Sorry, Shodan is not Enough! Assessing ICS Security via IXP Network Traffic Analysis

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\textbf{Abstract.} Modern Industrial Control Systems (ICSs) allow remote communication through the Internet using industrial protocols that were not designed to work with external networks. To understand security issues related to this practice, prior work usually relies on active scans by researchers or services such as Shodan. While such scans can identify public open ports, they are not able to provide details on configurations of the system related to legitimate Industrial Traffic passing the Internet (e.g., source-based filtering in Network Address Translation or Firewalls). In this work, we complement Shodan-only analysis with large-scale traffic analysis at a local Internet Exchange Point (IXP), based on sFlow sampling. This setup allows us to identify ICS endpoints actually exchanging Industrial Traffic over the Internet. Besides, we are able to detect scanning activities and what other type of traffic is exchanged by the systems (i.e., IT traffic). We find that Shodan only listed less than 2\% of hosts that we identified as exchanging Industrial Traffic. Even with manually triggered scans, Shodan only identified 7\% of them as ICS hosts. This demonstrates that active scanning-based analysis is insufficient to understand current security practices in ICS communications. We show that 75.6\% of ICS hosts rely on unencrypted communications without integrity protection, leaving those critical systems vulnerable to malicious attacks.

\textbf{Keywords:} Industrial Control Systems · Traffic Measurement.

\section{Introduction}

Industrial Control Systems are used to control and monitor industrial and critical infrastructure such as power grids, nuclear and chemical plants, water treatment systems and buildings. According to the Purdue model \cite{37}, which represents the reference architecture model for the ICSs, these systems were supposed to operate on air-gap environments, however, due to the rise of the Internet and
Ethernet technologies the industrial business move towards the connection to external networks, opening dangerous vulnerability surfaces. This digitization process requires the adaptation of legacy protocols that were not designed with security features (e.g., Modbus, DNP3, and BACnet) to the TCP/IP stack, to allow operations such as remote communication. The lack of encryption and authentication can be exploited for a malicious purpose such as data exfiltration, impersonification, and service disrupting.

The research interest and effort on ICS security increased with the number of incidents and the involvement of critical-infrastructures, from the most famous Stuxnet [14] that affected an Iranian nuclear power plant to the more recent Triton [13] that targeted Schneider Electric products. The list of famous attacks includes also recent events such as [6, 9, 38]. As reported by [12, 20], the attacks over the ICSs are growing year after year and the number of vulnerable devices is still very high. Many researchers estimated the vulnerable ICS landscape by looking for well-known ICS ports exposed to the Internet, by actively performing scanning of the IPv4 address space [15, 21] or leveraging public available information [1, 2, 17, 19] gathered by third-parties such as Shodan [33] and Censys [10]. However, many ICSs could not be indexed due to the presence of network devices like Network Address Translations (NATs) or Firewalls, leading to an incomplete estimation of the vulnerable ICSs. In [23] the authors analyzed the unprotected Industrial Traffic transmitted over the Internet, gathering information about the security status of the host systems, but they didn’t investigate their presence in public databases.

In this paper, we investigate the practical use of ICS protocols over the Internet, most importantly to learn about security issues. In particular, we aim to determine if scanning traffic (such as results from Shodan) provides accurate estimates of the actual use of ICS protocols (i.e., Is Shodan enough?). To achieve this, we present a framework to accurately identify the ICS host transmitting Industrial Traffic over the Internet, based on traffic observed at an IXP. We compare and correlate the obtained results with the information from a prominent scanner (Shodan). Our analysis results underline the lack of security in ICS infrastructures, emphasizing the current vulnerabilities and threats.

We summarize our contributions as follows:

– We propose, implement and validate a framework to identify legitimate industrial traffic and scanning activities, based on sFlow sampled traffic passively gathered at an IXP.
– We demonstrate that our method allows to obtain a more detailed understanding of security practices in ICS, in particular related to site-to-site communication with industrial protocols. We find that scanning results obtained actively (or via Shodan) to not accurately represent security configurations at the ICS.

The remainder of the paper is organized as follows. Section 2 briefly recalls the main concepts useful for the goal of the paper. Section 3 outlines our methodology to identify and filter ICS traffic based on sampled captures. Section 4 describes the data collection and the implementation of the filtering process.
Section 5 and Section 6 illustrate respectively the results related to our research questions and the results of additional analysis and insight. Section 7 discusses our findings and Section 8 provides an overview of the related work. Finally, Section 9 concludes the paper.

2 Background

In this Section we briefly recall the main concepts useful to understand the remainder of the paper. In particular, in Section 2.1 we introduce the ICSs and in Section 2.2 we recall the definition of Autonomous System (AS) and IXP which represent the main entities of our system model.

