDN is the adversarial attack/behavior. Adversarial Machine Learning is a Machine Learning technique that attempts to exploit models by taking advantage of obtainable model information and using it to create malicious attacks. In the last year of the collected dataset, we noticed an increased interest in this field with applications to analyzing such attacks both from an offensive point of view (generating them) and a defensive point of view (detecting them). A good (offensive) example can be found in [ds17] where, in order to investigate Adversarial Attacks in SDNs authors implemented an anomaly-based NIDS, Neptune, as a target platform that utilizes a number of different Machine Learning classifiers and traffic flow features. Then an adversarial test tool, Hydra, has been developed, to evaluate the impact of adversarial evasion classifier attacks against Neptune with the goal of lowering the detection rate of malicious network traffic.

From the defensive side, two interesting work exists. One can be found in [ds268], where three adversarial training procedures to improve the detection performance of a framework concerning adversarial attacks are proposed. The designed framework detects flooding DDoS attacks based on DL for SDN environments. The second one is otherwise [ds203] where authors use adversarial techniques for the availability

and reliability analysis of cloud computing under economic denial of sustainability (EDoS) attack

Insights

Machine Learning Trend:
There is a strong and clear trend indicating SDN as an enabling and supporting technology for the development of Machine Learning based solutions. Obviously, the application for the detection phase covers the majority of the works, but in recent years interesting trends are becoming increasingly popular such as:

- **Reinforcement Learning** which takes advantage of the ability of SDN networks to reconfigure in a very simple and fast way.
- **Adversarial Behavior** that uses SDN to simulate attacks that can test the robustness of rule-based IDS systems.

6) DoS CLASSIFICATION

The absolute majority of the dataset, as pointed out in V-B4, deals with the Denial of Service attacks. This attack aims at making services unavailable to the intended users by saturating the resources. Usually, these kinds of attacks flood the target with traffic to trigger crashes. Authors in [ds266] propose a solution to counter the flow table attack by adjusting hard and idle timeouts to reduce the number of flow rules. Using packet count, this solution adequately adapts the number of flow rules under a DoS attack. In [ds176] a security SDN solution against DDoS, man-in-the-middle, spoofing/masquerading attacks for IoT is shown. The environment was tested using ONOS. Work in [ds251] proposes a Kerberos-based authentication solution to verify the sanity of new hosts joining an SDN. This solution was designed to counteract controller and host impersonation attacks. Another interesting solution can be retrieved in [ds324] regarding an IDS-like solution to detect attacks in an SDN network using online clustering. This solution was evaluated with 48 databases attacked by DDoS and portscans, obtaining DDoS detection in a relatively short time in every scenario.

In [ds447] a flow message linear analysis model able to effectively detect malicious SDN switches in the Tactile Internet is proposed. It analyses attacks such as controller exhaustion attacks, flow table exhaustion attacks, and flow redirection attacks. In [ds296] indeed authors designed a scalable intrusion detection and prevention system (IDPS) to prevent large-scale SYN-flood attacks in an SDN environment. In [ds328] otherwise a point detector IDS to monitor performance metrics to detect DDoS attacks using constraint programming in software-defined wireless sensor networks (SDWSN) is introduced. In [ds269] authors developed a DDoS attack detection and mitigation system that uses a random forest Machine Learning algorithm. The solution was tested on a Mininet-Ryu testbed using Openflow. Finally, in [ds99] authors proposed a big data framework to contrast processing limitations during large-scale SDN networks DDoS attack, work that has been similarly proposed in [ds179] where the framework deploys a multi-agent autonomous system. Most of the works exploit a large number of external technologies like Machine Learning, NFV, Blockchain, and Convolutional Neural Networks. The literature is overall very scattered in terms of targets and environments considered.

Moreover, the literature strongly concentrates on different flavors of DoS attacks. For example, LDoS is a typology of Denial of Service that aims to intentionally degrade the quality of TCP links by throttling TCP flows to a small fraction of its ideal rate with a periodic small pulse sequence. Work such [ds212] analyzes LDoS attacks by proposing an attack detection system based on Bat Algorithm and BP Neural Network. In [ds418], on the other hand, authors analyzed Slow HTTP DoS (SHD) attacks, the flavor of LDoS that targets web servers. This solution adopts a credibility-based countermeasure against SHD attacks. In [ds373] author proposed a real-time framework to detect LDoS attacks in SDN, named Performance and Features (P&F), which uses Machine Learning. This type of DoS attack is hard to detect since it is effectively hidden in normal traffic and it does not produce a noticeable outcome such as service unavailability.

