Cross-platform Open Security Stack for Connected Device

D1.4 Use Cases Definition Final Version

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Table of Contents

List of Tables

List of Figures

List of Acronyms

Abbreviation / acronym	Description
BIOS	Basic Input/Output System
CoT	Chain of Trust
CRP	Challenge Response Pair
D1.1	Deliverable number 1 belonging to WP1
DM	Device Management
DoA	Description of Action
DoS	Denial of Service
EC	European Commission
FPGA	Field-Programmable Gate Array
HSM	Hardware Security Module
IoT	Internet of Things
MITM	Man-in-the-Middle
ODM	Original Design Manufacturer
OEM	Original Equipment Manufacturer
OTA	Over-the-Air
PUF	Physically Unclonable Function
RoT	Root of Trust
SBC	Single-board Computer
SoC	System on a Chip
TEE	Trusted Execution Environment
TPM	Trusted Platform Module
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
UC	Use Case
WP	Work Package

Executive Summary

This document revises and completes the initial version of the CROSSCON use cases, reported in D1.1, with two new use cases to offer a comprehensive and enriched context for demonstration and validation of the CROSSCON IoT security stack.

The CROSSCON stack aims at supporting IoT developers in the design and implementation of secure IoT applications across a highly fragmented landscape of devices with diverse security features and capabilities. The stack enables essential security mechanisms offering Root of Trust (RoT), Chain of trust (CoT), Trusted Execution Environment (TEE), and trusted services to guarantee an acceptable level of security throughout the entire IoT device ecosystem and minimise potential entry points for attackers.

Given the high ambition of the project, there is a need to define use cases (UC) and scenarios to validate and demonstrate the effectiveness of the results with high industrial and community relevance. To do so, the project consortium has defined a final set of five use cases: UC1) IoT device multi-factor authentication; UC2) Firmware updates of IoT devices; UC3) Commissioning and decommissioning of IoT devices; UC4) Remote attestation for identification and integrity validation of agricultural Unmanned Aerial Vehicles (UAVs); and UC5) Intellectual Property Protection for Secure Multi-Tenancy on FPGA.

Each use case is defined by its scenarios, architecture, workflow, threat model, security assumptions and properties, and testbed prerequisites. The definition of the use cases will serve and feed the next task in the project workplan on revision of requirements elicitation, validation criteria, and KPIs for the CROSSCON stack.

This document contributes to the completion of milestone MS3 on "First version of CROSSCON Open Specification, Use Cases finalised."

1 Introduction

1.1 Purpose of the document

This document defines the final set of the CROSSCON use cases based on the result of collaborations between application/service providers – BIOT, 3MDEB and CYSEC, and the academic (UNITN, UMINHO, UWU, TUD) and industrial partners (BEYOND, ATOS) of the project.

The use cases have been selected and defined based on their relevance and representation of significant instances of the security problems that IoT developers, integrators, consumers, and vendors face in the field as routine or even daily tasks. As such, the use cases will serve as demonstrators of the innovation results of the CROSSCON stack, produced by the technical work packages WP2, WP3, and WP4, and validated at the required TRL4 testbed implementations in WP5.

To address the ambitious scope of the project and the wide spectrum of platforms and security challenges, we adopted a comprehensive approach when defining the use cases. For each UC we targeted a specific demonstration in WP5 depending on factors such as the considered threat model, the class of devices supported by each UC provider, the type of connectivity and interactions among the different IoT entities, all according to the final UC provider's model and the end users' needs.

We consider this to be the right approach not only for the initial but also for the final version of the document, to avoid the danger of providing too narrow or restrictive use cases for the research activities.

1.2 Ambition of use cases

The final set of the CROSSCON use cases: **UC1)** IoT device multi-factor authentication – provided by 3MDEB; **UC2)** Firmware updates of IoT devices – provided by BIOT; **UC3)** Commissioning and decommissioning of IoT devices – provided by BIOT; **UC4)** Remote attestation for identification and integrity validation of agricultural UAVs – provided by CYSEC; and **UC5)** Intellectual Property Protection for Secure Multi-Tenancy on FPGA – provided by TUD.

As identified in D1.1, the initial and extended set of use cases reported in this document will be used to investigate security issues related to some of the IoT application domains explicitly challenged by the call[1] such as i) Effective management of cybersecurity patches for connected devices in restricted environments such as IoT devices; ii) Effective mechanisms for inventory management, detection of insecure components and decommissioning; and iii) Methods for secure authentication and secure communication for connected devices in restricted environments such as IoT devices.

The use cases will be used by CROSSCON to test and validate the effectiveness and efficiency of the CROSSCON research and innovation results. In essence, the ambition of CROSSCON use cases in the first version resides in delivering an effective solution for a) multi-factor device authentication, b) secure firmware updates, and c) secure commissioning and decommissioning of IoT devices; while in the final version of the document the ambition extends to two promising application domains of identification and integrity validation agricultural UAVs, and intellectual property protection in the context of FPGA workloads.

The ambition of CROSSCON remains the same since the first version in D1.1 and is further reinforced in the final version of the use cases in this document. Firstly, the use cases present security problems that could be solved with existing technology for some classes of devices, but it remains challenging and, in some cases, even impossible to solve for other classes of devices, typically, but not only, those more resources constrained. CROSSCON aims at extending the range of devices for which it is possible to provide a secure solution in the presented use cases. Secondly, CROSSCON aims at providing

[1] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl3-2021-cs-01-02

innovative technology that allows to implement some secure realizations of the use cases that are difficult to implement nowadays, or current implementations are not fully satisfactory. Thirdly, CROSSCON aims at demonstrating the interoperability of its solution using heterogenous devices from different vendors in its use cases.

In the initial and final version, every use case contains three essential elements, namely actors, goals and process steps that include functional requirements and anticipated behaviour. However, describing the requirements of a system exclusively from the end user's perspective might present a challenge in CROSSCON. Variations to the basic flow might be needed in different “layers” of CROSSCON stack. There is also an ambition to refer to the specific processes that must happen in various parts of the system, including dependencies, necessary supporting features, and the external environment.

2 CROSSCON Objectives

We will first recall the main objectives of CROSSCON with the aim to give a better context to the use cases discussed in the document. Particularly, presenting the project's targeted results will facilitate comprehension of why the selected use cases and scenarios for the validation of the project's results.

CROSSCON aims at designing a new open, modular, highly portable, and vendor-independent *IoT security stack* that allows OSes and applications on the layers above to leverage essential security mechanisms and trusted services across a wide range of devices and heterogeneous hardware architectures. The stack will offer a unified set of trusted APIs to the layers above to address interoperability issues from different hardware architectures and security mechanisms at lower levels.

It will feature a high-level of modularity. The stack will allow configuring only those security features necessary depending on the underlying hardware and firmware. It will flexibly leverage the security features implemented at the layers below and, in case security features are missing, like in bare metal devices, the stack will offer an entire TEE implementation suitable for such devices. The unified set of APIs will allow the use of TEE's functionalities and trusted services on a customizable and need-to-use basis. CROSSCON also aims at improving and enriching the traditional trusted services supported by existing TEEs to higher-level modules and applications.

As devices are getting more powerful and more security mechanisms and features are incorporated directly into the hardware, there is the need to extend the stack's primitives to leverage such advanced security features and open its scope to domain-specific hardware architectures.

The project will demonstrate that the CROSSCON stack supports the implementation of high-level security services such as device multi-factor authentication, secure updates, device commissioning, remote attestation and decommissioning. The security properties and guarantees offered by the stack's design will be formally verified. The project will provide a methodology and tools to formally verify the correctness of the code implementing the stack. Thus, CROSSCON's stack will guarantee trusted services with a high-level of assurance across an entire IoT system.

Table 1 shows the main CROSSCON objectives and their relevance to the different use case demonstrators. The table is revised and extended in its second and final version of the use cases including the additional use cases UC4 and UC5.

Table 1: CROSSCON Objectives and Use Cases

CROSSCON Objectives	UC1 Device Multi-Factor Authentication	UC2 Firmware Updates of IoT Devices	UC3 Commissioning & Decommissioning of IoT Devices	UC4 Remote Attest. for Identification and Integrity Validation of Agricultural UAVs	UC5 Intellectual Property Protection for Secure Multi-Tenancy on FPGA
Objective 1: Support IoT stakeholders with the design and implementation of an innovative IoT open-source security stack, that enables essential security mechanisms and trusted services.	✓	✓	✓	✓	✓

Objective 2: Strengthening memory protection and isolation in new and existing TEEs. Mitigate the impact of side-channels attacks		✓			✓
Objective 3: Provide IoT stakeholders with methodology, techniques, and related tools to formally verify "correct by design" secure open-source software and firmware for connected devices	✓	✓	✓	✓	
Objective 4: Support the IoT stakeholders with a set of additional novel and high assurance trusted services	✓	✓	✓	✓	✓
Objective 5: Provide IoT stakeholders with a toolchain that integrates and validates lightweight techniques for security assurance		✓		✓	
Objective 6: Provide IoT stakeholders with a validation and testing methodology, a replicable testbed, and testing and validation results for CROSSCON innovations	✓	✓	✓	✓	
Objective 7: Enable the valorisation and adoption of CROSSCON flagship results	✓	✓	✓	✓	✓

3 UC1: Device Multi-Factor Authentication

The Internet of Things (IoT) has revolutionized the way we live and work by connecting devices and allowing them to communicate with each other. However, this increased connectivity also introduces new challenges in terms of security. One of the main challenges is ensuring that only authorized devices can access the network, or other specific resources.

In recent years, Physically Unclonable Functions (PUFs) have been proposed as a solution for device authentication in low-end devices. This is because, some low-end devices, such as IoT devices, have limited computational resources and cannot use regular cryptographic operations. PUF-based authentication is therefore seen as a lightweight solution in such cases.

However, PUF-based authentication has proven to be difficult to implement in practice and is vulnerable to a variety of attacks. By combining multiple factors, we aim to overcome the limitations of existing PUF-based solutions and provide a more robust defense against MITM (Man-in-the-Middle).

As a final goal of this use case, we aim to propose a multi-factor authentication (MFA) solution for IoT devices to improve their security, as shown in Figure 1. While the initial idea emerged based on the devices that leverage PUFs and other device-specific factors, we may extend it further, to provide general-purpose MFA solution.

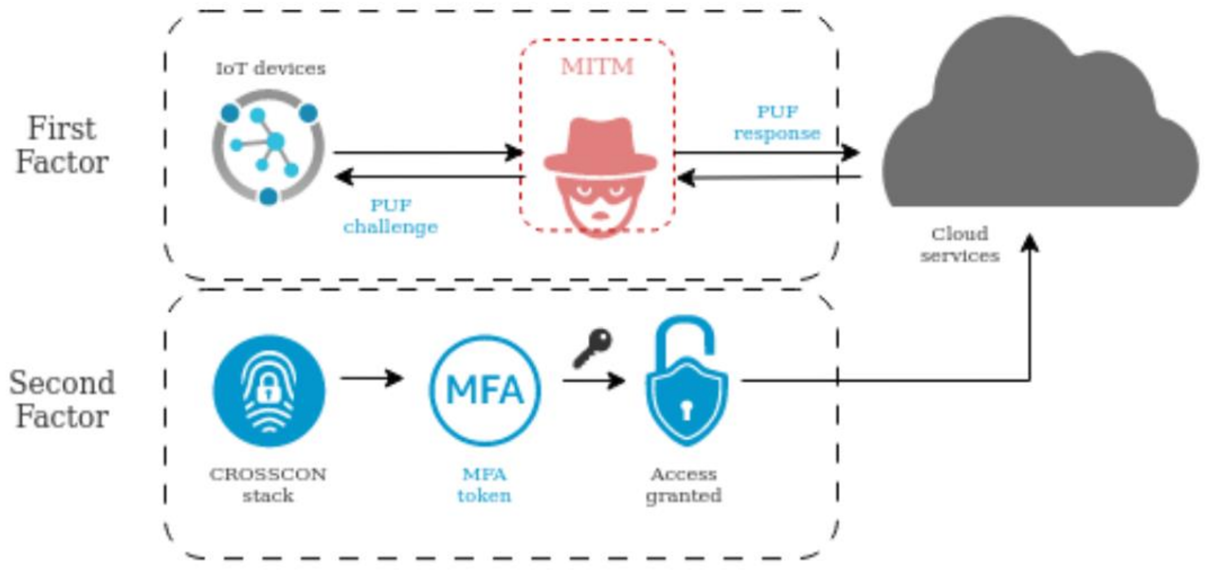


Figure 1: UC1 Device MFA High-level View

3.1 Scenarios Description

Description of stakeholders taking part in following scenarios:

Device - Network-connected equipment such as a sensor or gateway which is running the CROSSCON stack. One common attribute of all such devices is the ability to connect and exchange data with other devices.

Vendor - manufacturer of Device or its firmware, or both.

Owner - physical owner, administrator, or maintainer of one or more Devices connected into a network. It may not be equivalent to user, for example kiosks or infotainment systems are made available to people other than Owner.

Cloud - catch-all term for providers of various services external of Owner's infrastructure. In following scenarios, Cloud includes target services with which Devices communicate, but also the Internet and other networks not controlled by Owner.

Scenario 1

The Owner wants to send the data collected by valid Device to the Cloud. Owner needs assurance that no external actor can send data to the Cloud in name of valid Device.

