A Scalable Cyber Security Framework for the Experimentation of DDoS Attacks of Things

Davi D. Gemmer*, **Bruno H. Meyer**†, **Emerson R. de Mello**‡,
Marcos Schwarz¶, **Michelle S. Wangham**§, **Michele Nogueira***
*Department of Computer Science - Federal University of Minas Gerais, Brazil
†Department of Informatics - Federal University of Paraná, Brazil
‡Federal Institute of Santa Catarina, Brazil
§University of Vale do Itajaí, Brazil
¶National Research and Education Network, Brazil
Emails: ddgemmer@gemmer.com.br, bruno.meyer@ufpr.br, mello@ifsc.edu.br,
marcos.schwarz@rnp.br, wangham@univali.br, michele@dcc.ufmg.br

NOMS 2023-2023 IEEE/IFIP Network Operations and Management Symposium | 978-1-6654-7716-1/23/$31.00 ©2023 IEEE | DOI: 10.1109/NOMS56928.2023.10154400

***Abstract*—The Internet of Things (IoT) has amplified cyber security challenges for governments, businesses, and individuals. IoT is a straightforward attack target once it comprises resource-constrained and heterogeneous devices that often present security vulnerabilities easily exploited in different attack vectors. Recent Distributed Denial of Service (DDoS) attacks leverage thousands of IoT devices connected to the Internet called DDoS of things (a.k.a. DoT). DoT requires systematic cyber security research, but advancing the state-of-the-art depends on methods and tools that jointly manage scalability and performance. Experimentation is an essential and well-known tool for scientific research. However, experimental environments for investigating DoT are challenging, given limitations in scale and IoT heterogeneity. Hence, the main contribution of this work lies in presenting a cyber security framework for DoT experimentation that manages scalability and performance in scenarios under attack. It is the first initiative to create a framework of reference to assist in implementing cyber security testbeds. Hence, this work also presents an instantiation of this framework, called the MENTORED testbed, and the results of a case study using it.**

***Index Terms*—Cyber security framework, DDoS of Things, Experimentation, Testbed, Kubernetes.**

I. Introduction

The Internet of Things (IoT) has amplified cyber security challenges for governments, businesses, and individuals. IoT comprises many heterogeneous and resource-constrained connected devices, significantly increasing the volume of generated and transmitted data [1]. The manufacture of IoT devices rarely handles security and privacy issues, and there are no security standards for IoT [2]. These aspects make IoT devices easy targets for attackers, growing the number and volume of attacks leveraging IoT devices, such as Distributed Denial of Service of Things (a.k.a. DoT attacks or DDoS of Things) [3]. DoT has reached critical mass, i.e., each attack relies on hundreds of thousands of devices connected to the Internet [4]. This behavior highlights the urgent necessity of systematic cybersecurity research in this context.

Investigating and designing robust solutions to prevent, detect and mitigate DoT attacks require appropriate tools and methods to test and validate them [5]–[11]. Today, researchers rely on datasets or controlled environments to study DDoS attacks by simulations. Experimental environments allow the investigation of DDoS attacks close to real conditions. However, there is a lack of experimental environments that meet specific requirements for IoT cyber security. Also, it urges a framework to support and guide the development of environments to test solutions and study DoT [12]. Existing experimental environments encounter performance issues when the scale grows. But, scalability is a genuine feature of IoT and DDoS attacks, requiring serious consideration [13], [14]. Also, managing the diversity of devices, protocols, and communication technologies is a challenging task for experimental environments [15], which depend on dedicated hardware and customized software [16].

In a nutshell, there are two groups of cyber security testbeds for DoT: (i) those focusing on security but not on IoT; (ii) those focusing on IoT but either ignore security or present minimal functionalities related to it. These two groups stand out, led by two prominent testbeds: DETERLab [17] and FIT IoT-LAB [18]. The first has been a pioneer in cyber security large-scale experimental environment, whereas the second plays an essential role in IoT experimentation. Unfortunately, DETERLab presents limitations to wireless network experimentation, an important property for IoT experiments. Further, FIT IoT-LAB does not consider security as its primary focus and lacks traffic isolation between experiments of different users. Recently, Cámara *et al.* [19] proposed a network security testbed for IoT scenarios. However, scalability is still an issue. A common observation in these examples lies in the absence of a general reference to guide and design testbeds for cyber security, mainly regarding DoT attacks.

