GothX: a generator of customizable, legitimate and malicious IoT network traffic

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Full paper: https://inria.hal.science/hal-04629350

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Introduction

Internet of Things (IoT) increasing usage

MQTT and **Kafka** IoT data collection/processing

Defend IoT

Increase of attacks against IoT [1]

⇒ Development of Intrusion Detection Systems (IDS) performing anomaly detection using machine learning[2]

⇒ Need of datasets for training models

[1] Kolias et al. **"DDoS in the IoT: Mirai and Other Botnets".** In: *Computer* 50.7 (2017), pp. 80–84

[2] Lahesoo et al. **"SIURU: A Framework for Machine Learning Based Anomaly Detection in IoT Network Traffic".** In: AINTEC '23. Dec. 2023, pp. 87–95

Introduction

Expected properties of datasets

- Mix legitimate and malicious traffic
- Supervised training and validation ⇒ labels
- Robustness of IDS ⇒ diversity
  - Detection of different attacks
  - Avoid alerts when legitimate traffic varies

Get desired datasets

- Use publicly available dataset → single snapshot
- Generate own dataset:
  - Develop own traffic generator → requires time and expertise
  - **Use existing traffic generator → difficult to find and not very flexible**

Our contribution

GothX traffic generator

- IoT network traffic: **MQTT** and **Kafka**
- Generates **labeled dataset**
- **Open-source and modifiable** [3]

Automatically executing a customizable scenario

- **Legitimate actions**
- Attacker complete **kill chain from initial compromission to DDoS**
- **Customizable**: study impact on IDS of various parameters (eXplainable AI)

Ready-to-use new datasets

- Provide datasets generated using GothX

[3] Software and datasets available at https://github.com/fukuda-lab/GothX

Related works

GothX: a fork of Gotham[4]

Gotham uses GNS3® to **emulate virtual networks**

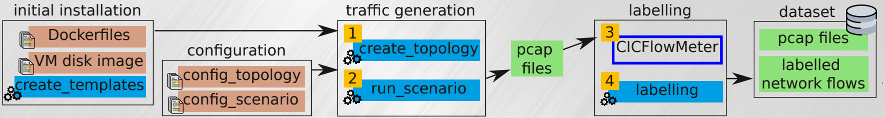
Features	Gotham	GothX
Open-source	✓	✓
Legitimate + malicious traffic	✓	✓
Virtualization (Docker + VM)	✓	✓
Automatic network initialization	✓	✓
Reproducible results	✓	✓
Labeled data		✓
Customizable node behavior		✓
MQTT service	✓	✓
MQTT-Kafka service		✓
Accompanying ready-made datasets		✓

GothX extends Gotham's features and add new ones

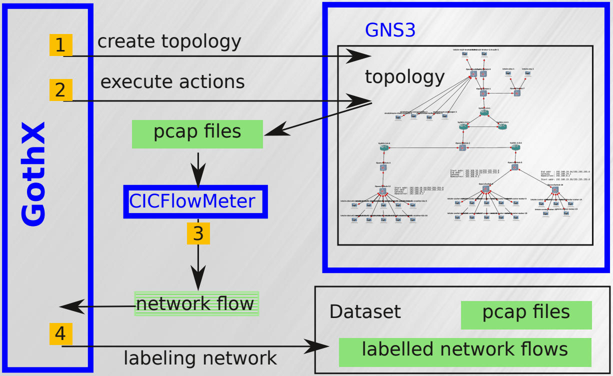
[4] Saez-de-Camara et al. **"Gotham Testbed: A Reproducible IoT Testbed for Security Experiments and Dataset Generation".** In: *IEEE Transactions on Dependable and Secure Computing* PP (Jan. 2023), pp. 1–18

GothX architecture and workflow

GothX's workflow



GothX's interaction with other tools



legend

- ▨ configuration
- ⚙ data creation
- 🟩 data

Customization

Benefits of customization

- Settings combinations ⇒ **diversity of the network traffic**
- Analyze the efficiency of anomaly detection when **legitimate traffic varies but the attack is the same, or vice-versa**
- Variation of settings independently ⇒ study the **impact of a specific parameter** on a machine learning model (XAI)