Scenario 2

The Vendor needs to authenticate his Devices, for instance, for updating the firmware of his devices' firmware. The Vendor does not want to send the update image to Devices other than his own.

Scenario 3

Owner has some Devices (e.g., sensors) that produce data that is an input to other Devices (e.g., actuators). Owner expects that only his Devices can communicate with each other.

3.2 Architecture and Workflow

Following the assumption that user has no control over Internet and cloud provider's network, the architecture can be generalized and simplified to the state presented on Figure 2. Note that this figure shows all possible interconnections, not all of them have to be present in each scenario.

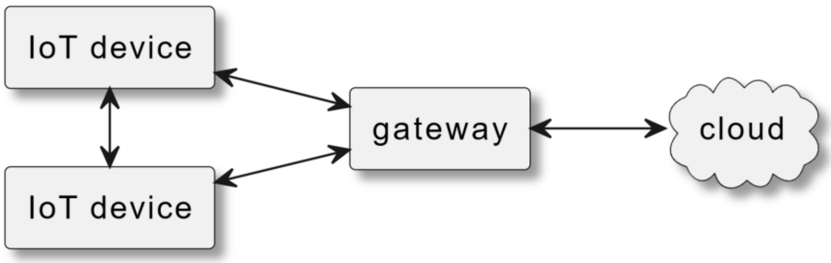


Figure 2: Simplified architecture

Figures 2-4 show different possible connections based on type of communication, with marked points that can be hit by man-in-the-middle attacks. Complex networks may have a combination of more than one kind of connections presented here, potentially with mesh topology or subnetworks.

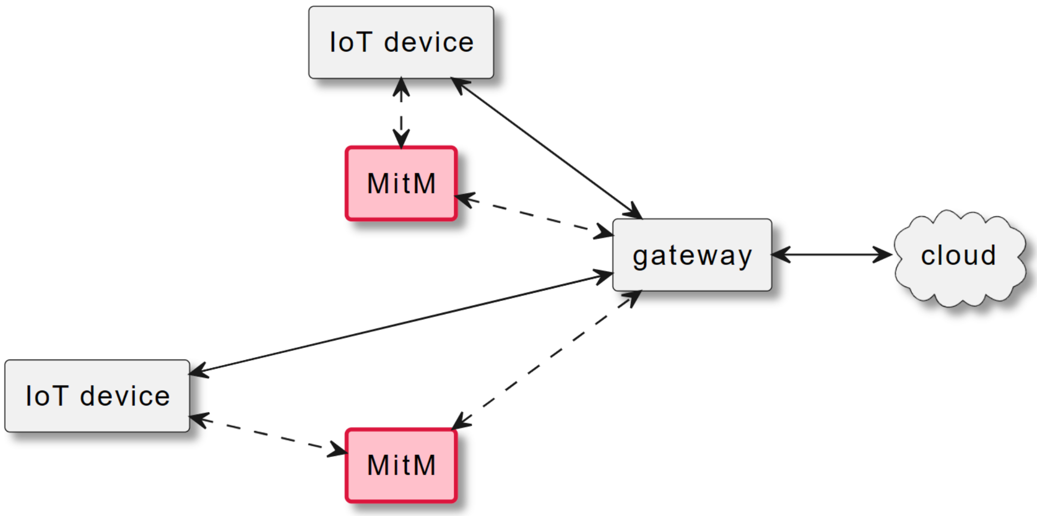


Figure 3: IoT devices communicate only through gateway

Figure 3 demonstrates a case where all devices connect directly only to a gateway or router, regardless of whether the device communicated with cloud or another device in the same network. Attackers have to access each connection between device and gateway for each device they are targeting.

Another option would be to hook into a connection between gateway and Cloud or in the Cloud itself, but attacks against infrastructure outside Owner's control are out of scope for this use case. In many cases, implementing countermeasures on the gateway is sufficient since it is the common point of all communication.

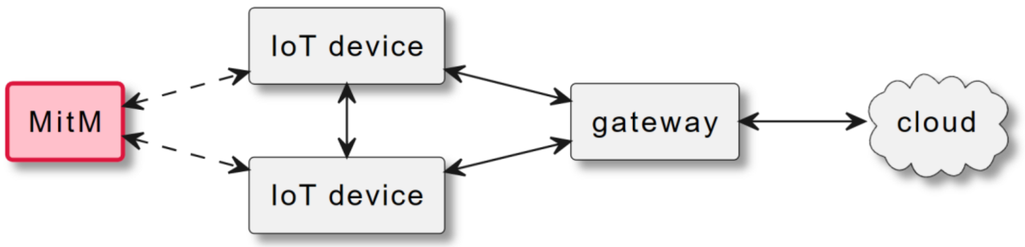


Figure 4: IoT devices can communicate with gateway and each other

Devices can also communicate with each other directly, without use of a gateway or router, as depicted in Figure 4. This can be used to offload the router by creating a mesh network, which may result in higher fault-tolerance, better coverage of wireless signal and lower cost of infrastructure. As the number of interconnections increases, so does the number of possible points that an attacker has to break into to get a full view of data exchange. Countermeasures have to be applied to all devices since there is no central device that all communication is passed through.

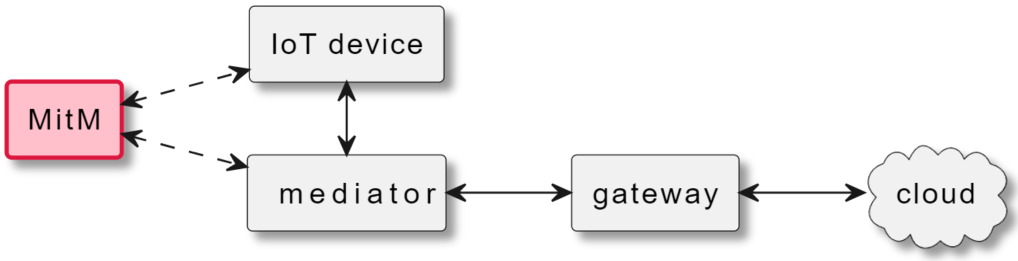


Figure 5: IoT devices must use intermediary to communicate with the rest of the world

A special case of a device-to-device connection is shown in Figure 5. It is very similar to the previous one, except now only one of the devices is capable of connecting to the gateway. This is often used by more constrained devices which cannot use protection mechanisms, data rates or other attributes enforced by the main network. It is possible to use this approach to connect devices using other wireless technology standards than Wi-Fi, for example Bluetooth, Zigbee, LoRaWAN. In that case, possible attack vectors depend on the topology of the subnetwork and may be the same as either of two previously described cases.

All presented topologies have to be taken into account. Even if they generally are not used for a given scenario (e.g., firmware update requests happen between an IoT device and some external server, they usually do not need device-to-device communication inside the local network), the possibility of having different flow of data opens up new attack vectors.

3.3 Threat Model

One of the most important attack vectors in the IoT device authentication is the MITM adversary. In the following attack models, we define the adversary:

- Has full access to the data flowing in the communication channel between devices (can freely eavesdrop and intercept the data transmitted between IoT devices).
- Can add own device to impersonate the device to be authenticated or the device being authenticated to.
- Can generate and send malicious/replayed packets to the communication channel (and so to the IoT devices).

- Does not have physical access to the IoT devices performing authentication as we consider it out of scope for MITM (it would resemble Evil Maid attack in such case).

While there are many existing protocols and methods to solve the problem of MFA in case of the interactive scenarios (involving user interaction) and high-end systems, the problem is still an open issue (thus, interesting for the project), if we consider non-interactive scenarios (i.e., no user interaction) and/or more constrained devices. Thus, the following use cases have been selected:

1. Use case 1: one-way authentication between a low-end device and a high-end device (like gateway).
2. Use case 2: mutual authentication between two high-end devices.

3.3.1 Use Case 1 - one-way authentication between a low-end device and a high-end device

For low-end device with limited resources, possible second factor options for the authentication are the wireless connection signal properties. Moreover, a low-end device may be equipped with less complex PUF circuit with a limited number of Challenge Response Pairs (CRPs).

Typically, such devices are compact, lightweight, and low-power sensors. Due to the limitation in memory and processing capability, they do not participate in Internet communication in a secure way. These devices usually communicate with the help of proxies or gateways using a protocol stack specifically designed for IoT device with constraints. [1]

3.3.1.1 Threat model

We specify the possible attacks need to be considered and recommendations to mitigate them for low-end devices:

1. **Brute-force attack**: cloning the CRP table by issuing all possible challenges.

   To mitigate the issue, one should limit the number of authentication attempts in time to make brute-force attacks more time consuming. Using PUF with large number of CRPs or use larger challenges and responses is not feasible for resource constrained devices.

2. **Replay attack**: issuing the same authentication request again (with the same challenge and response).
   To mitigate the issue do not allow to use the same CRP more than once. It may be difficult to achieve on low-end devices with PUFs having small number of CRPs. A workaround here may be to use device with reconfigurable PUFs to change the available CRP pool. Alternatively, obfuscate the challenges and responses and periodically change the obfuscation functions if the device runs out of all CRPs.

3. **Eavesdropping**: adversary can gain access to private information by monitoring transmissions between nodes.

   This attack can be mitigated with and end-to-end encryption. There exist lightweight symmetric-based encryption protocols that could be implemented even for some low-end devices. The problem always relies on protection of the cryptographic keys on such devices.

   Any encryption of the communication protocol (such as TLS) is not feasible for low-end devices, so more lightweight methods are proposed. Typical mitigation in such case would be to obfuscate challenges and responses or using any other methods that will not cause the challenges and responses to be transmitted in a plain form. It will successfully make the adversary’s job harder to figure out CRPs.

4. **Machine learning attack**: model PUF behaviour to predict its CRPs.

   This attack is an option available after successful eavesdropping the communication channel. Because of that challenge and response obfuscation is also a possible mitigation here. Additionally, one can consider using PUFs with low predictability rate when modelling or PUFs with different challenge and response word length to make it less predictable.

3.3.2 Use Case 2 - mutual authentication between two devices

High-end devices can support the typical communication protocol stacks, because are less constrained. Examples include an IP camera or a smart meter that is based on 32-bit processors. However, these devices also can benefit from using low-power and lightweight protocols, and from consuming less bandwidth [1]. They are also capable of supporting complex cryptographic operations (e.g., modular exponentiation) thus they could offer stronger security properties than low-end devices (more PUF options to choose from, secure storage capabilities, etc.). For a second factor, there are numerous options to choose from including hashes, keys and other secrets held in secure storage.

3.3.2.1 Threat model

We specify the possible attacks needed to be considered and the recommendations to mitigate them for high-end devices:

1. **Brute-force attack:** cloning the CRP table by issuing all possible challenges.

   To mitigate the issue, one should limit the number of authentication attempts in time to make brute-force attacks more time-consuming. Additionally use PUFs with large number of CRPs or use larger challenges and responses. Devices should be capable of having such PUF security properties.

2. **Replay attack:** issuing the same authentication request again (with the same challenge and response).
   To mitigate the issue do not allow to use the same CRP more than once. A device equipped with PUFs with high number of possible CRPs should not hit this problem quickly. If needed obfuscate the challenges and responses and periodically change the obfuscation functions (e.g., different hashing algorithm) if the device runs out of all CRPs. Challenges may also include timestamps, nonce or another randomly generated secret. Additionally use large enough challenges and responses to have a wide pool for CRP obfuscation.

3. **Eavesdropping**: adversary can gain access to private information by monitoring transmissions between nodes.

   Devices considered in this use case should be capable of performing heavyweight cryptographic operations. The communication protocol could be encrypted (using TLS for example) to effectively disable eavesdropping adversaries.

4. **Machine learning attack**: model PUF behaviour to predict its CRPs.

   This attack is an option available after successful eavesdropping the communication channel. Due to communication channel encryption, it should not be possible to catch CRPs and model PUF behaviour.

3.4 Assumptions and Security Properties

This section describes assumptions about device types and their security properties. The division of devices is made based on the threat model presented in Section 3.3 of the document.

Low-end devices:

- Devices with constrained resources
- Equipped with simple PUFs with limited number of CRPs (but some low-end devices may have a reconfigurable PUF)
- Not capable of performing heavyweight operations, like heavy cryptographic operations
- No secure storage, so authentication cannot store secrets on these devices
- Capable of one-way authentication only to a high-end device (no mutual authentication)
- Tamper-resistant by its nature (no exposure of external buses, integrated flash), any tampering automatically destroys PUF

High-end devices:

- Devices are not resource-constrained
- Equipped with more complex PUFs with high number of CRPs
- Capable of executing performance heavy operations like asymmetric cryptography
- Secure storage capabilities, so authentication may store secrets on these devices
- Capable of mutual authentication to another high-end devices
- Secure booting and additional tamper-resistant mechanisms present on the devices

3.5 Testbed Prerequisites

In this chapter, the impact of different factors on the testbed definition will be evaluated.

First Factor (PUF)

A PUF is required as the first authentication factor in all cases. However, PUF circuits are not commonly found on commonly available off-the-shelf development boards. As this research is not focused on the first authentication PUF factor but rather on adding another factor, it is possible to fall back to simulating the first authentication factor in software, focusing on the properties of the second factor. Alternatively, hardware providing dedicated PUF Emulation Services [1], such as the Microchip PolarFire SoC [2], or dedicated hardware modules providing PUF capabilities, such as the ChipDNA [3] series from MaximIntegrated, can be considered. The most flexible option would be to use an SoC providing both CPU and FPGA blocks, allowing for easier prototyping.

