hochschule mannheim

Conception, Implementation and Evaluation of a Modular Proxy Application for Testing Internet of Things Applications

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Mannheim, 31.03.2021

Moritz Laurin Thomas

Abstract

Conception, Implementation and Evaluation of a Modular Proxy Application for Testing Internet of Things Applications

TBD

Konzeption, Implementierung und Bewertung eines modularen Proxys zum Testen von Anwendungen im Internet der Dinge

TBD

Acknowledgements

TBD

Contents

Chapter 1

Introduction

This chapter will introduce the underlying motivation of this thesis. Then, it will give an overview of this thesis' purpose and structure. Lastly, this chapter will show the process that the work on this thesis went through, explaining the scientific methods applied and software engineering practices used.

1.1. Motivation

Today scientific and industrial parties work on connecting physical entities such as machines, buildings and even humans to the internet by equipping them with digital sensors and actuators, referred to as "Internet of Things (IoT)". While this progression promises many positive effects, such as simplifying tasks in our personal day-to-day life ("Smart Home" applications), monitoring our personal health ("eHealth") and increasing efficiency and safety of industrial plants ("Industrial Internet of Things (IIoT)", also referred to as "Industry 4.0"), it also yields the risk of introducing new attack-vectors to parts of our environment: "smart" devices used at home or at other sensitive places may implement weak security implementations or faulty security design, resulting in private and personal data being available to parties interested in violating the privacy of one's home (e.g. vaccum robots leaking information about the interior design of homes[10]) or conducting industrial espionage which is an acute threat [2, p. 14].
The diversity of both deployed smart devices and the internet services those devices are connected to lead to the need and use of ever-increasing complex technologies used for communication, data storage and access management, further adding to po-

tential attack-vectors of connected devices and distributed applications [5, p. 119]. This complexity and the sheer number of connected devices is actively being exploited by attackers today and the number of attacks on IoT devices is increasing [4].
There are security guidelines, best practices and innovative approaches for developing secure smart applications [5, p. 120][7, p.326-328], however testing such applications proves to be cumbersome: intercepting, dissecting, inspecting and manipulating the communication in these applications requires working on various abstraction layers. In order to evaluate the security of such applications, penetration testers often spend a considerable amount of time dissecting applications and setting up a test-environment.
The goal of this thesis is to conceptualize, implement and evaluate a modular proxy application that allows to evaluate the security of IoT applications by...

1.2. Purpose and Structure of the Thesis

This thesis is separated into eight chapters: chapter (2) will give an overview of and discuss related and previous work. After that, relevant fundamentals about computer networks, IoT applications and information security will be covered in chapter 3.
The chapters 4 to 7 describe the research and development process of the IoT proxy application in chronological order: the problem space of the application is shown and dissected in chapter 4, yielding essential insights into potential challenges and technical requirements. Building upon these, the conceptual design of the IoT proxy application is proposed in chapter 5. This included the process of collecting, documenting and analysing of software requirements, describing the application's work context and designing a software architecture that complies with the aforementioned requirements. Subsequently, chapter 6 involves a prototypical implementation of the aforementioned software concept, focusing on the goals and constraints of the implementation, the tools and frameworks used and the implementation of core components of the application.
The prototype is then evaluated in chapter 7 by conducting and examining two case studies that show how the IoT proxy application can be used in real-life scenarios, allowing insights in the efficiency or inefficiency of its use. Lastly, the results

yielded by this thesis are summarized in chapter 8 and the thesis is concluded in chapter 9.

Chapter 2

Related Work

This chapter will discuss related and previous work on topics in this thesis' context. This includes network analysis in general (and IoT in particular), homogenization and unification of various IoT related technologies and performance of security evaluations of these technologies.

2.1. Computer Network Analysis in General

TBD: Polymorph [8]

2.2. Homogenization of the IoT Landscape

TBD: IoT proxy for homogenization [6]

2.3. IoT Security Analysis

As part of their master's thesis, Bellemans conducted a study in 2020 that evaluated the security and privacy implementations of fifteen "*smart*" devices from a wide price range available on the market at the time. They performed automated analyses and requested data access from manufacturers [3]. The thesis showed that the devices made use of a variety of both standardized and proprietary transport and application protocols. It also found severe flaws in the devices' compliance to General

Data Protection Regulation (GDPR): about a third of the devices' manufacturers did not reply to GDPR requests at all, however Bellemans noted that the COVID-19 pandemic may have had an impact on their data access requests. The thesis suggests that the introduction of a quality label that guarantees appropriate implementation of security and privacy aspects could prove beneficial for customers.