2.1 Industrial Control Systems

ICS comprises devices that are used to monitor and control industrial processes. Most ICSs fall into either a continuous process control system, typically managed via Programmable Logic Controllers (PLCs), or Discrete Process Control systems (DPC), that might use a PLC or some other batch process control device. An ICS is responsible for a vast amount of critical processes, consequently, organizations need to adequately secure their infrastructures. The creation of strong boundaries between business and process control networks can reduce the number of vulnerabilities and attack pathways that an intruder may exploit to gain unauthorized access into these critical systems.

The monitoring of the physical processes is performed through Cyber-Physical devices. A CPS is an integration of computation with physical processes whose behavior is defined by both the cyber and physical parts of the system. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa.

Historically, ICS networks were isolated from the Internet for security reasons and used proprietary protocols whose specifications were not disclosed. From the security point of view there was no possibility of remote access, so the risk of cyber attacks was very low. However, in recent years, due to the growth of smart manufacturing, ICSs have been connected to the Internet, opening new dangerous surfaces of vulnerability.

2.2 ASs and IXPs

An Autonomous System (AS) consists of a group of IP prefixes under the control of a single well-defined administrative authority that defines the routing policies, typically an Internet Service Provider (ISP), uniquely identified by its Autonomous System Number (ASN). The routing within an AS is allowed via Interior Gateway Protocol (IGP) while the communication with other ASs relies on the Border Gateway Protocol (BGP). An IXP is a network facility that enables the interconnection and exchange of Internet traffic between more than two independent ASs according to their BGP routing configurations. Its typical
architecture consists of a single or multiple switches connected to the border routers of the adherent ASs, ensuring benefits in terms of bandwidth, costs, and latency.

3 ICS Security Assessment Through IXP

Our analysis relies on VSIX \cite{35}, a local IXP which manages the traffic circulating in the North East of Italy. This environment allows us to collect packets circulating through the Internet in a secure and privacy respectful way. In the following, we detail our system model in Section 3.1 while in Section 3.2 and Section 3.3 we outline respectively the research questions of this paper and the proposed framework for the traffic analysis.

3.1 System Model

We assume a system in which ICSs are connected to a local AS (e.g., as customers of an ISP), and are using Industrial Traffic over the Internet for supervision and control (depicted in Figure 1). The IXP provides the capability to sample traffic to understand the used protocols and involved parties.

In the considered model, an attacker could be a malicious end host located at another AS, or a Man-in-the-Middle attacker (e.g., by an ISP or IXP). The former attacker needs to be active (e.g., scanning the well-known ICS ports), while the latter is possibly passive. Their goals are to learn process data (i.e., eavesdrop), and/or manipulate the ICS actively (e.g., by changing or injecting operational commands).

3.2 Research Questions, Challenges, and Goal

Our main goal is to investigate the practical use of ICS protocols over the Internet, in particular with respect to security. The main questions are: RQ1: How often (insecure) ICS protocols are used over the Internet? RQ2: How often are ICS services exposed to third parties, in addition to the intended use by legitimate parties?

The main challenge we faced is that legitimate use of ICS traffic cannot be directly observed by third parties unless they are carrying the traffic (i.e., are in a Man-in-the-Middle/MitM position). Even in that case, efficiently filtering for ICS traffic out of large volumes of traffic can be challenging.

The outlined challenges raise the following additional research questions: If ICS protocols are used or exposed, can we identify such hosts using active scanning (e.g., Shodan), or IXP-based traffic collection? To which degree are results of both complementing each other? In other words, RQ3: Is active-scanning based enumeration of hosts a good estimator of (vulnerable) Industrial Traffic use on the Internet?

For practical reasons, we focused our work on a geographical region in our country served by a specific IXP.
Fig. 1: System model: ICS at AS X, AS Y, and AS Z communicate over the IXP. Scanners on the Internet (AS Z, AS K), which can be malicious or benign, look for exposed ICS services. The packets exchanged between two hosts belonging to AS Y and AS Z could still pass through the IXP, even if AS Z is not directly connected to it. We sat within the IXP network where we are able to collect and analyze sampled packets.