Scenarios

In this use case, we propose two scenarios for further testing and evaluation. The first scenario involves a low-end device in a one-way authentication scenario. The second scenario involves a more complex device in a mutual authentication scenario.

To implement the first scenario, at minimum, a low-end device and a gateway device are required. For the second scenario, at minimum, two more complex devices are required for mutual authentication.

Connectivity

IoT devices typically use wireless connectivity for several reasons, such as flexibility, ease of deployment, cost-effectiveness, efficient use of resources, scalability, and integration with mobile and remote devices. Wireless connectivity allows for greater flexibility and ease of deployment by eliminating the need for physical connections, making it easy to add new devices or move existing ones. Because of that, it is important to consider the connectivity aspects when designing a testbed.

Low-end devices have limited resources, such as processing power, memory, or battery life. Due to these limitations, the types of connectivity used by these low=end devices are typically low-power, low-bandwidth wireless technologies. There are multiple technologies in this area. One important group is the one based on the 2.4 GHz bandwidth.

The most common are Bluetooth Low Energy, Thread, and Zigbee. There are also other technologies, such as LoRaWAN or SigFox, which are focused on achieving greater ranges and even lower power consumption at the cost of bandwidth.

More complex IoT devices or gateway devices typically do not have such limitations on resources and power efficiency. They also might use the aforementioned technologies, but they can also use others, such as WiFi, or Bluetooth.

4 UC2: Firmware Updates of IoT Devices

Firmware update is a critical process for IoT device security. Not being able to update IoT device firmware is one of the most common sources of vulnerability during the device lifecycle. Furthermore, an insecure update process also presents a major issue as it allows an attacker to upload malicious logic on the device.

Typically, firmware updates are installed Over-The-Air (OTA). Updates and security patches can be digitally signed, such that their integrity and authenticity can be verified. However, despite digital signatures, the problem of secure updates still persists, since: i) updates often come as a bundle of libraries developed by different parties, ii) the signatures are not always issued by a mutually trusted certification authority, iii) digital signatures do not give any guarantee on the logic of the update. This use case, considers two types of updates:

- Full update: the package contains the full replacement of the old package to be installed regardless of what the previous firmware installed was.
- Partial update: the package contains just the binary difference between the new firmware version and the old firmware version. In this case, the device has to reassemble the firmware package using the binary difference (diff) and the old package.

As described in recent studies such as [8] and [9], it is very common to find IoT devices in the field without a secure firmware update system. Even those devices having firmware update mechanisms are in many cases not updated. The main reason is that current solutions cannot provide enough trust to device operators because they can't manage challenges such as poor network connectivity, management of the device resources to ensure minimal downtime or address a heterogeneous footprint of different hardware and software stacks within the same deployment. In [10] the authors present an analysis performed over a total of 1.061.284 devices in the field and show the average age of the installed firmware is 19.2 months, meaning device firmware is not even updated once a year, leading to many vulnerabilities uncovered during large periods of time.

4.1 Scenarios Description

The CROSSCON stack under investigation aims to serve complex IoT scenarios, as well as enable other techniques focused on edge computing in order to secure services in various real-world scenarios. There may be several actors that can add functionalities that will give the device a final use during the use of the CROSSCON stack.

Both the conventions regarding the common vocabulary to be used and the definition of the actors have been carried out following RFC 9019 "A Firmware Update Architecture for the Internet of Things" [6]. It includes:

- **Author**: the one that creates the firmware image. It could be several authors, according to the type of IoT device, that could be highlighted with the classification of devices described previously.
- **Device operator**: the day-to-day operator of a fleet of IoT devices.
- **Network operator**: responsible for the network to which IoT devices connect.
- **Trust Provisioning Authority (TPA)**: can be the original equipment manufacturer (OEM) or original design manufacturer (ODM). Manufacturers are responsible for the firmware update process of their products but may decide to share or delegate rights to other stakeholders.
- **User**: the end user of a device, who may use user interfaces and apps.

Moving forward in regard to scenarios, this section presents scenarios that define the use case for firmware updates on IoT devices. These scenarios serve as a basis to identify user actions, associated transactions, inherent risks, and potential security mitigations. The identified scenarios are presented in greater detail in the sections below.

4.1.1 Something has changed in the system BIOS

As described in the document NIST SP 800-155 – BIOS Integrity Measurement Guidelines [7], BIOS updates often fix bugs in the power management system, hard disk or network management, or another important component. However, a BIOS could also be changed for malicious purposes.

For this reason, system administrators must be able to tell what version of BIOS is loaded on a device to be able to correctly manage it. The update of the BIOS presents specific challenges as it might be part of the update process itself and end up with a malfunctioning device if not performed correctly.

4.1.2 Something has changed in the firmware – full update (changes controlled by the OEM)

The package contains the full replacement of the old package, regardless of the previously installed firmware. Being able to update the firmware allows to patch security vulnerabilities of the integrated third-party sub-modules in aa device's firmware (for example, libraries for managing SSL certificates), or to improve system performance (for example, optimizing power consumption. The update must be sent over a secure communications channel, including authentication and encryption.

4.1.3 Something has changed in the firmware – partial update (changes controlled by the OEM)

The package contains just the binary difference between the new firmware version and the old firmware version. In this case, the device must reassemble the firmware package using the binary difference (diff) and the old package.

4.1.4 Something has changed in the software (changes NOT controlled by the OEM)

In this scenario, the device operator wants to update the software, meaning specific applications or libraries containing the end user logic. The system should allow independent management of applications deployed on IoT devices. In these cases, changes might come in the form of updated binary libraries from third parties, and therefore it is very important to be able to check the integrity and security of the included software via Software Bill of Materials (SBOM) or similar techniques.

Other changes like user configuration or applications settings should be managed remotely, beyond pure system updates, such as applications parameters or network settings, however, this is not considered within the scope of this use case as it is not a software update.

4.1.5 Poor network conditions

Network conditions play a significant role in OTA updates, as in devices with more resources and computing power, full update packages can be in the range of hundreds of MB, and many IoT service providers charge high prices for data traffic, which is a significant barrier to any communication that is required between devices and servers in a deployment. This can cause, for example, an OTA update to take too long to download or to be interrupted, and it is a scenario that needs to be addressed in the use cases.

4.1.6 Existence of a multitude of dispersed devices with massive update needs

Distributing software updates to diverse devices with diverse trust anchors presents unique challenges. Devices have a broad set of constraints, requiring different metadata to make appropriate decisions. There may be many actors in the production of IoT systems, each of whom has some authority. Distributing firmware in such a multi-party environment presents additional challenges. Multiple signatures may be required from parties with different authorities.

4.2 Architecture and Workflow

Due to the very nature of IoT devices regarding their connection to the Internet, firmware updates must be provided over the Internet rather than traditional interfaces. Sending updates over the Internet requires the device to fetch the new firmware image as well as the manifest.

The architecture presented in the UC definition is shown in Figure 6.

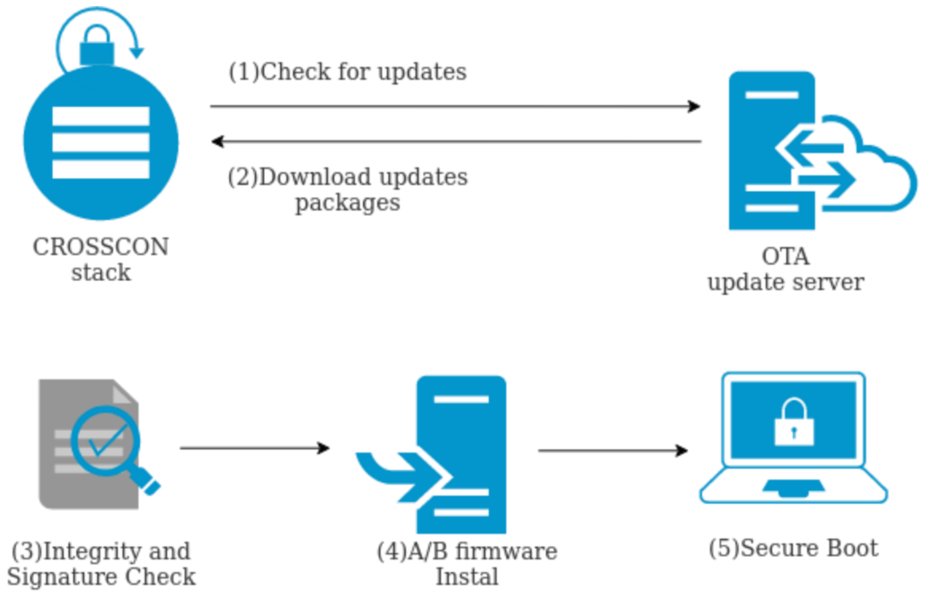


Figure 6: UC2 Firmware Updates of IoT Devices High-level View

In should include:

1. As a first step in the firmware update process, the OTA Update server needs to inform the CROSSCON stack client that a **new firmware update is available**. This can be accomplished via polling (client-initiated), push notifications (server-initiated), or more complex mechanisms (such as a hybrid approach).
2. If the update package is available, it should **download it**. The download step is the process of acquiring a local copy of the firmware image. When the download is client-initiated, this means that the firmware consumer chooses when to download and initiates the process. When a download is server-initiated, this means that the status tracker tells the device when to download or that it initiates the transfer directly to the firmware consumer.
3. **Integrity protection** ensures that no third party can modify the manifest or the firmware image. To accept an update, a device needs to **verify the signature** covering the manifest. There may be one or multiple manifests that need to be validated, potentially signed by different parties. The device needs to have trust anchors to verify those signatures.
4. **A/B system updates**, also known as rolling updates, ensure that a working bootable system remains on disk during an OTA update. A/B updates require changes on every system involved in the update process, from the firmware build server to the logic that is performing the update in the device itself. However, the OTA package server should not require changes: update packages are still served over HTTPS.
5. Executing a **secure boot process** includes verifying and invoking the new image. The invocation process is security sensitive. An attacker will typically try to retrieve a firmware image from the device for reverse engineering or will try to get the firmware verifier to execute an attacker-modified firmware image. Therefore, the firmware verifier will have to perform security checks on the firmware image before it can be invoked. These security checks by the firmware verifier happen in addition to the security checks that took place when the firmware image and the manifest were downloaded by the firmware consumer. The overlap between the firmware consumer and the firmware verify functionality comes in two forms, namely:
    a. A firmware verifier must verify the firmware image it boots as part of the secure boot process. Doing so requires metadata to be stored alongside the firmware image so

that the firmware verifier can cryptographically verify the firmware image before booting it to ensure it has not been tampered with or replaced. This metadata used by the firmware verifier may well be the same manifest obtained with the firmware image during the update process.

b. An IoT device needs a recovery strategy in case the firmware update/invocation process fails. In the latter case, the firmware consumer functionality is contained in the recovery image and requires the necessary functionality for executing the firmware update process, including manifest parsing.

Taking RFC 9019 as reference, the following components are necessary on a device for a firmware update:

- The protocol stack for firmware downloads. Firmware images are often multiple kilobytes, sometimes exceeding one hundred kilobytes, for resources constrained devices but can even be several megabytes for devices running full-fledged operating systems like Linux. The protocol mechanism for retrieving these images needs to offer features like congestion control, flow control, fragmentation and reassembly, and mechanisms to resume interrupted or corrupted transfers. It is not CROSSCON's intention to work with specific network protocols but to be generic enough to work with any network protocol out in the market.
- The capability to write the received firmware image to persistent storage (most likely flash memory).
- A manifest parser with code to verify a digital signature or a message authentication code (MAC).
- The ability to unpack, decompress, and/or decrypt the received firmware image.
- A status tracker.

Figure 7 shows the workflow of a typical firmware update process. This workflow is added in the use case for informational purposes, other workflows where firmware updates are done in a different way shall be also applicable to the future CROSSCON technical specification. The elements included in this architecture are:

- **IoT Device:** The device using the CROSSCON stack.
- **DM Server:** The device management server, serving the manifest and other required data for firmware download.
- **Firmware repository:** The shared repository where the binary images with the new firmware or the patches are stored.
- **Build server:** The server required for building and signing the new firmware. This could be subdivided into several components such as code repository, certification manager, signing server, etc. but it is not relevant to the use case addressed here.