Hence, the main contribution of this work is a cyber security framework for the experimentation of DoT attacks. The framework manages scalability and performance in experimentation scenarios. It serves as reference for implementing cyber security testbeds concerned with DoT. This work also presents the MENTORED testbed, an instantiation of the framework implemented in the scope of the Brazilian MENTORED project [20]. The testbed considers features as scalability and performance, as expected, and user experience.

This paper presents the results of a case study performed in the MENTORED testbed. The results express the network traffic throughput considering two evaluation scenarios under DDoS attacks. This work also analyzes the viability of defining and executing experiments in the testbed. Results from an evaluation scenario demonstrate the capacity of a high-performance processing node in the testbed infrastructure to emulate several small devices. The results show a DDoS attack experiment designed and performed in the testbed. The results show that the DDoS attack scales, although using a unique node as the attack target and attackers.

This paper proceeds as follows. Section II presents the related works. Section III details the proposed framework. Section IV describes the MENTORED testbed, including software and hardware available to users. Section V shows the performance evaluation of a case study using the testbed. Finally, Section VI concludes the paper.

II. Related Work

This section overviews the related works on experimental environments from the literature. Testbeds focusing simultaneously on cyber security and IoT are rare. Hence, the next paragraphs overview works from two separate groups: (1) testbeds focusing on cyber security, but not IoT; and (2) IoT testbeds. The two representative works for these two groups are DETERLab [17] and FIT IoT-LAB [18], respectively.

DETERLab [17] is a pioneer cyber security testbed designed for large-scale emulation and experimentation. It provides a set of tools for the creation, manipulation, and observation of experiments. DETERLab offers a controlled and secure environment, i.e., experiments do not threaten other testbed users or the Internet. FIT IoT-LAB plays a vital role in IoT experimentation. It offers a platform for researchers to build, evaluate and optimize protocols, applications, and services. It comprises various hardware boards, communications technologies, and different physical topologies. Despite its importance, DETERLab presents limitations related to the use of different virtualized topologies [21] and ignores the context of wireless network, which is necessary for IoT experimentation. In contrast, FIT-IoT Lab lacks traffic isolation between experiments of different users, which can result in hazards for all.

Recently, Cámara et al. presented the Gotham [19], a network security testbed for IoT. It is based on the GNS3 network emulator and provides a set of tools for experimenters to carry out DoS attacks. Although the testbed offers means for emulating scenarios with many devices, scalability is still an issue. Takeoglu and Tosun [22] proposed a low-cost testbed based on off-the-shelf hardware and open-source software. It investigates security and privacy on IoT devices connected by WiFi and Bluetooth. Although the testbed considers heterogeneity, it does not address scalability. Particular devices require specific software and configurations for capturing packets and analyzing data, and there is no standard or reference for performing a large-scale experiment.

EdgeNet [16] is a distributed system testbed from the PlanetLab family. Its infrastructure is software-only, and the environment comprises virtual machines (VM) interconnected by Kubernetes-based implementation. The project has 40 nodes distributed around the world. The work in [16] analyzes the benefits and challenges of building a testbed based on Kubernetes and highlights high performance with low overhead, being suitable for all types of experiments and systems. However, an analysis is not performed with heavy network loads or experiments that cause network stress, such as DDoS.

Sarirekha *et al.* [23] investigated the challenges and requirements of developing an IoT-based testbed. They highlight challenges such as the heterogeneity of protocols, operating systems, and types of attacks as challenges. The authors also defined requirements for an IoT testbed as (i) flexibility, (ii) handling a high volume of data and heterogeneous devices, networks, and communication protocols, (iii) having as basis open source software and firmware, and (iv) support for multiple use cases. The work analyzes neither aspects related to dense network traffic flows as DDoS attacks nor presents a framework of reference for IoT testbed design.

Each testbed provides specific features to its context [15], [24], and all these testbeds offer contributions to the academic community. However, there is still a place for improvement. A relevant observation is a need for well-defined references to assist in designing testbeds for cyber security, mainly concerned with DoT attacks and their genuine scalable nature. There is still a gap in defining the properties and requirements for such environments to guide the implementation of testbeds that encompass characteristics such as realistic and large-scale geographically distributed environments, considering IoT devices in their infrastructure, flexibility, and scalability.