In 2017, Apthorpe et al. presented a three stage strategy to examine metadata of network traffic of four smart devices [1]. By monitoring the devices' traffic, they showed that even though the communication between the devices and their corresponding internet servers were encrypted, passive observers could deduce information about users' behaviour by identification of the destination server and analysis of the rate of traffic being sent. A noteworthy aspect of their work is that they performed this analysis from an Internet Service Provider (ISP)'s point of view, exclusively examining metadata of the communication that took place. The strategy described in the paper consists of the following (greatly simplified) steps:

1. Identifying communication streams of individual devices (e.g. by examining the TCP packets' destination IPs).
2. Associating the streams with specific device models (e.g. by performing reverse-look ups of the aforementioned IPs).
3. Analysing traffic rates (presuming that traffic is generated upon taking measures).

Apthorpe et al. conclude that their strategy works well on inferring behaviour from regular internet traffic of smart devices, however they assume that shaping traffic or making use of proxies (that effectively mask the destination IPs) could be effective counter-measures. It is safe to assume that regular smart home setups do not make use of proxies or traffic shaping though, thus being vulnerable to this kind of attack.

TBD: NVISO Labs: Théo Rigas, IOXY [9]

Chapter 3

Theoretical Background

This chapter provides an overview of the technologies and concepts referred to in subsequent chapters. Starting with section 3.1, essential concepts of computer communication in networks will be presented and examined, covering the concept of network layers, intercepting of communication between two parties and analysis of transferred data. Building upon these fundamentals, section 3.2 introduces the fields of use of IoT applications, common architectures used today to implement them and popular protocols they make use of. Lastly, it will discuss security considerations important to IoT applications. After that, section 3.3 will provide insights into relevant concepts and the practices used and applied in information security. It covers key concepts and legal considerations, integration of information security in software development and common practices and methods involved.

3.1. Computer Networks

3.1.1. Network Layers

TBD Transmission Control Protocol (TCP)

3.1.2. Proxying Network Traffic

TBD; planned:

1. Definition; Working Principle
2. Use Cases

3. Abuse Cases

3.1.3. Deep Packet Inspection

TBD

3.2. (Industrial) Internet of Things

3.2.1. Fields of Use

3.2.2. Application Architectures

3.2.3. Common Protocols

Building up on pre-existing network infrastructure and in order to meet requirements specific to individual fields of use and use-case scenarios, the landscape of IoT attends with a great variety of *communication protocols* (further used to refer to both transport and application protocols). This section will provide a brief overview of the working principles, use cases and history of some protocols commonly used in IoT and IIoT applications today.

