Software and Firmware Updates for Internet of Things (WIP)

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Abstract

Sammanfattning

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Listings

Acronyms

ACE Authentication and Authorization for Constrained Environments

CA Certificate Authority

CBOR Concise Binary Object Representation

CoAP Constrained Application Protocol

DTLS Datagram Transport Layer Security

EST Enrollment over Secure Transport

HTTP Hypertext Transfer Protocol

IETF Internet Engineering Task Force

IoT Internet of Things

IP Internet Protocol

JSON JavaScript Object Notation

MCU Microcontroller Unit

PKI Public Key Infrastructure

SUIT Software Updates for Internet of Things

TCP Transmission Control Protocol

TLS Transport Layer Security

UDP User Datagram Protocol

URI Uniform Resource Identifier

Chapter 1

Introduction

1.1 Background

Internet of Things (IoT) is the notion of connecting physical objects to the world-spanning Internet in order to facilitate services and communication both machine-to-human and machine-to-machine. By having everything connected from everyday appliances to vehicles to critical parts of infrastructure, computing will be ubiquitous and the Internet of Things realized. The benefits from the IoT can range from quality of life services, such as controlling lights and thermostats from afar, to data gathering through wireless sensor networks, to enabling life critical operations such as monitoring a pacemaker or traffic system. IoT is a broad definition and fits many different devices in many different environments, what they all have in common is that they are physical and connected devices.

The Internet of Things is expected to grow massively in the following years as devices get cheaper and more capable. Ericsson expects the amount of IoT connections to reach 22.3 billion devices in 2024, of which the majority is short-range IoT devices [1]. However, cellular IoT connections are expected to have the highest compound annual growth rate as 4G and new 5G networks enable even more use cases for IoT devices.

In recent years the general public has become increasingly aware of digital attacks and intrusions affecting their day to day lives. In 2016 the DNS provider Dyn was attacked by a botnet consisting of heterogeneous IoT devices infected by the Mirai malware. Devices such as printers and baby monitors were leveraged to launch an attack on

Dyn's services which affected sites like Airbnb, Amazon, and CNN [2]. Cardiac devices implanted in patients were also discovered to be unsafe, with hackers being able to deplete the batteries of pacemakers prematurely [3]. These cases and many others make it clear that security in IoT is a big deal, and as IoT is expected to grow rapidly insecure devices can cause even more problems in the future.

Security in IoT is also closely related to its business potential. According to Bain & Company, the largest barrier for Internet of Things adaptation is security concerns, and customers would buy an average of 70% more IoT devices if they were secured [4]. Despite security being lacking today in IoT, the field is expected to grow rapidly and an increase in unsecured devices could spell disaster. Securing IoT equipment such as printers, baby monitors, and pacemakers is imperative to prevent future attacks. But what about the devices currently employed without security, or devices in which security vulnerabilities are discovered after deployment? They need to be updated and patched in order to fix these vulnerabilities, but sending a technician to each and every of the predicted 22.3 billion devices is not feasible. They need secure and remote updates which is a non-trivial task.

1.2 Problem Statement

There is a need for secure software and firmware updates for IoT devices as vulnerabilities must be patched. For many IoT devices this mean patches must be applied over long distances and possibly unreliable communication channels as sending a technician to each and every device is unfeasible. There are non-open, proprietary solutions developed for specific devices but no open and interoperable standard. The Internet Engineering Task Force (IETF) Software Updates for Internet of Things (SUIT) working group aims to define an architecture for such a mechanism without defining new transport or discovery mechanisms [5]. By expanding upon the work of the SUIT group, a standardized update mechanism suitable for battery powered, constrained, and remote IoT devices can be developed.

1.2.1 Problem

The thesis project will examine the architecture and information model proposed by SUIT in order to create and evaluate an updating mech-

anism for battery powered, constrained, and remote IoT devices with a life span exceeding five years. The update mechanism can be considered in three parts: communication, upgrading, and device management. Communication will happen over unreliable channels and the payloads must arrive intact and untampered with. The upgrade mechanism itself must ensure integrity of the target image and safely perform the upgrade with a limited amount of memory. Device management concerns managing devices in a network and seeing which devices are in need of updates.

The thesis will examine the update mechanism from the viewpoint of IoT devices running the Contiki-NG operating system on 32-bit ARM Cortex M3 processors. A suitable public key infrastructure developed by RISE will also be an underlying assumption for the work. The thesis aims to investigate the problem "How can the SUIT architecture be used to provide secure software and firmware update for the Internet of Things?".

1.2.2 Purpose

The purpose of the thesis project is to provide an open and interoperable update mechanism that complies with the standards suggested by the IETF SUIT working group. This will aid other projects trying to secure their IoT devices following accepted standards.

1.2.3 Goal

The goals of the thesis are to study current solutions and technologies and then propose lightweight end-to-end protocols that can be used when updating IoT devices. The degree project shall deliver specifications and prototypes of the protocols in an IoT testbed, as well as a thesis report.

1.3 Methodologies

The thesis will follow a mix of qualitative and quantitative methodologies. The SUIT group defines some goals or constraints a suitable updating mechanism should follow, but as their proposed architecture is agnostic of any particular technology these goals cannot be easily quantified. It is better to regard them as qualitative properties the

mechanism should have. In addition there are some relevant measurements, such as reliability of the communication and memory and power requirements of the updates, that can be used in an evaluation. The quantitative part of the evaluation will follow an objective, experimental approach, while the qualitative part will follow a interpretative approach.

1.4 Risks, Consequences, and Ethics

As IoT devices become more commonplace their security becomes more important. Incorrect or faulty firmware or software can lead to incorrect sensor readings, a common application of IoT devices, which in turn can lead to incorrect conclusions. This could have a large effect on businesses such as agriculture and healthcare. Insecure communication channels can expose confidential or personal data, something governments and international unions are taking more seriously.

As these devices can be connected on networks with other computers such as laptops, a compromised IoT device can cause an attack to proliferate throughout an entire network. This can affect other IoT devices as well as traditional computers, putting every connected device at risk. Furthermore hacked devices can leak data to attackers and cause service disruptions. All of these risks and more have to be accounted for as IoT is expected to boom.

1.5 Scope

The thesis will primarily focus on the use case of applying an entire update to one single device consisting of only one microcontroller. The use case of applying differential updates is considered important and the architecture will enable these kinds of updates, but the prototype will only support it with respect to time.

1.6 Outline

Chapter this will talk about that. Chapter whis will talk about what.

Chapter 2

Theoretic Background

This chapter presents the theoretical background needed to understand the thesis. Section 2.1 introduces the network protocols used and motivates their use over other protocols in an IoT context. The following section, Section 2.2 presents and explains the SUIT architecture and information model and their respective requirements as formulated by the IETF. Finally, Section 2.3 presents the Contiki-NG operating system which the updating mechanism will be developed for as well as the target hardware.

2.1 IoT Network Stack

Network protocols in IoT networks operate under different circumstances compared to traditional computer networks. Whereas traditional networks enjoy high reliability, high throughput, and high computational performance IoT networks are defined by their low power requirements, low reliability, and low computational performance on edge devices. This posts some constraints on the protocols used in IoT as they must properly handle these characteristics.

One of the most widely used network protocol stacks today in traditional networks is based on the Internet Protocol (IP). The stack uses Transmission Control Protocol (TCP) as a transportation protocol, usually with Transport Layer Security (TLS) for security, and a common application layer protocol is Hypertext Transfer Protocol (HTTP). TCP is however poorly suited for IoT networks as it is a connection based, stateful protocol which tries to ensure the guaranteed delivery of packets in the correct order. There is also advanced congestion control

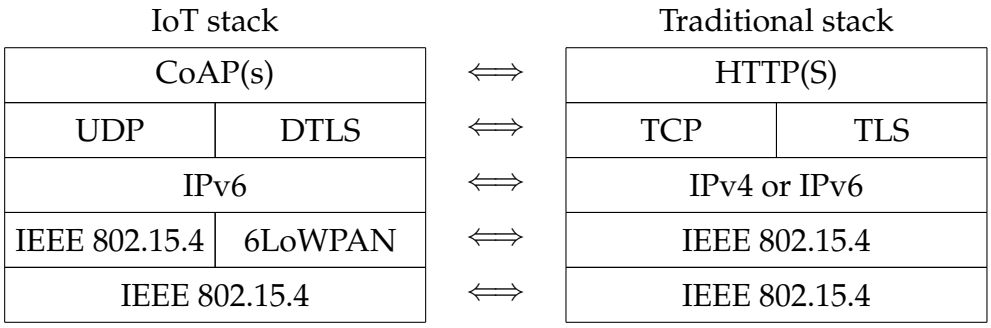


Figure 2.1: Comparison of network stacks between IoT networks and traditional networks.

mechanisms in TCP which are hard to apply on unreliable low-bandwidth networks. IoT networks often utilize User Datagram Protocol (UDP) as a transport protocol instead. UDP is also an IP-based protocol but is connectionless and less reliable than TCP, performing on a best-effort level instead. Despite being less reliable, UDP often performs better in IoT contexts.

As TLS is based on the same assumptions as TCP it is unsuitable for UDP networks. UDP networks still need confidentiality and integrity through some means and thus use Datagram Transport Layer Security (DTLS), which is a version of TLS enhanced for use in datagram oriented protocols. HTTP can be used over UDP for the application layer, but as HTTP is encoded in human readable plaintext it is unnecessarily verbose and not optimal for constrained networks. Instead, Constrained Application Protocol (CoAP) is a common protocol for the application layer in IoT networks. Figure 2.1 shows the equivalent protocols for IoT network stacks versus traditional network stacks.