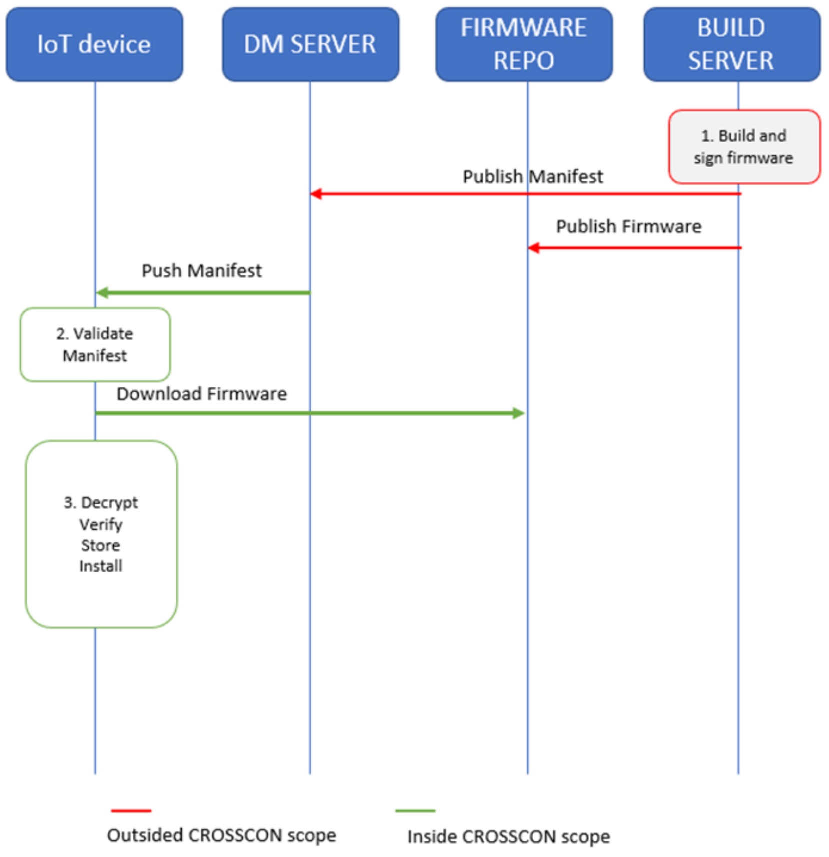


Figure 7: UC2 Typical IoT device firmware update process

The steps that are outside the scope of CROSSCON are added for completion, however, the CROSSCON stack is not involved, so there are no derived requirements. It is important to mention that the use case shall not be tied to specific network protocol implementations. The steps that are inside the scope of CROSSCON are the ones that will end up in specific requirements for the stack that will help execute the use case. The workflow contains the following steps shown in Table 2.

Table 2: UC2 Typical IoT Device Firmware Update Steps

#	Step	Description	Stakeholders involved
1	Build and sign firmware	This first step is outside the scope of CROSSCON. Here, the new image firmware is created. The firmware may consist of the firmware image or software, described similar to the firmware but typically dynamically loaded by an OS. Also, the considered firmware updates can be partial or full updates. The digital signature and MAC securing the firmware image must be applied to confirm that the firmware hasn´t been corrupted.	The author is the entity that creates the firmware image. The TPA (either OEM or ODM) distributes trust anchors and authorization policies.

2	Validate manifest	Here, the manifest is verified with information like: Does the firmware update apply to this device? (Vendor ID, Class ID, Device ID). Is the update older than the active firmware? (Sequence number in the manifest)	The TPA (either OEM or ODM) provides information such as Device ID and number of the latest firmware to the device operator. The device operator validates that the manifest is correct with its device information on the device management server. The user downloads the firmware.
3	Generate Unique ID	Finally, the IoT device should be able to unpack and interpret a format, decompress, and/or decrypt the received firmware image. The firmware must have a storage location and component identifier and a status tracker. The new configuration is then ready to start its use on the IoT platform or other devices.	Users start to use the device with the new firmware update.

4.3 Threat Model

Many IoT devices do not have firmware upgrade capabilities, or their firmware upgrade process is not secure enough, presenting a huge attack surface for DoS or privilege escalations attacks. In Table 3, we have identified relevant attacks or threats, their impact, and a corresponding countermeasure.

Table 3: UC2 Threat Model

Relevant attack or threat	Impact	Countermeasure
Information access	Firmware packages can present valuable insight for an attacker	Firmware package encryption Firmware sniffing protection
Firmware modification	Can cause privilege escalations, information leakage, or any type of device malfunction	Firmware integrity protections
Identity theft	Can cause a device to be updated by an illegal entity	Firmware downloads channel Authentication Firmware signature authentication
Firmware rollback	Can cause the device to run a previous vulnerable version	Firmware rollback protections
Denial of service - DoS	Can cause the device to fail using malformed updates or other techniques	Fail-safe mechanisms (A/B)

4.3.1 Firmware package encryption

Firmware package encryption can include encryption of the entire firmware package, or just specific sections of it, such as the bootloader or configuration settings. The encryption key is typically stored in a secure location on the device or on a separate authentication server and is used to decrypt the firmware when it is loaded onto the device.

4.3.2 Firmware sniffing protection

Firmware sniffing protection can include measures such as encrypting the firmware, using code obfuscation techniques, and implementing anti-debugging and anti-tampering measures.

- Encryption of firmware can be done using symmetric or asymmetric encryption algorithms, which makes it harder for an attacker to access the firmware without the decryption key. Code obfuscation is the technique of making the code difficult to read, which makes it harder for an attacker to identify vulnerabilities.
- Anti-debugging and anti-tampering measures are designed to detect an attacker that is attempting to debug or modify the firmware. These consist of techniques such as code signing, which ensures that firmware comes from a trusted source, and checksums, which can be used to detect changes to the firmware.

4.3.3 Firmware integrity protections

Firmware integrity protection can include measures such as code signing, checksums, and secure boot.

- Code signing is a process that uses digital signatures to ensure that the firmware comes from a trusted source and has not been tampered with. The signature is generated using a private key and can be verified using a public key. This ensures that the firmware has not been modified and is from a trusted source.
- Checksums are a simple way to ensure that the firmware has not been modified. A checksum is a mathematical value that is calculated based on the contents of the firmware. If the firmware is modified, the checksum will change, and the device will be able to detect this change.
- Secure boot is a process that ensures that only firmware that is digitally signed and verified can be loaded onto the device. This prevents malicious actors from installing unauthorized firmware on the device. Secure boot can include several stages of verification, including verifying the signature of the bootloader, the kernel, and the system firmware.

4.3.4 Firmware downloads channel authentication

Firmware download channel authentication can include measures such as digital signing, secure boot, and secure communication protocols.

- Using secure communication protocols such as HTTPS, SFTP, or SSH is also important to ensure that the firmware update is being transmitted securely over the network. This prevents attackers from intercepting or tampering with the firmware update during transmission.

4.3.5 Firmware rollback protections

Firmware rollback protection can be accomplished by using techniques such as version numbers, digital signatures, and secure boot. When a firmware update is released, it is typically given a unique version number that is higher than the previous version. The device checks the version number before installing the update and will only install the update if the version number is higher. This helps to ensure that the device is always running the latest version of the firmware.

In addition to version numbers, digital signatures can be used to ensure that the firmware update is authentic and has not been tampered with. The signature is generated using a private key and can be verified using a public key. This helps to ensure that the firmware update is from a trusted source and has not been tampered with.

4.3.6 Fail-safe mechanisms (A/B)

A/B partitioning, also known as A/B updates or dual partition, involves creating two partitions on the device's storage, usually called A and B, and keeping one partition active at a time. When a firmware update is available, the device downloads and installs it on the inactive partition. Once the update is installed, the device can then switch to the updated partition, thus making it active. This allows the device to boot into the updated firmware, while keeping the original firmware intact in case something goes wrong.

If the update causes any issues, the device can be rebooted back into the original partition, allowing the user to roll back to the previous firmware version without losing any data. This technique can also be used in other areas of device functionality, such as the bootloader, recovery, and system images, allowing for a safer and more robust system.

4.4 Assumptions and Security Properties

There are several assumptions that are often made when it comes to firmware updates on IoT devices, some of which include:

1. *Firmware updates will be available*: It is often assumed that firmware updates will be available for IoT devices, either from the manufacturer or through third-party sources.
2. *The device has an Internet connection*: It is also assumed that the IoT device will have an Internet connection, either through a wired or wireless connection, in order to download firmware updates.
3. *The device has the capability to install updates*: It is assumed that the device has the necessary hardware and software to install firmware updates, such as a bootloader, storage, and a processor.
4. *The device can be updated remotely*: Many IoT devices are designed to be updated remotely, without the need for physical access to the device.
5. *The updates are secure*: It is assumed that the firmware updates are secure and have been properly authenticated and verified using the CROSSCON stack as trust anchor before being installed on the device.
6. *The device is able to maintain its functionality after the update*: It is assumed that the device will continue to function properly after a firmware update and that any new features or bug fixes will not negatively impact the device's performance.
7. *The device is able to communicate with other devices*: In IoT, Device-to-Device (D2D) communication allows devices to connect and communicate with each other directly, without the need for a central hub or intermediary. This can lead to increased efficiency and reduced latency, as well as increased security, as the data does not have to be transmitted over the Internet or through a central server. It can also be used to:
    a. Create ad-hoc networks, where devices can connect and communicate with each other without the need for a pre-existing network infrastructure. This can be useful in situations where a traditional network infrastructure is not available or is not feasible to set up.
    b. Create mesh networks, where devices can pass data along to other devices until it reaches its destination. This allows for increased network coverage, and can also help to increase network resilience, as data can still be transmitted even if one or more devices in the network fail.

The security properties that we propose to be addressed within the scope of the CROSSCON project and considering this use case are the following:

Secure Provisioning:

AA process that is used to securely provision keys and other security-sensitive data to IoT devices during the manufacturing process. This can include the provisioning of encryption keys, secure boot keys, and other credentials that are used to secure the device and protect it against unauthorized access or modification. The CROSSCON stack could play a critical role here to ensure certain standards.

The secure provisioning process typically involves several steps, including:

- *Secure generation of keys*: The keys are generated using a secure key generation process, such as a hardware security module (HSM) or a secure random number generator.
- *Secure storage of keys*: The keys are securely stored, either on the device or on a separate secure server, in a way that ensures that they cannot be accessed or tampered with by unauthorized parties.
- *Secure transfer of keys*: The keys are securely transferred to the device during the manufacturing process, using secure communication protocols such as HTTPS, SFTP, or SSH.
- *Secure installation of keys*: The keys are securely installed on the device, and the device is configured to use them for secure boot and other security-sensitive operations.
- *Secure destruction of keys*: Once the keys are installed on the device, the keys stored on the server or other location are securely destroyed to prevent unauthorized access.

Isolated Execution:

AA security technique that is used to isolate the firmware update process from the rest of the system, to prevent malicious actors from modifying or tampering with the firmware update.

Isolated execution can be achieved by using a separate processor or co-processor, a secure element, or a secure boot process, to run the firmware update process. This ensures that the firmware update process runs in a secure and isolated environment, separate from the rest of the system.

The firmware update process can include several steps such as:

- *Firmware query*: The device contacts a firmware update server to check if a new firmware version is available.
- *Firmware verification*: The device verifies the authenticity and integrity of the firmware update, using digital signatures and/or other forms of authentication.
- *Firmware installation*: The device installs the firmware update and configures the device to use the new firmware.

Secure Storage, to store manifests and firmware package:

A technique that is used to securely store security-sensitive data, such as firmware packages and manifests, to protect them from unauthorized access or modification. Secure storage can be achieved by using a variety of techniques, such as encryption, secure boot, and secure communication protocols as described in previous sections. Testbed Prerequisites

The following points are prerequisites for the testing of the firmware updates use case:

- Devices: Raspberry-P4 and Beaglebone AI-64 with the CROSSCON prototype stack will be used
- Firmware: Barbara OS, a secure Linux distribution, built from the Kernel, or real time OS such as Free RTOS for smaller devices.
- DM Server: Barbara´s Device Management Server, hosted in Barbara Cloud

The following Figure 8 shows the testbed elements and its relationship:

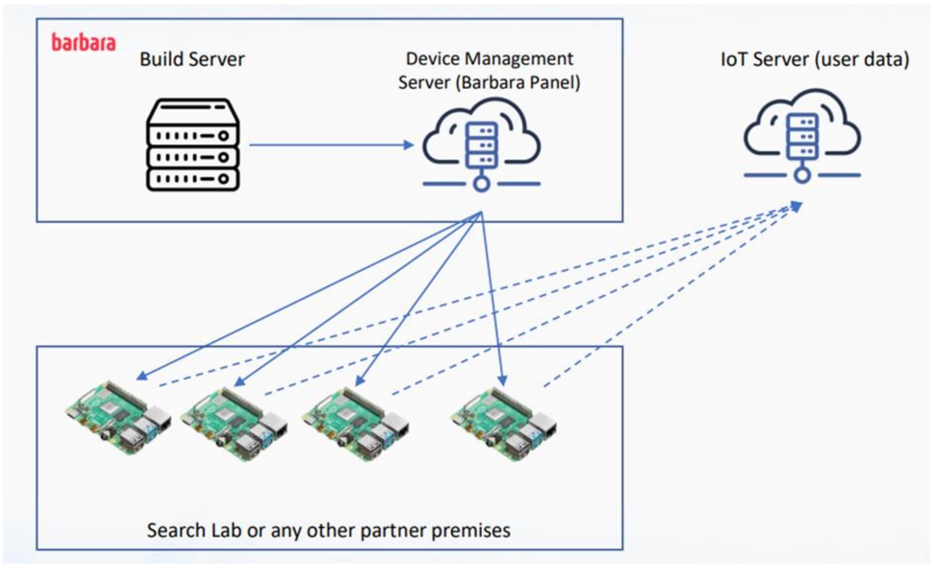

barbara
Build Server
Device Management Server (Barbara Panel)
IoT Server (user data)
Search Lab or any other partner premises