Hypertext Transfer Protocol (HTTP) *TBD*

WebSockets (WS) *TBD*

Message Queuing Telemetry Transport (MQTT) *TBD* Amazon Web Services (AWS) IoT

Modbus TCP *TBD*

Profibus/Profinet *TBD*

OPC Unified Architecture (OPCUA) *TBD*

3.2.4. Security Considerations

3.3. Information Security

TBD

3.3.1. Key Concepts

3.3.2. Legal Background

Compliance

Data Protection

3.3.3. Integration in Software Development

Traditional Approaches

Modern Approaches

3.3.4. Methodology

Risk Management

Incident Response

Reverse Engineering

(Physical) Penetration Testing

Source Code Audits

Application Configuration

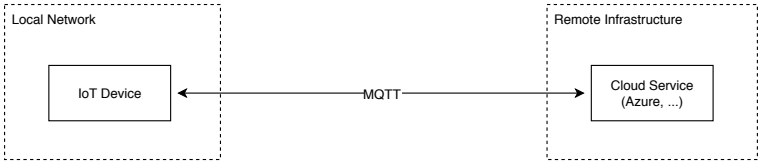
Chapter 4

Understanding the Problem Space

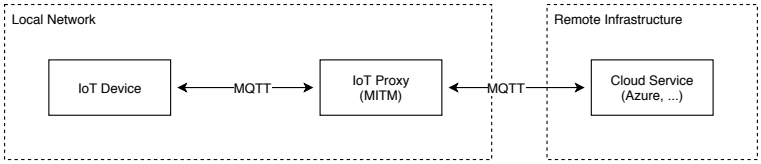
In order to provide a satisfying solution to the problem at hand, the problem itself and the environment it occurs in must be researched. This chapter aims to explore and examine the problem space, resulting in a set of artefacts (namely a domain model and a set of requirements) that aid in understanding the context and designing an appropriate solution. First, a prototypical network proxy is designed and implemented in section 4.1 to get an understanding of the problems and challenges involved in designing, implementing and using such software. Based on these experiences, interviews with experts in penetration testing are conducted and evaluated in section 4.2 to get a proper understanding of their everyday work and resulting problems. Lastly, existing software that aims to intercept communication for various scenarios and technologies is examined in section 4.3, compared to each other and their usefulness for the problem-specific scenarios is assessed.

4.1. Prototypical Implementation

The prototype was designed to be used in two realistic scenarios; one in an Industrial Control System (ICS) context and a more complex one in a cloud context. The goal of this section was to implement a prototype that could be used to intercept communication between an IoT device and its cloud service as shown in figure 4.1. It was developed incrementally so individual components could be derived from requirements, designed, implemented and evaluated in fixed sprints.



(a) Regular communication between an IoT device and a cloud service.



(b) Communication intercepted by a man-in-the-middle (MITM) proxy.

Figure 4.1.: Installing a MITM proxy to intercept network communication for penetration testing.

4.1.1. Example Scenarios

The following scenarios describe realistic configurations of IoT/IIoT devices that should be tested with the prototype:

Scenario #1: ICS Modbus TCP In this IIoT scenario, a human-machine interface (HMI) (*Siemens KTP400 Basic*) sends commands to and receives data from a programmable logic controller (PLC) (*Siemens S7-1200*) using Modbus TCP. The PLC continually counts up a value up to 100 and begins anew at zero while the HMI displays the current value and provides a button that, upon being pressed by a user, resets the current value to zero.
In this scenario, attackers could perform a variety of attacks on the system by intercepting and manipulating network traffic, for example:

- By dropping messages sent from the PLC to the HMI, the application may appear unresponsive as new data is not displayed on the HMI. In production environments, this could lead to dangerous situations as sensor readings that indicate harmful environmental conditions would not be presented to supervising personnel.
- When dropping messages sent from the HMI to the PLC, control commands can be suppressed. This attack can result in catastrophic situations when emergency shutdowns issued by supervising personnel is not registered by the affected machines.

Due to the rather simple nature of the Modbus TCP protocol, intercepting and manipulating communication is expected to be trivial.

Scenario #2: AWS IoT This IoT cloud scenario utilizes a local IoT device that is integrated into the AWS IoT platform. The device connects to the cloud platform, authorizes itself via HTTP and upgrades the HTTP-connection to a WS stream upon successful authorization. It eventually communicates to a remote MQTT broker by tunnelling HTTP over the WS stream. At this stage, it can publish information such as sensor readings to MQTT topics or subscribe topics and react on incoming value changes.
This scenario makes use of three communication protocols, uses these protocols dependent on the state of authentication (as seen in 4.2) and even tunnels one protocol through another one. Therefore, testing communication in this scenario is expected to involve more complex approaches than the first one.

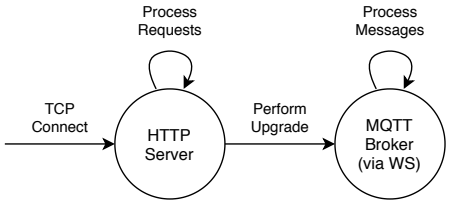


Figure 4.2.: State machine of AWS IoT communication

4.1.2. Requirements

To be able to operate in both of the aforementioned scenarios, the prototype had to implement a set of functional requirements:

F1 Protocols: The software must implement parsing/crafting messages/packets of the following communication protocols: HTTP, WS, MQTT and Modbus TCP.
Fit criterion: TBD

F2 Network Stacks: The software must be able to parse protocols that are tunnelled through other protocols ("*stacked*"). It must provide an interface to the user where they can specify which communication protocols are used and whether and how they are stacked (further referred to as *network stack*).
Fit criterion: The software processes a configuration file that lets users specify which protocols to be used and whether/how they are stacked.