In this chapter, Section 2.1.1 explains UDP and why it is the preferred transport protocol in IoT networks. Section 2.1.2 briefly explains TLS, why it is unsuitable for IoT networks, the differences between TLS and DTLS and why DTLS is used instead. Section 2.1.3 describes the CoAP protocol. Lastly, Sections 2.1.4 and 2.1.5 briefly introduces the EST-coaps protocol and ACE framework, enabling asymmetric cryptography and authorization in an IoT context.

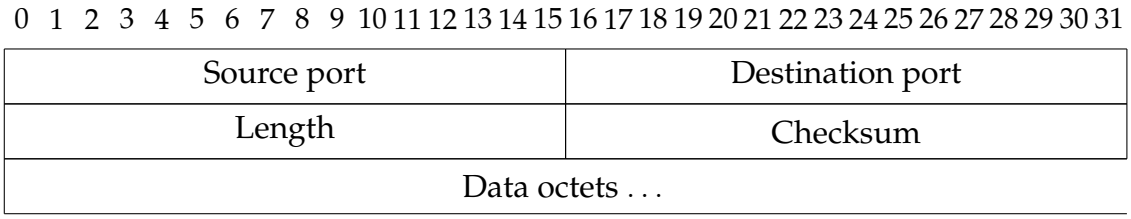


Figure 2.2: The UDP header format.

2.1.1 UDP

UDP is a stateless and asynchronous transfer protocol for IP [6]. It does not provide any reliability mechanisms but is instead a best-effort protocol. It also does not guarantee delivery of messages. For general purposes in unconstrained environments TCP is usually the favored transport protocol as it is robust and reliable, but in environments where resources are scarce and networks unreliable, a stateful protocol like TCP could face issues. Since TCP wants to ensure packet delivery, it will retransmit packages generating a lot of traffic and processing required for a receiver. Also, if the connection is too unstable TCP will not work at all since it can no longer guarantee the packets arrival. The best-effort approach of UDP is favorable in these situations, in addition to UDP being a lightweight protocol requiring a smaller memory footprint to implement.

Figure 2.2 shows the UDP header format. The source port is optional, the length denotes the length of the datagram (including the header), and the checksum is calculated on a pseudo-header constructed from both the IP header, UDP header, and data. UDP headers are minimalist which shows the point of it being a lightweight protocol with not many features available.

2.1.2 DTLS

DTLS is a protocol which adds confidentiality and integrity to datagram protocols like UDP [7]. The protocol is designed to prevent eavesdropping, tampering, or message forgery. DTLS is based on TLS, a similar protocol for stateful transport protocols such as TCP, which would not work well on unreliable networks as previously discussed. The main issues with using TLS over unreliable networks is that TLS decryption is dependant on previous packets, meaning the decryption

of a packet would fail if the previous packet was not received. In addition, the TLS handshake procedure assumes all handshake messages are delivered reliably which is rarely the case in IoT networks.

DTLS solves this by banning stream ciphers, effectively making decryption an independent operation between packets, as well as adding explicit sequence numbers. Furthermore, DTLS supports packet retransmission, reordering, as well as fragmenting DTLS handshake messages into several DTLS records. These mechanisms makes the handshake process feasible over unreliable networks.

By splitting messages into different DTLS records, fragmentation at the IP level can be avoided since a DTLS record is guaranteed to fit an IP datagram. IP fragmentation is problematic in low-performing networks since if a single fragment of an IP packet is dropped all fragments of that packet must be retransmitted, and thus fragmenting at the IP level should be avoided. Since DTLS is designed to correctly handle reordering and retransmission in lossy networks, splitting messages into several DTLS records is no problem, and if one record is lost only that record needs to be retransmitted in a single IP packet.

In order to communicate via TLS and DTLS, a handshake has to be carried out. The handshake establishes parameters such as protocol version, cryptographic algorithms, and shared secrets. The TLS handshake involves hello messages for establishing algorithms, exchanging random values, and checking for earlier sessions. Then cryptographic parameters are shared in order to agree on a shared premaster secret. The parties authenticate each other via public key encryption, generate a shared master secret based on the premaster secret, and finally verifies that their peer has the correct security parameters.

The DTLS handshake adds to this a stateless cookie exchange to prevent DoS attacks, some modifications to the handshake header to make communication over UDP possible, and retransmission timers since the communication is unreliable. Otherwise the DTLS handshake is as the TLS handshake. Since the (D)TLS handshake assumes asymmetric cryptography, and the SUIT standard does as well as explained in Section 2.2.1, devices must be able to enroll for certificates. EST-coaps is an enrollment protocol designed for use over CoAPs, and is introduced in Section 2.1.4.

2.1.3 CoAP

CoAP is an application layer protocol designed to be used by constrained devices over networks with low throughput and possibly high unreliability for machine-to-machine communication [8]. While designed for constrained networks, a design feature of CoAP is how it is easily interfaced with HTTP so that communication over traditional networks can be proxied. CoAP uses a request/response model similar to HTTP with method codes and request methods that are easily mapped to those of HTTP. Furthermore CoAP is a RESTful protocol utilizing concepts such as endpoints, resources, and Uniform Resource Identifier (URI). These features makes it easier to design IoT applications that seamlessly interact with traditional web services. Additionally CoAP offers features such as multicast support, asynchronous messages, low header overhead, and UDP and DTLS bindings which are all suitable for constrained environments.

As CoAP is usually implemented on top of UDP, communication is stateless and asynchronous. For this reason CoAP defines four message types: Confirmable, Non-confirmable, Acknowledgment, and Reset. Confirmable messages must be answered with a corresponding Acknowledgment, this provides one form of reliability over an otherwise unreliable channel. Non-confirmable messages do not require an Acknowledgment and thus act asynchronously. Reset messages are used when a recipient is unable to process a Non-confirmable message.

Since CoAP is based on unreliable means of transport, there are some lightweight reliability and congestion control mechanisms in CoAP. Message IDs allows for detection of duplicate messages and tokens allow asynchronous requests and responses be paired correctly. There is also a retransmission mechanism with an exponential back-off timer for Confirmable messages so that lost Acknowledgments does not cause a flood of retransmissions. Additionally, CoAP features piggybacked responses, meaning a response can be sent in the Acknowledgment of a Confirmable or Non-Confirmable request if the response fits and is available right away. This also reduces the amount of messages sent by the protocol.

The length of the payload is dependant on the carrying protocol and is calculated depending on the size of the CoAP header, token, and options as well as maximum DTLS record size. Section 4.6 of the CoAP standard says "If the Path MTU [Maximum Transmission Unit]

is not known for a destination, an IP MTU of 1280 bytes SHOULD be assumed; if nothing is known about the size of the headers, good upper bounds are 1152 bytes for the message size and 1024 bytes for the payload size" [8].

Since firmware images can be relatively large their size needs to be handled during transportation, which can be done via block-wise transfers [9]. A Block option allows stateless transfer of a large file separated in different blocks. Each block can be individually retransmitted and by using monotonically increasing block numbers, the blocks can be reassembled. The size of blocks can also be negotiated between server and client meaning they can always find a suitable block size, making the mechanism quite flexible. Another option of interest is the observe option, which allows a client to be notified by the server when a particular resource changes. This option can be used in a pull or hybrid update architecture, meaning the device does not have to continuously poll the server for a new manifest.

2.1.4 EST-coaps

EST-coaps is a protocol for certificate enrollment in constrained environments using CoAP. [10]. By allowing IoT devices to enroll for certificates, asymmetric encryption can be used even in a constrained environment. EST-coaps is heavily based on Enrollment over Secure Transport (EST) which was developed for traditional, less constrained networks and is thus incompatible with the SUIT standard, which is specified to work on very small devices [11]. EST-coaps retains much of the functionality and structure of EST but modifies it slightly to work over CoAP, DTLS, and UDP instead of HTTP, TLS, and TCP, for instance by making use of CoAPs block requests and responses to remedy the relatively large sizes of certificates.

2.1.5 ACE

Authentication and Authorization for Constrained Environments (ACE) is a framework for authorization and authentication for IoT contexts, based on the OAuth 2.0 framework [12]. ACE allows for clients in a network to access protected resources through authorization tokens. An authorization server is used to distribute tokens to clients, which they then pass on to resource servers. If a token is valid and the re-

source requested matches the level of authority associated with the token, access to the resource is granted. The framework is flexible regarding topologies, and clients can independently verify the validity of tokens or ask the authorization server for more information through an introspection request.

The ACE framework can be used to authorize clients in an IoT context. Authorization is important and distinct from identification, which can be achieve through for instance a PKI. As the architecture proposed in this thesis aims to be standardized it should prepare for different parties assuming different roles in the context of updating devices.Using authorization tokens is a scalable and configurable way of achieving that.

2.2 SUIT

The IETF Software Updates for Internet of Things (SUIT) working group aims to define a firmware update solution for IoT devices that is interoperable and non-proprietary [5]. The working group does not however try to define new transport or discovery mechanism, making their proposal agnostic of any particular technology. The solution shall be usable on Class 1 devices, defined by 10 KiB RAM and 100 KiB code size [13]. The solution may be applied to more powerful devices, such as the one used in this thesis described in Section 2.3.5.

Section 2.2.1 presents the SUIT architecture and Section 2.2.2 presents the SUIT information model.

2.2.1 Architecture

There is an Internet Draft by the SUIT group focusing on the architecture of a firmware update mechanism [14]. This draft describes the goals and requirements of such an architecture, although makes no mention of any particular technology. The overarching goals of the update process is to thwart any attempts to flash unauthorized, possibly malicious firmware images as well as protecting the firmware image's confidentiality and integrity. These goals reduces the possibility of an attacker either getting control over a device or reverse engineering a malicious but valid firmware image as an attempt to mount an attack.