3.3 Proposed Framework

We summarized the steps performed to address the research questions in Figure 2. The first step consists in the data collection and processing. Such data comes from two different sources. The first one is real Internet traffic captured at the local IXP, the second one are hosts information collected through Shodan public database, used for the definition of the baseline to evaluate the traffic-based approach. The main challenge of this step was to properly extract the Industrial Traffic from the IXP traffic collection. To solve this, we implemented a three-step filtering approach based on well-known tools (e.g., Wireshark) which are able to identify both scanning and legitimate ICS activities. In the second step, we analyzed the results of the first step to answer the research questions. We analyzed the legitimate Industrial Traffic, compared the hosts identified with the baseline, and investigated the exposure on Shodan of the hosts detected legitimately exchanging Industrial Traffic. Finally, to gather additional information about the current ICS security practices and threats, we investigated the data collected at the IXP to detect scanning activities and to deeply understand the network behavior and architecture (e.g., presence of a NAT) of the hosts. A port-scan approach, cannot identify industrial services hidden behind a NAT, Firewall or VLAN, instead, it is possible from our position. The presence of both Industrial and non-Industrial Traffic from a single host can be an indicator of such network mechanisms.
4 Implementation

In this Section we present the implementation of our framework of analysis. In particular, Section 4.1 defines the baseline that we use to compare our approach to a scan-based one and Section 4.2 outlines the packet filtering approach used to identify the ICSs hosts.

4.1 Collection of the Shodan Baseline

We used Shodan to identify the ICS hosts exposed to the Internet within the IXP area. We define the IXP area as the set of ASs directly connected to the IXP itself. Due to the limited access to the Shodan services we collected all the Italian ICS exposed according to the industrial-control-systems category offered by the Shodan platform. However, the list of protocols offered in such category is incomplete compared to our list, so we also collected the hosts indexed on Shodan according to protocol-specific filtering rules (e.g., ports and common terms). We then selected the ICSs of our interest discarding the hosts that do not belong to an AS of the IXP area. We reported the results of the analysis in Table 1.

4.2 Packet Filtering

To identify the ICS protocols we applied a port-based filter according to the most commonly used ones, using the official documentation of the protocols and the ports list [18] as main references. We reported the considered protocols in Appendix A in Table 7 followed by their port ranges and the Wireshark dissector availability. Due to the Wireshark limitations, we applied the following three-step approach.

1. In the first step we identified the correctly dissected ICS traffic by Wireshark, dividing scanning activities from legitimate activities.
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MQTT
NiagaraFox
Modbus/TCP
EtherCAT/IP
Siebrecht
CoAP
Codesys
BACnet/IP
AMQP
OMRON FINS
OPC-UA
DNP3
IEC60870-5-104
ProConOS
GE-SRTP
Crimson v3
MELSEC-Q

Italy
Hosts  1531 1382 1346 456 417 373 364 183 160 140 83 32 13 11 6 5 5  2 1
%     23.5 21.2 20.6 7  6.4 5.7 5.6 2.8 2.6 2.1 1.3 0.5 0.2 0.2 0.09 0.07 0.07 0.03 0.1

IXP
Hosts  206 50 70 16 37 2 3 10 26 4 6 7 1 0 0 0 1 0 1
%     47.8 11.3 15.9 3.6 8.4 0.4 0.7 2.3 5.7 0.9 1.4 1.6 0.2 0 0 0.2 0 0.2

Table 1: List of the ICS per-protocol exposed in Italy and IXP area according to Shodan with the corresponding overall percentage.

(a) We used Wireshark to identify all the Industrial Protocols supported and marked as not malformed;
(b) We cross-validated the data using nDPI [25], an open-source library able to dissect a wide range of industrial and non-industrial protocols, removing all the packets which were tagged as non-industrial protocols;
(c) We filtered out the packets where the IP-source is tagged as scanner by GreyNoise [16]. GreyNoise is a security company that collects, labels, and analyzes Internet-wide scan and attack data;
(d) We considered the difference between the results of b) and c) as legitimate ICS traffic;

2. In the second step we identified scanning activities targeting the ports of the protocols not correctly dissected in step 1.
(a) We used Wireshark to remove all the not malformed, industrial and non-industrial protocols (e.g., SSL, HTTP), keeping the packets generally tagged as TCP or UDP;
(b) We used nDPI to remove additional non-Industrial Traffic from the previous results;
(c) We used GreyNoise to identify scanning activities;

3. In the third step we gather the results of step 1 and step 2.
(a) We merged the scanners activities identified and we tagged them as ICS scanners;
(b) We considered the sum of the legitimate ICS traffic and the ICS scanners as ICS traffic.

We reported the result of the three-step filtering process in Table 2.

