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Trusted Internet of Things (IoT) Device Network-Layer Onboarding and Lifecycle Management:

Enhancing Internet Protocol-Based IoT Device and Network Security

Volume C:
How-To Guides

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As a private-public partnership, we are always seeking feedback on our practice guides. We are particularly interested in seeing how businesses apply NCCoE reference designs in the real world. If you have implemented the reference design, or have questions about applying it in your environment, please email us at iot-onboarding@nist.gov.

All comments are subject to release under the Freedom of Information Act.

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The documents in this series describe example implementations of cybersecurity practices that businesses and other organizations may voluntarily adopt. These documents do not describe regulations or mandatory practices, nor do they carry statutory authority.

KEYWORDS

application-layer onboarding; bootstrapping; Internet of Things (IoT); Manufacturer Usage Description (MUD); network-layer onboarding; onboarding; Wi-Fi Easy Connect.

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The Technology Partners/Collaborators who participated in this build submitted their capabilities in response to a notice in the Federal Register. Respondents with relevant capabilities or product components were invited to sign a Cooperative Research and Development Agreement (CRADA) with NIST, allowing them to participate in a consortium to build this example solution. We worked with:

Technology Collaborators		
Aruba, a Hewlett Packard Enterprise company	Foundries.io	Open Connectivity Foundation (OCF)
CableLabs	Kudelski IoT	Sandelman Software Works
Cisco	NquiringMinds	SEALSQ, a subsidiary of WISeKey
	NXP Semiconductors	Silicon Labs

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1 Introduction

Volumes C, D, and E show information technology (IT) professionals and security engineers how we implemented these example solutions. We cover all of the products employed in this reference design. We do not re-create the product manufacturers' documentation, which is presumed to be widely available. Instead, these three volumes show how we incorporated the products together in our environment.

Note: These are not comprehensive tutorials. There are many possible service and security configurations for these products that are out of scope for this reference design.

1.1 How to Use This Guide

This NIST Cybersecurity Practice Guide demonstrates a standards-based reference design for implementing trusted IoT device network-layer onboarding and lifecycle management. It describes various example implementations of this reference design. Each of these implementations, which are known as *builds,* is standards-based and is designed to help provide assurance that networks are not put at risk as new IoT devices are added to them and to help safeguard IoT devices from connecting to unauthorized networks. The reference design described in this practice guide is modular and can be deployed in whole or in part, enabling organizations to incorporate trusted IoT device network-layer onboarding and lifecycle management into their legacy environments according to goals that they have prioritized based on risk, cost, and resources.

This guide contains five volumes:

- NIST Special Publication (SP) 1800-36A: *Executive Summary* – why we wrote this guide, the challenge we address, why it could be important to your organization, and our approach to solving this challenge
- NIST SP 1800-36B: *Approach, Architecture, and Security Characteristics* – what we built and why
- NIST SP 1800-36C: *How-To Guides* – instructions for building the example implementations, including all the security-relevant details that would allow you to replicate all or parts of this project **(you are here)**
- NIST SP 1800-36D: *Functional Demonstrations* – use cases that have been defined to showcase trusted IoT device network-layer onboarding and lifecycle management security capabilities, and the results of demonstrating these use cases with each of the example implementations
- NIST SP 1800-36E: *Risk and Compliance Management* – risk analysis and mapping of trusted IoT device network-layer onboarding and lifecycle management security characteristics to cybersecurity standards and recommended practices

Depending on your role in your organization, you might use this guide in different ways:

Business decision makers, including chief information security, product security, and technology officers, will be interested in the *Executive Summary, NIST SP 1800-36A*, which describes the following topics:

- challenges that enterprises face in migrating to the use of trusted IoT device network-layer onboarding

- example solutions built at the NCCoE
- benefits of adopting the example solution

Technology, security, and privacy program managers who are concerned with how to identify, understand, assess, and mitigate risk will be interested in *NIST SP 1800-36B*, which describes what we did and why.

Also, Section 4 of *NIST SP 1800-36E* will be of particular interest. Section 4, *Mappings*, maps logical components of the general trusted IoT device network-layer onboarding and lifecycle management reference design to security characteristics listed in various cybersecurity standards and recommended practices documents, including *Framework for Improving Critical Infrastructure Cybersecurity* (NIST Cybersecurity Framework) and *Security and Privacy Controls for Information Systems and Organizations* (NIST SP 800-53).

You might share the *Executive Summary, NIST SP 1800-36A*, with your leadership team members to help them understand the importance of using standards-based trusted IoT device network-layer onboarding and lifecycle management implementations.

IT professionals who want to implement similar solutions will find the whole practice guide useful. You can use the how-to portion of the guide, *NIST SP 1800-36C*, to replicate all or parts of the builds created in our lab. The how-to portion of the guide provides specific product installation, configuration, and integration instructions for implementing the example solution. We do not re-create the product manufacturers' documentation, which is generally widely available. Rather, we show how we incorporated the products together in our environment to create an example solution. Also, you can use *Functional Demonstrations, NIST SP 1800-36D*, which provides the use cases defined to showcase trusted IoT device network-layer onboarding and lifecycle management security capabilities and the results of demonstrating these use cases with each of the example implementations. Finally, *NIST SP 1800-36E* will help explain the security functionality that the components of each build provide.

This guide assumes that IT professionals have experience implementing security products within the enterprise. While we have used a suite of commercial products to address this challenge, this guide does not endorse these particular products. Your organization can adopt this solution or one that adheres to these guidelines in whole, or you can use this guide as a starting point for tailoring and implementing parts of a trusted IoT device network-layer onboarding and lifecycle management solution. Your organization's security experts should identify the products that will best integrate with your existing tools and IT system infrastructure. We hope you will seek products that are congruent with applicable standards and recommended practices.

A NIST Cybersecurity Practice Guide does not describe "the" solution, but example solutions. We seek feedback on the publication's contents and value your input. Comments, suggestions, and success stories are welcome. Please contribute your thoughts to iot-onboarding@nist.gov.

1.2 Build Overview

This NIST Cybersecurity Practice Guide addresses the challenge of network-layer onboarding using standards-based protocols to perform trusted network-layer onboarding of an IoT device. Each build demonstrates one or more of these capabilities:

- Trusted Network-Layer Onboarding: providing the device with its unique network credentials over an encrypted channel
- Network Re-Onboarding: performing trusted network-layer onboarding of the device again after a device reset
- Network Segmentation: assigning a device to a particular local network segment to prevent it from communicating with other network components, as determined by enterprise policy
- Trusted Application-Layer Onboarding: providing the device with application-layer credentials over an encrypted channel after completing network-layer onboarding
- Ongoing Device Authorization: continuously monitoring the device on an ongoing basis, providing policy-based assurance and authorization checks on the device throughout its lifecycle
- Device Communications Intent Enforcement: Secure conveyance of device communications intent information, combined with enforcement of it, to ensure that IoT devices are constrained to sending and receiving only those communications that are explicitly required for each device to fulfill its purpose

Five builds, including the factory provisioning builds, have been implemented and demonstrated as part of this project. They serve as examples of how to onboard IoT devices using the protocols described in NIST SP 1800-36B. The remainder of this practice guide provides step-by-step instructions on how to reproduce all builds.