Customizable topology and scenario parameters

Legitimate traffic	Malicious traffic
Sensors count	Parameters of attack tools
Messages rate* (periodic/random)	Intensity of DDoS attack (e.g. payload size)
(In)activity duration*	% of compromised sensors
Which data, from a dataset of real sensors, is sent*	Sleep time between attack steps
Traffic volume (MQTT/Kafka)*	

*customizable for each sensor independently

2 case examples

Case 1: MQTTSet reproduction

- Multiple MQTT behavior patterns
- 5 types of denial of service (DoS)

Case 2: Full, multi-step, attack scenario

- Legitimate MQTT and Kafka traffic
- Attacker spread in the network
  (different techniques to take control of multiple nodes)
- DDoS

Case 1: MQTTSet reproduction

The MQTTSet dataset [5]

Legitimate traffic
10 sensors publishing periodically or randomly

5 types of denial of service in MQTTSet

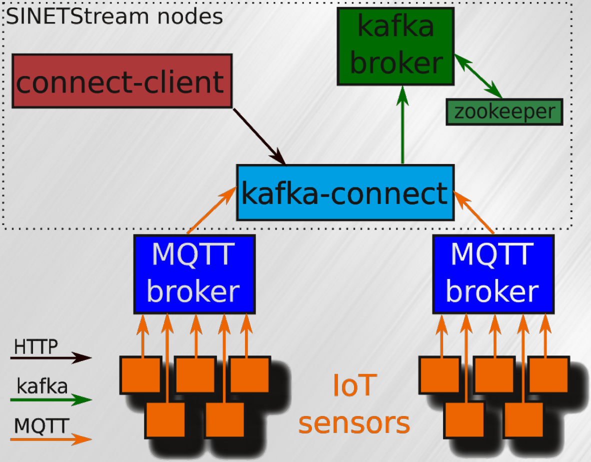
- 1 file with legitimate traffic only, 1 file per attack type
- Synthetic legitimate traffic (no real broker) ⇒ **impossible to visualize DoS impact**

Our contribution

Reproduction of MQTTSet: similar characteristics of legitimate and attack traffic.
GothX is more realistic: **mix legitimate/malicious** traffic

[5] Vaccari et al. **"MQTTset, a New Dataset for Machine Learning Techniques on MQTT".** en. In: *Sensors* 20.22 (Jan. 2020). Number: 22 Publisher: Multidisciplinary Digital Publishing Institute, p. 6578

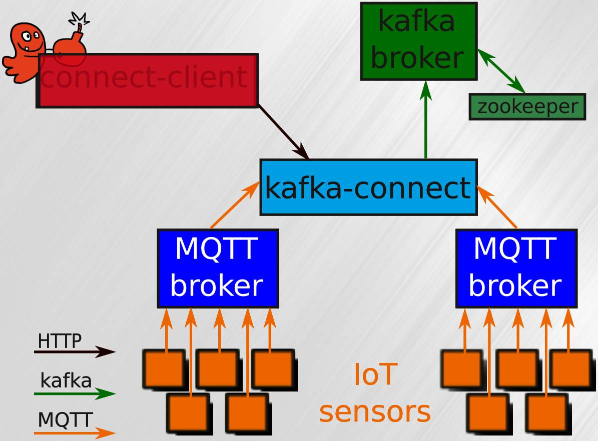
Case 2: Full scenario: topology



Assumptions

- Some IoT sensors with SSH open ports
- *kafka-connect*
  - version 7.3.1 (December 2022)
  - `enableUnsafe Serialization=true`
  - ⇒ CVE-2023-25194