Figure 8: UC2 Testbed Elements and Relationship

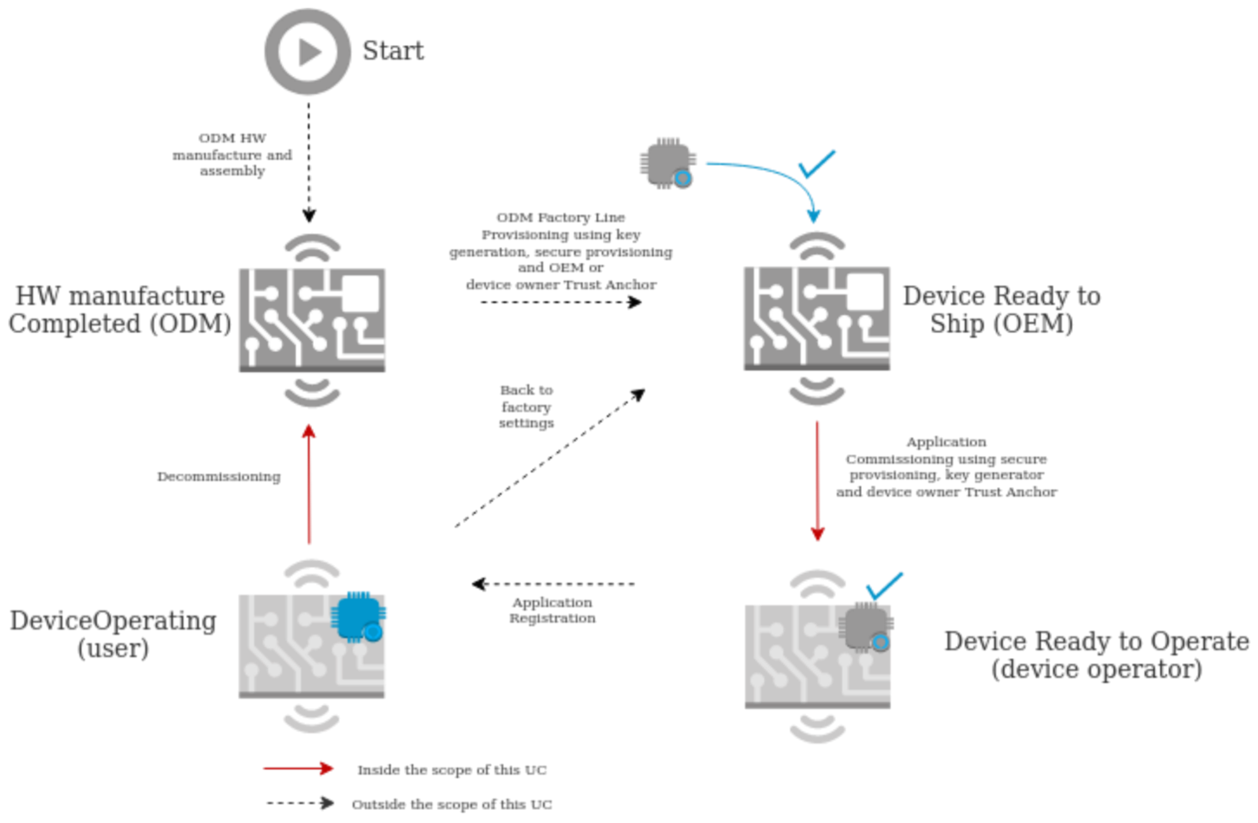
We also propose to build updates and the rest of the consortium partners can push them through the DM Server. To check whether the update information is accessible and working as expected, an IoT Server is required. It can be individual per partner or a common infrastructure (e.g., Azure or AWS IoT Platforms.).

5 UC3: Commissioning and Decommissioning of IoT devices

IoT Device Commissioning is the process by which connected devices acquire the necessary information and configuration parameters for their intended use or application: this can include security certificates, credentials, application configuration such as URLs, and others. Commissioning is a critical step in the IoT device lifecycle, and it needs to happen before the device starts to perform its regular operation.

As opposed, IoT Device **Decommissioning** is the process by which the commissioned information is removed from the device. This way the device gets back to its original state when it will no longer be used or used for a different purpose or customer. This is important, especially in the case of industrial devices that may contain sensitive information.

Figure 9 shows a typical state diagram of an IoT device lifecycle around the commissioning and decommissioning processes in a multi-stakeholder case, marking in red those processes which are part of the use case addressed by CROSSCON in this project:



Start
ODM HW manufacture and assembly
ODM Factory Line Provisioning using key generation, secure provisioning and OEM or device owner Trust Anchor
HW manufacture Completed (ODM)
Device Ready to Ship (OEM)
Back to factory settings
Decommissioning
Application Commissioning using secure provisioning, key generator and device owner Trust Anchor
Application Registration
DeviceOperating (user)
Device Ready to Operate (device operator)
Inside the scope of this UC
Outside the scope of this UC

Figure 9: UC3 IoT Device Lifecycle Commissioning and Decommissioning Processes

Once the hardware is assembled, a **Factory Line provisioning** process is required. This happens in the factory lines. Thereby, the device read-only memory is flashed with specific information that are required for bootstrapping, such as:

- Serial Number
- Model Number
- Hardware version
- Bootstrap configurations (Server URI, Server CA Certificate)

Then, once the device is shipped to its owner, at first boot there is a second step of provisioning which is the **Application Commissioning,** understood as the process that sets user-related configuration such as:

- Device Private Key
- Device Certificate
- Trusted Public Keys
- Application endpoints
- etc.

Once the Application Commissioning is done, the device should be able to communicate with IoT Servers and other devices as expected. Application Commissioning presents in general more security challenges than Factory Provisioning because Factory Provisioning is done in a controlled environment (the Factory), while Application Commissioning is not. Therefore, this CROSSCON use case will focus on how Application Commissioning and Decommissioning are done, however, this will need a sort of simplified Factory Line Provisioning before the Application Commissioning.

In each state the name written in parenthesis shows the main stakeholder involved, and each process includes the basic security properties used and the trust anchor typically used. The current solutions in the market, especially for resource constrained devices, do not allow in many cases to generate unique random keys per device in a multi-stakeholder environment. This ends up in many cases with devices shipping with default and hard-coded credentials. Adversaries can have access to one device and using brute force or privilege escalations attacks, steal device credentials and therefore gain access to the wider footprint of devices in the field and escalate to higher impact attacks such as DDoS, as it happened in the Mirai Botnet attack [11].

5.1 Scenarios Description

During the processes of commissioning and decommissioning, multiple stakeholders are involved and may use the CROSSCON stack at different stages and in different ways. Similar to the previous use case, these are defined in the bullet list below. Some of the stakeholders can be combined in one company, or in other words, a company can have multiple combined roles in the commissioning and decommissioning processes.

- **OEM (Original Equipment Manufacturer):** This is the company who is designing and commercializing the devices to the end customers, and it is typically the “owner” of the factory commissioned root of trust. OEM does not own manufacturing facilities.
- **ODM (Original Device Manufacturer):** This is the company that owns the manufacturing facilities and does not typically own any data that needs to be commissioned in the device.
- **Device Operator:** the day-to-day operator of a fleet of IoT devices, or in other words the company who buys the device to the OEM, and typically the owner of the application commissioned data such as IoT Platform Credentials and so on.
- **Trust Provisioning Authority (TPA)**: can be the original equipment manufacturer (OEM) or original design manufacturer (ODM). It is responsible for the firmware update process of their products but may decide to share to delegate rights to other stakeholders.
- **User:** This is the human person who is operating the device.

The way commissioning and decommissioning is done today in many IoT devices is not ideal from the security point of view, and lead to several threats that are addressed in Section 7.3. Many devices have hard coded or guessable IDs and weak credentials. This poses a constant threat to the IoT device. Therefore, the ideal provisioning process downloads securely and dynamically the information from a server, normally called bootstrap or device management server. This can be hosted by the Device operator or the OEM on behalf of the Device operator.

The objective of this use case is to exemplify a secure commissioning and decommissioning process which can be enabled by the CROSSCON stack.

5.1.1 Application Commissioning

Application commissioning in the scope of CROSSCON will be done using a device management server. The Device Management server must have the capability to securely produce keys and certificates that will be delivered to the device during the commissioning process, however, this is outside the scope of the use case. The pre-requisites for the Application Commissioning process are:

- There is Device Management Server that can serve the Application Provision information.
- The device has already gone through a Factory Provision performed by the ODM on behalf of the OEM, which enables the device to communicate with the Device Management Server.
- The Commissioning process is triggered by the device operator using the Device Management Server and starts the Device has network connectivity with the Device Management Server.

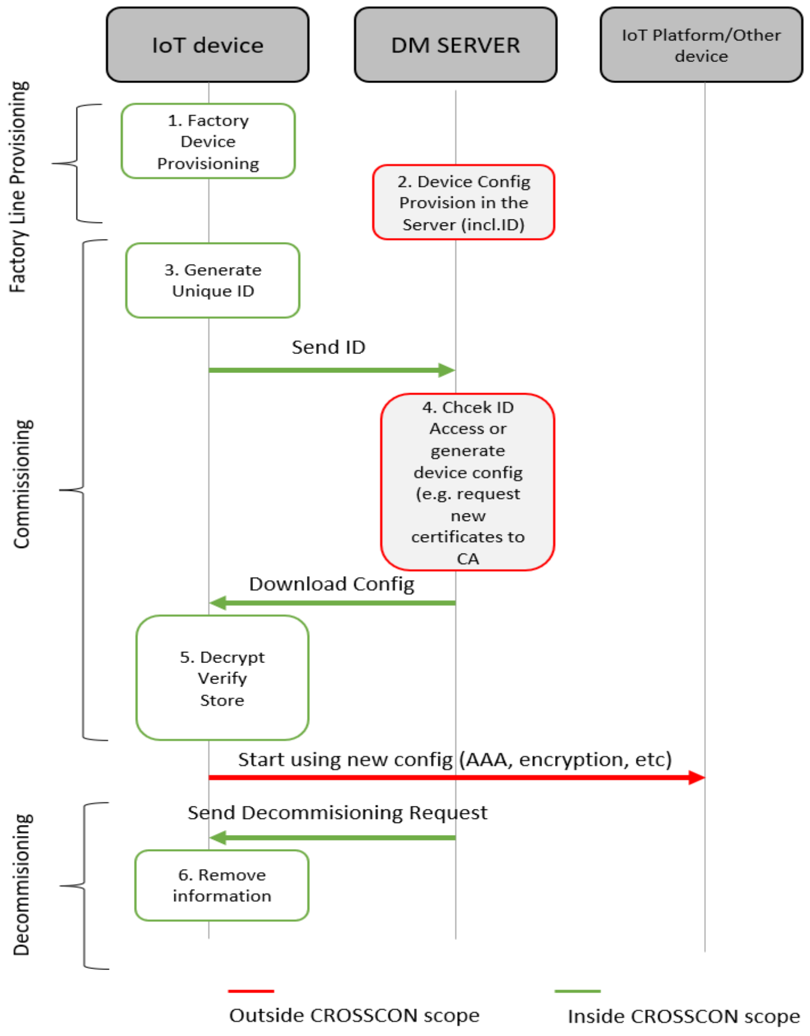
5.1.2 Decommissioning

Like the Commissioning process, the Decommissioning is performed using a Device Management server. This doesn’t prevent the device from having other decommissioning processes (for example, automatic decommissioning if suspicious activities are detected), but this would be outside the scope of the use case.

The prerequisites for the Commissioning process are:

- There is a Device Management Server that the device operator or the End User can use to send a Decommissioning Request.
- The Decommissioning process is triggered by the device operator using the device management server and starts when the device has network connectivity with the device management server.

5.2 Architecture and Workflow



IoT device
DM SERVER
IoT Platform/Other device
Factory Line Provisioning
1. Factory Device Provisioning
2. Device Config Provision in the Server (incl.ID)
Commissioning
3. Generate Unique ID
Send ID
4. Chcek ID Access or generate device config (e.g. request new certificates to CA
Download Config
5. Decrypt Verify Store
Start using new config (AAA, encryption, etc)
Decommisioning
Send Decommisioning Request
6. Remove information
Outside CROSSCON scope
Inside CROSSCON scope

Figure 10: UC3 Commissioning and Decommissioning Processes Workflow

Figure 10 describes the workflow including the commissioning and decommissioning processes. This workflow is added in the use case for informational purposes, other workflows where commissioning and decommissioning are done in a different way shall be also applicable to the future CROSSCON technical specification. The elements included in this architecture are:

- **IoT Device:** The Device running the CROSSCON stack.
- **DM Server:** The Device management server.
- **IoT Platform or Other Device:** The elements that the device needs to connect to after a successful commissioning process.

The use case and elicited requirements shall be generic enough to not force specific communications between the IoT Device and the DM Server, IoT Platforms, or other devices. There are multiple network protocols for this, such as MQTT, HTTP, COAP, LwM2M, etc.

The focus of the CROSSCON project is on the IoT device hardware/software stack that enables to perform those communications securely, but that has to be independent from the communication protocols chosen in each commissioning scenario. In other words, the use case has to be agnostic to the protocol stack.

The steps that are outside the scope of CROSSCON are added for completion, however, CROSSCON stack is not involved in them so there won't be requirements derived. The steps that are inside the scope of CROSSCON are the ones that will end up in specific requirements for the stack that will help execute the use case.

The workflow contains the steps described in Table 4.