Another DoS trend in literature is detecting and mitigating Economic Denial of Service (EDoS), an attack that aims to scale up the pay-per-use resource usage to make the cloud user pay an unexpected amount. In [ds100], for example, the authors presented a Neural Networks-based scheme that produces anomaly scores by learning a multivariate attribute. In [ds333] on the other hand, a model to mitigate TCP SYN flooding-based EDoS attacks is implemented. In [ds203] authors proposed a semi-Markov approach aimed to evaluate the availability and reliability of cloud computing under an economic denial of sustainability attack. This kind of attack is very different from traditional DoS since it only focuses on generally producing an economic loss to the target. Moreover, we argue that these kinds of attacks should be studied by also analyzing the carbon footprint they imply.

Moreover, the dataset shows that the scientific community is increasingly focusing on different flavors of DoS, such as LDoS and EDoS. We claim that these new kinds of attacks can be an interesting topic of study for SDN in the future. Another very important task that literature generally poses is to enhance the explainability of these attacks by exploiting the SDN paradigm, by being able to track down the source of DoS attacks, and then develop more fine-grained mitigation solutions and policies to punctually counteract these threats.

TABLE 2. ML-based classification of the paper of the dataset.

ML Technique	Generic DDoS	LDoS	Adversarial Attack
Generic Machine Learning	[ds7], [ds391], [ds45], [ds262], [ds90], [ds182], [ds70], [ds317], [ds364], [ds252], [ds338], [ds115], [ds49], [ds215], [ds302], [ds309], [ds245], [ds295], [ds436], [ds383], [ds322], [ds221], [ds150], [ds103], [ds291], [ds27], [ds116], [ds435], [ds132], [ds135], [ds134], [ds127], [ds380], [ds109], [ds242], [ds171], [ds250]	[ds14], [ds321], [ds128], [ds417], [ds437], [ds155], [ds445], [ds259], [ds327]	[ds253], [ds8], [ds218] [ds62], [ds17], [ds378]
Deep Learning	[ds407], [ds205], [ds227], [ds208], [ds389], [ds16], [ds350], [ds189], [ds450], [ds217], [ds427], [ds288], [ds458], [ds86], [ds348], [ds190], [ds422]	[ds384], [ds353], [ds238], [ds365], [ds105], [ds387], [ds434]	[ds268]
Reinforcement Learning	[ds189], [ds90]	[ds189]	[ds156], [ds444]

Insights

Flavours of Denial of Service: the rise of new flavors of Denial of Service attacks considered in literature outlines new challenges for the scientific community. LDoS and EDoS change the paradigm of tackling DoS attacks, making SDN a useful paradigm to mitigate them.

7) BLOCKCHAIN USAGE IN PROGRAMMABLE NETWORKS

Blockchains [8] and, more broadly, Distributed Ledger Technologies are one of the most trending topics of the last years [10]. In thecontext of network programmability, the main applications of Blockchain-related technologies are related to SDN security [ds263]. The main contribution of Blockchain technologies applied to SDN can be found in [ds263]. As stated in this work, the main solutions exploit the immutable state of the Blockchain to create authentication layers or to increase the overall reliability of the network. One of the adopted solutions is to enforce security policies in the distributed ledger [ds340].

Aside from works described in [ds263], we describe the most popular approaches observed in the dataset. The straightforward application of Blockchains, tied to the design of this technology, is the possibility to build Authentication-Authorization-Accounting (AAA) systems. One of the main examples of this approach can be seen in [ds141], in which the authors propose a system that manages the AAA proprieties through a Blockchain to achieve immutability of the database and native decentralization. This is similar to the work proposed by [ds72], where the authors describe an authentication process, verifiable through the data saved in a Blockchain. In [ds199], the ledger is used to authenticate an IP address that originates traffic. Using this approach, DDoS protection can be easily built. A theme related to AAA is the monitoring of the infrastructure, this feature can be easily certified by a Blockchain. This is the approach employed by [ds399], which verifies the probe's data and commits them using a distributed ledger.

Blockchains can be used to create *collaborative networks*. References [ds112], [ds240], [ds353], [ds388] create networks of this kind to set up a collaborative intrusion detection system, in which the Blockchain is used to build trust in collaboration. Using this kind of setup, the network could be created in a secure way, without rogue intrusion detection and prevention systems.