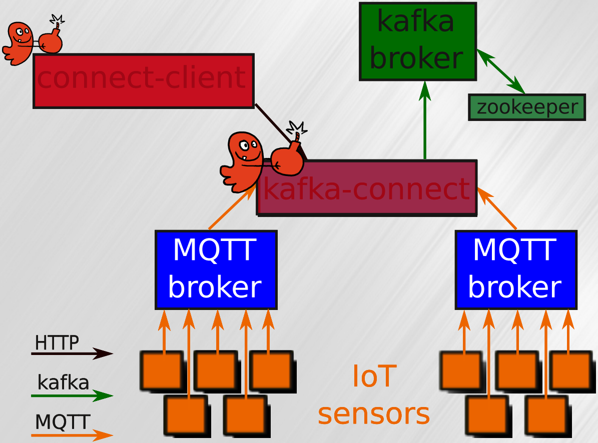
Case 2: Full scenario: attack steps



1. Attacker controls *connect-client*

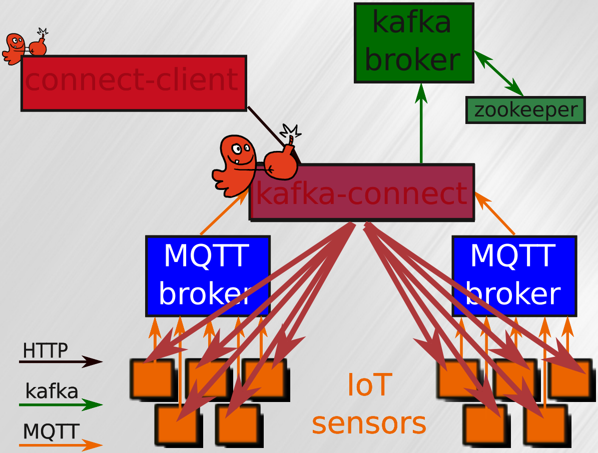
Internal attack:
device *connect-client* sent legitimate requests.
It starts to be malicious.

Case 2: Full scenario: attack steps



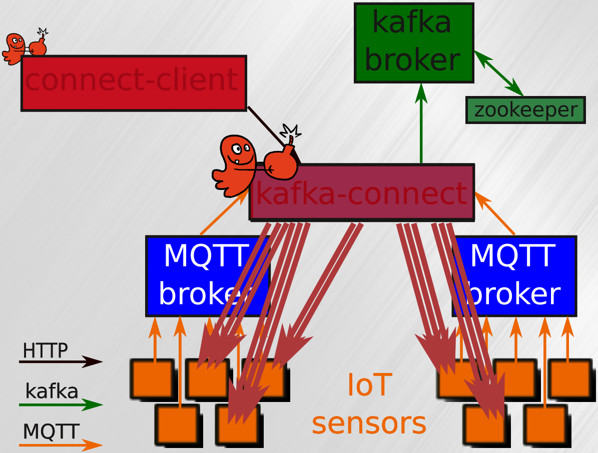
1. Attacker controls *connect-client*
2. Exploit CVE-2023-25194 on *kafka-connect* ⇒ RCE

Case 2: Full scenario: attack steps



1. Attacker controls *connect-client*
2. Exploit CVE-2023-25194 on *kafka-connect* ⇒ RCE
3. Discover of devices responding to SSH

Case 2: Full scenario: attack steps



1. Attacker controls *connect-client*
2. Exploit CVE-2023-25194 on *kafka-connect* ⇒ RCE
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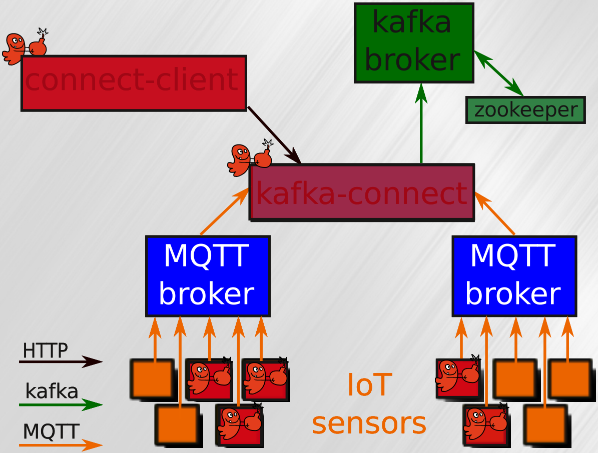
4. Bruteforce SSH credentials

Case 2: Full scenario: attack steps



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2. Exploit CVE-2023-25194 on *kafka-connect* ⇒ RCE
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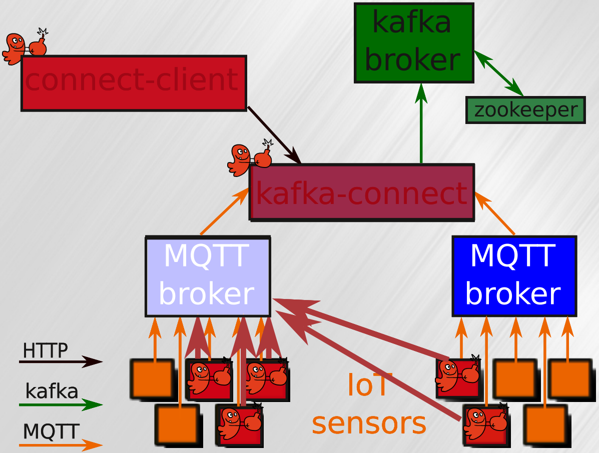
5. Transfert payload (via SSH)