F3 State Machine: The software must be able to switch network stacks dependent on configurable *states*. It must provide an interface for the user to specify

when to switch to using another network stack, represented using state machines and rule sets for transmission between states.
Fit criterion: The software processes a configuration file that lets users specify when to switch between network stacks.

F4 Integration: The software shall provide interfaces for integration of third-party software.
Fit criterion: The software allows sending requests/responses to "Burp Suite" for manipulation.

F5 Scripting: The software shall provide scripting capabilities for automated manipulation of messages/packets.
Fit criterion: Users can define script-snippets to be executed on messages/-packets.

The following non-functional requirements were defined:

N1 Extensibility: To allow for future implementation of further communication protocols the software shall be implemented in a modular fashion.

N2 Platform Compatibility: In order to support a broad spectrum of target platforms, the software shall be implemented platform-independently.

N3 Reusability: The software shall be reusable so it can be used in future tests that may feature new configurations of network stacks.

N4 Open Source: The software shall be available as open source software so programmers and members of the IT community may contribute to improving it.

Due to this implementation serving as a prototype and being of an academic nature, no specific constraints were defined. It was to be developed strictly ignoring aspects of usability and stability as it should not be used in production environments but in laboratories exclusively.

4.1.3. Design

The prototype was designed to be fit for use in the second scenario as, regarding network communication, it was more complex than the first one. Specifically, the second scenario demanded the implementation of the network stack and a state machine to switch between states and process protocols dependent on thereon.

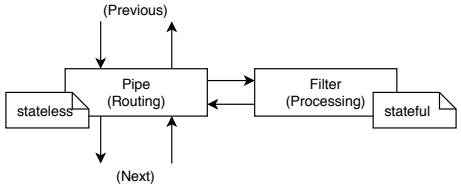


Figure 4.3.: The variation of the *"pipes and filters"*/*"pipeline"* design pattern used in the prototype.

Parsing protocols that were tunnelled through other protocols appeared to be a potentially challenging requirement. In order to tackle it, a variation of the /*"pipeline"* (sometimes referred to *"pipes and filters"*) design pattern was used as can be seen in 4.3. It was designed to be used as follows:

1. Data sent to a *pipe* is processed by its associated *filter*.
2. Filters can manipulate the data, for example parsing protocol-specific packets from raw binary data or serializing packets back to binary data.
3. After processing, pipes route data either to the succeeding pipe or, in case a pipe does not have a succeeding pipe associated to it, back to its previous pipe.
4. Eventually, data is deserialized and manipulated on multiple levels and serialized back to the originating format.

4.1.4. Implementation

4.1.5. Insights Gained

- Due to the maximum transmission unit (MTU), large messages are broken into chunks that are transferred sequentially. This requires the proxy to work on streams of incoming data and reassemble messages from said chunks.
- Support of multiple clients is non-trivial as communication between clients and servers is not necessarily connection-oriented (e.g. HTTP). Question: Do penetration testers need to test multiple devices at the same time?
- Increasing the size of the payload of a messages can result in the payload being split upon multiple messages (e.g. WS). Question: Do penetration testers require exact control over the implementation of protocols?

- Manipulating messages, on the fly via scripting or by hand using third-party integrations (e.g. to *Burp Suite*), can introduce latency to the communication. Question: Are there strict timing requirements during penetration tests?
- Many libraries offer high-level functions to the programmer while avoiding exposure of low-level functionalities like crafting or parsing messages.

TBD; implementation is completed, needs to be written down; include its diagrams

4.2. Interviewing Experts for Insights

Interviews may be an efficient way to get an expert's opinion on something they are a professional in. Thus, expert interviews were conducted to let security researchers give insight into their everyday work and the challenges they face. The information and insights gathered in these interviews were then used to model a persona, various work scenarios and use-cases that as a whole aim to represent their work.