In order to accept an image and update itself, a device must make several decisions about the validity and suitability of the image. The

information needed comes in form of a manifest. The next section will describe the requirements posted upon this manifest in more detail. The manifest helps the device make important decisions such as if it trusts the author of the new image, if the image is intact, if the image is applicable, where the image should be stored and so on. This in turns means the device also has to trust the manifest itself, and that both manifest and update image must be distributed in a safe and trusted architecture. The draft [14] presents ten qualitative requirements this architecture should have:

- Agnostic to how firmware images are distributed:
  The mechanism should not assume a particular technology is used to distributed manifests and images, but instead be able to be carried over different mediums. This means decisions about formats and distribution methods must not rely on features of a particular technology. This thesis will propose a technology agnostic update architecture and implement a prototype of it using a DTLS/CoAP stack.

- Friendly to broadcast delivery:
  The mechanism should be broadcast friendly, meaning the mechanism can not be reliant on security on the transport layer or below. Also, devices receiving broadcast updates not meant for them should not incorrectly apply the update.

- Use state-of-the-art security mechanisms:
  The SUIT standard assumes a Public Key Infrastructure (PKI) is in place. As previously mentioned, EST-coaps will be used for device enrollment. The PKI will allow for signing of the update manifest and firmware image.

- Rollback attacks must be prevented:
  The manifest will contain metadata such as monotonically increasing sequence numbers and best-before timestamps to avoid rollback attacks.

- High reliability:
  This is an implementation requirement of the update procedure and depends heavily on the hardware of the target device.

- Operate with a small bootloader:
  This is also an implementation requirement of the update procedure.
- Small parser:
  It must be easy to parse the fields of the update manifest as large parser can get quite complex. Validation of the manifest will happen on the constrained devices which further motivates a small parser and thus less complex manifests.
- Minimal impact on existing firmware formats:
  The update mechanism itself must not make assumptions of the current format of firmware images, but be able to support different types of firmware image formats.
- Robust permissions:
  Updates must be authorized before they are applied, and different configurations might have different requirements for authorization. The architecture should enable a flexible and robust permission model.
- Operating modes:
  The draft presents three broad modes of updates: client-initiated updates, server-initiated updates, and hybrid updates, where hybrids are mechanisms that require interaction between the device and firmware provider before updating. The thesis will look into all three of these broad classes. Some classes may be preferred over others based on the technologies chosen in the thesis.

The distribution of manifest and firmware image is also discussed, with a couple of options being possible. The two approaches are shown in Figure 2.3 and Figure 2.4. The first figure shows the manifest and image distributed together to a firmware server. The device then receives the manifest either via pulling or pushing and can subsequently download the image from the same server. Alternatively, as shown in the second figure, the manifest itself can be directly sent to the device without a need of a firmware server, while the firmware image is put on the firmware server. After the device has received the lone manifest through some method, the firmware can be downloaded from the firmware server. The SUIT architecture does not enforce a specific method to be used when delivering the manifest and firmware, but states that an update mechanism must support both types.

Figure 2.3: Distributing both manifest and image through a firmware server.

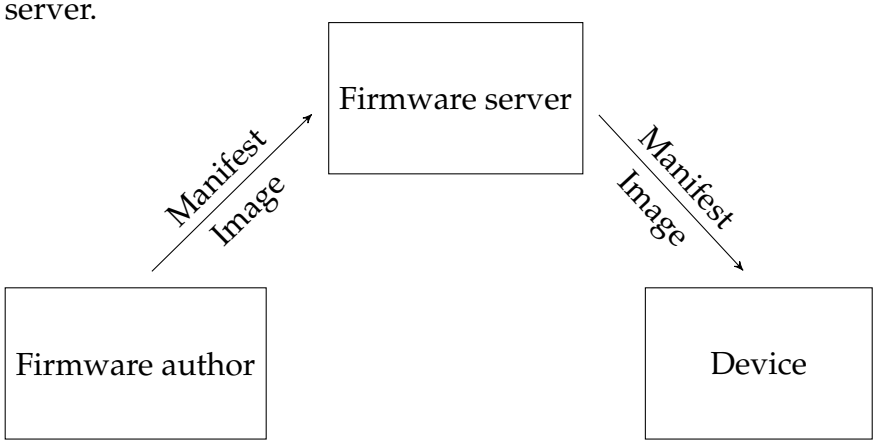
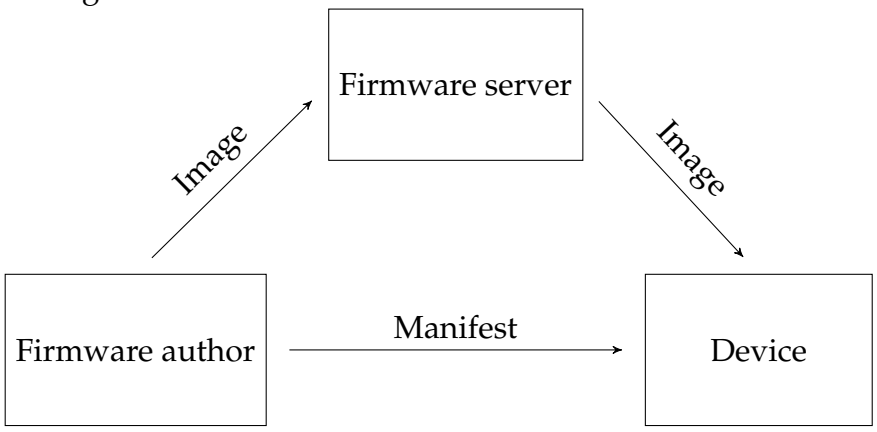


Figure 2.4: Distributing the manifest directly to the device and image through a firmware server.



2.2.2 Information Model

The Internet Draft for the SUIT information model presents the information needed in the manifest to secure a firmware update mechanism [15]. A manifest is needed for a device to make a decision about whether or not to update itself, and if the image related to the manifest is valid and its integrity ensured. The draft also presents threats, classifies them according to the STRIDE model, and presents security requirements that map to the threats [16]. Finally it presents use cases and maps usability requirements to the use cases in order to motivate the presence of the manifest elements. Since the thesis makes a choice about specific technologies to use not all use cases, usability requirements, and manifest elements are deemed necessary. The threats and security requirements however are. Note that the information model does not discuss threats outside of transporting the updates, such as physical attacks.

The proposed mandatory and recommended manifest elements and their brief motivations can be seen in Table 2.1. For the optional elements and more detailed motivations, use cases, and requirements refer to [15].

Table 2.1: The proposed mandatory and recommended manifest elements of the SUIT information model. Adapted from [15].

Manifest Element	Status	Motivation/Notes
Version identifier	Mandatory	Describes the iteration of the manifest format
Monotonic Sequence Number	Mandatory	Prevents rollbacks to older images
Payload Format	Mandatory	Describes the format of the payload
Storage Location	Mandatory	Tells the device which component is being updated, can be used to establish physical location of update

Table 2.1: The proposed mandatory and recommended manifest elements of the SUIT information model. Adapted from [15].

Manifest Element	Status	Motivation/Notes
Payload Digest	Mandatory	The digest of the payload to ensure authenticity. Must be possible to specify more than one payload digest indexed by XIP Address
XIP Address	-	Used to specify which address the payload is for in systems with several potential images
Size	Mandatory	The size of the payload in bytes
Signature	Mandatory	The manifest is to be wrapped in an authentication container (not a manifest element itself)
Dependencies	Mandatory	A list of digest/URI pairs linking manifests that are needed to form a complete update
Precursor Image Digest Condition	Mandatory (for differential updates)	If a precursor image is required, the digest condition of that image is needed
Content Key Distribution Method	Mandatory (for encrypted payloads)	Tells how keys for encryption/decryption are distributed
Vendor ID Condition	Recommended	Helps distinguish products from different vendors
Class ID Condition	Recommended	Helps distinguish incompatible devices in a vendors infrastructure

Many of the mandatory and recommended elements are there to enable certain use cases that might not always be relevant. As the SUIT architecture tries to be a standardized solution it must account for different use cases and different combinations of use cases. This means certain information must be prepared for in advance even if it is not going to be used in all cases. There is however a trade off

with flexibility and size, as the devices of interest are constrained it is of interest to reduce the size of the manifest as much as possible. With these two considerations in mind, a manifest for the architecture proposed in this thesis must be designed to facilitate as many different use cases as possible while keeping sizes to a minimum.

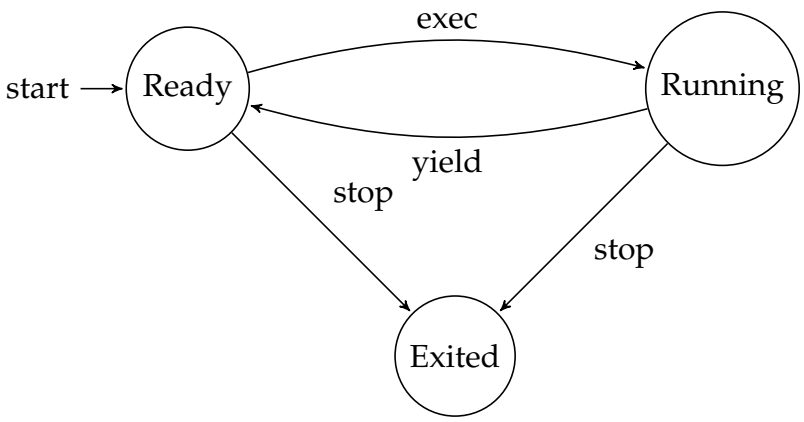
To summarize, the SUIT information model proposes to use a signed manifest that is distributed to each device in need of an update through some method. The device then parses the manifest in order to determine if the update is trusted, suitable, and up to date, with many other optional elements such as if special processing steps or new URIs to fetch the images are needed. The model does not make assumptions about technology which is one of the reasons there are optional elements, not all of them are applicable to all solutions. Nevertheless, the architecture and information model together provides a solid base on which to design a secure update mechanism for IoT.