1.2.1 Reference Architecture Summary

The builds described in this document are instantiations of the trusted network-layer onboarding and lifecycle management logical reference architecture described in NIST SP 1800-36B. This architecture is organized according to five high-level processes: Device Manufacture and Factory Provisioning, Device Ownership and Bootstrapping Information Transfer, Trusted Network-Layer Onboarding, Trusted Application-Layer Onboarding, and Continuous Verification. For a full explanation of the architecture, please see NIST SP 1800-36B: *Approach, Architecture, and Security Characteristics*.

1.2.2 Physical Architecture Summary

Figure 1-1 depicts the high-level physical architecture of the NCCoE IoT Onboarding laboratory environment in which the five trusted IoT device network-layer onboarding project builds and the two factory provisioning builds have been implemented. The NCCoE provides virtual machine (VM) resources and physical infrastructure for the IoT Onboarding lab. As depicted, the NCCoE IoT Onboarding laboratory hosts collaborator hardware and software for the builds. The NCCoE also provides connectivity from the IoT Onboarding lab to the NIST Data Center, which provides connectivity to the internet and public IP spaces (both IPv4 and IPv6). Access to and from the NCCoE network is protected by a firewall.

Additionally, access to and from the IoT Onboarding lab is protected by a pfSense firewall, represented by the brick box icon in Figure 1-1. This firewall has both IPv4 and IPv6 (dual stack) configured. The IoT Onboarding lab network infrastructure includes a shared virtual environment that houses a domain controller and a vendor jumpbox. These components are used across builds where applicable. It also

contains five independent virtual local area networks (VLANs), each of which houses a different trusted network-layer onboarding build.

The IoT Onboarding laboratory network has access to cloud components and services provided by the collaborators, all of which are available via the internet. These components and services include Aruba Central and the UXI Cloud (Build 1), SEALSQ INeS (Build 1), Platform Controller (Build 2), a Manufacturer Authorized Signing Authority (MASA) server (Build 3), Kudelski IoT keySTREAM application-layer onboarding service and Amazon Web Services (AWS) IoT (Build 4), and a Manufacturer Provisioning Root (Build 5).

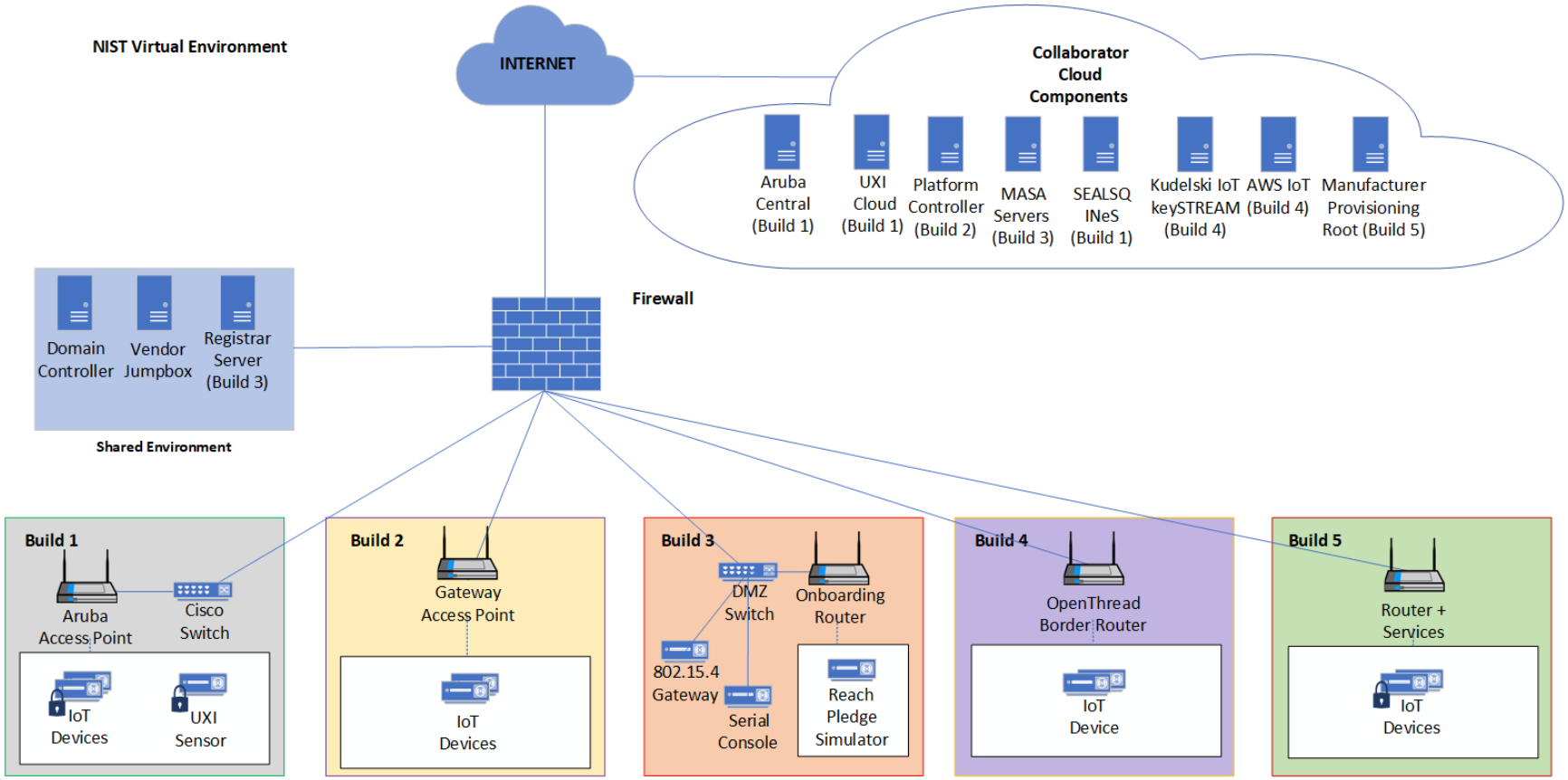


Figure 1-1 NCCoE IoT Onboarding Laboratory Physical Architecture

All five network-layer onboarding laboratory environments, as depicted in the diagram, have been installed:

- Build 1 (i.e., the Wi-Fi Easy Connect, Aruba/HPE build) network infrastructure within the NCCoE lab consists of two components: the Aruba Access Point and the Cisco Switch. Build 1 also requires support from Aruba Central for network-layer onboarding and the UXI Cloud for application-layer onboarding. These components are in the cloud and accessed via the internet. The IoT devices onboarded using Build 1 include the UXI Sensor and the Raspberry Pi.
- Build 2 (i.e., the Wi-Fi Easy Connect, CableLabs, OCF build) network infrastructure within the NCCoE lab consists of a single component: the Gateway Access Point. Build 2 requires support from the Platform Controller, which also hosts the IoTivity Cloud Service. The IoT devices that are onboarded using Build 2 include three Raspberry Pis.
- Build 3 (i.e., the BRSKI, Sandelman Software Works build) network infrastructure components within the NCCoE lab include a Wi-Fi capable home router (including Join Proxy), a DMZ switch (for management), and an ESP32A Xtensa board acting as a Wi-Fi IoT device, as well as an nRF52840 board acting as an IEEE 802.15.4 device. A management system on a BeagleBone Green serves as a serial console. A registrar server has been deployed as a virtual appliance on the NCCoE private cloud system. Build 3 also requires support from a MASA server that is accessed via the internet. In addition, a Raspberry Pi 3 provides an Ethernet/802.15.4 gateway, as well as a test platform.
- Build 4 (i.e., the Thread, Silicon Labs, Kudelski IoT build) network infrastructure components within the NCCoE lab include an Open Thread Border Router (OBTR), which is implemented using a Raspberry Pi, and a Silicon Labs Gecko Wireless Starter Kit, which acts as an 802.15.4 antenna. Build 4 also requires support from the Kudelski IoT keySTREAM service, which is in the cloud and accessed via the internet. The IoT device onboarded in Build 4 is the Silicon Labs Dev Kit (BRD2601A) with an EFR32MG24 System-on-Chip (SoC). The application service to which it onboards is AWS IoT.
- Build 5 (i.e., the BRSKI over Wi-Fi, NquiringMinds build) includes 2 Raspberry Pi 4Bs running a Linux operating system. One Raspberry Pi acts as the pledge (or IoT Device) with an Infineon Trusted Platform Module (TPM) connected. The other acts as the router, registrar, and MASA, all in one device. This build uses the open-source TrustNetZ distribution, from which the entire build can be replicated easily. The TrustNetZ distribution includes source code for the IoT device, the router, the access point, the network onboarding component, the policy engine, the manufacturer services, the registrar, and a demo application server. TrustNetZ makes use of NquiringMinds tdx Volt to issue and validate verifiable credentials.
- The BRSKI factory provisioning build is deployed in the Build 5 environment. The IoT device in this build is a Raspberry Pi equipped with an Infineon Optiga SLB 9670 TPM 2.0, which gets provisioned with birth credentials (i.e., a public/private key pair and an Initial Device Identifier (IDevID)). The BRSKI factory provisioning build also uses an external certificate authority hosted on the premises of NquiringMinds to provide the device certificate signing service.
- The Wi-Fi Easy Connect factory provisioning build is deployed in the Build 1 environment. Its IoT devices are Raspberry Pis equipped with a SEALSQ VaultIC Secure Element, which gets provisioned with a DPP uniform resource identifier (URI). The Secure Element can also be provisioned with an IDevID certificate signed by the SEALSQ INeS certification authority, which is

independent of the DPP URI. Code for performing the factory provisioning is stored on an SD card.

1.3 Typographic Conventions

The following table presents typographic conventions used in this volume.

Typeface/Symbol	Meaning	Example
Italics	file names and path names; references to documents that are not hyperlinks; new terms; and placeholders	For language use and style guidance, see the *NCCoE Style Guide*.
Bold	names of menus, options, command buttons, and fields	Choose **File** > **Edit.**
`Monospace`	command-line input, onscreen computer output, sample code examples, and status codes	`mkdir`
`Monospace Bold`	command-line user input contrasted with computer output	**`service sshd start`**
blue text	link to other parts of the document, a web URL, or an email address	All publications from NIST's NCCoE are available at https://www.nccoe.nist.gov.

2 Build 1 (Wi-Fi Easy Connect, Aruba/HPE)

This section of the practice guide contains detailed instructions for installing and configuring all the products used to build an instance of the example solution. For additional details on Build 1's logical and physical architectures, see NIST SP 1800-36B: *Approach, Architecture, and Security Characteristics*.

The network-layer onboarding component of Build 1 utilizes Wi-Fi Easy Connect, also known as the Device Provisioning Protocol (DPP). The Wi-Fi Easy Connect standard is maintained by the Wi-Fi Alliance [1]. The term "DPP" is used when referring to the network-layer onboarding protocol, and "Wi-Fi Easy Connect" is used when referring to the overall implementation of the network onboarding process.

2.1 Aruba Central/Hewlett Packard Enterprise (HPE) Cloud

This build utilized Aruba Central as a cloud management service that provided management and support for the Aruba Wireless Access Point (AP) and provided authorization and DPP onboarding capabilities for the wireless network. A cloud-based application programming interface (API) endpoint provided the ability to import the DPP Uniform Resource Identifiers (URIs) in the manner of a Supply Chain Integration Service. Due to this capability and Build 1's support for Wi-Fi Easy Connect, Build 1's infrastructure fully supported interoperable network-layer onboarding with Build 2's Reference Clients ("IoT devices") provided by CableLabs.

2.2 Aruba Wireless Access Point

Use of DPP is implicitly dependent on the Aruba Central cloud service. Aruba Central provides a cloud Infrastructure-as-a-Service (IaaS) enabled architecture that includes initial support for DPP in Central 2.5.6/ArubaOS (AOS) 10.4.0. Central and AOS support multiple deployment formats:

1. *Underlay deployment*: In this mode, the APs function as access points only, bridging traffic locally without additional processing.
2. *Overlay deployment*: All data is securely tunneled to an on-prem gateway, where advanced services can route, inspect, and analyze it. After processing, the data is either bridged locally or routed to its next hop.
3. *Mixed-mode deployment*: This combines underlay and overlay approaches. A returned "role/label" determines how the data is processed and forwarded, offering flexibility in handling traffic.
4. At the time of this publication, a user can leverage any 3xx, 5xx, or 6xx-series APs to support a DPP deployment, with the view that all future series APs will implicitly include support. For an existing or new user, creating a Service Set Identifier (SSID) is a prerequisite. In the 2H of 2025, support will be added for the new range of AP7xx, which also adds support for WiFi7. Additionally, this release will include support for DPP in the 6GHz range and WPA3.

Assuming an SSID exists or a new one is created based on the above security restrictions, the next step is to enable DPP (as detailed below in Section 2.2.1) so that the SSID can support multiple authentication and key management (AKM) processes on a Basic Service Set (BSS). If the chosen security type is DPP, only a single AKM will exist for that BSS.

A standards-compliant 802.3at port is the easiest method for providing the AP with power. An external power supply can also be used.