5 Results

We collected data for a period of 31 days from the 14th of January 2020 to the 14th of February 2020 at the considered IXP. The traffic was sampled according
| Packets | % |
|---------|---|
| Total   | ~1.6B |
| Port-based filtering | 43584 0.0027 |
| **Step 1** | |
| Wireshark filtering | 3188 |
| nDPI validation | 2075 65.1 |
| Scanning activities | 1360 42.6 |
| Legitimate ICS traffic | 715 22.4 |
| **Step 2** | |
| Wireshark filtering | 32741 |
| nDPI validation | 26171 80 |
| Scanning activities | 3019 9.2 |
| **Step 3** | |
| ICS traffic | 5094 |
| ICS scanners | 4379 86 |
| Legitimate ICS traffic | 715 14 |

| Overall [%] |
|------------|
| ICS traffic | ~0.0003 |
| ICS scanners | ~0.0003 |
| Legitimate ICS traffic | ~0.00005 |

Table 2: Packet filtering results step by step. Overall [%] represents the percentage of industrial filtered traffic with respect to the total number of collected packets.

to the sFlow standard, with a sampling rate of $2^{-12}$ and packet truncation at 128 bytes. The sampling process provides an estimation of the effective traffic passing through the exchange point, while the truncation gives access to the full link layer, network layer, transport layer and few bytes of the payload. The collection resulted in ~1.6B packets for more than 189GB of data.

In the following Section we present the results of the analysis of the traffic capture obtained after the collection phase. In particular, Section 5.1 discusses the legitimate ICS traffic, Section 5.2 compares our approach with Shodan, while Section 5.3 reports an analysis of the Shodan-indexed hosts.

### 5.1 Legitimate ICS Traffic

We identified 168 ICS endpoints and 12 different industrial protocols, with 8 hosts using two different ICS protocols. The percentage of legitimate ICS traffic over the total number of packets is $5 \cdot 10^{-5}$. In Appendix A, we reported that MQTT and AMQP protocols together count more than 55% of the overall legitimate ICS traffic. This result is not surprising since both the protocols are also widely used for IoT communication in non-industrial environments. ANSI C12.22 covers almost 21% of the overall number of packets, followed by Modbus/TCP with 9% and Zigbee with 8%. Other very common ICS protocols as Profinet, Ethercat, IEC60870-5-104 and Ethernet/IP together count less than
7%. Another interesting result is that despite MQTT official documentation [5] specifies port 8883, and AMQP port 5671 respectively, for communicating over TLS, our results show that all the MQTT and AMQP communication rely on insecure ports, implying all the relative vulnerabilities [3,27].

### 5.2 Comparison with the Shodan Baseline

To address RQ3 we compared the hosts identified on Section 5.1 with the hosts identified on Section 4.1. We define $H$ as the set of ICS hosts detected by us and $H_S$ as the set of ICS hosts identified by Shodan. Our interest is to identify the number $i = |H \cap H_S|$ of ICS hosts commonly detected by the two approaches. We quantified which method detected more ICS hosts by computing the ratio:

$$r = \frac{|H|}{|H \cup H_S|} = \frac{h}{h + h_S - i}$$

where $h$ is the cardinality of $H$, and $h_S$ is the cardinality of $H_S$. The value of $r$ can be interpreted as follows: if $r = 0$ our approach did not detect any endpoint compared to Shodan, if $0 < r < 0.5$ Shodan did better than us, if $r = 0.5$ the two methods detected the same number of ICS hosts, if $0.5 < r < 1$ our approach is better and if $r = 1$ we identified at least an endpoint while Shodan no one. We reported the results in Table 3. Despite we detected an overall amount of 168 ICS hosts and 440 hosts were by Shodan, just 2 were common to both the approaches, respectively an MQTT and a Modbus/TCP endpoint, meaning that the two methods are complementary. Our approach, according to the resulting values of $r$, performed better than Shodan for 8 protocols, 6 of which with a value of 1. The port-scanning approach, instead, performed better for 12 protocols. However, by further analysis 6 of them were not possible to detect following our approach due to the limited number of Wireshark dissectors (as reported in Appendix A).
Table 4: Top-5 port and product detected by Shodan.

| Product                      | % | Port | %   |
|------------------------------|---|------|-----|
| MikroTik bandwidth-test server | 25 | 443  | 11.8|
| Apache httpd                 | 12.5 | 80   | 11.5|
| nginx                        | 9  | 2000 | 7   |
| Open SSH                     | 9  | 8080 | 6   |
| MQTT                         | 7.9 | 22   | 4.1 |

5.3 Hosts Exposure on Shodan

Among the ICS hosts involved in a legitimate ICS communication, we were interested in checking how many of them were also indexed by Shodan, and what kind of information Shodan was able to gather (i.e., RQ2). We found that 64.3% of such hosts were successfully identified by Shodan and 11% of them were found with ICS ports exposed, more specifically Modbus/TCP, MQTT, and AMQP.