Table 4: UC3 Commissioning and Decommissioning Workflow Steps

#	Step	Description	Stakeholders involved
1	Factory Device Provisioning	Here, the initial device information, such as serial number, device management URL and related certificates, or other information, is flashed into the device in the factory line. CROSSCON stack will enable secure provisioning of this data. This will enable the device to communicate first with the DM Server.	OEM provides information to be provisioned. ODM executes the factory line provisioning.
2	Device Configuration in the DM Server	This step is outside the scope of CROSSCON. Here, the information required to start the application commissioning of a specific device is set up in the device management server. This will include, at minimum, a Device ID that the server can use to identify a specific device after boot.	OEM provides information such as Device ID and other data to the device operator. Device operator configures the device Management Server with that information.
3	Generate Unique ID	The device at first boot, using the CROSSCON stack, generates a unique ID and send it to the Device Management server using any secure communications protocol (generally any, using two-way TLS).	User boots the device for first time.
4	Check ID	This step is outside the scope of CROSSCON. The DM Server identifies the device and retrieves from its database, or generates dynamically, the application information that needs to be commissioned to that device. This might include, but not limited to, IoT Platform certificates, URLs, and others.	None (this is automatic).
5	Decrypt, verify, store	The device downloads the commissioning information using any secure communications protocol (generally any, using two-way TLS) and decrypts, verifies, and stores the information using the CROSSCON stack so that it can be further used by the device in its normal operations.	None (this is automatic).
6	Remove information	When decommissioned, the device uses the CROSSCON stack to remove all previously commissioned information, both in the factory line provisioning as	The User or the device operator triggers the decommissioning process.

		well as the application commissioning, so that it can’t be further used.	

5.3 Threat Model

Commissioning and decommissioning are one of the most critical processes of the IoT device life cycle in terms of security. A wrong designed or insecure commissioning or decommissioning process can open big attack surfaces that will remain there for the whole operation life of the device.

Relevant attack or threat	**Impact**	**Countermeasure**
Information access	If there is not enough randomness and strength in the keys and algorithms used to encrypt commissioning information at rest or in transit, attackers can use brute force attacks to access this information and steal critical information such as private certificates, keys, or credentials that can be further used for eavesdropping, spoofing or other high impact attacks. Considering devices are unattended, and the capability to perform brute force attacks will increase with quantum computing, as quantum computers speed up random number generation and can reduce exponentially the time to break a cryptography algorithm This risk is currently medium but will become high in the short-term future.	Data encryption at rest. Data encryption in transit.
Configuration modification	If the authentication and authorization process between the device and the device management server is vulnerable, an attacker can impersonate the DM Server and send wrong configurations to devices which can lead to DoS or similar attacks. Since this can significantly impact all devices without requiring physical access to them, the risk is high.	Device unique and secure identities. Device to server 2-way authentication and authorization. Data integrity mechanisms.

5.4 Assumptions and Security Properties

The following security properties are expected in the device’s the security stack:

- Secure Provisioning, for provisioning keys in the factory during the Factory Line provisioning.
- Isolated Execution, for executing the commissioning and decommissioning logic.
- Secure Storage, to commissioning information, that has to be deleted once decommissioned.

5.5 Testbed Prerequisites

To test the device commissioning and decommissioning use case, Raspberry-P4 and Beaglebone AI-64 with the CROSSCON prototype stack will be used. Additionally, more resource constrained devices can be also tested to ensure CROSSCON benefits are maximized through different classes of devices. The information to be commissioned/decommissioned in the use case will be URL and certificates to access an IoT Server.

Apart from the devices, the following elements will be needed:

- **Device Management Server:** while there are a number of DM Servers out there, Barbara will provide free of cost to the consortium partners a license of Barbara Panel, a secure device management server that can be used in SaaS model, meaning that it does not require any hardware installation by partners. Barbara Panel uses secure MQTT to manage IoT devices in the field.
- **IoT Server:** once commissioned, it is important to be able to check the commissioned information is accessible and working as expected. In order to do this, an IoT server is required, such as AWS or Azure.

Figure 11 shows the UC3 testbed elements and their relationship:

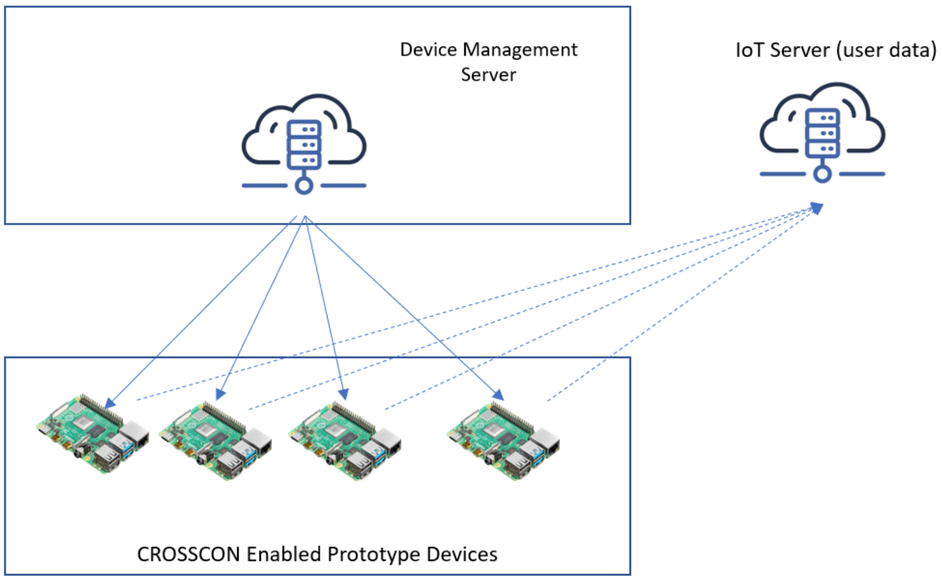


Figure 11: UC3 Testbed Elements and Relationship

6 UC4: Remote Attestation for Identification and Integrity Validation of Agricultural UAVs

Agricultural UAVs (Unmanned Aerial Vehicles), also known as agricultural drones, are becoming an increasingly important tool in modern agriculture. These UAVs are equipped with sensors and cameras that can gather data on crops and soil, allowing farmers to make more informed decisions about planting, fertilization, irrigation, and pest control.

Some of the benefits of using agricultural UAVs include:

- Improved efficiency: UAVs can cover large areas of farmland quickly and accurately, reducing the time and cost of traditional methods such as manual labour or satellite imaging.
- Precision agriculture: UAVs can provide detailed, high-resolution data on soil moisture, nutrient levels, and plant health, enabling farmers to apply fertilizers, pesticides, and water precisely where they are needed, reducing waste and increasing yields.
- Reduced environmental impact: By providing farmers with precise data, agricultural UAVs can help reduce the amount of pesticides and fertilizers that are applied to crops, minimizing their impact on the environment.
- Increased safety: UAVs can be used to monitor crops and livestock without putting farmers at risk of injury or exposure to hazardous chemicals.

While agricultural UAVs offer many advantages, they also pose some security-related challenges that need to be addressed such as:

- Privacy concerns: Agricultural UAVs can gather a large amount of data on crops, soil, and other aspects of farmland, raising concerns about privacy and data security.
- Unauthorized access: Agricultural UAVs can be stolen, hacked or used for malicious purposes if they fall into the wrong hands, potentially causing damage to crops, property, or even human life.
- Legal and regulatory compliance: Agricultural UAVs are subject to a range of regulations and restrictions, such as registration requirements, flight restrictions, and privacy laws, which can be complex and difficult to navigate.

Addressing these challenges is not an easy task especially when the UAVs can be operated by third parties, do not have a permanent internet connection and are geographically scattered (large scalability), and require a comprehensive approach that involves technological solutions, such as Remote attestation for identification and integrity validation.

6.1 Scenarios Description

Here we are considering the use of agricultural UAVs entirely dedicated to vineyard protection in big Swiss wine fields. In this use-case, the company who is manufacturing and managing the drones offer two types of services to its clients:

- *Direct intervention:* where the devices are operated by **the manufacturer** according to a mission co-designed with **the vineyard owner**. This service can be quite costly as it involves the travel and operation of the company employees to perform the necessary treatment.
- *UAVs loan:* where **the vineyard owner** is given a training on how to operate the device so he can use it autonomously during a pre-defined period of time and give it back after its completion.

In both cases, **the UAVs are shared resources and are used for multiple different vineyards, that's why identification and integrity checks are very important to detect any SW or HW tempering, potentially done by a malicious user.**

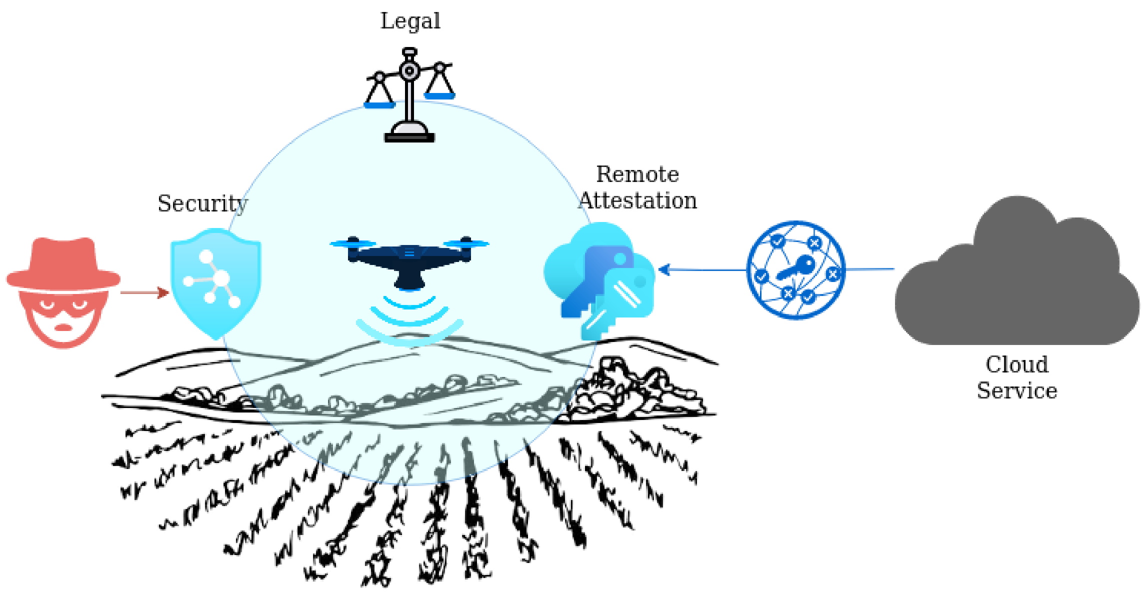


Figure 12: UC4 Remote Attestation of Agricultural UAVs Overview

Figure 12 illustrates a high-level view of the UC4 scenario description. The devices manufacturer can benefit from remote attestation to perform the following checks:

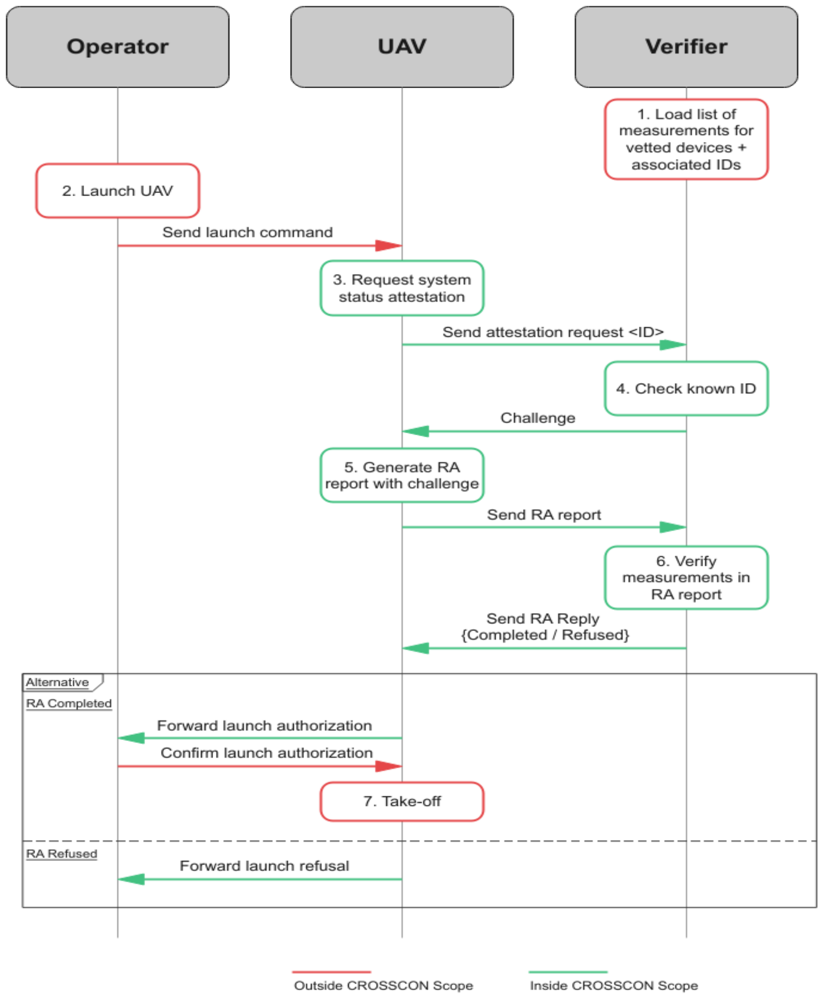
1. Fleet Identification and authentication to ensure communication with a vetted device and not with an imposter and deny take-off of devices known to have issues / have not been cleared after maintenance.
2. In-Flight Software Integrity Validation: Recurrent validation of the system parameters to ensure integrity and compliance with strict regulations and if possible, to ensure the UAV does not deviate from the prescribed path and altitude.
3. Hardware and Software Tampering Detection: the drones are not necessarily operated by the manufacturer that needs a way to remotely ensure that his device is not tampered with.