4.2.1. Interview Guideline

An interview guideline (shown in *TBD*) was created to keep focus on key points during interviews so that interviewees would not stray too far from the relevant points. The guideline also served as a checklist so the interviewer could make sure that all questions and points that should be covered initially, were in fact covered by the end of the interviews. It was composed of three sections:

1. Experiences with IoT The answers to these questions would give insights into what kind of applications the security researchers had worked on in the past. Answers to question *1.1.* were of particular interest as they might represent what technologies were being examined by security researchers and may be popular in today's applications.

2. Processes in Everyday Life This section aimed to cover questions about the processes and tasks security researchers perform during penetration tests of IoT applications in their everyday life. Ideally, answers to those questions would show

the approaches taken and challenges faced during their work, uncovering potential needs and underlying motivation.

3. The Future of IoT This section had security researchers assess what the future of IoT may be like from their point of view. This required the interviewees to make a critical assessment of the status quo.

4.2.2. Conducting Interviews

Interviews were conducted with six *NVISO* employees that all had worked on security assignments on IoT or IIoT applications in the past. There is considerable variety in

- the experience they had in working on security assignments in general: all interviewees had a strong background in cyber security that reached back multiple years except one who was a working student at *NVISO Labs*.
- and the experience they had in working on IoT/IIoT applications: two interviewees worked on assessing IoT/IIoT applications only occasionally, one was part of a car manufacturer's automotive security team and three were part of *NVISO Labs* and worked with smart devices on a regular basis.

The duration of the interviews varied from 45 minutes to two hours depending on the amount and level of detail of information provided by the interviewees and the number of times that the interviewer had to ask further questions.

TBD: Summary of the interviews and conclusions drawn + personas and use cases

4.3. Analysis of Existing Software

Wireshark 3,690,000 lines of code[1] *TBD*

MITMf *TBD*

Ettercap *TBD*

[1] This number was returned by the *cloc* utility run on commit *3a8111e1c2adcdc0603993c6ed5d20a40f162125* of Wireshark's Github mirror.

bettercap *TBD*

mitmproxy *TBD*

mProxy *TBD*

IOXY *TBD*

TBD; planned: paragraph about each program including a general description, uses, capabilities and usefulness

Name	*Latest Release*	*Implemented in*	*Supported Protocols*	*R*	*W*	*D*
Wireshark	2020-07-01	C	Various	Y	N	N
MITMf	2015-08-28	Python	Various	?	Y	Y
Ettercap	2019-07-01	C	Various	Y	Y	Y
bettercap	2020-03-13	Go	Various	Y	Y	Y
mitmproxy	2020-03-13	Python	HTTP/S, WS	P	P	P
mProxy	Pre-Releases only	Go	MQTT	?	Y	-
IOXY	Source only	Go	MQTT	Y	Y	Y

Table 4.1.: Comparison of existing software where R, W and D describe read, write and deletion capabilities, respectively. Y, N and P indicate full, no or partial functionality, respectively.

Chapter 5

Conceptual Design

This chapter will detail the process of conceptualizing the design of the modular proxy application based on the results of the preceding chapter. First, the requirements are analyzed for their potential design implications in section 5.1. Afterwards the user interactions and domain entities identified in chapter 4 are examined and broken down into communication flows between actors and systems in section 5.2 and individual software components that complete the design are discussed in section 5.3. Lastly, an overview of the complete design concept is given in section 5.4, discussing potential advantages and constraints.

Note: sections 5.1 and 5.2 should probably be merged as they overlap a lot

5.1. Requirements: Design Implications

TBD

5.2. User Interactions: Designing the Intended Workflow

TBD

5.3. Inferring Software Components

TBD

5.4. Summary: An Abstract Design Concept

TBD

Chapter 6

Implementing the Modular Proxy Application

This chapter covers an exemplaric implementation of the concept that was worked out in chapter 5, starting with formally describing the goals and constraints of this implementation in section 6.1. Afterwards, an overview and comparison of available and suitable tools for the task is performed in section 6.2. The chapter concludes with details about the implementation of individual components in section 6.3, describing how specific challenges were overcome and what design patterns were used.