In Table 4 we reported the Top-5 products and exposed ports based on the Shodan collected data. Due to the high percentage of Web Servers detected, we investigated deeply to understand what kind of services these devices were exposing. We found IP Cameras, Printers, Routers and Network Attached Storage (NAS) login pages other than energy monitoring and alarm systems. In this work we were not interested in performing any kind of active penetration test to the identified devices. For this reason, we analyzed the Common Vulnerabilities and Exposures (CVEs) information provided by Shodan to identify possible vulnerabilities caused by unpatched systems or well-known critical products. We found that 10.2% of the systems indexed were affected by at least one CVE. We then associated with each vulnerability the corresponding Common Vulnerability Scoring System (CVSS) v2.0 score [24]. According to the National Institute of Standard and Technology (NIST) the severity of a score between 0.0-3.9 is considered low, 4.0-6.9 medium and 7.0-10.0 high. We found an overall amount of 207 CVEs, 30% of which have a score greater than 7.0 affecting 81% of the vulnerable hosts, 4.3% greater than 8.0, 2.9% greater than 9, and 2.4% equal to 10.0 all affecting 27.3% of the vulnerable hosts. We must note that all these vulnerabilities can be exploited remotely.

5.4 Summary of Main Results

RQ1: How often (insecure) ICS protocols are used over the Internet? We observed 12 different industrial protocols during our collection period. By analyzing these 12 protocols, 6 of them (i.e., EtherCAT, PROFINET, IEC60870-5-104, Ethernet/IP, Modbus/TCP, FF HSE) do not implement any encryption, authentication or integrity protection features by design and were used by 59 hosts. In addition, protocols such as MQTT and AMQP support TLS (enabling confidentiality and authentication), but we did not see this being employed in practice.
The use of insecure protocols and missing use of TLS affected an overall amount of 127 hosts, meaning that 75.6% of the hosts are using vulnerable ICS communications.

RQ2: *How often are ICS services exposed to third parties, in addition to the intended use by legitimate parties?* We found that only a small subset of hosts that we identified as legitimately using ICS protocols (i.e., 7.1% corresponding to 12 hosts) also have ICS protocols ports exposed to the public Internet. Furthermore, for the hosts that we identified as legitimately using ICS protocols, we found that a good subset (i.e., 64.3% corresponding to 108 hosts) also has general IT ports exposed to the Internet. By analyzing these 108 hosts, 11 of them were affected by at least a CVE, instead 9 of them were affected by different CVEs with a CVSS score greater than 7.0.

RQ3: *Is active-scanning based enumeration of hosts a good estimator of (vulnerable) Industrial Traffic use on the Internet?* The $r$ value we calculated indicates that *Shodan* finds three times as many hosts as our method, while the $i$ value we calculated indicates that only about 1.2% of the hosts collected by our framework were also detected by *Shodan*. This means *Shodan* missed most hosts that are actually implementing ICS protocols. We conclude that while *Shodan* returns the higher number of hosts, even with manual direction to the right hosts *Shodan* is largely unable to identify hosts that actually use industrial protocols for legitimate applications.

6 Additional Analysis and Insights

In the following Section we reported further results we obtained beyond the research questions defined in Section 3.2. In particular, we Section 6.1 provided a detailed analysis of the origin of scanning campaigns. Section 6.2 reports an analysis of the hosts implementing both Industrial communication and non-Industrial communication (i.e., IT traffic). Finally, Section 6.3 presents a validation procedure for the IXP on which we relied on.

6.1 Scanning Activities

In this analysis, we associated any scanning activity identified during the packet filtering process to the relative ICS protocol, according to the targeted port.

**Scanned protocols.** We identified a total of 442 different IPs performing scanning activities. The most scanned port was 5683 used by CoAP with more than 50% of the scan packets, followed by BACnet/IP, Automated Tank Gauge (ATG) systems and DNP3. Almost 30% of the scan packets were crafted with protocol-specific requests, like `readProperty` function for BACnet/IP, `GET /well-known/core` for CoAP, `List Identity` for Ethernet/IP, `Session Initiate Request` for HART IP and `Controller Data Read` for OMRON FINS. The remaining 70% of the packets consisted of 61% of UDP packets, 32% of simple SYN packets, 35% of RST and less of the 1% for SYN-ACK and other combination, which confirms an established TCP connection.
Scanning actors. We used the Greynoise platform \cite{Greynoise} to tag the scanners as Malicious, Benign or Unknown, according to their logged activities. Greynoise reported the 3.5% of the host as Malicious, 37.4% as Benign and the remaining 59% as Unknown. A malicious actor, for instance, was associated with a behavior indicating a Mirai or a Mirai-like variant infection, while another one was found opportunistically scanning for Siemens PLC devices. We also identified well-known services that periodically scan the Internet address space such as Shodan and Censys \cite{Shodan}, as reported in Table 5. In Appendix B we reported an analysis of the origin of the scanning IP addresses. Instead, in Appendix A we reported a detailed summarizing of the protocols scanned by malicious actors.