2.3 Contiki-NG

Contiki-NG is an open-source operating system for resource constrained IoT devices based on the Contiki operating system [17, 18]. Contiki-NG focuses on low-power communication through standard protocols and comes with IPv6/6LoWPAN, DTLS, and CoAP implementations which makes it a suitable operating system for this thesis. Furthermore Contiki-NG is open source and licensed under the permissive BSD 3-Clause license and targets a wide variety of boards which makes it align with SUITs goal of creating an open standard for updating IoT devices.

Section 2.3.1 explains processes and events, Section 2.3.2 explains memory management in Contiki-NG, and Section 2.3.3 presents the different timers available in Contiki-NG. These internals are heavily based on the previous Contiki operating system and much of the information is gathered from there. Section 2.3.4 presents part of the network protocol stack that is implemented in standard Contiki-NG. Finally, Section 2.3.5 presents the target hardware Contiki-NG will run on in this thesis.

Figure 2.5: The state machine of Contiki threads. Adapted from [20].



2.3.1 Processes and Events

Contiki-NG has a process abstraction which is built on lightweight protothreads [19]. Protothreads can be seen as a combination of threads and event-driven programming. Threads or multi-programming provides a way of running sequential programs concurrently, enabling the use of flow-control mechanisms. This however requires a thread-local stack which is too resource heavy on small IoT devices. Event-driven programming on the other hand does not require a thread-local stack but programs are limited to computation as callbacks on event triggers, meaning sequential programs are more difficult to program.

Protothreads combine these paradigms in a lightweight way, keeping the yield semantics of threads and stacklessness of event-driven programming. All protothreads in a system are run on the same stack, meaning each protothread has a very low memory overhead, and by providing a conditional blocking wait statement protothreads can execute cooperatively. A process is declared through a `PROCESS` macro and can be automatically started after system boot or when a specific module is loaded.

Contiki-NGs execution model is event based, meaning processes often yield execution until they are informed a certain event has taken place, upon which they can act. Figure 2.5 shows the states of the processes and their transitions. User-space processes are run in a cooperative manner while kernel-space processes can preempt user-space processes. Examples of events are timers expiring, a process being polled, or a network packet arriving.

2.3.2 Memory Management

Memory can be allocated either statically, dynamically, or using a hybrid of static and dynamic allocation. Static allocation happens at compile-time, and while deterministic it limits the functionality of a program. Dynamic memory allocation allocates memory of various sizes on a heap, which can lead to fragmentation of heap memory. This is a problem in IoT devices as they are already resource constrained. The hybrid approach statically allocates pools of memory which can then dynamically allocate memory segments inside the pools. The hybrid approach does not suffer from external fragmentation as segments in the pool are perfectly divided. However, that does not mean fragmentation cannot occur, as sometimes segments will not be fully used and cause internal fragmentation [21].

Contiki-NG provides two memory allocators in addition to using static memory. They are called `MEMB` and `HeapMem` and are semi-dynamic and dynamic, respectively. `MEMB` is a hybrid allcator that allocates pools of static memory as arrays of constant sized objects. After a memory pool has been declared, it is initialized after which objects can be allocated memory from the pool. All objects allocated through the same pool have the same size. Pools can be freed, and it is possible to check whether a pointer resides within a certain memory pool or not.

`HeapMem` solves the issue of dynamically allocating objects of varying sizes during runtime in Contiki-NG. It can be used on a variety of hardware platforms, something a standard C `malloc` implementation could struggle with. To allocate memory on the heap, the number of bytes to allocate must be provided and a pointer to a contiguous piece of memory is returned (if there is enough contiguous memory). Memory can be reallocated and deallocated such as using a normal `malloc`.

2.3.3 Timers

Contiki-NG provides different timers used by both the kernel and user-space applications. The timers are based on the clock module which is responsible for handling system time. The definition of system time is platform dependent.

The different timers and their usages are:

- `timer` - A simple timer without built-in notification.

- `stimer` - Counts in seconds and has a long wrapping period.
- `etimer` - Schedules events to processes. Since events in Contiki-NG can put yielding processes in the execution state, `etimer` can be used to periodically schedule code by setting up an `etimer` to signal a specific event when it expires then waiting on that event.
- `ctimer` - Schedules calls to a callback function. `ctimer` works in similar ways to `etimer` but with callbacks to callback functions instead of events.
- `rtimer` - Schedules real-time tasks. Since real-time tasks face different requirements than normal tasks, rtimer uses a higher resolution clock. Real-time tasks preempt normal execution so that the real-time task can execute immediately. This mean there are constraints on what can be done in real-time tasks as many functions cannot handle preemption.

`timer`, `stimer`, and `rtimer` are stated to be safe from interrupts while `etimer` and `ctimer` are unsafe [17]. All timers are declared using a timer struct, which is also how the timer is interacted with.

2.3.4 Networking in Contiki-NG

Contiki-NG features an IPv6 network stack designed for unreliable, low-power IoT networks. There are many protocols implemented in the stack, this thesis will look at UDP and CoAP secured by DTLS. Beneath IPv6 Contiki-NG supports IEEE 802.15.4 with Time Slotted Channel Hopping [22].

The CoAP implementation in Contiki-NG is based on Erbium by Mattias Kovatsch but has become part of core modules in the operating system itself [23]. The default implementation supports both unsecured (CoAP) and secured (CoAPs) communication. CoAPs uses a DTLS implementation called TinyDTLS which handles encryption and decryption of messages [24]. The CoAP implementation consists of [25]:

- A CoAP engine which registers CoAP resources.
- A CoAP handler API that allows for implementations of resource handlers. The handlers act upon incoming messages for their corresponding resource.

- A CoAP endpoint API allowing handling of different kinds of CoAP endpoints.
- A CoAP transport API which hands CoAP data from the CoAP stack to the transport protocol.
- CoAP message functions for parsing and creating messages.
- A CoAP timer API providing timers for retransmission mechanisms.

2.3.5 Firefly

Zolertia Firefly is a supported hardware platform in Contiki-NG and the targeted board for this thesis. It is a breakout board designed for IoT application development sporting an ARM Cortex-M3 with 512 KB flash and 32 KB RAM, making it more powerful than the Class 1 devices the SUIT standard specifies as a lower bound. This is not an issue but should be kept in mind as less capable devices are supposed to be able to use an update mechanism that is complying with SUIT. Furthermore the board supports IEEE 802.15.4 communication in the 2.4 GHz band and SHA2 and RSA hardware acceleration [26].

Chapter 3

Update Mechanism Architecture

With the required background information, an architecture for an update mechanism can be proposed. Four key areas that the architecture must deal with have been identified:

- Key distribution and management
- Authorization and access control
- Means of communication
- Upgrading images

The architecture must propose solutions for these four areas while complying with SUIT as much as possible in order to make the architecture interoperable and suitable as a standard. Certain elements, such as how to locally flip an image and which kinds of authorization tokens to issue, are implementation dependant. The architecture must however support different means of achieving these goals and not restrict engineers to one certain implementation.

Alongside these four key areas is the concern of a devices life cycle from an update perspective. The life cycle should be intertwined with the mechanisms of the architecture and show how devices can enroll, communicate, and receive updates throughout their long expected lifetimes.

Section 3.1 defines what a server and operator means in the context of the update mechanism. Section 3.2 discusses what is needed for devices to enroll in a PKI and how keys are handled during updates. Section 3.3 describes the purpose of issuing authorization tokens, how devices can use them, and who is to be authorized. Section 3.4 describes

how devices, servers, and operators can communicate and shows an example workflow of communicating an update. Section 3.5 discusses different means of handling the payload when applying an update. Section 3.6 introduces the notion of a life cycle for devices, and Section 3.7 shows different examples of possible architectures.

3.1 Roles

This Section explains the notion of servers and operators in the architecture and their responsibilities. Section 3.1.1 covers the topic of servers while Section 3.1.2 covers operators.

3.1.1 Who Is a Server and What Do They Do?

Servers are responsible for transporting manifests and images to the devices and keeping track of device profiles. Upon enrollment devices register at a server and the server creates a profile for that device. The profile contains the vendor and class IDs and firmware version of the device. This allows the server to know through which protocols the device can be contacted and which version it should be updated to. Operators, discussed in the next section, send signed manifests and images to servers, and can query them for device status.

Devices should contain a list of servers and by trusting the certificate authority, they can validate those machines certificates after being enrolled. A server is thus any machine that is enrolled, has a valid certificate, and is included in the devices list of servers. The reasoning behind this decision is that a standard solution for updates should not assume the topology of an IoT network. The server may be a machine acting as a proxy between a traditional network containing the operator and a constrained network with IoT devices. The server could be a more capable IoT device located entirely within the constrained network and be contacted through a proxy. The server could be located entirely within the traditional network and use a proxy to communicate with devices of the constrained network.

A device could also be aware of several servers, and different devices can be mapped to different servers. This can make device management easier as certain classes of devices can be handled by certain servers. By allowing a device to receive updates from several servers, the update mechanism architecture displays a form of robustness. If

one server is a machine located entirely within the constrained network and the connection between that server and the operator is severed, updates can still be distributed through other servers. If devices are pulling updates, they can query the servers in order of their list of servers. If updates are pushed, devices keep the connection with the server pushing the update.