This document does not cover the specifics of radio frequency (RF) design and placement of APs. Guidance and assistance are available on the Aruba community site, https://community.arubanetworks.com, or the Aruba Support Portal, https://asp.arubanetworks.com. Additionally, we do not cover the onboarding and licensing of Aruba Central hardware. Documentation can be found here: https://www.arubanetworks.com/techdocs/ArubaDocPortal/content/docportal.htm.

2.2.1 Wi-Fi Network Setup and Configuration

The following instructions detail the initial setup and configuration of the Wi-Fi network upon powering on and connecting the AP to an existing network.

1. Navigate to the Aruba Central cloud management interface.
2. On the sidebar, navigate under **Global** and choose the AP-Group you want to configure/modify. (This assumes you have already grouped your APs by location/functions.)
3. Under **Devices,** click **Config** in the top right side.
4. You will now be in the Access Points tab and WLANs tab. Do one of the following:
    a. If creating a new SSID, click on **+ Add SSID.** After entering the Name (SSID) in Step 1 and configuring options as necessary in Step 2, when you get to Step 3 (Security), the slide-bar defaults to the Personal Security Level; the alternative is the Enterprise Security Level.
        i. If you choose the **Personal Security Level,** under **Key-Management,** ensure you select either **DPP** or **WPA2-Personal.** If you choose **WPA2-Personal,** expand the **Advanced Settings** section and enable the toggle button for DPP so that the SSID can broadcast the AKM. Note that this option is not available if choosing DPP for Key-Management.
        ii. If you choose the **Enterprise Security Level,** only WPA2-Enterprise Key-Management currently supports DPP. Expand the **Advanced Settings** section and enable the toggle button for **DPP** so that the SSID can broadcast the AKM.
    b. If you plan to enable DPP on a previously created SSID:
        i. Ensure you are running version 10.4+ on your devices. You also need an SSID that is configured for WPA2-Personal or WPA2-Enterprise.
        ii. When ready, float your cursor over the previously created SSID name you wish to configure and click on the edit icon.
        iii. Edit the SSID, click on **Security**, expand the **Advanced Settings** section, and enable the toggle button for **DPP.**
        iv. Click **Save Settings.**

For SSIDs that have been modified to add DPP AKM, it's also necessary to enable DPP within the radio profile.

1. Under the **Access Point** Tab, click **Radios.**
2. Expect to see a **default** radio-profile. If a custom one has been created, you will need to review your configuration before proceeding.
3. Assuming a **default** radio-profile, click on the **Edit** icon, expand **Show advanced settings,** and scroll down to **DPP Provisioning.** You can selectively enable this for 2.4 GHz or 5.0 GHz. In the 2H of 2025, support will be added for the new range of AP7xx, which adds support for WiFi7. Additionally, this release will include support for DPP in the 6GHz range and WPA3.

2.2.2 Wi-Fi Easy Connect Configuration

Configuration of the Access Point occurred through the Aruba Central cloud management interface. Standard configurations were used to stand up the Build 1 wireless network. The instructions for enabling DPP capabilities for the overall wireless network are listed below:

1. Navigate to the Aruba Central cloud management interface.
2. On the sidebar, navigate to **Security > Authentication and Policy > Config.**
3. In the **Client Access Policy** section, click **Edit.**
4. Under the **Wi-Fi Easy Connect™ Service** heading, ensure that the name of your wireless network is selected.
5. Click **Save.**

2.3 Cisco Catalyst 3850-S Switch

This build utilized a Cisco Catalyst 3850-S switch minimally configured with two separate VLANs to allow for IoT device network segmentation and access control. The switch also provided Power-over-Ethernet support for the Aruba Wireless AP.

2.3.1 Configuration

The switch was configured with two VLANs and a trunk port dedicated to the Aruba Wireless AP. You can find the relevant portions of the Cisco iOS configuration below:

```
interface Vlan1
 no ip address
interface Vlan2
 no ip address
interface GigabitEthernet1/0/1
 switchport mode trunk
interface GigabitEthernet1/0/2
```

```
 switchport mode access
 switchport access vlan 1
interface GigabitEthernet1/0/3
 switchport mode access
 switchport access vlan 2
```

2.4 Aruba User Experience Insight (UXI) Sensor

This build utilized an Aruba UXI Sensor as a Wi-Fi Easy Connect-capable IoT device. Models G6 and G6C support Wi-Fi Easy Connect, and all available G6 and G6C models support Wi-Fi Easy Connect within their software image. This sensor successfully utilized the network-layer onboarding mechanism provided by the wireless network and completed onboarding to the application-layer UXI cloud service. The device automatically initiates the network-layer onboarding process on boot.

2.4.1 Configuration

All of Aruba's available G6 and G6C UXI sensors support the ability to complete network-layer and application-layer onboarding. No specific configuration of the physical sensor is required. As part of the supply-chain process, the cryptographic public key for your sensor(s) will be available within the cloud tenant. Each device's public/private key pair is created as part of the manufacturing process. The public key effectively identifies the sensor to the network and is part of the Wi-Fi Easy Connect/DPP onboarding process. This allows unprovisioned devices straight from the factory to be onboarded and subsequently connect to the UXI sensor cloud to obtain their network-layer configuration. An administrator will have to define the 'tasks' the UXI sensor is going to perform, such as monitoring SSIDs, performing reachability tests to on-prem or cloud services, and making the results of these tests available within the UXI user/administrator portal.

2.5 Raspberry Pi

In this build, the Raspberry Pi 3B+ acts as a DPP enrollee. In setting up the device for this build, a DPP-capable wireless adapter, the Alfa AWUS036NHA network dongle, was connected to enable the Pi to send and receive DPP frames. Once fully configured, the Pi can be onboarded with the Aruba AP.

2.5.1 Configuration

The following steps were completed for the Raspberry Pi to complete DPP onboarding:

1. Set the Raspberry Pi's management IP to an IP address in the Build 1 network. To do this, add the following lines to the file *dhcpcd.conf* located at */etc/dhcpcd.conf*. For this build, the IP address was set to 192.168.10.3.

```
# Example static IP configuration:
interface eth0
static ip_address=192.168.10.3/24
#static ip6_address=fd51:42f8:caae:d92e::ff/64
static routers=192.168.10.1
static domain_name_servers=192.168.10.1 8.8.8.8
```

2. Install Linux Libraries using the apt package manager. The following packages were installed:
    a. autotools-dev
    b. automake
    c. libcurl4-openssl-dev
    d. libnl-genl-3-dev
    e. libavahi-client-dev
    f. libavahi-core-dev
    g. aircrack-ng
    h. openssl-1.1.1q
3. Install the DPP utilities. These utilities were installed from the GitHub repository https://github.com/HewlettPackard/dpp using the following command:

```
git clone https://github.com/HewlettPackard/dpp
```

2.5.2 DPP Onboarding

This section describes the steps for using the Raspberry Pi as a DPP enrollee. The Pi uses a DPP utility to send out chirps to make its presence known to available DPP configurators. Once the Pi is discovered, the DPP configurator (Aruba Wireless AP) initiates the DPP authentication protocol. During this phase, DPP *connectors* are created to onboard the device to the network. As soon as the Pi is fully authenticated, it is fully enrolled and can begin normal network communication.