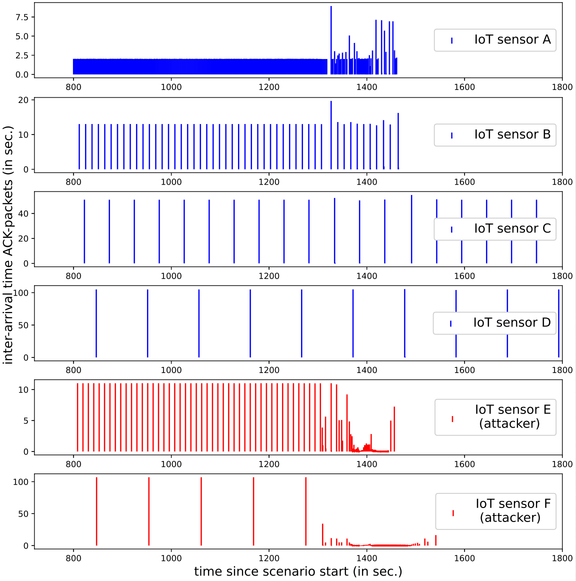
Case 2: Full scenario: attack steps



1. Attacker controls *connect-client*
2. Exploit CVE-2023-25194 on *kafka-connect* ⇒ RCE
3. Discover of devices responding to SSH
4. Bruteforce SSH credentials
5. Transfert payload (via SSH)
6. Simultaneous payload execution ⇒ DDoS
7. Target (MQTT Broker) crash

Case 2: Full scenario: DDoS analysis

DDoS impact:
Inter-arrival time
of ACK-packets
during scenario



Case 2: Full scenario: DDoS analysis

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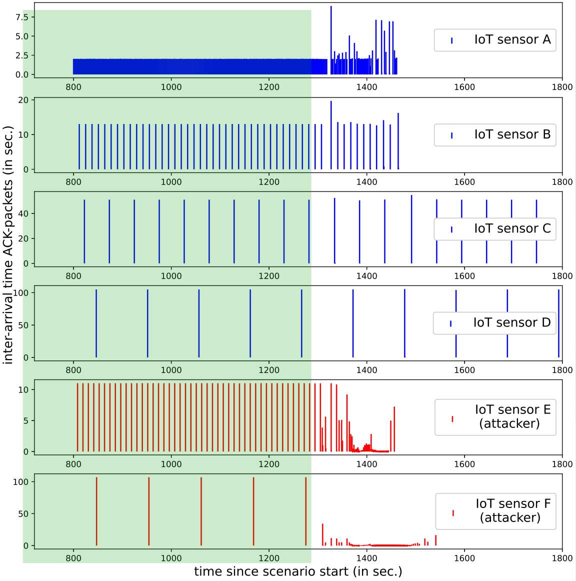
Before DDoS



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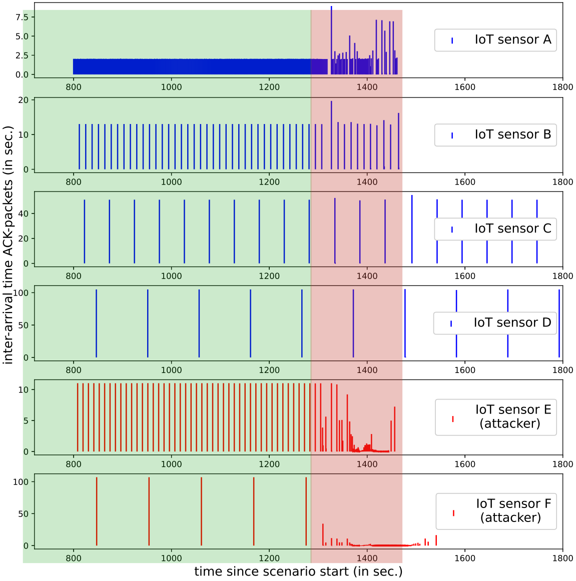