III. The Cyber Security Framework for DDoS of Things

This section details 'the MENTORED framework', a cyber security framework conceived as a reference for designing and implementing scalable experimental environments to DoT attacks. The framework considers existing terminologies among cyber security testbeds [24] and presents three main actors: managers, clients, and users. Managers are an abstract concept representing those responsible for implementing, maintaining, and managing the environment and network. Clients are non-necessary natural persons (e.g., institutions) that require access to an experimental environment. In contrast, users are natural persons associated with clients and use resources.

The main characteristics of the MENTORED framework encourages collaborations between several partnerships, each providing different resources, benefiting a research community composed of teams, projects, and institutions (clients). The framework considers security and safety issues, including authorization, authentication, accountability, and isolation of experiments. It follows a distributed infrastructure, i.e., it manages resources over different physical locations. The infrastructure is essential, considering the need for scalable experiments involving several real or emulated devices.

The MENTORED framework is founded on a set of requirements: fidelity, validity, scale, reproducibility, transparency,

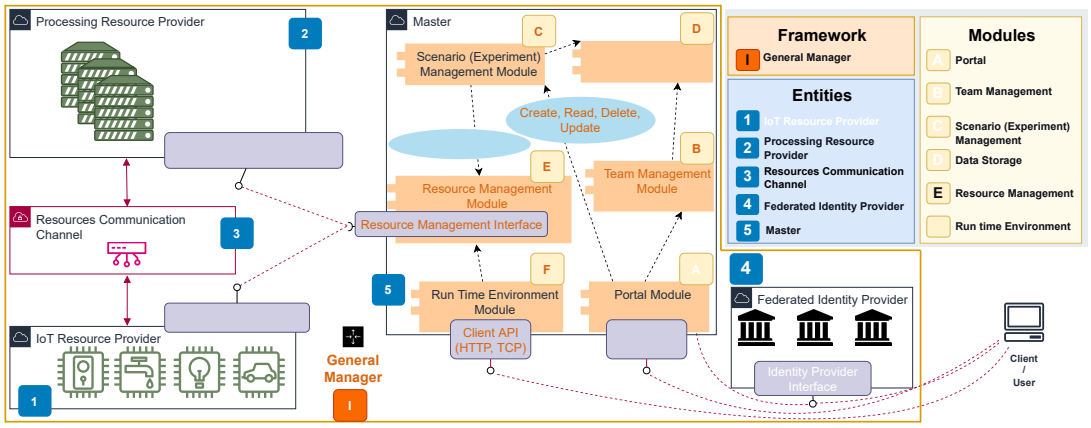


Fig. 1: The MENTORED framework

user-centric perspective and real-time access. These requirements guide the framework as follows.

- Fidelity: capability to obtain sufficient precision in reproducing a phenomenon under study in a experiment.
- Validity: the results of experiment must be agnostic to the limitations of the environment and those limitations should not accidentally distort them. The environment must identify and report violations, alerting the user to possible failures.
- Scale: support experiments of representative size to capture complex effects of attacks related to massive data traffic at Internet scale.
- Safety: no code or malicious users can gain unauthorized access or harm other network infrastructures, information, or code of the environment itself or the Internet.
- Reproducibility: ensures that an experiment, once runs, can be exported and then run in an identical environment later to produce comparable results.
- Transparency: enable real-time and non-intrusive monitoring of network traffic and computing resources, and employ tools to visualize these resources graphically and via the command line.
- User-Centric Perspective: give to users the possibility to develop tools that facilitate experimental research and to use the traditional experimental research functions, such as setting up experiments and monitoring traffic.
- Real-time Access: provide real-time access to devices. Then, a user can reset, reschedule, and monitor the state of each device while experiments are running.

The framework defines a set of entities as a general manager, master, IoT resource provider, federated identity provider, and resource communication channels. Similarly, it presents a set of modules such as portal, team management, scenario management, data storage, resource management, and run-time environment. Fig. 1 shows the entities, modules, and their relations. Each element in this framework can be implemented using different technologies. The framework serves as a reference for implementation specification with the primary goal of jointly managing scalability and performance. The description of these entities follows.

- **General Management**: has a general and complete view of the available resources, preferably being able to manage their use. It provides technologies and infrastructure to implement each entity and module of the framework.
- **Master**: responsible for connecting clients with the resources and managing their authorization for each action allowed in the experimental environment.
- **IoT Resource Provider**: bare-metal IoT devices that can communicate with other IoT devices, processing servers, and the master. It should provide an API to allocate, manage and control each device.
- **Processing Resource Provider**: servers with processing capabilities that can communicate with other servers, IoT devices, and the master. It provides an API to allocate resources in each device through simulation or emulation.
- **Resources Communication Channel**: directs resource requests to resource providers. This entity is optional if devices are directly connected to the Internet, which is not recommended concerning isolation.
- **Federated Identity Provider**: manages authentication and user information in a domain (e.g., an university).