The Blockchains can be used with protected models to avoid a problem called *Model Poisoning*. This problem can arise using a detection system based on a model trained over a dataset if the dataset gets *poisoned* - e.g. some rogue values get injected with a specific label - the system can be manipulated in order to be controllable by the attacker. As described in [ds29], Blockchain technologies can be used to validate the model and make this attack unfeasible. While being totally transparent by design, the work described in [ds29] protects a model distributed as an Intellectual Propriety, without making proprietary information available to every user. Another interesting path we can identify is represented by the usage of the blockchain throughout machine learning techniques, in order to verify the reputation of a node for several goals, as showcased in [ds171] for crypto miners.

This kind of technology can be integrated into the SDN internal workflow. For instance, [ds5] employs a distributed verifiable ledger to filter and maintain a secure flow database. In this same field deserves to be mentioned the work in [ds239] which is one of few works of this dataset that addresses the insider threat problem, enhancing a challenge-based collaborative intrusion detection network against insider attacks using blockchain. The last technology presented is the integration of the Blockchain in the data plane parsing procedure itself. This strategy is implemented by [ds440]. This work leverages the features of P4 language and blockchain to implement trackable and inspectable policies,

securing that the data plane parser will implement policies certified by the Blockchain.

In Table 3 we summarize the main classes of contributions in the field of Blockchain and network programmability.

Insights

Distributed Ledgers: The adoption of distributed ledgers and Blockchains can undoubtedly help the security of SDN and Programmable data plane ecosystem in various fields. Certified models and monitoring are performed using a so-called Blockchain layer. Whereas most publications are focused on Security, works on performances are present in literature.

8) TECHNOLOGY POPULARITY

A number of different technologies are employed in research activities regarding programmable data planes and Software Defined Networks. These technologies can be divided into research tools and business-related infrastructures and protocols.

One of the most notable examples is the ubiquitous[5] adoption of mininet.[6] This tool is mainly used to generate realistic network topologies, making the experiments reproducible and easy to configure thanks to Python programming language. Python plays a central role in the ease of use, as stated by the literature. Another example of this is the Ryu controller (present in 29 works in our dataset including [ds228], [ds343]). This controller is written in Python and implements themost common switch behaviors. A different controller, which implements also practical web interfaces is ONOS [3]. This controller can be considered easier to configure than Ryu, but a little more cumbersome to extend, due to its core language: Java.[7]

New network programmability paradigms such as P4 or 5g-related technologies (e.g. MEC) are trending in the Network programmability scenario. These technologies, when compared to older technologies such as SDN and containers are still not on the same level of popularity (10 references for P4 and a single reference for the 5g MEC). The possibility offered by these technologies as enablers is the main point of adoption in academic research.

Insights

Technology trends: The flexibility offered by new paradigms is getting more and more traction in the network programmability research field. Ease of use and programming is, probably, one of the main factors that favor the adoption of tools such as mininet or Ryu.

[5]In the dataset there are 62 works that use or refer to mininet, for instance: [ds56], [ds157], [ds175], [ds210], [ds228], [ds233], [ds341], [ds343], [ds360], [ds372], [ds373], [ds378].

[6]http://mininet.org/

[7]https://pypl.github.io/PYPL.html

VI. CONCEPT AND CROSS-CORRELATIONS

In this section, we close our analysis with other two relevant evaluations. First, we created and discussed a keyword text analysis in order to discover any other potential interesting trend. Second, in order to validate the results of our research questions analysis we provide a correlation analysis of the questions, with a quantitative look over the relationships between them.

We conclude with a discussion of potential threats to validity, aimed at preventing bias issues in our methodology.

A. WORD NET CLOUD

The first correlation analysis provides a graphical representation of the most used keywords in the abstract of the contributions in our dataset. To conduct our analysis, we used VOSviewer by [26], a software that offers text mining functionalities for constructing and visualizing co-occurrence networks of important terms extracted from a given corpus. Specifically, we ignored basic words and copyright statements and performed a full count of the words present in the text. We considered only words occurring more than fifteen times, sizing them by their relevance in terms of occurrences. The resulting graph, however, is still too large and complex to convey useful information: for the sake of clarity, we present here a visualization including only the top 75% of most-occurring words.

We report the visualization of the analysis in Fig. 10.

VOSviewer automatically clustered the words in 3 areas using its modularity-based clustering algorithm, which is a variant of the cluster algorithm developed by [4] to detect communities (clusters) in a network that also considers modularity.