Which machines are allowed to act like servers can be boiled down to a few important points no matter the topology of choice:

- The server is enrolled and has a valid certificate
- The server is included in a devices list of servers (meaning it is authorized to transport updates to the device)
- An operator can reach the server and is authorized by the server to upload updates

What servers are allowed to do must also be predetermined. Imagine a device running an operating system and an application. The operating system is developed by some party different than the one developing the application, and thus the device is aware of two update servers, one for the operating system and one for the application. If receiving an update from the application update server, the device should allow for the update to happen but also make sure the correct parts of code are updated. The application vendor should not be allowed to touch the operating system if they are not authorized to do so, and vice versa. This introduces the topic of authorizing updates. Authorization and access control is discussed in Section 3.3.

3.1.2 Who Is an Operator and What Do They Do?

Operators are people authorized to upload manifests and images to a server. They can also optionally upload manifests directly to a device depending on the architecture. Operators prepare manifests and images and signs them before transporting them to a server, which forwards them to a device. The signing ensures end-to-end security for images and manifests between operators and devices.

Like a list of servers introduced in Section 3.1.1, devices also need a list of operators. This is because if an operator wishes to send a manifest directly to a device, the device needs to know if the operator is

authorized to do so, otherwise it is discarded. Just like with mapping devices to servers, devices can receive manifests from several operators and different devices may interact with different operators. This creates opportunities to logically divide a network between different operators. An example use case is a constrained network supported by different vendors; the respective vendors should only be able to service their respective devices despite all devices belonging to the same network. It can also create a hierarchy, where certain operators may directly interact with devices but other operators must interact with devices through servers. Yet again the point is to prepare for as many different scenarios as possible and create a flexible architecture.

As with servers, the essence of being an operator can be captured in a few points:

- An operator is enrolled and has a valid certificate
- An operator is included in a devices list of operators (and therefore can send manifests to the device)
- An operator is trusted by a server to send manifests and images to the server, causing devices to update

Access control for operators is an important topic. Operators should only be able to send updates to devices they are authorized for, and the updates should cover parts of the device within the operators rights. Section 3.3 discusses access control for operators and servers.

3.2 Key Management

The architecture will, in order to align with the goals of SUIT, be based on asymmetric cryptography. The availability of EST-coaps makes this feasible in IoT contexts but other enrollment protocols could also be used. This means a Certificate Authority (CA) is needed to act as a trusted third party distributing certificates. The certificates are linked to a public key which has a private key partner and are used to verify the correctness of a public key. Certificates are signed by the CA and in order to trust them, device have to trust the CA itself.

In order to enroll, a pre-shared key is proposed. This is the approach used in EST-coaps, but it is not chosen for that reason. If a pre-shared key is not used the CA cannot be sure the device asking to

enroll really should be part of the trusted network. An attacker that obtained a valid certificate could communicate with devices and servers alike and no one would be able to tell it is a malicious actor. CAs must know they are issuing certificates to the correct devices and pre-shared gives devices a means of identifying themselves. Pre-shared keys could be used for encrypting all traffic but as they are less scalable and harder to manage than certificates, they are just used for enrolling.

A device that is enrolling has to trust the CA issuing the certificate. If it cannot do so, how could it know it received a valid certificate? An attacker would love for a device to use the attackers public key instead, and if an attacker poses as a CA it could issue a certificate with its own public key and then sign it. In order to trust the CA, a device needs to have the certificate of the CA it is enrolling with or some other CA further down the chain of trust. By verifying the signature on the newly enrolled certificate with the CAs own certificate, a device can be certain they are using the correct keys.

When applying updates, certificates might not be valid anymore. This is implementation dependant and might not always be a problem, but the architecture should be prepared for these situations. In the case an update breaks a certificate, the certificate cannot be used for communication and thus the device cannot use it to re-enroll either. In this case, a new pre-shared key should be part of the update so that the device can enroll as if it was factory new. The process of issuing pre-shared keys might be difficult to automate as the CA must be aware of which keys to accept, but it is needed to ensure the security of future device communication.

3.3 Authorization

A flexible architecture enables different configurations of servers, operators, and devices. An operator might be authorized to update all parts of all devices, or be constrained to updating a specific piece of functionality for a subset of the devices. Operating system vendors might be allowed to push security updates for the operating system but not change the application code. Controlling access rights is a security issue and the architecture must support it.

How clients can access a protected resource through authorization tokens is described in [12] and Figure 3.1 shows an adaptation of the

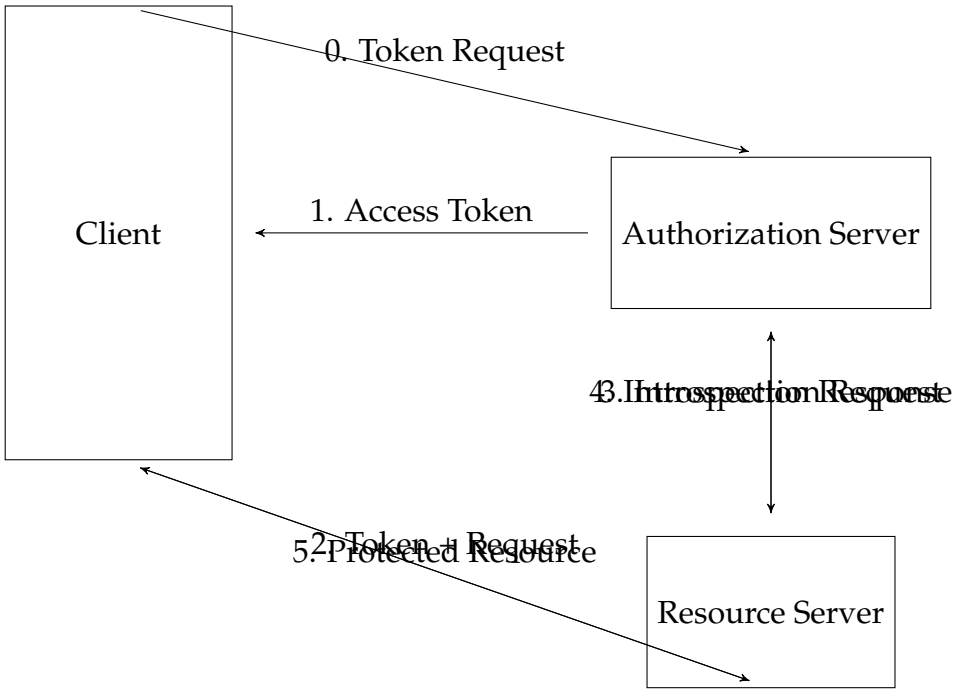
protocol flow from that document. The figure shows how a client wanting to access a resource requests a token from an authorization server. The token is returned to the client, which can then send a request and token to the server holding the resource. If necessary, the resource server can send an introspection request to the authorization server asking for more information about the token in order to verify it. If everything goes as planned, the client is allowed the resource.

In the context of the update architecture, the client would be a party needing to authorize themselves, i.e. an operator or server. The access token would have to be of a lightweight variant since they are to be used on constrained devices, but which variant is implementation specific. Tokens will be sent with updates (signed manifests and images) to devices, the resource sought for is the ability to update the device. The device will thus not respond with a particular resource, but instead if the token is valid recognize the originator of the update as an authorized one and proceed with the update. Introspection is an interesting feature of ACE since it requires less from the device concerning validating tokens. Instead of doing everything on its own, the device can ask the server for additional information making the validation procedure easier. This however means some extra communication which is power consuming for an IoT device. To use introspection or not is yet again an implementation issue, but authorization servers should be both enrolled and reachable for devices to send introspection requests if necessary.

Who is supposed to authorize? As updates will be sent from operators through servers to devices, the devices need to know the originator of an update is authorized to issue the update. The proposition is to only require operators to authorize. No matter how updates are initiated or distributed (pull vs push and manifest and image together vs separately), updates at some point must be crafted, signed, and sent by an operator. The operator is making the decisions about updating, and thus must authorize these decisions through tokens. Servers deliver the updates to devices, but do so as a relay for operators, as well as acting as repositories for images and device profiles. The messages forwarded by servers will contain the authorization token granted to an operator. This token can in addition to authorizing the update on a device be used by the server to authorize the usage of the server by the operator.

Not requiring servers to authorize should not pose any issues as

Figure 3.1: The protocol flow of ACE. Adapted from [12].



the update must be prepared in a previous step by an operator that authorizes. Also, it makes the flow of applying an update easier by not needing communication to the authorization server by an update server. Requiring update servers to authorize would not add any security to the devices as the update already will be shipped with a token authorizing the update.

3.4 Communication

In heterogeneous networks of IoT devices, each device might sport a specific protocol stack. In order to enable different devices to be updated, servers must be aware of how to reach these devices. This problem introduces the notion of device profiles containing information about device capabilities and software versions.

When devices have enrolled and obtained a valid certificate, they must contact their respective servers so the servers can create profiles of the devices. The profiles will tell through which protocols to reach a device and what software versions the device is using. In order to achieve this, devices must first know which servers to contact. This can be solved through shipping devices with a list of servers. This list can later on be updated like any other software. Furthermore, the devices use vendor and class IDs as described in the SUIT information model. The information model uses these pieces of information to verify an update is intended for a specific device by matching the IDs, but they can also be sent to a server to tell it what kind of device is contacting it. The server can infer a profile based on the IDs it is sent, or simply use the protocols the device chose to contact it. The devices also need to be aware of how to register, for instance by POSTing to a specific server endpoint.

When updating there are possibilities regarding how the updating process is initiated. An operator can query the server for the status of one or several devices, prepare an update for them, and have the update pushed through the server. Optionally the operator could send a manifest to the device explaining when the update is to be applied and put the image on the server. Later when the device should update, the device pulls the image from the server, validates it using the already received manifest, and updates. Both the pull and push approaches assume the devices are already enrolled and registered at the server.

Figure 3.2: Example workflow of communication in the architecture.