The description of the modules follows.

- **Portal**: an interface to the user. The master offers the initiation of the federated authentication, interacts with Team Management module, and manages the user environment to define access and store data related to the experiments. Different options must be considered for different types of users.
- **Team Management**: module triggered by users associated to a collaborative project to create and manage virtual teams (identify their users, organize them in groups, assign them roles) and share common resources (defining access rights) using federated identities. This module is responsible for generating authorization tokens for a project user to conduct experiments.
- **Scenario (Experiment) Management**: the master entity implements policies to restrict which resources can be accessed by users. Syntaxes define experiments, indicating how the resources can be used and if the Data Storage Module must save any resulted data. This module

orchestrates user requests and makes available resources.
- **Data Storage**: datasets record two main types of data: 1) data related to experiments, such as descriptions, network traffic, and log files; 2) user environment and authorization data, used for controlling tasks and access.
- **Resource Management**: implements the operations required to consume Resource Providers APIs and enables the master to control different actions of the Resource Providers, like the run-time access to experiments or the deployment and destruction of experiment definitions.
- **Run-Time Environment**: the definition of processes that enables direct access to the experiments in execution.

Users access the federated authentication interface, the portal and the run-time environment interface. The federated authentication interface depends on the Team Management Module and the Federated Identity Provider. The portal enables actions to define, execute and manage the environment. Then, the run-time environment interface monitors experiments in execution. With these interfaces, it is possible to trigger modules in the master, which acts as an intermediate entity managing users and computation resources. The framework focuses on DoT attacks, which enable several IoT devices and robust processing servers to simulate or emulate nodes. Hence, experiments that try to define large topologies take advantage of all assets offered by the resource providers because they will be able to communicate according to the Resources Communication Channel entity.

The lifecycle of any experiment is composed by: experiment definition, resource management, execution and monitoring. First, the user needs to define what topology, resources, and software will be used in an experiment by a description language with a syntax. Users may define this by a GUI interface in the portal, simplifying user experience. Users specify the resources and settings required by his/her experiment, which can be crucial to guarantee validity, scalability, and safety requirements.

Assuming a multi-use of resources simultaneously by multiple users, an experimental environment must address security issues concerning the experiments and provide individualized settings for all users. Hence, the general management predefines policies to divide assets available on the resource providers for different clients and verify if a user experiment definition is valid. Also, an optional verification can be implemented to isolate the resource providers from the Internet. Then users access them only through the master entity. If an experiment is validated, the user requests its execution. The master guarantees that different experiments running in the environment do not have access to each other, preserving all requirements.

A consistent analysis of DoT attacks depends on faithful representations of network traffic in real-world scenarios. A key point to implement a testbed following this framework lies in defining the technology to deploy experiments and the communication methods among the topology nodes. The MENTORED framework assumes the existence of an infrastructure able to support the network communication of several real (or simulated) IoT devices. The infrastructure management is performed by the resource communication channel entity. Hence, an user monitors the experiment by the Run-Time Environment Module, logs, and saved data.

IV. The MENTORED Testbed

This section details the MENTORED testbed, an instantiation of the proposed framework, conceived for the experimentation of DoT attacks. First, it introduces the testbed architecture, its entities, and modules correlating them with the framework. Second, it describes user experience when defining, executing, and monitoring an experiment in the testbed (experiment life cycle).

Fig. 2 shows the architecture of the testbed, highlighting the MENTORED Master (in the blue external frame) and the Software-Defined Infrastructure of the National Education and Research Network (IDS-RNP) (white external frame). The MENTORED Master implements the MENTORED portal, the orchestrator (backend), REST API, and the command-line interface (CLI). The MENTORED Master mediates the interaction of users with the resources present in IDS-RNP, authenticating, controlling, and managing user permissions.