We can interpret the clusters as follows:

- The blue (■) area at the top of the figure marks the technical terms of this study, grouping words like *packet* and *layer*. The result is not surprising, since those words describe the building blocks of the domain.
- The green (■) area at the bottom-left corner marks the main terms of the study as *controller* or *attack*. Directly related to the query used to get papers, the results reflect the process as the base of this systematic literature review.
- The red (■) area on the right-hand side identifies properties and application fields, e.g., security, blockchain, and Machine Learning. We find for instance the word *ddos-attack*, as it is mainly cited as a specific property to analyze or protect, rather than a tool to use.

B. CORRELATION BETWEEN RESEARCH QUESTIONS

The amount of data collected in our dataset is large enough to represent a statistically-relevant sample. In this section, we leverage this to study correlations between our research questions, by way of the answers that the publications in our dataset give to each of them. Correlations can be used to understand which of the different aspects of SDN security

TABLE 3. Summary of the analyzed blockchain technologies applied within SDN/Programmable data networks, architecture.

Category	Papers
Authorization or authentication or accountability	[ds141], [ds72], [ds199]
Collaborative Networks	[ds388], [ds112], [ds353], [ds240], [ds239]
Secure Models for IDS or ML	[ds29], [ds171], [ds216]
Secure Monitoring	[ds399]
Security Dataplane-based solutions	[ds5], [ds440]

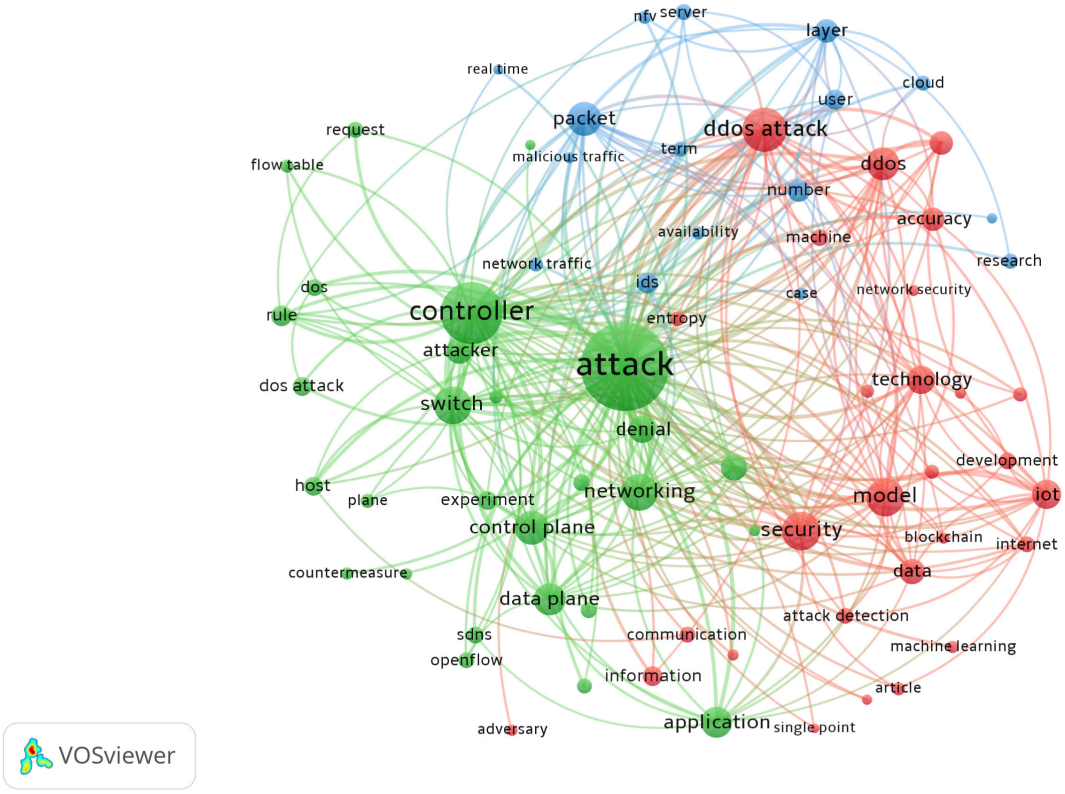


FIGURE 10. Representation of the main keywords found in the abstract of the articles in the dataset. This image was generated with VOS viewer.

offensive or defensive are most commonly in a positive correlation (paired) in the dataset, and which ones are negatively correlated (mutually exclusive).