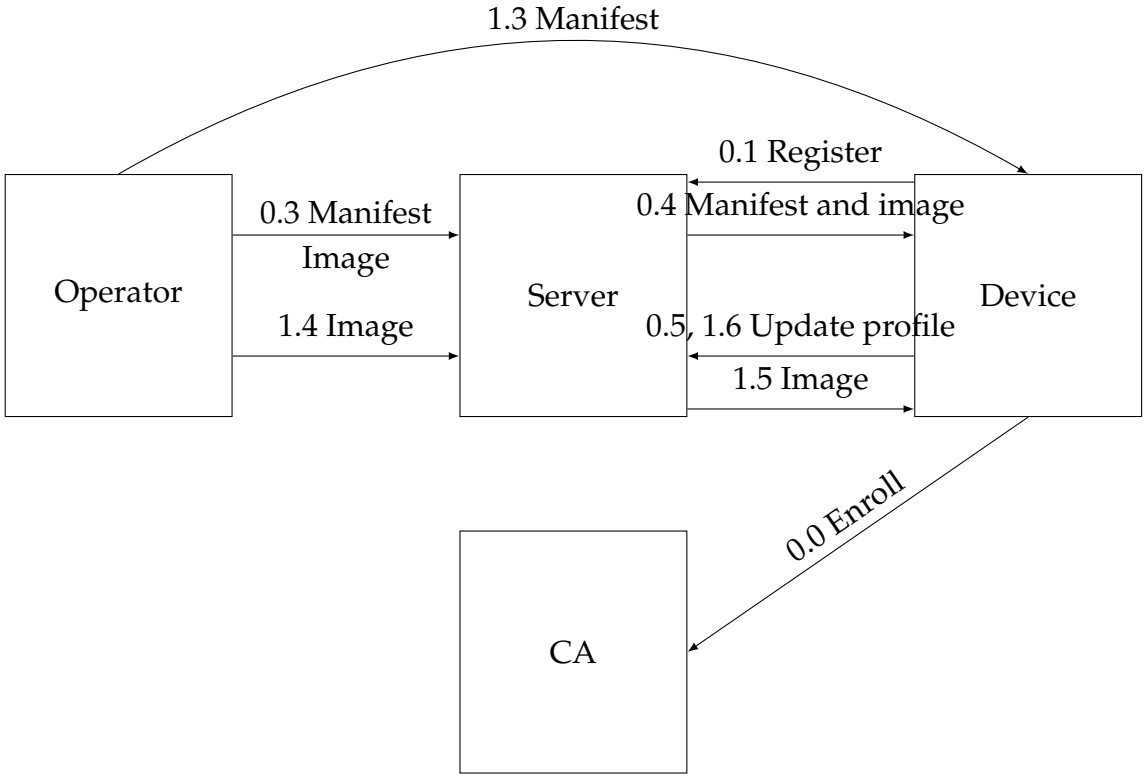


Figure 3.2 shows an example update flow in the architecture. This update is initiated by the operator by querying the server for device status and then pushing an update. The manifest and image are distributed together.

0.0 Enrolling the device at the certificate authority.

0.1 Registering at the server. This creates a profile for the device on the server.

0.2 The operator prepares a manifest and signs it.

0.3 The operator requests an access token from the authorization server in order to gain access to applying the update.

0.4 The manifest and image are both signed and sent to the server with the authorization token.

0.5 The signed manifest and image are sent with the authorization token to the device.

0.6 The device optionally requests introspection data from the authorization server to verify the authorization token.

0.7 The device confirms the update if successful and causes the server to update its device profile.

After updating, the devices capabilities might have changed, for instance by having a new protocol implemented in software. The version has also changed due to applying an update. After an update, a device should notify all its servers so they can update the device profile (or simply discard the old one and generate a new, as if the device registered for the first time). This ensures the servers view of the devices is up to date and that communication will always happen through the intended and supported protocols. The functionality of registering is the same as when a device is new and thus not costly to implement.

There are alternatives to using device profiles. One alternative is to instead keep a list of known protocols implemented by devices in the network, and when pushing updates to a device trying each protocol in sequence. This has the benefit of not needing to keep and continuously update profiles, but also has some issues. One issue is

that you still need to keep some state of the devices on the server regarding firmware version. If the server does not know what the status of device versions are, it cannot help a human operator decide about deploying updates.

Another drawback is that devices might implement common protocols but have different preferences. If two devices implement some common protocols but one of them supports hardware operations for encrypting one of the protocols, it will prefer using that protocol with the server, whereas the other device might not. The server will however, with no information about device preference, try the same sequence of protocols with both devices.

Furthermore, as communication can be unreliable over these networks, the server cannot know for sure if a device does not respond due to not understanding the protocol and therefore dropping the packets, or if the response just got lost in transmission. It is more robust to keep track of which protocols devices support and conform to the preferences of the constrained devices.

Lastly, instead of using profiles all communication could be initiated from the device side, meaning updates are only done through a pulling mechanism. This would not enable the use case of pushing updates which could be critical if a vulnerability must be patched right away. Operators must be given the choice to push updates to their devices, and thus servers must be able to initiate contact with devices.

3.5 Updates

When an update has finally arrived to the device, it must be processed and then installed. The process of decrypting, validating, and installing the image is heavily implementation specific with most of the details being out of scope for the architecture. However, since devices operate using different hardware and bootloaders they must be given the freedom to update in the way that makes most sense for them. The architecture should support this.

By delivering optional fields such as decryption instructions, processing steps, and postconditions, update handlers and bootloaders can take care of updates in various ways. This enables different ways of applying updates within the same architecture. What the update handlers and bootloaders of all devices have in common is that they

must trust the source of the update, they must be able to decrypt the update, they must be able to verify the validity of the update, and they must be able to do this safely such that an unexpected power cycle does not brick the entire device.

Still being in the realm of very constrained devices, the bootloader should be as simple as possible. This is also a requirement stated by SUIT on the architecture. By decrypting and verifying the image at every boot the boot procedure will be secure but quite complex. Also if a power cycle occurs during decryption, the device might not be able to recover. Decrypting the image as part of the update mechanism and writing it unencrypted to flash would allow for a simpler bootloader, but is less secure as the device would boot from an unencrypted image.

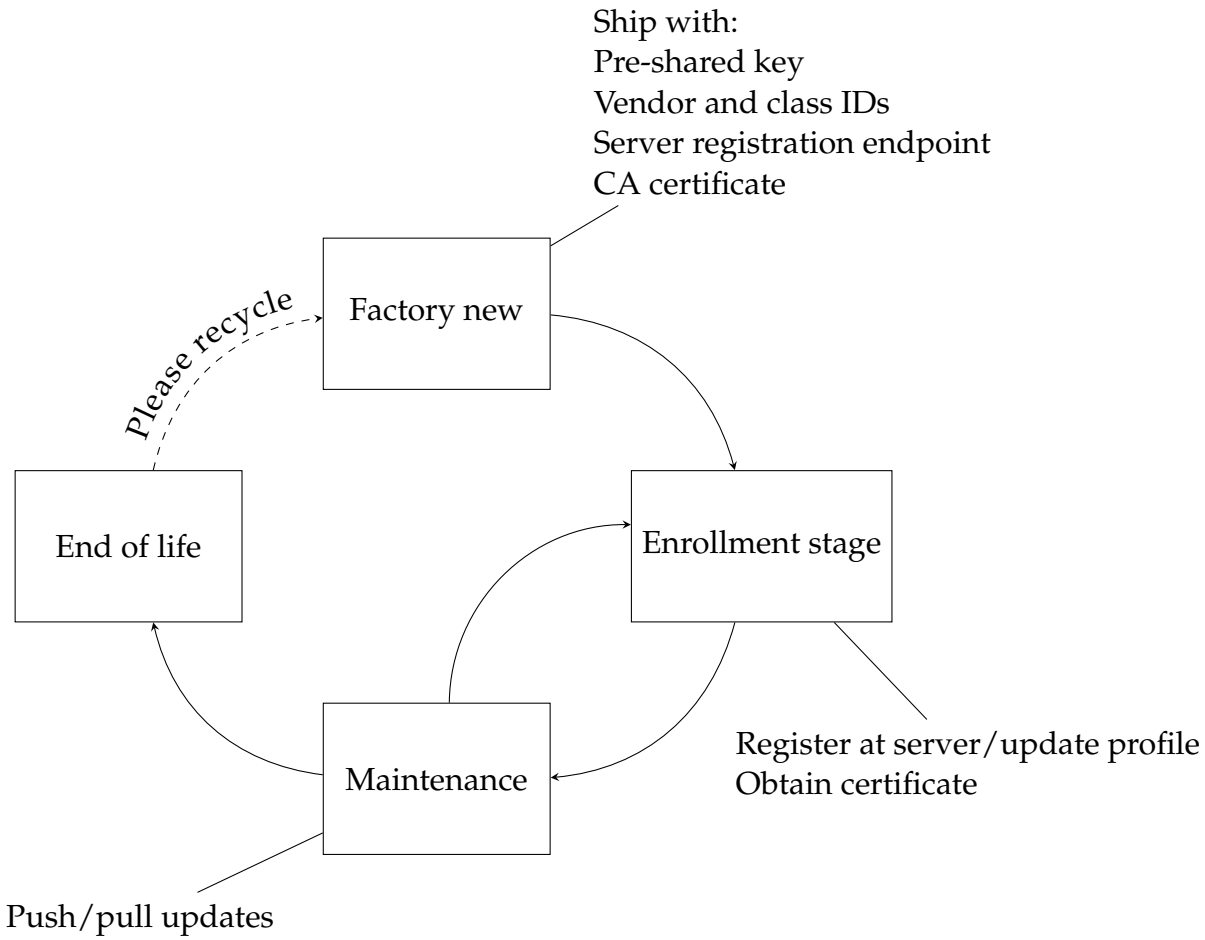
By storing the manifest containing the image digest, unencrypted images can be verified by comparing their digest to the one in the manifest. Digests are easier to calculate than decryption is, and a power cycle would just interrupt the digest calculation instead of the decryption of the actual bootable image. In order to make sure the manifest is correct upon boot, the digest of the manifest can be calculated and stored alongside the manifest and image. The manifest also has to be stored in order to prevent rollback attacks. It contains monotonically increasing sequence numbers to ensure devices do not install older, possibly vulnerable images, but in order to compare sequence numbers the most recent manifest has to be kept around. Manifests should be kept for the update handler to compare sequence numbers, and for the bootloader to verify images.