1. Navigate to the DPP utilities directory that was installed during setup:

```
cd dpp/linux
```

2. From the DPP utilities directory, run the following command to initiate a DPP connection:

```
sudo ./sss -I wlan1 -r -e sta -k respp256.pem -B respbkeys.txt -a -t -d 255
```

```
build1@Build1Pi:~/dpp/linux $ sudo ./sss -I wlan1 -r -e sta -k respp256.pem -B respbkeys.txt -a -t -d 255
adding interface wlan1...
wlan1 is NOT the loopback!

getting the interface!
got phy info!!!
interface MAC address is 00:c0:ca:98:42:37
wiphy is 1
wlan1 is interface 4 from ioctl
wlan1 is interface 4 from if_nametoindex()
max ROC is 5000
got driver capabilities, off chan is ok, max_roc is 5000

ask for GAS request frames

ask for GAS response frames

ask for GAS comeback request frames

ask for GAS comeback response frames

ask for DPP action frames
socket 4 is for nl_sock_in
role: enrollee
interfaces and MAC addresses:
        wlan1: 00:c0:ca:98:42:37
chirping, so scan for APs
scanning for all SSIDs
scan finished.
didn't find the DPP Configurator connectivity IE on
didn't find the DPP Configurator connectivity IE on
didn't find the DPP Configurator connectivity IE on
didn't find the DPP Configurator connectivity IE on
didn't find the DPP Configurator connectivity IE on
didn't find the DPP Configurator connectivity IE on
didn't find the DPP Configurator connectivity IE on
didn't find the DPP Configurator connectivity IE on
didn't find the DPP Configurator connectivity IE on
didn't find the DPP Configurator connectivity IE on
didn't find the DPP Configurator connectivity IE on
didn't find the DPP Configurator connectivity IE on
didn't find the DPP Configurator connectivity IE on
didn't find the DPP Configurator connectivity IE on
didn't find the DPP Configurator connectivity IE on
didn't find the DPP Configurator connectivity IE on
FOUND THE DPP CONFIGURATOR CONNECTIVITY IE on Build1-IoTOnboarding, on frequency 2462, channel 11
```

3. Once the enrollee has found a DPP configurator, the DPP authentication protocol is initiated.

```
------- Start of DPP Authentication Protocol ---------
chirp list:
        2437
        2412
        2462
start chirping...
error...-95: Unspecific failure
changing frequency to 2437
sending 68 byte frame on 2437
chirp on 2437...
error...-95: Unspecific failure
changing frequency to 2412
sending 68 byte frame on 2412
chirp on 2412...
error...-95: Unspecific failure
changing frequency to 2462
sending 68 byte frame on 2462
chirp on 2462...
processing 222 byte incoming management frame
enter process_dpp_auth_frame() for peer 1
        peer 1 is in state DPP bootstrapped
Got a DPP Auth Frame! In state DPP bootstrapped
type Responder Bootstrap Hash, length 32, value:
05d54478 eaa59dfa 768d8148 f119f729 060c8d3b b9e917dc 4b34d654 32f403cb

type Initiator Bootstrap Hash, length 32, value:
2795ec93 1b5b17c9 e0e5e5ad b2ce787d 413ab0c2 bb29cfbf 554668fe a090eeea

type Initiator Protocol Key, length 64, value:
bbb37f18 0839880d 7d5bb455 c6702cde fe51d0ee 2c93b895 0edb368d 23d9eca1
d8fc9568 c7af6542 e97aeeb4 bbae7885 05745f8d 82cac4c5 376cc6fb 30d956af

type Protocol Version, length 1, value:
02

type Wrapped Data, length 41, value:
62ceb78b 1b27d2d0 726b9f12 918736a3 ba0d8c68 00ab1509 9e2ebbc5 e61250fe
b90fc9e3 0e97cd5b b6

responder received DPP Auth Request
peer sent a version of 2
Pi'
x:
bbb37f18 0839880d 7d5bb455 c6702cde fe51d0ee 2c93b895 0edb368d 23d9eca1

y:
d8fc9568 c7af6542 e97aeeb4 bbae7885 05745f8d 82cac4c5 376cc6fb 30d956af

k1:
8de1c000 01b44e44 dbaf5bd5 273f4621 bb33bd6f f48e1dc1 3db71ba2 8852d293

initiator's nonce:
378708d9 2985f2a6 239e7ffa 0ee1649a

initiator role: configurator
my role: enrollee
```

2.6 Certificate Authority

The function of the certificate authority (CA) in this build is to issue network credentials for use in the network-layer onboarding process.

2.6.1 Private Certificate Authority

A private CA was provided as a part of the DPP demonstration utilities in the HPE GitHub repository. For demonstration purposes, the Raspberry Pi is used as the configurator and the enrollee.

2.6.1.1 *Installation and Configuration*

The following instructions detail the initial setup and configuration of the private CA using the DPP demonstration utilities and certificates located at https://github.com/HewlettPackard/dpp.

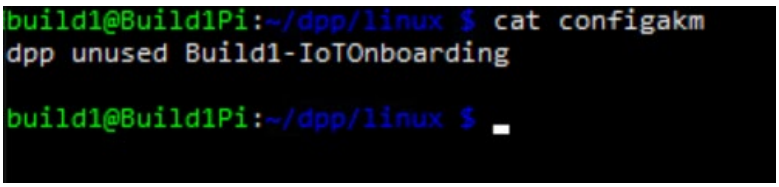
1. Navigate to the DPP utilities directory on the Raspberry Pi: *~dpp/linux*

   ```
   cd dpp/linux/
   ```

2. The README in the GitHub repository (https://github.com/HewlettPackard/dpp/blob/master/README) references a text file called *configakm,* which contains information about the network policies for a configurator to provision on an enrollee. The format is: `<akm> <EAP server> <ssid>`. Current AKMs that are supported are DPP, dot1x, sae, and psk. For this build, DPP is used. For DPP, an Extensible Authentication Protocol (EAP) server is not used.