IDS-RNP incorporates functionalities from the Processing Resource Provider and the Resource Communication Channel defined in the framework (Fig. 1). RNP and its administrators play the role of general managers defined by the framework. Using small and high-performance nodes as the resources offered by the Processing Resource Provider, it is possible to use nodes to emulate IoT devices in IDS-RNP. Also, Kubernetes allows the insertion of IoT devices like Raspberry in the cluster. This feature enables an IoT Resource Provider (from the framework) and increases fidelity and scalability in the testbed. The MENTORED master implements the Data Storage Module, which uses a database to save all experiment-related data. The scenario management and resource management modules are implemented in the MENTORED testbed through the Orchestrator features. The next sections detail IDS-RNP and the components of the MENTORED testbed architecture in Fig. 2.

A. The RNP Infrastructure

IDS-RNP is a core component of RNP's Testbed Service. The IDS-RNP testbed is spread over 15 locations of its dedicated physical servers hosted at RNP's Points of Presence and interconnected by Rede Ipê, the Brazilian national-wide academic network, encompassing all five regions of Brazil, and relies on different network virtualization technologies.

IDS-RNP offers KNetLab, an extension of Kubernetes implemented to introduce network topology as a resource and enhance the experience in IDS-RNP. For KNetLab, a network topology consists of 'devices' and 'links'. A 'device' is an application with the location attribute that explicitly defines in which node it is deployed. A 'link' is an adjacency declaration between two devices to provide a layer-2 circuit. Each container instance deployed in a given 'namespace' is

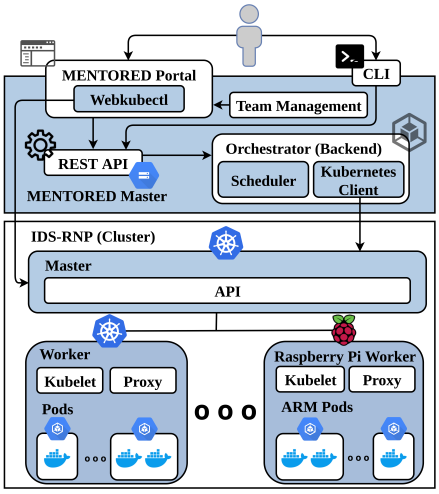


Fig. 2: The MENTORED Testbed

interconnected by a private network employed as the experiment control plane and a set of user-defined links that provides the data plane topology. KNetLab implements the user-defined topology by Open vSwitch (OVS) [25] through virtual Ethernet connections (veth). These connections implement a link between devices on the same node and a VXLAN tunnel over Rede Ipê for devices on different nodes. KNetLab integrates two additional mechanisms: DPDK acceleration on OVS and offload tunnels between nodes to EVPNs, dynamically provisioned on Rede Ipê. This supports wire-rate packet processing up to 100 Gbps.

B. The MENTORED Master

The MENTORED Master operates as a software layer on top of the Kubernetes API, which handles the iterations between modules, as shown in Fig. 2. It controls the MENTORED Portal, CLI, REST API, Team Management and the orchestrator. The MENTORED Portal is a Federated Service Provider that manages user interactions, delegates user authentication to federated identity providers, interacts with the team management service, and establishes a secure remote connection with the REST API. The portal offers several GUI options to the users in their web browsers once they are authenticated. These options include actions as the creation, visualization, update and exclusions of accounts and experiments. Team management service provides flexible enrollment flows to bring experimenters and their federated identities in the testbed and creates a virtual team for the collaborative experimentation project. This service manages users, projects, and access rights for the resources in IDS-RNP.

The Webkubectl [26] is a technology incorporated by the MENTORED Portal, and provides specific commands for reaching the requirements of the Run-Time Environment module. This module enables users to access a UNIX-based environment in their web browser, in which it directly accesses the IDS-RNP Master. This tool goes inside the MENTORED Portal and is based on the same authorization context implemented by the Team Management module using the Namespaces elements of Kubernetes and KNetLab.

C. Experiment lifecycle

The experiment's lifecycle comprises the creation, execution, and analysis of the results. Users can analyze the results during and after the execution of the experiment. An experiment represents the simulation of a network topology where several nodes are connected no software defined by the user. The experiment definition describes i) the network topology that will be deployed; ii) the definition of each node related to that topology, including all softwares and limitations. This definition is created in a text file following a pre-defined syntax using a YAML file format. The syntax used to describe each node extends the standard and well-known Kubernetes definition. Users familiar with Kubernetes can easily define nodes in the experiments definitions of the MENTORED testbed. Also, each node can be associated with a specific Kubernetes worker related to any region among the possibilities of IDS-RNP.