We report in Table 4 the correlation matrix. While the obtained matrix is symmetric and we could report just one half, in Table 4 we report the full matrix for convenience, to provide a more immediate view of how each question correlates with all of the other ones. We conditionally colored the cells of the Table, first, attributing color intensity according to correlation absolute value—maximal intensity for 100% and degrading towards 0%, second, setting a transition threshold above 23% (absolute value) from blue to orange, to help to spot relevant correlations. Looking at the Table, we notice the predominance of light-colored cells. This result can be interpreted as an indication that the research questions used in this work are mostly orthogonal, and thus suited to cover the reviewed subject with almost no wasteful overlap. In the following, we comment on all positive and negative correlations above/below 23%.

- **Q6-Q7(49.02%):** This strong correlation indicates how IPS and IDS are strictly related. Questions Q6 an Q7 ask if the publication mentions IPS or IDS functionalities respectively. Indeed, in practice, IDS may exist without IPS, but not the opposite, because prevention mechanisms are typically built as a reaction to a detected attack.
- **Q2-Q14(39.34%):** The questions ask if the paper mentions one or more features of STRIDE without mentioning it explicitly and if the paper deals with Denial of Service. The high correlation suggests that a large number of papers treat the topic of Denial of Service since it is the "D" contribution in STRIDE and has Denial of Service as the main goal. Having Denial of Service as the main goal implies that it is a topic of discussion in the paper.
- **Q8-Q10(23.89%):** This "light" correlation maps a link between Threat Intelligence techniques and Insider Threat attacks. If the paper mention/deal with Threat

TABLE 4. Research question correlation table. Color intensity represents correlation absolute value where maximal intensity for 100% and degrading towards 0%, with a transition threshold above 23% (absolute value) from blue to orange, to help to spot relevant correlations.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14
Q1		5.53%	-11.41%	-6.97%	-4.76%	-7.22%	-4.39%	-1.81%	11.05%	12.96%	-5.25%	-5.58%	-3.96%	-0.02%
Q2	5.53%		8.60%	-10.52%	-7.60%	-18.99%	-21.40%	1.28%	0.14%	-2.02%	3.94%	12.72%	8.30%	39.34%
Q3	-11.41%	8.60%		10.78%	0.22%	-1.26%	-16.77%	5.37%	6.65%	5.26%	-12.34%	11.71%	-9.19%	-10.95%
Q4	-6.97%	-10.52%	10.78%		11.09%	6.05%	3.03%	18.60%	14.75%	21.26%	4.06%	5.25%	-4.92%	-23.45%
Q5	-4.76%	-7.60%	0.22%	11.09%		6.45%	5.24%	-4.76%	-2.85%	1.31%	2.87%	5.21%	-0.28%	-12.60%
Q6	-7.22%	-18.99%	-1.26%	6.05%	6.45%		49.02%	-7.22%	-7.34%	11.64%	14.78%	-13.87%	21.81%	-13.58%
Q7	-4.39%	-21.40%	-16.77%	3.03%	5.24%	49.02%		-4.39%	-3.70%	6.59%	6.50%	-14.76%	9.24%	-8.14%
Q8	-1.81%	1.28%	5.37%	18.60%	-4.76%	-7.22%	-4.39%		20.92%	23.89%	-0.85%	5.78%	-10.16%	-12.70%
Q9	11.05%	0.14%	6.65%	14.75%	-2.85%	-7.34%	-3.70%	20.92%		22.01%	3.20%	4.25%	-7.83%	-15.81%
Q10	12.96%	-2.02%	5.26%	21.26%	1.31%	11.64%	6.59%	23.89%	22.01%		5.61%	2.99%	-8.34%	-21.26%
Q11	-5.25%	3.94%	-12.34%	4.06%	2.87%	14.78%	6.50%	-0.85%	3.20%	5.61%		-12.76%	5.89%	-7.11%
Q12	-5.58%	12.72%	11.71%	5.25%	5.21%	-13.87%	-14.76%	5.78%	4.25%	2.99%	-12.76%		7.56%	-1.51%
Q13	-3.96%	8.30%	-9.19%	-4.92%	-0.28%	21.81%	9.24%	-10.16%	-7.83%	-8.34%	5.89%	7.56%		20.42%
Q14	-0.02%	39.34%	-10.95%	-23.45%	-12.60%	-13.58%	-8.14%	-12.70%	-15.81%	-21.26%	-7.11%	-1.51%	20.42%	

Intelligence then it is likely that it also works on the mitigation or detection of Insider Threat attacks.