6.2 Architecture and Workflow

Any of the aforementioned security checks should be executed by a trusted party, but as the confidentiality of the UAV in question is the system that is being validated, it cannot be trusted to perform these tests itself. Hence, an external party (called the *Verifier*) will be used to attest the status of the UAV remotely. Using Remote Attestation, the status of the UAV at any moment in time can be attested with a remote verifier, which will request the UAV to prove to it that it is currently in an authorized operational state.

6.2.1 Fleet Identification and Authentication Workflow

For example, any checks related to *Fleet Identification and authentication* follow a workflow similar to that of UC3, regarding commissioning and decommissioning of IoT devices, as illustrated in Figure 13.



Operator
UAV
Verifier
1. Load list of measurements for vetted devices + associated IDs
2. Launch UAV
Send launch command
3. Request system status attestation
Send attestation request <ID>
4. Check known ID
Challenge
5. Generate RA report with challenge
Send RA report
6. Verify measurements in RA report
Send RA Reply {Completed / Refused}
Alternative
RA Completed
Forward launch authorization
Confirm launch authorization
7. Take-off
RA Refused
Forward launch refusal
Outside CROSSCON Scope
Inside CROSSCON Scope

Figure 13: UC4 Fleet Identification and Authentication Workflow

Before launch, a list of the Remote Attestation measurements is loaded into the verifier, to which it will attest any remote attestation requests from the UAVs. Afterwards, when the operator wants to launch the drone, the UAV must request the verifier to provide a positive attestation report before it is allowed to start the take-off procedure. This could be achieved by, for example, encrypting the partition in which the take-off procedure is loaded, with only the verifier who has the decryption key.

When the verifier receives an attestation request, it first checks if the ID provided with the request matches any of its known IDs. If so, the verifier challenges the UAV to generate a Remote Attestation based upon the current status of the system, and to send it back to the verifier. Next, the verifier checks whether the measurements within the generator Remote Attestation report fit the pre-loaded measurements for this specific ID and sends a reply whether or not the Remote Attestation has been completed successfully, or whether the current status of the UAV is refused. If the attestation reply is positive, the launch authorization is forwarded to the operator to indicate that the attestation was accepted, and that the device is ready for launch (e.g., because the UAV was able to decrypt the partition containing the code for the take-off procedure). If, however, the Remote Attestation is refused, the UAV forwards the refusal to the operator and remains stationary.

6.2.2 In-Flight Software Integrity Validation Workflow

In a similar manner, using a recurrent remote attestation system that can be triggered by predetermined events, the status of the UAV can be verified while in-flight. The workflow for this specific scenario is illustrated in Figure 14:

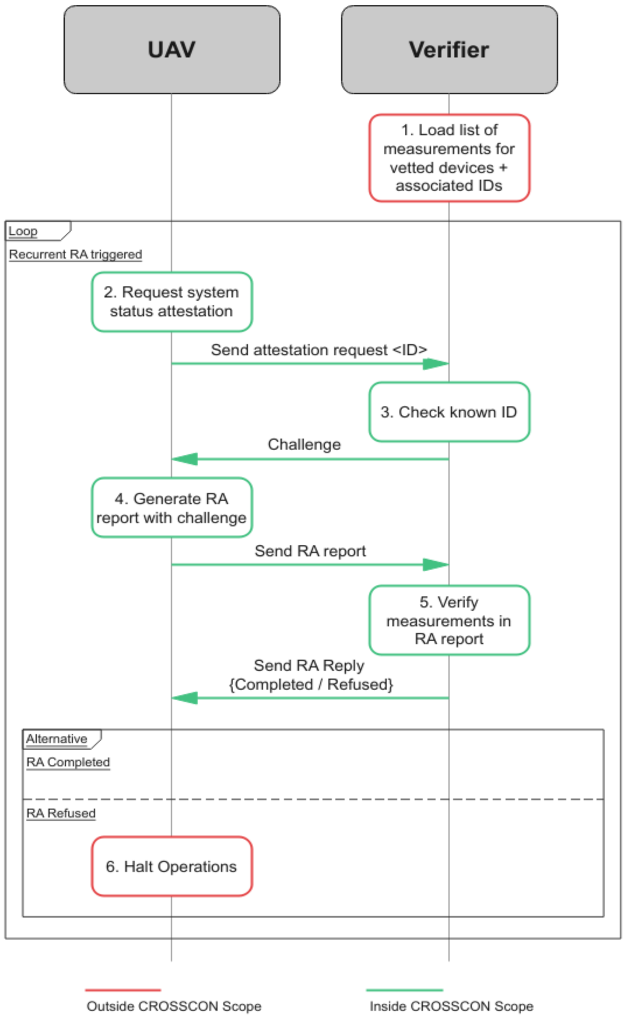

UAV
Verifier
1. Load list of measurements for vetted devices + associated IDs
Loop
Recurrent RA triggered
2. Request system status attestation
Send attestation request <ID>
3. Check known ID
Challenge
4. Generate RA report with challenge
Send RA report
5. Verify measurements in RA report
Send RA Reply {Completed / Refused}
Alternative
RA Completed
RA Refused
6. Halt Operations
Outside CROSSCON Scope
Inside CROSSCON Scope

Figure 14: UC4 In-Flight Software Integrity Validation Workflow

Unlike the scenario described in Figure 14, the Remote Attestation request is not triggered by the operator of the UAV, but rather by the UAV itself: If a certain predefined chain of suspicious events occurs, e.g. GPS points that are outside of the regulated airspace, and/or a certain amount of time has elapsed since the last Remote Attestation, the UAV starts a similar verification request as for the *Fleet Identification and authentication*. Afterwards, the UAV checks whether or not it received a positive reply from the verifier. If it did, the operations resume and the UAV resets the timer for the recurrent Remote Attestation procedure. If, however, the verifier refuses the attestation from the UAV, the manufacturer can implement actions to be undertaken to safely halt all operations of the UAV. As this depends on the requirements of the manufacturer, these final operations are outside of the scope of the CROSSCON stack.

6.2.3 Hybrid Tampering Detection Workflow

Lastly, the UAV manufacturer would like to ensure that their drones are not tampered with, neither in terms of software, nor hardware. After all, if an operator that is leasing the UAV from the manufacturer decides to replace one of the sensors and/or motors with a replacement that is not vetted or qualified by the manufacturer, this can cause significant risks in terms of safety and liability.

To avoid this, the Remote Attestation procedures introduced in both sections 6.2.1 and 6.2.2 will need to be capable of not only measuring the software state of the UAV, but also the state of the hardware of the system, including but not limited to:

- Status of any connected actuator (e.g., motors, spray nozzles, etc.).
- Status of any connected sensor (e.g., GPS, camera, etc.).
- Verification whether all hardware parts required for nominal operation are present.
- Verification whether any unauthorized hardware is inserted (e.g., USB sticks).

These measurements would be performed during the procedures introduced in sections 6.2.1 and 6.2.2, their workflows would not change depending on the type of measurement performed.

6.3 Threat Model

Agricultural UAVs are vulnerable to a range of cybersecurity threats that can compromise the confidentiality, integrity, and availability of data and systems.

In our use-case **the attacker** can be a malicious client or a third-party who managed to get unauthorized access to the UAVs (at the manufacturer premises, at the client premises, during operation…). The attacker can also be an ill-intentioned employee of the manufacturing company.

Here are some of the most common cybersecurity threats that the agricultural UAVs can be suggested to within the scope of our use-case.

Threat	Description	Impact
Malware injection	The UAVs can be infected with malware, such as viruses, worms, and trojans propagated through vulnerabilities in the UAV's software or firmware, phishing attacks, or physical access to the UAV's hardware.	Once the malware is injected into the UAV's system, it can perform various malicious activities, such as taking control of the UAV's flight path, stealing sensitive data, or causing the UAV to malfunction or crash.
Data interception	The data collected by agricultural UAVs, such as images and sensor readings, can be intercepted by attackers during its transmission to the ground control system. The attacker can intercept the data by eavesdropping on the communication channel or by hacking into the communication network. The intercepted data can include sensitive information such as the UAV's location, altitude, speed, camera footage, and other sensor data.	The intercepted data can be used for malicious purposes such as espionage, theft, or sabotage. For example, the attacker could use the UAV's camera footage to spy on the farm owner's activities or steal valuable crop data. They could also use the intercepted data to take control of the UAV and manipulate its flight path or payload.
Unauthorized access	Agricultural UAVs can be accessed by unauthorized individuals who gain access to the UAV's system without the owner's knowledge or consent. The attacker can use various methods to gain unauthorized access to the UAV's system, such as exploiting vulnerabilities in the UAV's software or firmware, stealing login credentials, or physically accessing the UAV's hardware.	The attacker can manipulate the UAV's flight path and cause it to crash, resulting in damage to the UAV and potential harm to people and property. Additionally, the attacker can steal sensitive data such as the UAV's location, altitude, speed, camera footage, and other sensor data, which can compromise the owner's privacy and business operations.
Denial-of-service attacks	Agricultural UAVs can be targeted by denial-of-service (DoS) attacks that	DoS attacks can render the UAV unable to perform its intended

	can occur when an attacker floods the UAV's communication network with traffic or exploits vulnerabilities in the communication protocols to overload the UAV's system resources, making it unable to transmit data or receive commands from the ground control system or other connected devices.	functions, leading to a loss of productivity and revenue for the farm owner. Additionally, it can compromise the safety of the UAV and the surrounding environment if the UAV is unable to receive commands to avoid obstacles or respond to emergencies.
GPS jamming	Agricultural UAVs rely on GPS technology to navigate and collect data, but this technology can be jammed when an attacker uses a jamming device to broadcast radio signals that interfere with the GPS signals received by the UAV. This attack can also be performed by exploiting vulnerabilities in the GPS receiver software.	GPS jamming can cause the UAV to lose its GPS lock, resulting in a loss of control and stability. Additionally, it can cause the UAV to deviate from its intended flight path, collide with obstacles or other UAVs, or crash, causing damage to the UAV and potential harm to people and property.
Physical attacks	Physical attacks on UAVs refer to any physical manipulation or damage done to the UAV, either intentional or accidental. Physical attacks can include physical tampering with the UAV's hardware, such as removing or replacing components, cutting wires, or applying destructive forces such as heat or pressure.	Physical attacks can result in the destruction of the UAV, leading to significant financial losses for the owner. It can also cause damage to property or people in the surrounding area if the UAV is out of control. Physical attacks also facilitate the performance of all the previous attacks.

To mitigate these cybersecurity threats, agricultural UAVs need to be equipped with strong security measures, such as encryption, authentication, and access controls. Remote attestation will not mitigate all the attacks mentioned above but it will help with the detection of most of them at the earliest stage.

6.4 Assumptions and Security Properties

To perform remote attestation on UAVs, the following security properties are required:

- **Root of Trust**: To perform remote attestation, the UAV must have a trusted root of trust that can generate, and store cryptographic keys and certificates used for remote attestation.
- **Secure Boot**: To perform remote attestation, the UAV must have a secure boot mechanism that verifies the integrity of the firmware and software components before they are loaded.
- **Code and Data Integrity**: To perform remote attestation, the UAV must have mechanisms in place to ensure the integrity of the code and data loaded onto the UAV. This can be achieved using digital signatures, checksums, or other cryptographic mechanisms.
- **Secure Communication**: To perform remote attestation, the UAV must have a secure communication channel that can be used to transmit the attestation data to the remote verifier. The communication channel must be encrypted and authenticated to prevent eavesdropping and tampering.

6.5 Testbed Prerequisites

The agricultural UAVs are based on the combination of a Raspberry Pi 4B and a Pixhawk 4 auto-pilot system. This combined system can be simulated using a similar RPi with the following technical specifications:

- 4 Gb of RAM.
- A GPS dongle used for the positioning of the UAV.
- A 4G LTE (Long-Term Evolution GSM connection) dongle, in order to provide internet to the UAV.
- A 2.4G (2.4 GHz WiFi) dongle used to connect to the remote controller of the drone.

Within the UAV, the remote attestation service needs to be hosted inside a TEE or similar on the Raspberry Pi and will connect to the remote verifier using the internet connection provided by the LTE dongle. As such, in order to assess the functionality of the system in the testbed, this implementation will have to be performed in a similar manner.

On the other end of the communication link, the verifier server, needs to be hosted on a routable and remotely accessible server.

7 UC5: Intellectual Property Protection for Secure Multi-Tenancy on FPGA

Due to limitations in computational and memory capacity, many IoT nodes are limited in what kind of workloads can be executed on them. Especially compute-intensive tasks related to, e.g., training and inference of AI algorithms can be too heavy operations for IoT devices to handle themselves. There is therefore a need to offload compute-intensive tasks to accelerator nodes that are accessible over the network. In particular, FPGA-based accelerators offered by Cloud Service providers are here of interest, as they offer the possibility for highly efficient computations of compute tasks optimised for the task at hand.

To reduce the cost of such “FPGA as a service” offerings, it is highly desirable for the cloud service providers to be able to provision the compute workloads of several different clients onto the same FPGA fabric, thereby enabling multi-tenancy on the FPGA. A key question here is, how secure multi-tenancy can be assured so that workloads of one tenant cannot have adverse effects on the workloads of other tenants or the FPGA fabric itself and does not lead to unintended leakage of private information processed on the FPGA.