The experiment, described in YAML, must then be uploaded to the Mentored PORTAL. Once loaded, the researcher can start executing it whenever and as many times as desired. Once the experiment is executed, the MENTORED Portal invokes the Orchestrator, which after validating that the description is correct, instantiates the resources (pod, nodes, etc.) in the IDS-RNP. The researcher will be able to monitor the execution of the experiment through Webkubectl, available on the MENTORED Portal. Once the experiment has ended, the Orchestrator makes the log files available, and the researcher can get them through a good REST API.

V. The MENTORED Testbed - Case Study

This section presents a case study for the MENTORED testbed. This case study considers different scenarios to evaluate their viability in enabling users to easily perform DDoS experiments. Subsection V-A shows a simple experiment scenario and its deployment on the MENTORED testbed. Subsection V-B describes an experiment that aims to identify the capacity to extend the previously presented experiment scenario to be executed with more devices.

A. Evaluation Scenarios

The DDoS attack was carried out using IDS-RNP nodes at Vitória, Salvador and São Paulo. The victim node implements a standard NGINX server at Vitória. There are two attackers configured with hping3 to make 100 requests per second in Salvador's node, and three clients responsible for requests every 0.5 seconds in São Paulo's node. The attack has a duration of 300s comprising the phases: pre-attack (0-59s), where there is only clients traffic; attack (60-240s) composed of the traffic of the clients and the attackers; and post-attack (241-300s) with clients traffic only.

The MENTORED testbed implements a predefined policy for authentication and authorization. Considering as previous step the federated authentication, an user can access the REST

API through any type of interface using HTTP. A experiment description code [27] describes the scenario. The container definitions follow the exact syntax of container definitions in Kubernetes. The rest of the YAML code contains information about the MENTORED context, and topology (e.g., replicas, connections). This demonstrative example employs a default topology architecture named "ovs_fully_connected" where all nodes of the same worker will be connected with other worker nodes through an OVS.

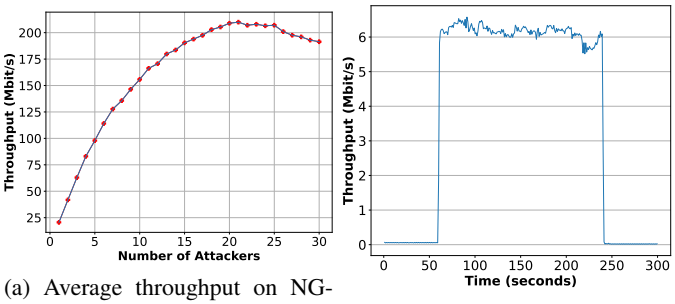
The experiment implements the NGINX software and a program that monitors CNI (Container Networking Interface). Since each experiment execution produces different results, log data is stored in the server and accessed at the end of the experiment. With data, the average network throughput per second was measured to detect the DDoS performed by attackers. In Fig. 3b, the effects of the DDoS attack is between instants 60s and 240s, the exact time the attackers execute their activity. Although it is a simple experiment scenario, this evaluation serves as proof-of-concept for using the MENTORED framework and the proposed testbed to define and execute DDoS research experiments. The interaction with the testbed is made by a simple syntax definition and is based on an infrastructure that scales with several high-performance servers and IoT devices.

Real DDoS attacks usually consider thousands or millions of devices attack and generate traffic to one or few targets. Testbeds struggle to reproduce this level of infrastructure due to computational resource constraints. In order to identify these limits on the MENTORED testbed, a stress test experiment was performed with the goal of analyzing the computational capacity of one IDS-RNP worker to simulate several small devices. The stress testing evaluation scenario used the Vitória IDS-RNP node. The Pod resource management enabled by Kubernetes limits CPU and memory employed to the definition of attacker pods. Each attacker pod uses the equivalent of half CPU and 128M RAM. These limitations influence the hping3 tool to perform DDoS attacks and generate network traffic. The main purpose of the stress test was to identify what is the maximum number of devices that can be added to a DDoS attack simulation, then the size of the DDoS attack keeps growing. The network traffic throughput in the target identifies the size of the DDoS attack. When the increase in the number of device attacks does not impact the throughput in the server, it means that adding new devices does not contribute to the increase the attack size.

B. Stress Testing Evaluation

The stress scenario experiment follows the previous scenario as base. A NGINX server runs as target, and different number of attackers from a range between 1 and 30 perform different DDoS attacks. The duration of the experiment was in total of 300s and the average throughput in Fig. 3a refers to the attack period from instants 59 to 240s. Each point of the graphic is the average of five executions for each number of attackers.