6.1. Goals and Constraints

6.2. Tool Selection

6.2.1. Requirements to The Tools

6.2.2. Comparison of Modern Tools and Toolchains

6.3. Individual Components

6.3.1. Finite State Machine

States

Transitions

6.3.2. Configuration Parsing and Building

Factories and Builders

6.3.3. Network Stack

Managing Flow of Traffic

Chapter 7

Evaluation

This chapter covers an attempt to measure the fitness for use of both the design concept developed in chapter 5 and the prototype implemented in chapter 6. First, two case studies and the methodology of how they were performed is described in 7.1, detailing their individual setups, the tests that were conducted and the results they yielded. Then, feedback given by experts is discussed in 7.2, providing insights to their perception of the prototype.

7.1. Case Studies

7.1.1. Methodology

7.1.2. Case Study I: Smart-Home MQTT Application

Lab Setup

Conducted Tests

Conclusion

7.1.3. Case Study II: Industrial Modbus Application

Lab Setup

Conducted Tests

Conclusion

7.2. Expert Feedback

Chapter 8

Summary

This chapter provides a summary of the concept shown in chapter 5 and the implementation thereof in chapter 6.

8.1. Concept

8.2. Implementation

Chapter 9

Conclusion

TBD

List of Abbreviations

AWS Amazon Web Services
GDPR General Data Protection Regulation
HMI human-machine interface
HTTP Hypertext Transfer Protocol
ICS Industrial Control System
IIoT Industrial Internet of Things
IoT Internet of Things
ISP Internet Service Provider
MITM man-in-the-middle
MQTT Message Queuing Telemetry Transport
MTU maximum transmission unit
PLC programmable logic controller
TCP Transmission Control Protocol
OPCUA OPC Unified Architecture
WS WebSockets

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Bibliography

[1] Noah Apthorpe, Dillon Reisman, and Nick Feamster. *A Smart Home is No Castle: Privacy Vulnerabilities of Encrypted IoT Traffic*. 2017. arXiv: 1705.06805 [cs.CR].

[2] Michael Bartsch et al. *Spionage, Sabotage und Datendiebstahl - Wirtschaftsschutz in der Industrie 2018*. Oct. 2018. URL: https://www.bitkom.org/sites/default/files/file/import/181008-Bitkom-Studie-Wirtschaftsschutz-2018-NEU.pdf.

[3] Jonah Bellemans. "The state of the market: A comparative study of IoT device security implementations". MA thesis. KU Leuven, 2020.

[4] Dan Demeter, Marco Preuss, and Yaroslav Shmelev. *IoT: a malware story*. Oct. 2019. URL: https://securelist.com/iot-a-malware-story/94451/ (visited on 02/17/2020).

[5] Jens Jäger et al. "Advanced Complexity Management Strategic Recommendations of Handling the "Industrie 4.0" Complexity for Small and Medium Enterprises". In: *Procedia CIRP*. Factories of the Future in the digital environment - Proceedings of the 49th CIRP Conference on Manufacturing Systems 57 (Jan. 2016), pp. 116–121. DOI: 10.1016/j.procir.2016.11.021.

[6] Wenquan Jin and DoHyeun Kim. "Development of Virtual Resource Based IoT Proxy for Bridging Heterogeneous Web Services in IoT Networks". In: *Sensors* 18 (May 2018), p. 1721. DOI: 10.3390/s18061721.

[7] Christian Lesjak et al. "Security in industrial IoT – quo vadis?" In: *e & i Elektrotechnik und Informationstechnik* 133.7 (Nov. 2016), pp. 324–329. DOI: 10.1007/s00502-016-0428-4. URL: https://doi.org/10.1007/s00502-016-0428-4.

[8] Santiago Hernández Ramos. *Polymorph: A Real-Time Network Packet Manipulation Framework*. Apr. 2018. URL: https://github.com/shramos/polymorph (visited on 02/17/2020).

[9] Théo Rigas. *IOXY - MQTT intercepting proxy*. July 2020. URL: https://blog.nviso.eu/2020/07/06 /introducing-ioxy-an-open-source-mqtt-intercepting-proxy/ (visited on 07/10/2020).