Malicious scanners. We observed that ATG port is the most scanned by malicious actors, even more than well-known ICS protocols such as BACnet/IP, Modbus/TCP, and DNP3. Remote access to the control port of an ATG could provide an attacker the ability to reconfigure alarm thresholds, reset the system, and to disrupt the operation of the fuel tank \cite{ATG, ATG2}. However, since ATG is mainly used in the USA, this amount of scan traffic can be due to port 10001 shared with other services. According to \cite{Shodan} several malware leverages this port to spread over the devices, furthermore Shodan reports that almost all the devices with such exposed port are network antennas.

6.2 IT Traffic

We identified that more than 91.6% of the industrial endpoints were also communicating via non-industrial protocols. This can be due to the use of more than one protocol by a single device or by the presence of a NAT on the network border that manages the traffic incoming or outgoing from the enterprise and manufacturing zone. In the first column of Table 6 we reported that almost half of the traffic consists of encrypted TLS traffic, which could be due to the use of HTTP over TLS or to other secure communications such as VPNs. Moreover, HTTP covers 41.3% of the overall traffic, DNS covers 0.1%, while others interesting findings not mentioned in the table that represents less than 1% are OpenVPN, ESP, Wireguard, STUN, BitTorrent, FTP, and Telnet.

Due to the high amount of non-Industrial Traffic, we investigated if such behavior happened also between two endpoints of a legitimate ICS communication. We found out that 69.5% of the legitimate ICS endpoints exchange also non-Industrial Traffic. In order to have a clear view of the identified protocols,
we applied a flow-based approach, since the high amount of packets sent from a single host could affect significantly the statistics. As we can see in Table 6, this behavior is strongly evident in the amount of HTTP traffic, where just 23.7% of the hosts were using the HTTP protocol with respect to 41.3% found on the packet-based approach. Moreover, to reduce the number of the not precisely tagged TCP protocol, we mapped the lower port of each communication with the corresponding port registered by the Internet Assigned Numbers Authority (IANA). This approach significantly changed the results of the flow-based approach for the two ICS-endpoints analysis. We must also note that the low percentages obtained are due to the high frequency to which some ports changed within the same communication.

### 6.3 Validation

In order to verify the correct functioning of our environment, we injected our self-crafted traffic to the IXP. To do this, we deployed a Modbus/TCP server and a Mosquitto MQTT broker in an Amazon EC2 server instance. Instead, within the IXP network we deployed a synchronous Modbus/TCP and a MQTT client based on pymodbus and paho-mqtt python modules. During the communication between clients and servers, the Modbus client sends a Write Single Register request and the MQTT client sends a Publish Message request. Considering that the 3-way handshakes were already accomplished, the overall amount of packets for each transaction is the following:

- Modbus/TCP:
  1. Client sends Write Single Register request;
  2. Server sends Write Single Register response;
  3. Client sends TCP ACK to server;

| Protocol | % Flow-based Overall | Protocol | % Flow-based ICS-to-ICS |
|----------|---------------------|----------|------------------------|
| TLS      | 50.7                | TLS      | 45                     |
| HTTP     | 41.3                | UDP      | 17.8                   |
| UDP      | 4.8                 | TCP      | 15.8                   |
| TCP      | 2.7                 | TLS      | 1.8                    |
| DNS      | 0.1                 | UDP      | 0.4                    |

Table 6: Top-5 non-industrial protocols.
1. Client sends *Publish Message* request;
2. Server sends *TCP ACK* to client;

We sent 10 *Write Single Register* and 10 *Publish Message* requests per second for 24 hours. In this particular topology, the sFlow Agent samples just the traffic outgoing from the IXP network. It resulted in 2572852 overall packets exchanged, 1477915 outgoings and 346 of which were successfully sampled: 164 MQTT requests, 91 Modbus/TCP requests and 91 TCP ACK of the Modbus communication. Furthermore, all the packets were correctly dissected by Wireshark. The sampling rate computed as the ratio between the sampled packets and the overall outgoing traffic results in about $2 \cdot 10^{-4}$ packets, which is what we expected, considering a sFlow sampling rate of $2^{-12}$. This validation confirms the correct functioning of our IXP environment, the correct sampling functioning of sFlow and the correct dissection function of the network packets by Wireshark.