Although using a unique node to implement the target of the DDoS attacks and attackers, results show that the DDoS attack



(a) Average throughput on NGINX during DDoS vs. # of attackers

(b) Throughput on NGINX during a DDoS attack

Fig. 3: Experimental results

scales up to 21 device simulations using a single node and considering the capacity to increase DDoS networking traffic generation. The throughput average in Fig. 3a serves as a basis for using multiple nodes in a DDoS attack that simulates attackers in different regions of the MENTORED testbed. The thoughput peak has been reached in the presence of 21 pods employed to simulate attackers and the throughput average is close to 210 Mbps. Higher than 21 pods, a reduction in throughput is observed even under an increase in the number of attackers. The MENTORED testbed users should consider this limit when defining their experiments. Similar results should be expected to other nodes of the testbed. The MENTORED testbed documentation will include the information about these limits to guide users in the experiment definition and benefit from the full capacity of the testbed infrastructure to scale attackers in DDoS attacks.

VI. Conclusion

Experimental environments are essential in investigating cybersecurity issues, such as Distributed Denial of Service of Things, i.e., DoT attacks. However, designing and implementing such environments are challenging given limitations in scale, particularly for this specific type of attack. This work presented the MENTORED framework, a reference to designing scalable testbeds for DoT investigation. The framework defines requirements, actors, entities, and modules composing a cybersecutity testbed for DoT, their relations, and scalability and performance management. This work also presented an instantiation of the framework, called the MENTORED testbed, deployed over the national-wide Academic Brazilian network. Evaluations of the MENTORED testbed followed a DDoS attack scenario composed of a web server and attackers using NGINX and hping3 software. Experiments could be easily defined and sent through the Portal using a simple and flexible syntax. A unique high-performance server could effectively reproduce the traffic generation of up to 21 simulated small devices in a controlled scenario where the attackers and server were in the same Kubernetes worker.

Acknowledgments

This work was supported by National Council for Scientific and Technological Development (CNPq/Brazil), grants #141179/2021-0 and by São Paulo Research Foundation (FAPESP), grants #2018/23098-0 and #2021/13598-8.

REFERENCES

[1] K. Doshi, Y. Yilmaz, and S. Uludag, "Timely detection and mitigation of stealthy DDoS attacks via IoT networks," *IEEE Transactions on Dependable and Secure Computing*, vol. 18, no. 5, pp. 2164–2176, 2021.

[2] F. Alsubaei, A. Abuhussein, and S. Shiva, "Quantifying security and privacy in internet of things solutions," in *IEEE/IFIP Network Operations and Management Symposium (NOMS)*. IEEE, 2018, pp. 1–6.

[3] A. A. Santos, M. Nogueira, and J. M. F. Moura, "A stochastic adaptive model to explore mobile botnet dynamics," *IEEE Communications Letters*, vol. 21, no. 4, pp. 753–756, 2017.

[4] A. Khalimonenko and O. Kupreev, "DDoS attacks in Q1 2017," A10 Networks, Tech. Rep., 2017.

[5] B. H. Schwengber, A. Vergütz, N. G. Prates, and M. Nogueira, "Learning from network data changes for unsupervised botnet detection," *IEEE Transactions on Network and Service Management*, vol. 19, no. 1, pp. 601–613, 2022.

[6] F. Nakayama, P. Lenz, and M. Nogueira, "A resilience management architecture for communication on portable assisted living," *IEEE Transactions on Network and Service Management*, vol. 19, no. 3, pp. 2536–2548, 2022.

[7] F. Nakayama, P. Lenz, A. LeFloch, A.-L. Beylot, A. Santos, and M. Nogueira, "Performance management on multiple communication paths for portable assisted living," in *IFIP/IEEE International Symposium on Integrated Network Management (IM)*, 2021, pp. 340–348.

[8] J. Steinberger, B. Kuhnert, C. Dietz, L. Ball, A. Sperotto, H. Baier, A. Pras, and G. Dreo, "DDoS defense using MTD and SDN," in *IEEE/IFIP Network Operations and Management Symposium (NOMS)*, 2018, pp. 1–9.

[9] A. L. Santos, C. A. V. Cervantes, M. Nogueira, and B. Kantarci, "Clustering and reliability-driven mitigation of routing attacks in massive iot systems," *Journal of Internet Services and Applications*, 2019.