[10] Tilman Wittenhorst. *Ferngesteuert ins Smart Home: Saugroboter verrät Grundriss der Wohnung*. June 2019. URL: https://www.heise.de/security/meldung/Ferngesteuert-ins-Smart-Home-Saugroboter-verraet-Grundriss-der-Wohnung-4436657.html (visited on 02/17/2020).

Appendix A

Diagrams

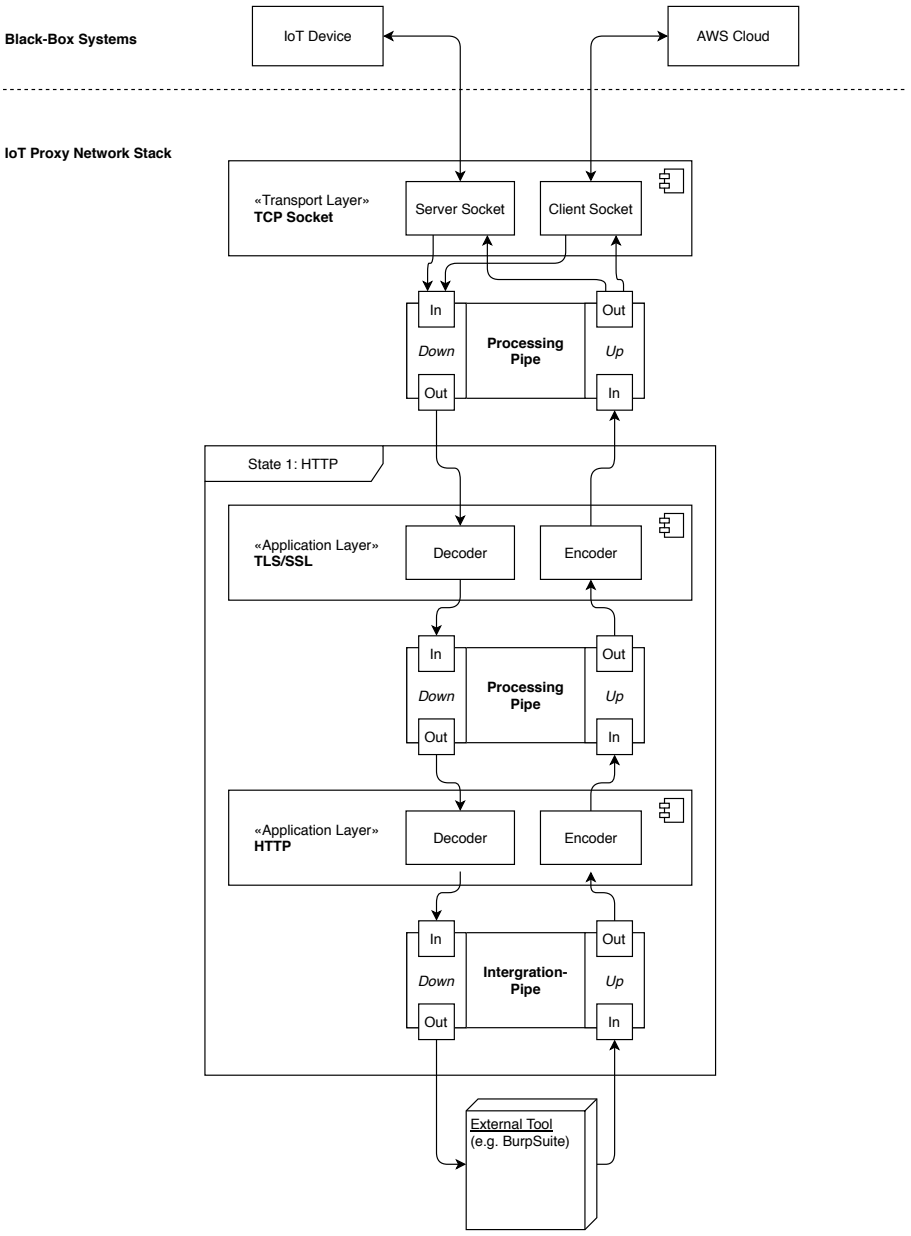

Figure A.1.: AWS IoT Scenario - State 1: HTTP Server

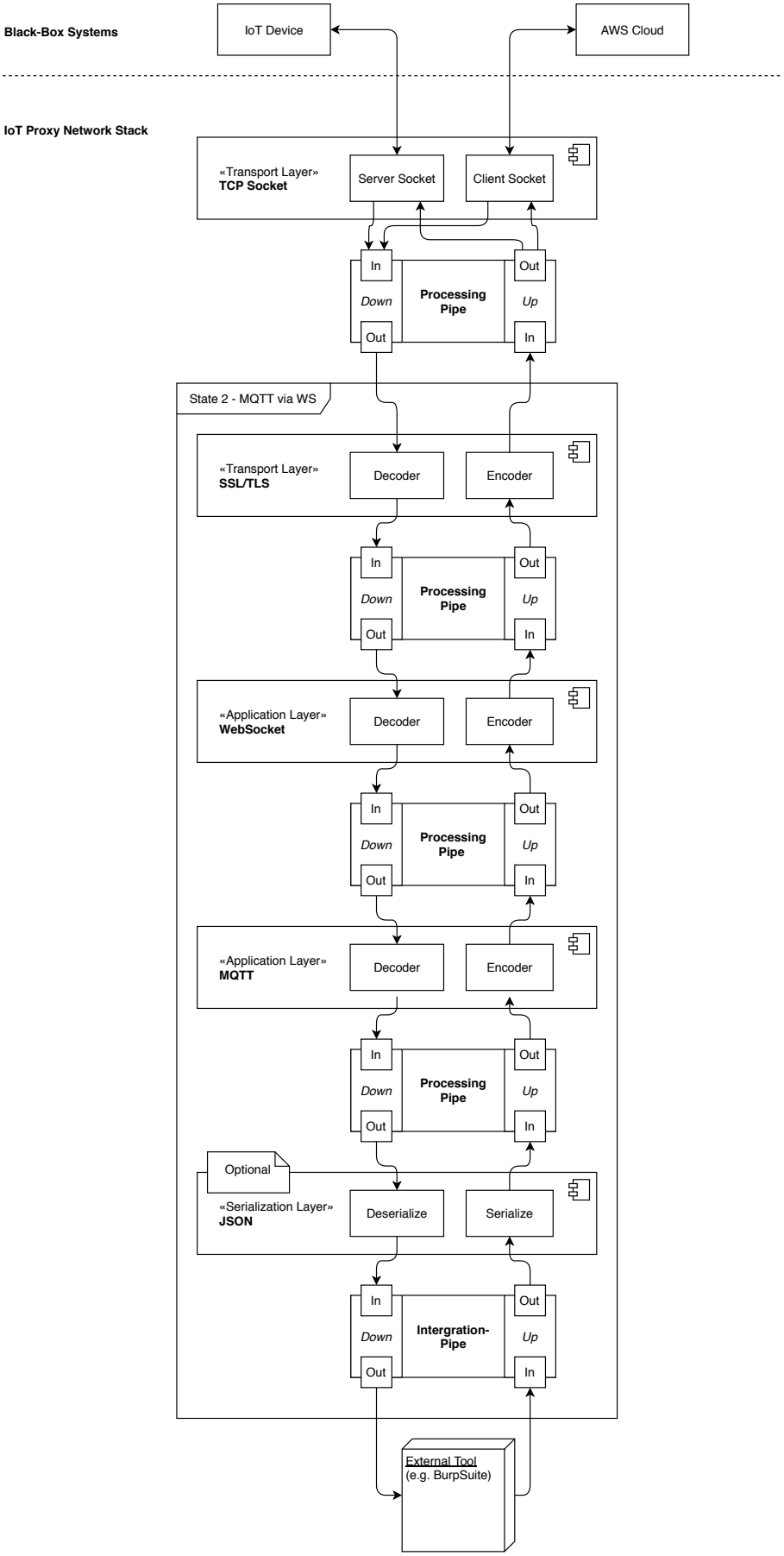

Figure A.2.: AWS IoT Scenario - State 2: MQTT via WS