- **Q4-Q14(-23.45%):** This anti-correlation is probably the most interesting. In this case, if the article mentions a threat model or even just one of its aspects (Q4) then it does not include any details relating to a specific attack (Q14). This means that in SDN solutions vertical for a specific attack it is very likely that there is no Threat Model consideration, even partially. This could be advocated by the fact that SDN is used as a complementary tool and for this reason, these types of threats do not properly suit a specific attack scenario.

C. THREATS to VALIDITY

Our study is subject to limitations that can be categorized into a construct validity, external validity, internal validity, and reliability following the guidelines of [ds17].

Construct validity "reflects to what extent the operational measures that are studied really represent what the researcher has in mind and what is investigated according to the research questions.". To mitigate a potential misinterpretation and making sure that the constructs discussed in the interview questions are not interpreted differently by the researchers, we adopted various triangulation rounds using online meetings and we designed a set of binary research questions to foster objectivity in answering them.

Another potential risk regards whether we were exhaustive during the data collection, i.e., whether we may have missed any significant publication in our review. This risk cannot be completely mitigated but to minimize this risk we deliberately chose to have simple and broad keywords giving more initial hits that later were further filtered out.

External validity regards the applicability of a set of results in a more general context and is not a concern for this study since we focus on the the intersection of the fields of SDN and security for offensive and defensive solutions without any attempt of generalizing the findings to a broader context. We do not claim that either our qualitative or quantitative findings should also hold for other large fields.

Internal validity is of concern when causal relations are examined when there is a risk that the investigated factor is also affected by a third factor. This thread is not a concern for this study because we presented only correlations between different factors but did not examine causal relations.

Reliability concerns to what extent the data collection and analysis depend on the actual researchers. This risk has been partially mitigated by selecting as many objective criteria as possible for the filtering and by requiring at least a two-people consensus in case of more subjective decisions. In particular, the retrieval of the publications was performed by using search engines. The first results filtering (Step 2, III) was conducted by running a script that uses objective criteria such as counting the number of present keywords and the length of the publication. These automatically computed results were double-checked by at least two authors to prevent problems due to the parsing of PDFs and to make sure that the language of the publication was English. The second filtering (Step 3,

III) performed by reading the title, abstract, and (if needed) the body of the publication, was performed in parallel by two authors. Decision conflicts were solved by discussion involving at least two authors until a consensus was reached. For the publication analysis (Step 4, III), due to the binary nature and formulation of the questions, the 14 research questions were answered by the author assigned to the publication. To detect possible observer bias and errors, we selected a random subset of 20 papers and had a different author answer the research questions. The calculation of the kappa index of agreement as proposed in [ds5] over the two result sets yielded a value of $\kappa = 0.99996$, giving us statistical confidence over the perceived precision of questions and objectiveness of answers. The reliability of the study is strengthened by being open and explicit about the process of data collection and analysis. For transparency, reproducibility, and reuse, we report the data used in this study at https://doi.org/10.5281/zenodo.6959369, which includes both the final dataset with the answers to all the research questions and also the set of rejected publications.

VII. OPEN CHALLENGES AND FUTURE WORKS

In this section, we draw a summary of the main open challenges that emerged from our study, which forms a call for action for the community of researchers and practitioners working in the field of SDN security and its neighboring areas. The insights that we highlighted in the Sections above have been used to frame some final remarks on open issues and possible future research topics.

A. ATTACK OVER SDN ARCHITECTURE

Indeed a clear message stemming from the analysis is the possible vulnerability of the SDN architectural approach. We do not want to argue intrinsic vulnerabilities of SDN architecture which is not the scope of this article but, from our analysis, many defensive solutions for attack mitigation and detection are conceived by exploiting the strengths of the SDN paradigm. For this reason as future works, we claim that, while adopting SDN technologies for defensive purpose, a deep analysis of what challenges SDN itself introduce must be performed. For instance, the SDN controller, even if distributed and equipped with recovery mechanisms, is clearly a target for security threats, as is the communication channel between the controller and the switches. This is inherent in the original idea of SDN. Nonetheless, the current technological trends may provide methods to overcome this weakness.

B. CONTROLLER AWARENESS

Since the SDN controller is often a single point of failure due to its centralized nature, we argue that future works should focus on providing measures to enforce security policies over SDN architectures. To do this, both architecture-aware tools that check the health of the entire SDN system and the use of new technologies such as P4 can help in preventing, detecting, and mitigating attacks.