3. Configure the file *configakm* located in *~/dpp/linux/*. This file instructs the configurator on how to deploy a DPP connector (network credential) from the configurator to the enrollee. As shown below, the *configakm* file is filled with the following fields:

   ```
   dpp unused Build1-IoTOnboarding.
   ```

4. The file *csrattrs.conf* contains attributes to construct an Abstract Syntax Notation One (ASN.1) string. This string allows the configurator to tell the enrollee how to generate a certificate signing request (CSR). The following fields were used for this demonstration:

   ```
   asn1 = SEQUENCE: seq_section

   [seq_section]

   field1 = OID:challengePassword

   field2 = SEQUENCE:ecattrs

   field3 = SEQUENCE:extnd

   field4 = OID:ecdsa-with-SHA256


   [ecattrs]

   field1 = OID:id-ecPublicKey

   field2 = SET:curve


   [curve]

   field1 = OID:prime256v1
   ```

```
[extnd]

field1 = OID:extReq

field2 = SET:extattrs


[extattrs]

field1 = OID:serialNumber

field2 = OID:favouriteDrink
```

```
asn1 = SEQUENCE:seq_section
[seq_section]
field1 = OID:challengePassword
field2 = SEQUENCE:ecattrs
field3 = SEQUENCE:extnd
field4 = OID:ecdsa-with-SHA256

[ecattrs]
field1 = OID:id-ecPublicKey
field2 = SET:curve

[curve]
field1 = OID:prime256v1

[extnd]
field1 = OID:extReq
field2 = SET:extattrs

[extattrs]
field1 = OID:serialNumber
field2 = OID:favouriteDrink
```

2.6.1.2 *Operation and Demonstration*

Once setup and configuration have been completed, the following steps can be used to demonstrate utilizing the private CA to issue credentials to a requesting device.

1. Open three terminals on the Raspberry Pi: one to start the certificate program, one to show the configurator's point of view, and one to show the enrollee's point of view.
2. The demonstration uses an OpenSSL certificate. To run the program from the first terminal, navigate to the following directory: *~/dpp/ecca/,* and run the command:

   ```
   ./ecca
   ```

   ```
   build1@Build1Pi:~/dpp/ecca $ ./ecca
   not sending my cert with p7
   ```

3. On the second terminal, start the configurator using the following command:

   ```
   sudo ./sss -I lo -r -c signp256.pem -k respp256.pem -B resppbkeys.txt -d 255
   ```

```
build1@Build1Pi:~/dpp/linux $ sudo ./sss -I lo -r -c signp256.pem -k respp256.pem -B respbkeys.txt -d 255
[sudo] password for build1:
adding interface lo...
role: configurator
AKM: dpp, auxdata: unused, SSID: Build1-IoTOnboarding
interfaces and MAC addresses:
        lo: b8:9d:1c:2e:82:35
configured channel 2437
we are not the initiator, version is 1
my private bootstrap key:
0bd4de71 b0001946 ddc1d011 4e0dddb2 0b1ae219 915db220 6e7470fb cfcf9721

my public bootstrap key
x:
cb87856e 544a055e eb97ab88 72eb08f2 0ee36ea2 fc5fc7e5 75070dba a69a9ae2

y:
95020fc7 965def6c ebf10337 ab2850ca 2f370eb9 3d02d1ac fb9d977c be0f8f

DER encoded ASN.1:
3039301306072a8648ce3d020106082a8648ce3d03010703220003cb87856e544a055eeb97ab8872eb08f20ee36ea2fc5fc7e575070dbaa69a9ae2


------- Start of DPP Authentication Protocol ---------
```

As shown in the terminal where the ecca program is running, the configurator contacts the CA and asks for the certificate.

```
build1@Build1Pi:~/dpp/ecca $ ./ecca
not sending my cert with p7
got a new request!
adding 4 to the service context
DER-encoded CA cert in a P7 is 517 bytes
b64-encoded message is 703 bytes









said message is 703
write 703 message
```

4. On the third terminal, start the enrollee using the following command:

   ```
   sudo ./sss -I lo -r -e sta -k initp256.pem -B initbkeys.txt -t -a -q -d 255
   ```

   From the enrollee's perspective, it will send chirps on different channels until it finds the configurator. Once found, it sends its certificate to the CA for signing. The snippet below is of the enrollee generating the CSR.

```
authenticated initiator!
start the configuration protocol....
exit process_dpp_auth_frame() for peer 1
        peer 1 is in state DPP authenticated
beginning DPP Config protocol
sending a GAS_INITIAL_REQUEST dpp config frame
processing 198 byte incoming management frame
got a GAS_INITIAL_RESPONSE...
response len is 155, comeback delay is 0
got a DPP config response!
Configurator said we need a CSR to continue...
CSR Attributes:
4d457747 43537147 53496233 4451454a 427a4156 42676371 686b6a4f 50514942
4d516f47 43437147 534d3439 41774548 4d423447 43537147 53496233 4451454a
0a446a45 5242674e 56424155 4743676d 534a6f6d 54386978 6b415155 47434371
47534d34 3942414d 430a

adding 88 byte challengePassword
an object, not an attribute
a nid for challengePassword
CSR Attr parse: got a SET OF attributes... nid for ecPublicKey
 an elliptic curve, nid = 415
CSR Attr parse: got a SET OF attributes... an extension request:
        for serial number
        for favorite drink
an object, not an attribute
a nid for ecdsa with sha256
using bootstrapping key for CSR...
CSR is 537 chars:
```

5. In the ecca terminal, the certificate from the enrollee is shown.

```
Write out database with 1 new entries
Data Base Updated
DER-encoded P7 is 681 bytes
b64-encoded message is 923 bytes









said message is 923
write 923 message
```

2.6.2 SEALSQ INeS

The SEALSQ INeS Certificate Management System provides CA and certificate management capabilities for Build 1. Implementation of this system provides Build 1 with a trusted, public CA to support issuing network credentials.

2.6.2.1 Setup and Configuration

To support this build, a custom software agent was deployed on a Raspberry Pi in the Build 1 network. This agent interacted with the cloud-based CA in SEALSQ INeS via API to sign network credentials. Network-level onboarding of IoT devices was completed via DPP, with network credentials being successfully requested from and issued by SEALSQ INeS.

Additional information on interacting with the SEALSQ INeS API can be found at https://inesdev.certifyiddemo.com/. Access can be requested directly from SEALSQ via their contact form: https://www.sealsq.com/contact.

2.7 UXI Cloud

The UXI Cloud is a web-based application that serves as a monitoring hub for the UXI sensor. It provides visibility into the data captured by the sensor's performance monitoring. For the purposes of this build, the dashboard was used to demonstrate application-layer onboarding, which occurs once the UXI sensor has completed network-layer onboarding. Once the application-layer onboarding was completed and the application configuration was applied to the device, our demonstration concluded.

2.8 Wi-Fi Easy Connect Factory Provisioning Build

This Factory Provisioning Build included many of the components listed above, including Aruba Central, SEALSQ INeS, the Aruba Access Point, and Raspberry Pi IoT devices. A SEALSQ VaultIC Secure Element was also included in the build and provided secure generation and storage of the key material and certificates provisioned to the device.