Besides offering encryption, authorization, communication, and manifests, the architecture cannot influence the update procedure further. Locally upgrading an image is a concern of the target device that is to be updated. Chapter NUMBER will present the prototype architecture implementation, and touch upon subjects such as manifest format and secure boot.

3.6 Device Life Cycle

The four key areas discussed in sections 3.2, 3.3, 3.4, and 3.5 are all part of the life cycle of a device. From the moment a new device is deployed in a network to the point where it is taken out of action possibly several years later, the life cycle describes a holistic view of the

Figure 3.3: The life cycle of a device.



state and operations of devices.

Figure 3.3 summarizes the life cycle of a device from an update perspective. The figure shows the different stages of a device from being manufactured to ending its service. There are also annotations showing what needs to be done in each stage. These stages are discussed in further detail in this section.

As discussed, a factory new device that is to be installed in an IoT network needs some information in order to enroll and register at a server. A pre-shared key, CA certificate, vendor and class IDs, list of servers and operators, and and endpoint for registration is needed. These parts make sure the device can take part of the network and move to the next step of the life cycle.

Entering the enrollment state, devices obtain certificates by enrolling

at the CA. For this the pre-shared key and CA certificate is needed. After obtaining a certificate the device can be trusted by the servers. It registers at its designated servers who all create a profile for the device. The device is now ready to be updated, and proceeds to the maintenance stage.

The maintenance stage can be expected to last for several years, and this is where the device receives and applies updates. As updates can change the capabilities of devices, by for instance implementing a new transport protocol in software, devices should confirm successful updates at the server so the server can build a new profile for that device. Servers also need to be updated with the new version the device is running, which further motivates the update confirmation. This means after an update, the device will either move back to the enrollment or registration stage.

If certificates are broken after updates, as discussed in Section 3.2, devices move back to the enrollment stage to obtain a new certificate. If the certificate is still valid after the update, the device moves back to the registration stage, updates the profile at the servers, and then moves back to maintenance. The device will remain in the maintenance stage until it either breaks or is taken out of service. If you are a manufacturer of IoT devices please consider recycling or (securely) re-using devices, starting the life cycle anew.

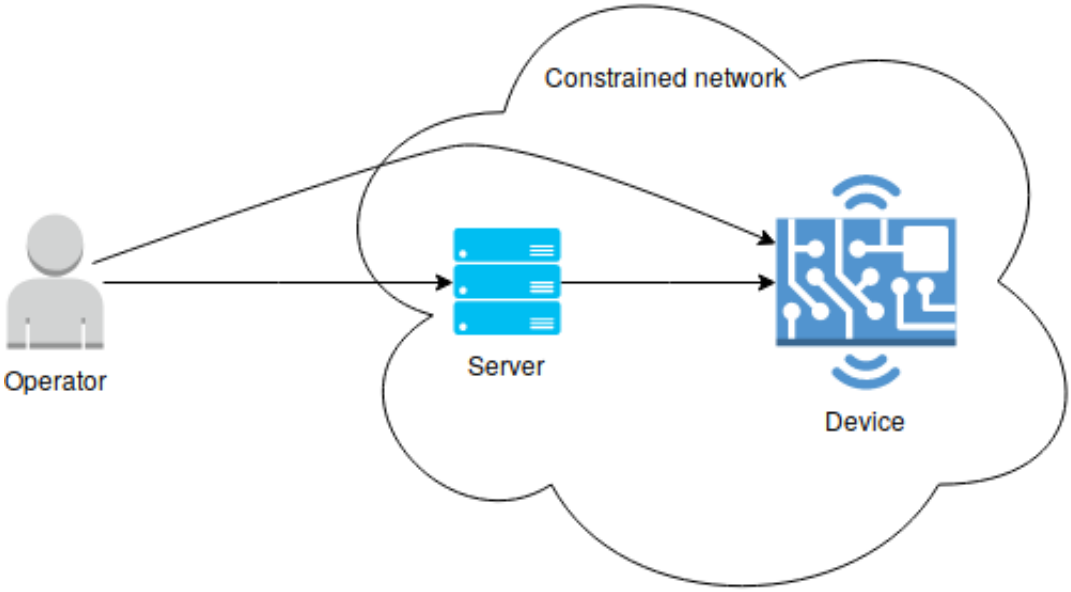
3.7 Different Architectures

As discussed, operators, servers, and devices can interact in many ways. The architecture tries to be flexible allowing for different network topologies and configurations. The important parts are that devices can enroll, all actors have valid certificates, and that devices know which certificates belong to which roles beforehand.

Figure 3.4 shows an example architecture with one operator, one server, and one device. The operator is capable of running the protocols needed to communicate in the constrained network, and can thus interact both directly with the device to send manifests and interact with the server residing within the constrained network. A architecture like this allows for servers to be distributed within the constrained network.

Figure 3.5 shows an operator interacting with a proxy which in turn

Figure 3.4: An operator communicating directly with machines in the constrained network.



interacts with the server. Note that since the operator is not capable of contacting the server directly it can not contact the device directly either. All traffic, manifest and image, goes through the server to the device.

Figure 3.6 shows a third alternative where the server acts as a proxy between the operator and the device. The operator is yet again unable to reach the devices directly and relies on a server. In this scenario, there are two devices who both receive updates from the server. If the devices use the same transport protocols, broadcasting could be used from the server to send updates to both devices at the same time.

There are many other possible architectures and configurations. What these three examples have in common is that the operator always resides outside the constrained network, devices always reside within the constrained network, and that servers transport images to devices. In turn, devices register and update their statuses to the servers. Since operators reside in traditional networks using traditional protocols such as HTTP over TCP, a proxy mechanism may be necessary to communicate with the often UDP based constrained networks. Remember from Section 2.1.3 that CoAP can easily be proxied to and from HTTP

Figure 3.5: An operator using a proxy to reach the constrained network.

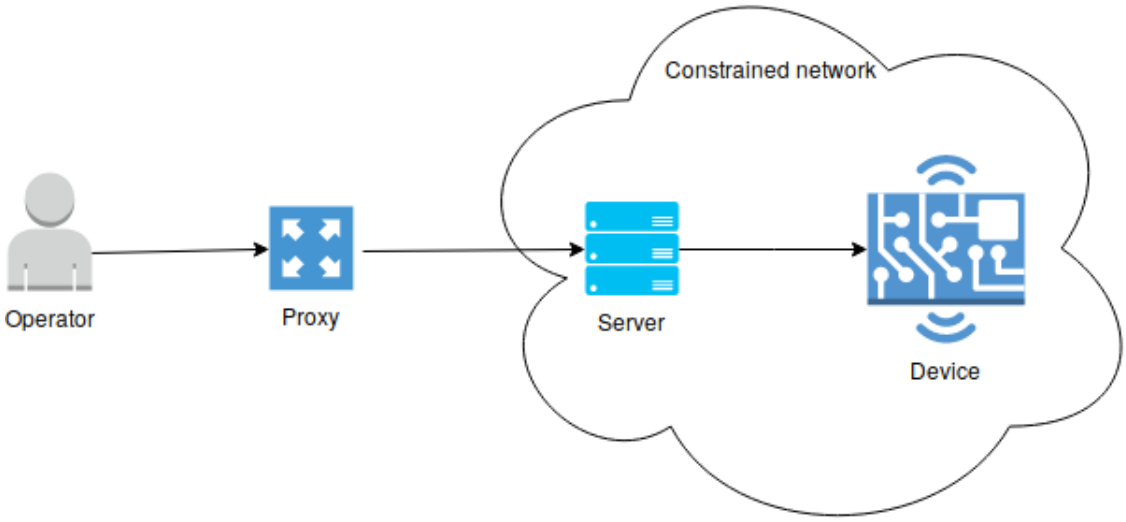
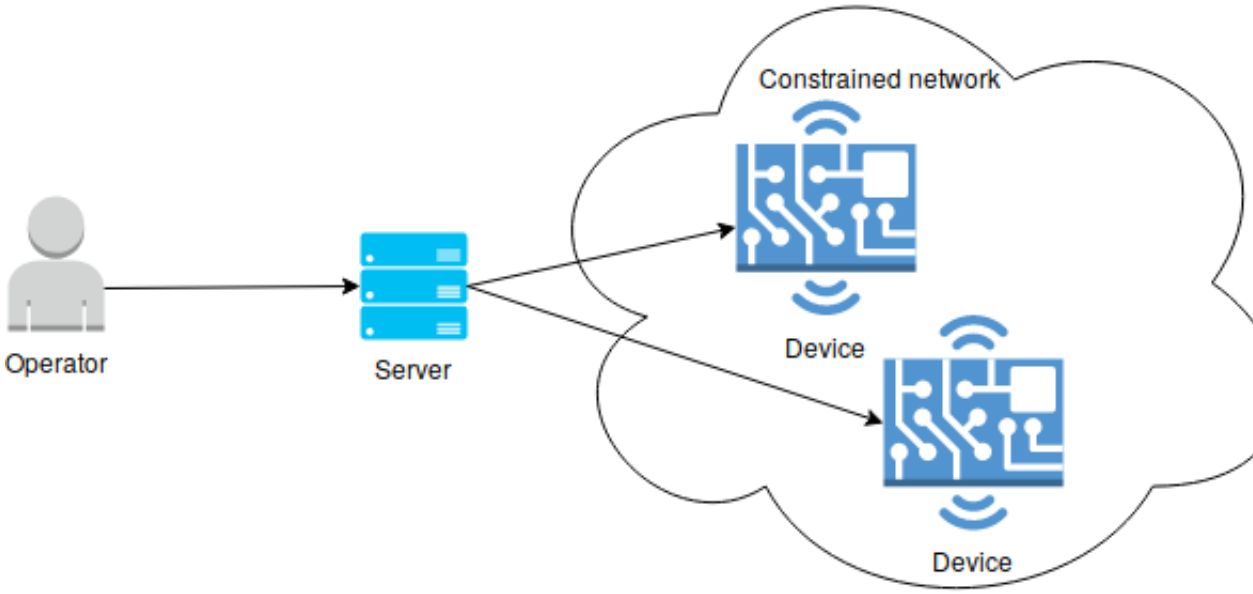