Before DDoS
During DDoS

Case 2: Full scenario: DDoS analysis

DDoS impact:
Inter-arrival time
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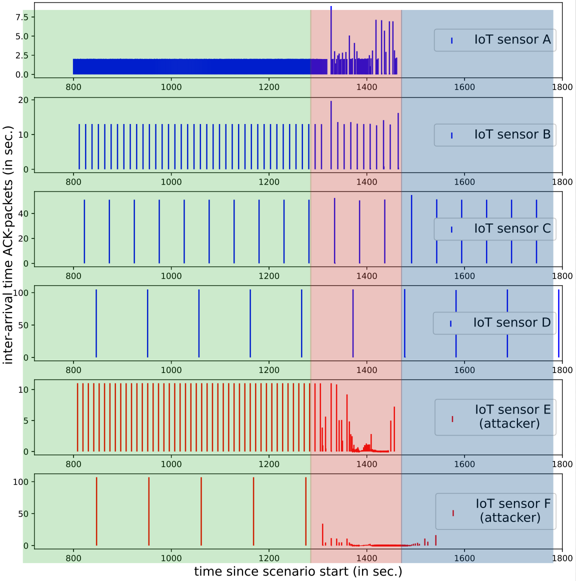


Before DDoS
During DDoS
After DDoS

Case 2: Full scenario: provided dataset

pcap files and details

- **All generated traffic captured**

  3 pcap files mixing legitimate and malicious actions (like in real world network traffic)
- Text file **describing configuration** and **command line** executed

TCP flows labelling

1. Automatic flows' features extraction with *CICFlowMeter*[6]
2. **Attack steps labelling adaptative to customization** with provided custom script

Usage of variations of this dataset

Atsuya et al. **"Dynamic Fixed-point Values in eBPF: a Case for Fully In-kernel Anomaly Detection".** In: AINTEC '24. Aug. 2024, p. 8

[6] https://github.com/GintsEngelen/CICFlowMeter

GothX scalability and replication

Scalability

Definition: more IoT devices running simultaneously ((•))((•))((•)) → ((•))((•))((•))((•))((•))((•))((•))((•))((•))

- **Hardware ressources**:
  - RAM: 20GB for 450 sensors
  - CPU: depends on DDoS intensity
- **Realism**:
  - do not simply duplicate sensors with exactly the same behavior
  - use customization to send different data for each sensor
- **Execution time**:
  - data generation: fully customizable, depends on scenario duration
  - topology deployment: 4 VM and 498 Docker containers →≈ 26 minutes

Replication

- ✓ public source code and documentation
- ✓ GothX's installation and usage on different computers using documentation
- ✓ Executions with the same configuration ⇒ Generation of similar datasets

Conclusion

Delivery of the **traffic generator GothX**

- Open-source[7]
- Customizable

Producing **IoT network datasets**

- Labeled
- Legitimate and malicious traffic

Delivery of **2 datasets**

1. MQTTSet reproduced
2. New dataset on ≈ 14h from our customizable multi−steps scenario

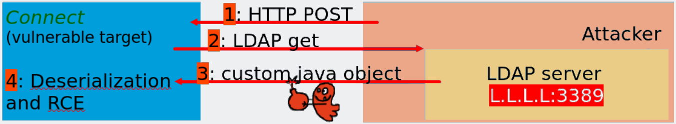
Customizable full (attack) scenario

- Legitimate MQTT and Kafka messages
- Exploitation of recent, highly critical vulnerability (CVE-2023-25194)
- Ports scan and credentials bruteforce
- DDoS

[7] Software and datasets available at https://github.com/fukuda-lab/GothX

Details on the attack

CVE-2023-25194



CVE-2023-25194 exploitation

Type of DDoS

SlowITe[8]: exhaust the number of simultaneous connections to the broker
Using tool mqttsa