2.8.1 SEALSQ VaultIC Secure Element

The SEALSQ VaultIC Secure Element was connected to a Raspberry Pi via the built-in GPIO pins present on the Pi. SEALSQ provided demonstration code that generates a public/private key pair within the secure element, creates a Certificate Signing Request, and uses that CSR to obtain an IDevID certificate from SEALSQ INeS. This code supports the Raspberry Pi OS Bullseye. The demonstration code can be found in the official GitHub repository.

HPE also provided a custom DPP-based implementation of the SEALSQ code, which generates supporting material within the secure element and then generates a DPP URI. This DPP URI is available in a string format, PNG (QR Code), and ASCII (QR Code). The DPP URI can then be used for network onboarding, as described in the rest of the Build 1 section. This code is included in the demonstration code located at the repository linked above.

2.8.1.1 Installation and Configuration

Full instructions for installation and configuration can be found in the INSTALL.txt file from the SEALSQ demonstration code mentioned above. A general set of steps for preparing to run the demonstration code is included below.

1. Install prerequisites on Raspberry Pi
    a. cmake
    b. git
    c. gcc
2. On the Raspberry Pi, run the `sudo raspi-update` command to update drivers

3. Before plugging the VaultIC Secure Element into the Raspberry Pi connector, configure the jumpers:
    a. Set _VCC_ jumper
        i. CTRL = VaultIC power controlled by GPIO25 (default)
        ii. 3V3 = VaultIC power always on
    b. Set J1&J2 to select I2C or SPI
        i. If using SPI, set J1 to SS and J2 to SEL (default)
        ii. If using I2C, set J1 to SCL and J2 to SDA
4. Using the `raspi-config` command, enable the SPI or I2C interface on the Raspberry Pi
5. Run `git clone https://github.com/sclark-wisekey/NCCoE.factory.pub` to pull down the demonstration code.

2.8.1.2 *Running the demonstration code*

1. Navigate to the folder containing the demonstration code. Inside that folder, navigate to the VaultIC/demos folder.
2. Edit the file config.cfg and change the value of VAULTIC_COMM to match the jumpers configured during setup.
3. The demonstrations are available with wolfSSL stacks and organized in dedicated folders. The README.TXT file in each demonstration subfolder explains how to run the demonstrations.

3 Build 2 (Wi-Fi Easy Connect, CableLabs, OCF)

This section of the practice guide contains detailed instructions for installing and configuring all of the products used to build an instance of the example solution. For additional details on Build 2's logical and physical architectures, see NIST SP 1800-36B: *Approach, Architecture, and Security Characteristics*.

The network-layer onboarding component of Build 2 utilizes Wi-Fi Easy Connect, also known as the Device Provisioning Protocol (DPP). The Wi-Fi Alliance maintains the Wi-Fi Easy Connect standard [1]. The term "DPP" refers to the network-layer onboarding protocol, and "Wi-Fi Easy Connect" refers to the overall implementation of the network onboarding process.

3.1 CableLabs Platform Controller

The CableLabs Platform Controller provides an architecture and reference implementation of a cloud-based service that provides management capability for service deployment groups, access points with the deployment groups, registration and lifecycle of user services, and the secure onboarding and lifecycle management of users' Wi-Fi devices. The controller also exposes APIs for the purpose of integrating various business flows with third-party systems (e.g., integration with the manufacturing process for device management).

The Platform Controller would typically be hosted by the network operator or a third-party service provider. It can be accessed via a web interface. Additional information for this deployment can be accessed at the official CableLabs repository.

3.1.1 Operation and Demonstration

Full operation can commence once the Platform Controller, Gateway, and Reference Client configurations have been completed. Instructions for this are located at the official CableLabs repository.

3.2 CableLabs Custom Connectivity Gateway

In this deployment, the gateway software runs on a Raspberry Pi 3B+, which acts as a router, firewall, wireless access point, Open Connectivity Foundation (OCF) Diplomat, and OCF Onboarding Tool. The gateway is also connected to the CableLabs Platform Controller, which manages much of the gateway's configuration and functions. Due to Build 2's infrastructure and support of Wi-Fi Easy Connect, Build 2 fully supported interoperable network-layer onboarding with Build 1's IoT devices.

3.2.1 Installation and Configuration

Hardware requirements, pre-installation steps, installation steps, and configuration instructions for the gateway can be found at the official CableLabs repository.

3.2.2 Integration with CableLabs Platform Controller

Once the initial configuration has occurred, the gateway can be integrated with the CableLabs Platform Controller. Instructions are available at the official CableLabs repository.

3.2.3 Operation and Demonstration

Full operation can commence once the Platform Controller, Gateway, and Reference Client configurations have been completed. Instructions for this are located at the official CableLabs repository.

3.3 Reference Clients/IoT Devices

Three reference clients were deployed in this build, each on a Raspberry Pi 3B+. They were each configured to emulate either a smart light switch or a smart lamp. The software deployed also included the capability to perform network-layer onboarding via Wi-Fi Easy Connect (or DPP) and application-layer onboarding using the OCF onboarding method. These reference clients were fully interoperable with network-layer onboarding to Build 1.

3.3.1 Installation and Configuration

Hardware requirements, pre-installation, installation, and configuration steps for the reference clients are detailed in the official CableLabs repository.

3.3.2 Operation and Demonstration

Full operation can commence once the Platform Controller, Gateway, and Reference Client configurations have been completed. Instructions for this are located at the official CableLabs repository.

For interoperability with Build 1, the IoT device's DPP URI was provided to Aruba Central, which allowed Build 1 to successfully complete network-layer onboarding with the Build 2 IoT devices.

4 Build 3 (BRSKI, Sandelman Software Works)

This section of the practice guide contains detailed instructions for installing and configuring all of the products used to build an instance of the example solution. For additional details on Build 3's logical and physical architectures, see NIST SP 1800-36B: *Approach, Architecture, and Security Characteristics*.

The network-layer onboarding component of Build 3 utilizes the Bootstrapping Remote Secure Key Infrastructure (BRSKI) protocol. Build 3 is representative of a typical home or small office network.

4.1 Onboarding Router/Join Proxy

The onboarding router quarantines the IoT device attempting to join the network until the BRSKI onboarding process is complete. The router in this build is a Turris MOX device, which is based on the Linux OpenWrt version 4 operating system (OS). The Raspberry Pi 3 contains software that functions as the Join Proxy for pledges to the network. If another brand of device is used, a different source of compiled Join Proxy might be required.

4.1.1 Setup and Configuration

The router needs to be IPv6-enabled. In the current implementation, the join package operates on an unencrypted network.

4.2 Minerva Join Registrar Coordinator

The Join Registrar determines whether a new device is allowed to join the network. The Join Registrar is located on a virtual machine running Devuan Linux 4 within the network.

4.2.1 Setup and Configuration

The Minerva Fountain Join Registrar/Coordinator is available as a Docker container and as a VM in OVA format on the Minerva Fountain page. Further setup and configuration instructions are available on the configuration page of the Sandelman website.