Figure 3.6: A server is used as a proxy to reach two devices.



meaning a server running for instance CoAP could also be used as a proxy for the operator. If the operator has the proper protocols implemented, they could communicate manifests directly to a device.

Chapter 4

Transportation of Firmware Images

4.1 Manifest Format

As the target devices of the update mechanism are constrained IoT devices, the manifest format must be designed with careful consideration. The format must be easy to parse in order to reduce power consumption on devices and be small so that transportation of the manifest is done as quickly as possible, but still contain all necessary information to perform secure updates. This section will present the manifest format which is based on the SUIT specification. It consists of mandatory, always present elements as well as optional elements. The reasoning for splitting it into mandatory and optional elements is to reduce the size of the common case, a singular update for a single Microcontroller Unit (MCU), while still allowing more complex updates (such as differential updates or specifying components). The manifest format can be created or generated by some party in JavaScript Object Notation (JSON), encoded in Concise Binary Object Representation (CBOR) for efficient compression, then signed and sent over the network. Preferably the base manifest should fit in a single CoAP message, but the CoAP block option can be used if the manifest adds many options and thus grows.

Section 4.1.1 explains the structure of the manifest. Optional elements and their structure are explained in Section 4.1.2.

4.1.1 Mandatory Elements

The mandatory elements of the manifest should facilitate singular updates for a homogeneous device supporting one MCU as this is the simplest use case for secure updates. This use case updates the entire image at once, OS and code, and does not need to care for different storage locations or components. By restricting the mandatory elements to supporting these kinds of updates, the size of the always occurring elements can be reduced.

Different versions of manifests can feature different fields as an update mechanism evolves, therefore the device needs to know what to expect from the manifest. This can be encoded in a **manifest version ID**. Rollback attacks need to be prevented so that old, vulnerable images cannot be applied. They can be mitigated through a **sequence number**. Furthermore the **format** (ELF, binary, etc) and the **size** of the image must be included. **Vendor and class IDs** must also be included so that the device knows the image is applicable and will work. Lastly, a **digest** of the image must be included so the device can be sure the image has not been tampered with during transport. The **URI** from which the image can be fetched is bundled together with the digest. The manifest structure expressed as a C struct can be seen in Listing 4.1.

Listing 4.1: The mandatory manifest format.

```
1  struct Manifest {
2      int version;
3      int sequenceNumber;
4      int format;
5      int size;
6      Condition* condition;
7      URIDigest* digest;
8      Option* option;
9  } Manifest;
```

These elements are deemed absolutely necessary and form the very minimum upon which an update mechanism can operate. A manifest containing these and only these elements can be used to perform a singular update for a device containing one MCU and one means of storage (no ambiguity about which components/locations are being updated).

The digests, conditions, and options are nested structures that can possibly be repeated depending on how many digests, conditions, and options are necessary. In order to implement this, each of these structures contain an element which is a pointer to another structure of the same type. This allows a parser to traverse the link of structures, and thus parse several URI/Digest pairs, conditions, or options. Their structures can be seen in Listing 4.2, Listing 4.3, and Listing 4.4 in the next section.

Listing 4.2: The format of URI/digest pairs.

```
1  struct URIDigest {
2      int URILength;
3      char* URI;
4      char* digest;
5      URIDigest* next;
6  } URIDigest;
```

Listing 4.3: The format of vendor and class ID conditions.

```
1  struct Condition {
2      int type;
3      char* UUID;
4      Condition* next
5  } Condition;
```

4.1.2 Options

The options provide additional value to the mechanism, but as the manifest aims to be as small as possible they are not accounted for in the base manifest. Instead they can be optionally included using the options field of the manifest. The included options must be sorted by their option code in ascending order to calculate a delta between the current and preceding option. This is the way CoAP implements options, and it allows for a smaller amount of bits to encode the option code when the codes get larger. The options and their codes are presented in Table 4.1.

Table 4.1: The optional elements of the manifest and their option codes.

Option Code	Option Name
1	directives (Instruction struct)
2	processingSteps (Instruction struct)
3	URIs (mirrors)
4	component
5	dependencies (URIDigest struct)
6	precursors (URIDigest struct)
7	aliases (URIDigest struct)
8	storage
9	keyDist
10	best-before
11	payload (if small enough)

The option field in the manifest format will contain a list of option structures, each structure consisting of an option delta, option length, option value, and a pointer to the next option as seen in Listing 4.4. As with the mandatory elements, some options consist of nested structs. The dependencies and precursor options list digests of images or parts of images that must be acquired before applying the update, along with their URLs. Aliases lists alternative mirrors for each image that could be used instead. Directives and processingSteps both use a different kind of structure, an Instruction struct, that maps types of instructions to their values. Examples of directives could be whether to install the update right away or just cache the image and install at some later point, and examples of processingSteps could be which decompression algorithm to use. The Instruction struct can be seen in Listing 4.5.

Listing 4.4: The format of the option field.

```
1    struct Option {
2        int delta;
3        int length;
4        char* value;
5        Option* next;
6    } Option;
```

Listing 4.5: The format of directives or processing steps.

```
struct Instruction {
    int type;
    int value;
    Instruction* next;
} Instruction;
```

4.1.3 Example Manifest

JSON is a human readable and easily modified format. It is easy to convert JSON, which is quite verbose, into CBOR as a more efficient means of encoding the data. CBOR was designed around the same principles and elements as JSON, but is not very readable for humans. For these reasons, the thesis proposes to craft manifests in JSON, then convert into CBOR, and finally sign and send to the device requiring an update. An example manifest could look as in Listing 4.6.

Listing 4.6: An example manifest.

```
{
    "versionID": 1,
    "sequenceNumber": 1,
    "format": 0,
    "size": 512,
    "conditions": [
        {
            "type": 0,
            "UUID": "74738ff5-5367-5958-9aee-98fffdcd1876"
        },
        {
            "type": 1,
            "UUID": "28718ff5-9302-8217-7auu-14llldsd1276"
        }
    ],
    "digests": [
        {
            "URI": "coap://fake.uri/image",
            "digest": "b924842b4f42 ... ecf3301985"
        }
    ],
```

```
        "options": [
            {
                "delta": 4,
                "length": 1,
                "value": 0
            },
            {
                "delta": 6,
                "length": 10,
                "value": 1548683522
            }
        ]
    }
```

This manifest contains all the mandatory information and two options. There are two conditions telling the vendor and class ID so that the device knows the update is correctly targeted. There is only one URI/digest pair, giving the device the URI to download the image from and the digest to validate the image with. The two options specified are the component and best-before timestamp options. The component option value can for instance map integers to components to be updated, and the best-before timestamp prevents the device from applying the device if that moment in time has been exceeded. The manifest is easy to read but as it is JSON it is unnecessarily verbose. By encoding it in CBOR, which is a binary encoding, it will shrink in size and thus cost less to receive.

Listing 4.7: The first four elements of the example manifest in CBOR encoding.

```
A7                                      # map(7)
   69                                   # text(9)
      76657273696F6E4944                # "versionID"
   01                                   # unsigned(1)
   6E                                   # text(14)
      73657175656E63654E756D626572      # "sequenceNumber"
   01                                   # unsigned(1)
   66                                   # text(6)
      666F726D6174                      # "format"
   00                                   # unsigned(0)
   64                                   # text(4)
```

```
12        73697A65                                # "size"
13     19 0200                                    # unsigned(512)
```

Listing 4.7 shows the first four elements of the example manifest when encoded in CBOR. The structure of mapping keys to values is the same, but each element is preceded by an indication of type and length. This allows for arbitrarily nested elements and indefinite length items. It also allows for a more efficient encoding of elements since if the size is known beforehand, only the required amount of bits can be used instead of preallocating bits and wasting them on shorter items.

The example manifest would be transmitted to a device and then parsed. The parser would divide the manifest into the structures shown in sections 4.1.1 and 4.1.2. The parsed manifest structure would have an option struct referencing another option struct, meaning the chain is of length 2. The reason for having the nested structs carry a reference to its own type is to make memory allocation easier. While parsing, when the parser detects a new nested struct will be created it can simply allocate that memory and add it in the chain of structs. There is no need to preallocate a large enough block of memory to make sure the structs will fit. Finally, when the manifest is parsed and analyzed, the update itself can take place. This is a topic for the next chapter.

Chapter 5

Updating of Firmware Images

Chapter 6

Evaluation and Results

Chapter 7

Discussion

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Appendix A

Appendix Title