7 Discussion

**Approaches Comparison.** Our traffic analysis approach give us a very different point of view with respect to *Shodan* approach. While *Shodan* collects data performing, for instance, active port scanning and fingerprinting of the exposed services, having thus a wider overview of the exposed hosts, our approach allows to identify hosts that are currently active and communicating. In fact, only 2 of the overall amount of hosts identified by *Shodan* are actively performing industrial communication. This may be due because the ports were hidden behind a firewall, a NAT or VLAN. Furthermore, the 98.8% of the ICS that we were able to identify were not recognized as ICS by *Shodan*. The 50% of the ICS protocols identified in the legitimate traffic were not implementing any kind of encryption mechanism, due to insecure protocols by design (e.g., Modbus/TCP) or bad configurations (i.e., MQTT, AMQP), exposing the whole systems to potential attacks. However, we must take into consideration that these devices may also be Honeypots. The 91.6% of hosts that exchange both Industrial traffic and non-Industrial traffic could be exploited by an attacker to investigate which protocols are used and what is the payload of the packets. For instance, the attacker could gather information about the servers that are commonly involved, analyze the DNS, FTP and HTTP content to collect information about the employees and use social engineering techniques to spoof them.

**Limitations.** However our approach has some limitations. The sFlow protocol has a physical limitation due to the sampling rate, therefore we cannot have a complete overview of the Industrial traffic. Moreover, the sFlow protocol truncates the packets at 128 bytes. This last limit, together with the lack in Wireshark dissector of specific protocols, may lead to not an incomplete analysis of the traffic, in particular it could lead to false negatives samples. Finally, if a host implements a dynamic port range, instead of using the standard ports reported in Table 7, both our approach and Shodan approach scanning fail to correctly identify the host because both the approaches are port-based.
8 Related Work

ICS Security. The security of ICS is a widely studied research topic. Many research groups study new security solutions to implement in order to mitigate the threats on which ICSs are exposed to. A low cost and effective solution is represented by the Anomaly detection systems. Anomaly detection systems do not require any hardware substitution from the point of view of the company, indeed their aim is to passively monitor the state of the system, focusing for example on the physical state of the network [7], network traffic [4] or considering both of them [8], and raising an alert when the normal behavior of the system is violated.

Scan-Based Analysis. If, on one hand, there are many contributions in literature which present security solutions for the ICSs, on the other hand, there are not many contributions that analyze their current security implementation. Several works [1, 2, 11, 17, 19] leveraged public available information, like Shodan, to identify internet-reachable industrial devices, while [21] and [15] manually performed an active scan of the IPv4 address space. For a better understanding of the threat landscape, Serbanescu et al. [31] deployed a low-interaction honeynet, showing also how the number of attacks increased after being indexed by Shodan.

Industrial Traffic Analysis. For what concerns Industrial Traffic analysis, there is not much contribution literature. In [23] the authors, investigated the industrial communications passing through an IXP and an Internet Service Provider (ISP). During their analysis, they were able, via correlation techniques, to identify scanning activities, possible firewall implementation other than unprotected Industrial Traffic. In our work we are not interested in implementing any new tool for identifying Industrial Traffic, however we wanted to exploit a wider range of protocols so we proposed a slightly different packet filtering process to identify possible Industrial communications and more scanning activities. Furthermore, from a security point of view we analyzed the critical issues deriving from implementing both Industrial and non-Industrial communication within the same network infrastructure and we argued what are the Shodan and Shodan-like services limits compared to a wide-view analysis of sampled traffic.

9 Conclusions

The increasing using of insecure industrial protocols through the Internet exposed ICS and critical infrastructure to a wide range of cyber threats. Active scanning of the IP address space performed by services such as Shodan is a common practice to detect exposed ICS, however it does not properly represent the real ICS landscape. In this paper, we addressed three research questions to investigate the current state of the art implementation of the Industrial systems. To do this, we proposed, implemented and validated an analytic framework to detect legitimate Industrial Traffic communication and scanning activities, based on a 31 days long sampled traffic capture collected at a local IXP. We compared
our results with the information available on Shodan, proving that Shodan is not enough. In fact, while Shodan was able to identify a higher number of hosts, it detected only 1.2% of the hosts found by us. We also shown that 64.3% of the hosts have IT services exposed, 11 of which have an alarming CVE vulnerability score and 75.6% of the Industrial protocols implemented to communicate over the Internet do not implement any security feature.

Additional analysis, such as the analysis of the IT traffic confirmed the convergence of the Information Technology and Operational Technology networks in many systems (in our case the 91.6% of the identified hosts), providing a deeper point of view of the network architecture and security, such as the high rate of unencrypted IT traffic and insecure protocols. These network vulnerabilities could be exploited by malicious users which, as our results show, are constantly performing scanning campaigns. Finally, we validated our system model by auto-injecting our traffic showing that it respects our assumptions.