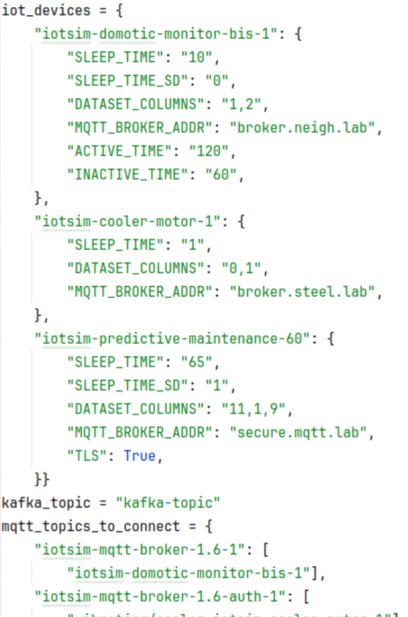
[8] Ivan Vaccari, Maurizio Aiello, and Enrico Cambiaso. **“SlowITe, a Novel Denial of Service Attack Affecting MQTT”.** In: *Sensors* 20 (May 2020), p. 2932

Attacks in MQTTSet

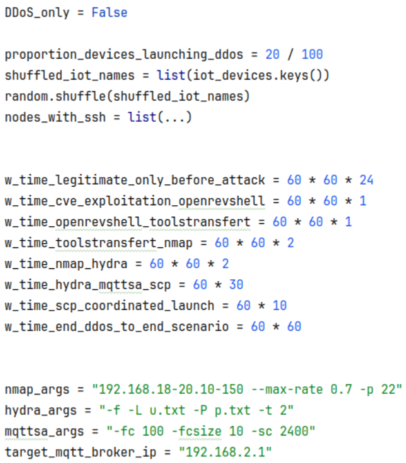
Attack type	Tool
Flood DoS	MQTT-malaria
MQTT publish flood (CVE-2018-1684)	IoT-Flock
SlowITe	SlowTT
Maleformed data	MQTTSA
Authentication bruteforce	MQTTSA

[8] Ivan Vaccari, Maurizio Aiello, and Enrico Cambiaso. **"SlowITe, a Novel Denial of Service Attack Affecting MQTT".** In: *Sensors* 20 (May 2020), p. 2932

Example of a configuration



```
iot_devices = {
    "iotsim-domotic-monitor-bis-1": {
        "SLEEP_TIME": "10",
        "SLEEP_TIME_SD": "0",
        "DATASET_COLUMNS": "1,2",
        "MQTT_BROKER_ADDR": "broker.neigh.lab",
        "ACTIVE_TIME": "120",
        "INACTIVE_TIME": "60",
    },
    "iotsim-cooler-motor-1": {
        "SLEEP_TIME": "1",
        "DATASET_COLUMNS": "0,1",
        "MQTT_BROKER_ADDR": "broker.steel.lab",
    },
    "iotsim-predictive-maintenance-60": {
        "SLEEP_TIME": "65",
        "SLEEP_TIME_SD": "1",
        "DATASET_COLUMNS": "11,1,9",
        "MQTT_BROKER_ADDR": "secure.mqtt.lab",
        "TLS": True,
    }}
kafka_topic = "kafka-topic"
mqtt_topics_to_connect = {
    "iotsim-mqtt-broker-1.6-1": [
        "iotsim-domotic-monitor-bis-1"],
    "iotsim-mqtt-broker-1.6-auth-1": [
        "vibration/cooler-iotsim-cooler-motor-1"]
```



```
DDoS_only = False

proportion_devices_launching_ddos = 20 / 100
shuffled_iot_names = list(iot_devices.keys())
random.shuffle(shuffled_iot_names)
nodes_with_ssh = list(...)


w_time_legitimate_only_before_attack = 60 * 60 * 24
w_time_cve_exploitation_openrevshell = 60 * 60 * 1
w_time_openrevshell_toolstransfert = 60 * 60 * 1
w_time_toolstransfert_nmap = 60 * 60 * 2
w_time_nmap_hydra = 60 * 60 * 2
w_time_hydra_mqttsa_scp = 60 * 30
w_time_scp_coordinated_launch = 60 * 10
w_time_end_ddos_to_end_scenario = 60 * 60


nmap_args = "192.168.18-20.10-150 --max-rate 0.7 -p 22"
hydra_args = "-f -L u.txt -P p.txt -t 2"
mqttsa_args = "-fc 100 -fcsize 10 -sc 2400"
target_mqtt_broker_ip = "192.168.2.1"
```