[10] S. Hameed and U. Ali, "Efficacy of live ddos detection with hadoop," in *IEEE/IFIP Network Operations and Management Symposium (NOMS)*, 2016, pp. 488–494.

[11] B. M. Rahal, A. Santos, and M. Nogueira, "A distributed architecture for ddos prediction and bot detection," *IEEE Access*, vol. 8, pp. 159 756–159 772, 2020.

[12] S. Siboni, V. Sachidananda, Y. Meidan, M. Bohadana, Y. Mathov, S. Bhairav, A. Shabtai, and Y. Elovici, "Security testbed for internet-of-things devices," *IEEE transactions on reliability*, vol. 68, no. 1, pp. 23–44, 2019.

[13] M. Antonakakis, T. April, M. Bailey, M. Bernhard, E. Bursztein, J. Cochran, Z. Durumeric, J. A. Halderman, L. Invernizzi, M. Kallitsis *et al.*, "Understanding the mirai botnet," in *USENIX security symposium (USENIX Security)*, 2017, pp. 1093–1110.

[14] P. Schwaiger, D. Simopoulos, and A. Wolf, "Automated iot security testing with seclab," in *IEEE/IFIP Network Operations and Management Symposium (NOMS)*. IEEE, 2022, pp. 1–6.

[15] A. Gluhak, S. Krco, M. Nati, D. Pfisterer, N. Mitton, and T. Razafindralambo, "A survey on facilities for experimental internet of things research," *IEEE Communications Magazine*, vol. 49, no. 11, pp. 58–67, 2011.

[16] B. C. Şenel, M. Mouchet, J. Cappos, O. Fourmaux, T. Friedman, and R. Mcgeer, "Edgenet: a multi-tenant and multi-provider edge cloud," in *Proceedings of the 4th International Workshop on Edge Systems, Analytics and Networking*, 2021, pp. 49–54.

[17] J. Wroclawski, T. Benzel, J. Blythe, T. Faber, A. Hussain, J. Mirkovic, and S. Schwab, "Deterlab and the deter project," in *The GENI Book*. Springer, 2016, pp. 35–62.

[18] C. Adjih, E. Baccelli, E. Fleury, G. Harter, N. Mitton, T. Noel, R. Pissard-Gibollet, F. Saint-Marcel, G. Schreiner, J. Vandaele *et al.*, "Fit iot-lab: A large scale open experimental iot testbed," in *IEEE World Forum on Internet of Things (WF-IoT)*. IEEE, 2015, pp. 459–464.

[19] X. Sáez-de Cámara, J. L. Flores, C. Arellano, A. Urbieta, and U. Zurutuza, "Gotham testbed: a reproducible IoT testbed for security experiments and dataset generation," *arXiv preprint arXiv:2207.13981*, 2022.

[20] "MENTORED Project," https://www.mentoredproject.org/, accessed: 2023-01-24.

[21] C. Dietz, M. Antzek, G. Dreo, A. Sperotto, and A. Pras, "Dmef: Dynamic malware evaluation framework," in *IEEE/IFIP Network Operations and Management Symposium (NOMS)*, 2022, pp. 1–7.

[22] A. Tekeoglu and A. Ş. Tosun, "A testbed for security and privacy analysis of IoT devices," in *IEEE International Conference on Mobile Ad Hoc and Sensor Systems (MASS)*. IEEE, 2016, pp. 343–348.

[23] G. Sasirekha, T. Adhisaya, P. Aswini, J. Bapat, and D. Das, "Challenges in the design of an iot testbed," in *2019 2nd international conference on intelligent Communication and computational techniques (ICCT)*. IEEE, 2019, pp. 14–19.

[24] M. M. Yamin, B. Katt, and V. Gkioulos, "Cyber ranges and security testbeds: Scenarios, functions, tools and architecture," *Computers & Security*, vol. 88, p. 101636, 2020.

[25] B. Pfaff, J. Pettit, T. Koponen, E. Jackson, A. Zhou, J. Rajahalme, J. Gross, A. Wang, J. Stringer, P. Shelar *et al.*, "The design and implementation of open {vSwitch}," in *USENIX symposium on networked systems design and implementation (NSDI)*, 2015, pp. 117–130.

[26] "Web Kubectl," https://github.com/KubeOperator/webkubectl, accessed: 2023-01-24.

[27] "DEMO NOMS 2023 yaml topology," https://github.com/KubeOperator/webkubectl, accessed: 2023-01-24.