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Appendix A  Protocols Identified

In the following Appendix, we reported further details about the protocols we identified during our analysis. In particular, in Table we reported the complete list of the industrial protocols of our interest, the communication ports used and if the current version of Wireshark (currently version is 3.0.5-1) is able to dissect them. Instead, in Figure we reported the number of packets identified for each protocol both for the legitimate traffic and for the scanning activities.

Appendix B  Scanning activities origins

In this Appendix, we reported an analysis of the origin of the source IPs of the packets marked as scanning activities. We reported in Figure an heatmap with the origin of the IP associated with each scanning packet. The scanning activities come from 30 different countries. The 24.4% of the malicious actors come from China, 22% Netherlands, 12% Italy, 10% USA and 7% Russia, while 8 other countries count for less than 5%. However, we must note that the authors of the scanning campaigns could also hide their source by using, for instance, a VPN, in that case, the IP origin represented in the map corresponds to the last VPN hop.
| Protocol          | Port Ranges          | Wireshark | %\text{legit} | %\text{scan} | %\text{mscan} |
|-------------------|----------------------|-----------|---------------|--------------|--------------|
| AMQP              | 5671-5672            | ✓         | 27.1          | 2.7          | 3.9          |
| ANSI C12.22       | 1153 1153            | ✓         | 21.4          | 0.2          | 0.6          |
| Automated Tank Gauge | 10001              |           | 6.8           | 19.3         |              |
| BACnet/IP         | - 47808             | ✓         | 10.3          | 5.8          |              |
| CoAP              | 5683 5683            | ✓         | 0.3           | 50.2         | 13.5         |
| Codesys           | 2455                 |           | 0.8           | 1.3          |              |
| Crimson v3        | 789                  |           | 1.1           | 1.9          |              |
| DNP3              | 20000 20000          | ✓         | 4.8           | 9.7          |              |
| EtherCAT          | 34980 34980          | ✓         | 1.5           | 0.2          |              |
| Ethernet/IP       | 44818 2222           | ✓         | 0.7           | 0.9          |              |
| FL-net            | - 55000-55003        |           | 0.3           | 0.6          |              |
| FF HSE            | 1089-1091 1089-1091  | ✓         | 0.1           | 2.4          |              |
| GE-SRTP           | 18245-18246          |           | 1.6           | 3.9          |              |
| HART IP           | 5094 5094            | ✓         | 0.8           |              |              |
| ICCP              | 102                  | ✓         | 2.7           | 14.2         |              |
| IEC61850          | 2404                 | ✓         | 0.7           | 0.9          | 5.2          |
| Modbus/TCP        | 102                  | ✓         | 2.7           | 14.2         |              |
| MELSEC-Q          | 5007 5006            |           | 9.1           | 2.1          | 3.9          |
| MQTT              | 1883,8883            | ✓         | 28            | 1.5          | 5.2          |
| Niagara Fox       | 1911.4911            |           | 2.9           | 5.8          |              |
| OMRON FINS        | - 9600               | ✓         | < 0.1         |              |              |
| OPC UA            | 4840                 | ✓         | 0.3           | 0.9          |              |
| PCWorx            | 1962                 |           | 1             | 2.6          |              |
| ProConOS          | 20547 20547          |           | 0.9           |              |              |
| PROFINET          | 34962-34964 34962-34964 | ✓ | 2.7 | 0.7 | 1.3 |
| STcomm            | 102                  | ✓         | 2.7           | 14.2         |              |
| Zigbee IP         | 17754-17756 17754-17756 | ✓ | 8.1 | 0.7 | |

Table 7: Industrial protocols with relative ports, Wireshark dissector availability (✓ = wireshark is able to dissect it) and the traffic percentages identified during the analysis (%\text{legit} legitimate traffic, %\text{scan} scanning activities and %\text{mscan} malicious scanning activities).
### Fig. 3: Protocols found among the legitimate and scanning ICS traffic. The X-axis is log-scaled.

| Protocol          | Number of Packets |
|-------------------|-------------------|
| MQTT              | 2                 |
| AMQP              | 5                 |
| ANSI C12.22       | 10                |
| Modbus/TCP        | 2                 |
| ZigBee IP         | 5                 |
| PROFINET          | 100               |
| EtherCAT          | 2                 |
| Ethernet/IP       | 5                 |
| IEC60870-5-104    | 1                 |
| CoAP              | 2                 |
| OPC UA            | 5                 |
| FF HSE            | 10                |

### Fig. 4: Heatmap of the malicious scanning activities origin.

![Heatmap of the malicious scanning activities origin](image_url)