C. PROGRAMMABLE DATA PLANE

Data plane programmability, for instance, implemented with the P4 language, seems to become the new trend in increasing the strength of SDN defensive solutions. P4 can keep the switches working without the need for a software controller and could provide fine-grained statistics that can be used to perform detailed network traffic analysis, offloading the intelligence from the control plane to the data plane.

D. DEDICATED ATTACK TREES AND THREAT MODELS

Software Defined Networks are subject to a variety of attacks that leverage the architecture to cause threats, in particular denial of service attacks. The literature suggests that there is not a dedicated threat model to help developers to be aware of those threats. This clarifies how security implemented with SDN, even if the paradigm is mature and largely studied, is still not a standard topic. We argue there should be a threat model to help developers to focus on more granulated threat categorization. The effort of building a standard threat model could help the development of security-compliant applications and analyze architectures to attest to their security coverage.

E. ACTIVE DEFENSE AND MITIGATION SOLUTIONS

The vast majority of the literature focuses on attack prevention and detection. There is little to no work that includes or even considers mitigation techniques. We argue that the future challenge in SDN will be to build active defense mechanisms that are able to take actions in the system to counteract attacks. This will help on bringing new perspectives on how to make secure architectures that are able to detect and automatically counteract threats.

F. COMPREHENSIVE TECHNOLOGICAL REFERENCES

There is not a very large number of adopted technologies to build SDN architectures: these technologies need to be properly documented and referenced to avoid the most common threats. Moreover, we argue that having more variety of available technologies could help to design more secure solutions. Studying new SDN technologies is the starting point to enforce security by design since some of them could be designed to counteract the most known vulnerabilities of the SDN architectures.

G. MACHINE LEARNING

Machine Learning (ML) in its various flavors is strongly considered to develop prevention and detection mechanisms in support of SDN. Recently, some promising ML trends are becoming increasingly popular. Reinforcement Learning (RL) exploits reward functions to train the Machine Learning model to solve vertical problems. RL is not the first choice in SDN right now but we argue that it could be used to train models that are able to reconfigure the network in real-time in order to mitigate the detected attacks.

Adversarial Behaviour is another ML technique that is spreading fast in SDN since it allows to use of this paradigm to simulate attacks that can stress the IDS. We argue that ML will provide even better results if applied to mitigation scenarios since are now only limited to detection and prevention.

H. DENIAL-OF-SERVICE-CENTRIC

Denial of service is the most considered attack in literature. In fact, it is the most dangerous scenario for both the data and control plane, since it is able to fully shut down network devices and compromise connectivity. Other than that, almost every attack considered in the literature that is not necessarily DoS attacks usually follows the behavior of making resources unavailable rather than stealing data or compromising it. Moreover, the works usually do not consider the industrial scenario, which demonstrates how SDN is usually not the first choice for security industrial solutions. We argue that SDN's native features could be exploited to find and track the source of these attacks. This could be done both in data centers and industrial networks, for example with the help of data plane telemetry frameworks that offer standard methodologies to collect data plane statistics in real time. The most famous P4-related telemetry framework is In-band Network Telemetry (INT) [22], which is a valuable starting point.

Also, new flavors of Denial of Service are gaining diffusion recently. Among them, as already mentioned, we can distinguish Low-rate denial of service (LDoS) attacks, which send attacking bursts of packets to degrade the network connectivity, and Economic denial of service (EDoS) attacks, which target cloud environments to inflate the billing of the end user by injecting malicious code into vulnerable machines. This new kind of attack poses various challenges: detecting and mitigating LDoS is not trivial since they follow very unpredictable patterns. New studies should be performed to identify these patterns, perhaps using ML mechanisms. On the other hand, EDoS attacks are difficult to detect since they gain complete access to the resources. For this reason, more effort should be put into designing and analyzing policies to monitor and allow access to cloud resources, exploiting the flexibility and feature of SDN.

I. DISTRIBUTED LEDGERS

The adoption of distributed ledgers and Blockchains can undoubtedly help the security of SDN and Programmable data plane ecosystem in various fields. Certified models and monitoring are performed using a so-called Blockchain layer. Where most publications are focused on Security, there are works on performances

VIII. CONCLUSION

In this article, we presented a systematic review of the literature on SDN security, i.e. work about the security of SDN networks, not about the use of SDN for network security n general.

To conduct our research, we followed a structured approach that allowed us to gather 466 peer-reviewed publications, which, to the best of our knowledge, constitutes the largest curated dataset on the topic.