One can distinguish between temporal and spatial multi tenancy. In temporal multi-tenancy, only one client has access to the entire FPGA fabric at a time. Multi-tenancy is thus achieved through alternation of the entire FPGA resource to different clients at different times. In previous work, TUDa has developed a solution for secure temporal multi-tenancy. In the context of CROSSCON, however also spatial multi-tenancy will be of high interest, as this allows clients to have access to FPGA-accelerated services in parallel in a continuous manner. This is particularly important, e.g., for tasks related to ongoing AI-based on-line inference. The goal of this use case is therefore to demonstrate secure spatial multi-tenancy on an FPGA fabric offered as a cloud-based service. The particular challenge to be solved here is related to the confidentiality of the proprietary IP to be provisioned on the FPGA: How can the cloud service provider verify that the IP does not contain any malicious payloads potentially having adverse effects on the FPGA or leading to data leakage of other tenants, while at the same time preserving the confidentiality of the IP in order to protect the client’s intellectual property?

7.1 Scenarios Description

Individual Players:

- FPGA vendors (or platform vendors in general)
- Clients
- Cloud Service Provider (CSP)

Clients’ capabilities and goals: Clients may share physical resources on the cloud. We focus here on FPGA clients only. They can be malicious and try to attack the platform or co-clients. The clients can perform only remote attacks. We consider in this work package remote physical attacks only, which are enabled due to the configurable nature of FPGAs and the fact that clients can freely configure cloud FPGAs.

CSP’s capabilities and goals: CSP provides paid services for clients and allows them to rent computing resources for a given time. Currently, CSPs allocate the entire FPGA resources to one client at a time. This is known as temporal multi-tenancy. Nevertheless, since FPGA resources can be configured partially, spatial multi-tenancy is feasible, i.e., FPGA resources can be split among several clients simultaneously, and is likely to be adopted to maximize profit. Clients upload their workloads, including applications and hardware designs and data, to be processed on the cloud. Unless security countermeasures are in place, the CSP can access clients’ private or confidential data or designs.

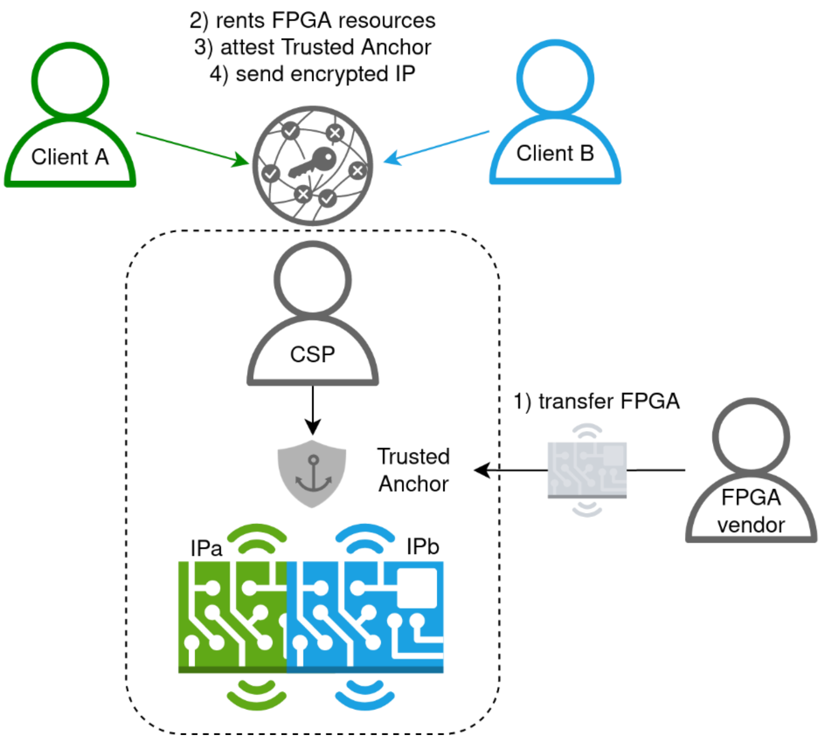


Figure 15: UC5 Intellectual Property Protection for Secure Multi-Tenancy on FPGA – A Workflow View

Figure 15 shows the workflow view of the UC5 scenario description, which will be presented in more details in the next section.

7.2 Architecture and Workflow

First, the FPGA Vendor provides FPGAs equipped with a trust anchor (TA) to the CSP as shown in Figure 16. There are several options for how the trust anchor can be implemented. The trust anchor functionalities are demonstrated in the workflow, while we discuss the different implementation options at the end of this section.

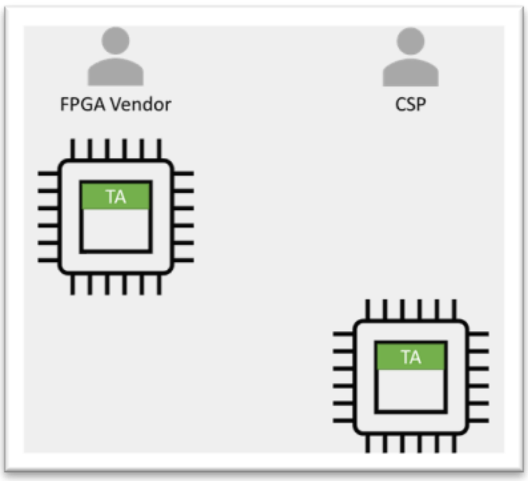


Figure 16: UC5 Vendor-provisioned FPGA equipped with a trust anchor

When client A wants to run a proprietary design (IP_A) on a cloud FPGA, it first rents the required FPGA resources. Next, the client attests the integrity of the TA on the allocated FPGA using information made available by the FPGA vendor (similar to attesting enclaves on a TEE). Then, the client exchanges a session key with the TA to encrypt its IP design and sends the encrypted IP_A to the FPGA. Note that the client does not have to communicate directly to the FPGA, the communications can be performed through any device of the CSP. Figure 17 illustrates the steps above.

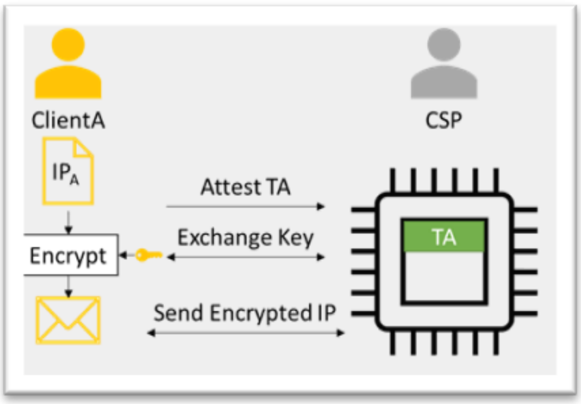


Figure 17: UC5 Client to cloud FPGA communications to upload a proprietary design (IP)

Once received by the TA on the FPGA, the TA decrypts the encrypted IP_A and vets IP_A using a virus scanner to ensure no rogue circuits are included. If confirmed, the TA can configure IP_A on the allocated resources on the FPGA. Figure 18 illustrates the steps above.

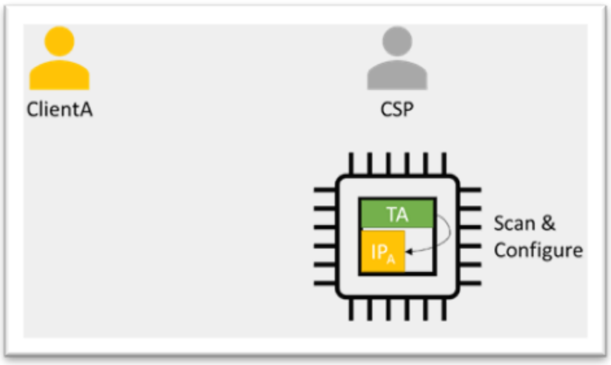


Figure 18: UC5 Trust anchor's steps to allocate an IP on the FPGA

Now, client B wants to rent enough FPGA resources to fit its proprietary design IP_B. Client B follows the same steps as demonstrated for client A. The TA decrypts the encrypted IP_B, scans IP_B to ensure no rogue circuits are included. If confirmed, the TA can configure IP_B on the allocated resources on the FPGA. Figure 19 shows the multi-tenancy view of the two proprietary designs.

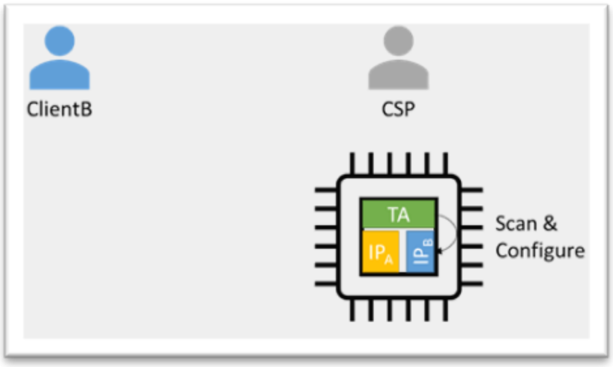


Figure 19: UC5 FPGA multi-tenancy view of two different clients' proprietary designs (IP_A, IP_B)

Trust anchor functionalities. the trust anchor, which is implanted by the FPGA vendor in the FPGA chip, should perform the following security functions:

- Prove its integrity and authenticity to clients.
- Exchange secret session keys with clients for the encryption of their IP designs.
- Decrypt and verify the integrity of clients' IP designs.
- Scan the clients' IP designs prior to configuration on the allocated FPGA resources.
- Configure clients' IP designs on the FPGA and prevent unauthorized read back of clients' IP configurations from the FPGA.

The trust anchor can be designed to be entirely implemented in hardware or can be implemented with the help of HW-SW co-design. The hardware components of the trust anchor can be further implemented as hardwired logic and reconfigurable logic to allow patching and updating. The hardwired components constitute the root-of-trust on the FPGA and allow for extending trust to other components (reconfigurable HW components as well as the SW components) of the trust anchor.

7.3 Threat Model

Recent research demonstrated remote physical attacks specific to the FPGA hardware on commercially deployed cloud FPGAs. One of the attacks allows clients to potentially damage FPGAs hosted in the cloud and consequently disable the computing resources of other clients. A malicious client can perform such a denial-of-service (DoS) attack by only uploading a design circuit that drains an excessive amount of current from the power supply of the FPGA until the whole platform stops functioning. Further, side and covert-channel attacks have been demonstrated for different sharing scenarios, i.e., temporal and spatial multi-tenancy.

On the other hand, cloud FPGAs do not support client IP protection through IP encryption & authentication. One of the main reasons is session key generation and management.

Our focus is mainly on the security issues of cloud FPGAs.

FPGA vendors are trusted players. Both CSP and clients trust the platforms delivered by the vendors.

The goal of a malicious client is to perform:

i. A denial-of-service attack on cloud FPGAs.

ii. A fault injection or side/covert channel attack based on power or thermal leakage on co-clients on the same FPGA or other computing resources sharing the same power supply system.

A malicious client would only need to configure rogue IP designs containing delay sensors or power-draining circuits to perform such attacks.

The goal of a malicious CSP is to gain access to clients' data or private designs. The CSP can access the client's data if no IP protection mechanism is enabled on the FPGA for remote clients.

7.4 Assumptions and Security Properties

To allow secure spatial multi-tenancy on cloud FPGAs, the following security properties are required:

- A trust anchor on the FPGA to support IP decryption, verification, configuration on the FPGA, and protection after configuration.
- FPGA vendor support for remote secret key generation: To enable IP protection on cloud FPGAs for different clients, each client needs to share a secret key with the allocated FPGA to decrypt and verify the IP configuration's integrity before configuring the FPGA. Thus, FPGA vendors must support remote secret key generation and provisioning on the FPGA such that a client can exchange a session key with the pertinent FPGA.
- An up-to-date FPGA virus scanner: CSP must have access to a virus scanner to vet clients' IP configurations.
- Secure Communication: the CSP, the clients, and the FPGA vendors communicate with each other over secure channels to transmit the attestation data to the remote verifier. The communication channel must be encrypted and authenticated to prevent eavesdropping and tampering.

7.5 Testbed Prerequisites

To prototype the FPGA trust anchor and the proposed workflow, an FPGA-SoC will be used to emulate the setup. The trust anchor components will be implemented/emulated using the processing system, i.e., the ARM cores, of the FPGA-SoC. We propose the use of Xilinx Zynq UltraScale+ MPSoC ZCU102 Evaluation Kit with the following features that would be sufficient to implement our trust anchor: A quad-core Arm Cortex-A53 with TrustZone enabled and 4GB RAM.

8 Conclusions

CROSSCON aims to develop a new, open, flexible, and highly portable IoT security stack that can operate on various edge devices and multiple hardware platforms. This stack will enable essential security mechanisms and trusted services, providing a consistent security baseline throughout the entire IoT system.

We have presented the definition of the final use cases of the project, including two new use cases UC4 and UC5. The final version of the use cases represents significant challenges of their application domains and will serve to test, validate, and demonstrate the effectiveness of the CROSSCON stack and its relevance from both industrial standpoint but also from the EC's expected outcomes from the call topic.

This document contributes to the completion of milestone MS3 on "First version of CROSSCON Open Specification, Use Cases finalised." The document also marks the finalisation of the T1.1 activities.

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