To study our dataset, we conducted first an investigation on the metadata of the publications, which gave us some insight to map what are the publication outlets, the communities, and the key research concepts that characterize the field. Then, we performed an analysis, associating each element in our dataset to a vector of 14 different markers—presented in the form of 14 research questions. Since our markers belong to four micro-groups (threat model, offensive/defensive goal, infrastructure, and technology), we used that partition to provide an overview of the literature through the lenses of each cluster. As a byproduct of our analysis of the content of each publication, we found concepts and topics that we did not include in our questions but that recur in multiple publications, e.g., the usage of blockchain or Machine Learning technologies. To provide a more comprehensive picture of the field, we described and contextualized also these additional elements. Since our dataset forms a statistically relevant vector field, we also performed a correlation study over the components of the vectors and reported the strongest correlations (e.g., between intrusion detection (IDS) and intrusion-prevention (IPS) systems usage) along with possible explanations of the identified phenomena.

In summary, the analysis of this large amount of papers showed an evident trend in focusing on anti-DoS techniques for Software Defined Networking. Secondly, it showed the absence of an exhaustive threat model, which can effectively respond to the security need of a complex architecture such as SDN. Finally, we noticed a scarce diversity of the technologies adopted in the works present in the dataset, as well as a broad correlation of these studies with Machine Learning solutions and technologies (considering the number of implementations of IDS, IPS, or simple detection/mitigation methodologies).

APPENDIX A ACRONYMS

A. TECHNICAL ACRONYM/GLossario

The following legend is for the acronyms of the journals considered:

SDN Software Defined Networks
NFV Network Function Virtualization
ML Machine Learning
RL Reinforcement Learning
DL Deep Learning
PASTA Process for Attack Simulation and Threat Analysis
STRIDE Spoofing Tampering Repudiation Information disclosure Denial of service Elevation of privilege
DoS Denial of Service
DDoS Distributed Denial of Service
LDoS Low-latency Denial of Service
EDoS Economic Denial of Service
IDS Intrusion Detection System
IPS Intrusion Prevention System

P4 Portal Programmable Pipeline
INT Internet Network Telemetry

B. JOURNALS

The following legend is for the acronyms of the journals considered:

IEEE-Access
CN Computer Networks
NCA Journal of Network and Computer Applications
IJCS International Journal of Communication Systems
TN IEEE/ACM Transactions on Networking
CC Concurrency and Computation: Practice and Experience
IJNM International Journal of Network Management
FGCS Future Generation Computer Systems
ACM/CC Computer Communications
IEEE-IoTJ IEEE Internet of Things Journal
SCN Security and Communication Networks
IEEE-TNSM IEEE Transactions on Network and Service Management
IEEE-JSAC IEEE Journal on Selected Areas in Communications
TETT Transactions on Emerging Telecommunications Technologies
CS Procedia Computer Science
ESA Expert Systems with Applications
C-and-S Computers & Security
IEEE-TIFS IEEE Transactions on Information Forensics and Security
WPC Wireless Personal Communications
FIT Future Internet

C. CONFERENCES

The following legend is for the acronyms of the conferences considered:

Netsoft IEEE International Conference on Network Softwarization
IMCOM International Conference on Ubiquitous Information Management and Communication
SIGSAC ACM SIGSAC Conference on Computer and Communications Security
SysCon IEEE International Systems Conference
FCST International Conference on Frontier of Computer Science and Technology
NFV-SDN IEEE Conference on Network Function Virtualization and Software Defined Networks
ICC IEEE International Conference on Communications
SDN-NFV ACM International Workshop on Security in Software Defined Networks & Network Function Virtualization
SACMAT ACM on Symposium on Access Control Models and Technologies
SOSR Symposium on SDN Research
ICCSP International Conference on Cryptography, Security and Privacy
ICFNDS International Conference on Future Networks and Distributed Systems
CSR International Conference on Cyber Security and Resilience
CCWC IEEE Annual Computing and Communication Workshop and Conference
DISCOVER IEEE International Conference on Distributed Computing, VLSI, Electrical Circuits and Robotics
SPAC International Conference on Security, Pattern Analysis, and Cybernetics
APNOMS Asia-Pacific Network Operations and Management Symposium
ICCCI International Conference on Computer Communication and Informatics
RIVF RIVF International Conference on Computing and Communication Technologies
CNSM International Conference on Network and Service Management
CONIT International Conference on Intelligent Technologies
ACMI International Conference on Automation, Control, and Mechatronics for Industry 4.0
I2CT International Conference for Convergence in Technology

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