For the Build 3 demonstration, the VM deployment was installed onto a VMware vSphere system.

A freshly booted VM image will do the following on its own:

- Configure a database
- Configure a local certificate authority (fountain:s0_setup_jrc)
- Configure certificates for the database connection
- Configure certificates for the registrar Hypertext Transfer Protocol Secure (HTTPS) interface
- Configure certificates for use with the Bucardo database replication system
- Configure certificates for the Locally Significant Device Identifier (LDevID) certification authority (fountain:s2_create_registrar)
- Start the JRC

The root user is permitted to log in on the console ("tty0") using the password “root” but is immediately forced to set a new password.

The new registrar will announce itself with the name minerva-fountain.local in mDNS.

The logs for this are put into */var/log/configure-fountain-12345.log* (where 12345 is a new number based on the script's PID).

4.3 Reach Pledge Simulator

The Reach Pledge Simulator acts as an IoT device in Build 3 that is joining the network and is hosted on a Raspberry Pi 3. More information is available on the Sandelman website on the Reach page.

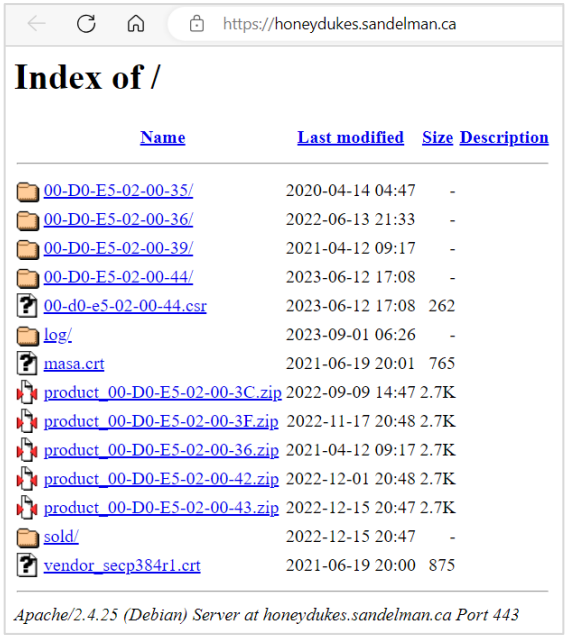
4.3.1 Setup and Configuration

While this device functions as an IoT device, it runs on the same software as the Join Registrar Coordinator. This software is available in VM and Docker container formats. Please see Section 4.2.1 for installation instructions.

When setting up the Reach Pledge Simulator, the pledge automatically determines the address of the Join Registrar Coordinator.

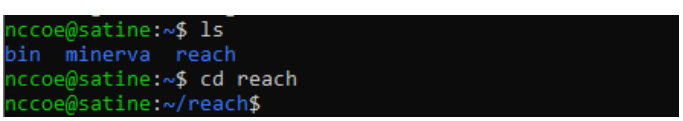
Currently, the Reach Pledge Simulator obtains its IDevID using the following steps:

1. View the available packages by visiting the Sandelman website.



2. Open a terminal on the Raspberry Pi device and navigate to the Reach directory by entering:

```
cd reach
```



3. Enter the following command while substituting the URL for one of the available zip files containing the IDevID of choice on the Sandelman website.

```
wget https://honeydukes.sandelman.ca/product_00-D0-E5-02-00-42.zip
```

```
nccoe@satine:~/reach$ wget https://honeydukes.sandelman.ca/product_00-D0-E5-02-00-42.zip
--2023-09-01 15:49:54--  https://honeydukes.sandelman.ca/product_00-D0-E5-02-00-42.zip
Resolving honeydukes.sandelman.ca (honeydukes.sandelman.ca)... 2a01:7e00:e000:2bb::3d:b021, 176.58.120.209
Connecting to honeydukes.sandelman.ca (honeydukes.sandelman.ca)|2a01:7e00:e000:2bb::3d:b021|:443... connected.
HTTP request sent, awaiting response... 200 OK
Length: 2722 (2.7K) [application/zip]
Saving to: 'product_00-D0-E5-02-00-42.zip'

product_00-D0-E5-02-00-42.zip 100%[=================================================>]   2.66K  --.-KB/s    in 0.001s

2023-09-01 15:49:57 (3.27 MB/s) - 'product_00-D0-E5-02-00-42.zip' saved [2722/2722]
```

4. Unzip the file by entering the following command, substituting the name of your zip file (the IDevID is the *device.crt* file):

```
unzip product_00-D0-E5-02-00-42.zip
```

```
nccoe@satine:~/reach$ unzip product_00-D0-E5-02-00-42.zip
Archive:  product_00-D0-E5-02-00-42.zip
   creating: 00-D0-E5-02-00-42/
  inflating: 00-D0-E5-02-00-42/device.crt
  inflating: 00-D0-E5-02-00-42/masa.crt
  inflating: 00-D0-E5-02-00-42/vendor.crt
  inflating: 00-D0-E5-02-00-42/key.pem
```

Typically, this would be accomplished through a provisioning process involving a Certificate Authority, as demonstrated in the Factory Provisioning builds.

4.4 Serial Console Server

The serial console server does not participate in the onboarding process but provides direct console access to the IoT devices. The serial console server has been attached to a multi-port USB hub, and USB connectors and/or USB2TTL adapters have been connected to each device. The ESP32 and the nRF52840 are both connected to the serial console and receive power from the USB hub. Power to the console and IoT devices is also provided via the USB hub. A BeagleBone Green device was used as the serial console, using the "screen" program as the telecom device.

4.5 Minerva Highway MASA Server

In the current build implementation, the MASA server provides the Reach Pledge Simulator with an IDevID Certificate and a public/private key pair for demonstration purposes. Typically, this would be accomplished through a factory provisioning process involving a Certificate Authority, as demonstrated in the Factory Provisioning builds.

4.5.1 Setup and Configuration

Installation of the Minerva Highway MASA is described on the Highway configuration page. Additional configuration details are available on the Highway development page.

The availability of VMs and containers is described on the Minerva page.

5 Build 4 (Thread, Silicon Labs, Kudelski IoT)

This section of the practice guide contains detailed instructions for installing and configuring all of the products used to build an instance of the example solution. For additional details on Build 4's logical and physical architectures, see NIST SP 1800-36B: *Approach, Architecture, and Security Characteristics*.

This build utilizes the Thread protocol and performs application-layer onboarding using the Kudelski keySTREAM service to provision a device to the AWS IoT Core.

5.1 Open Thread Border Router (OTBR)

The OTBR forms the Thread network and acts as the router on this build. The OTBR is run as software on a Raspberry Pi 3B. The Silicon Labs Gecko Wireless Devkit is attached to the Raspberry Pi via USB and acts as the 802.15.4 antenna for this build.

5.1.1 Installation and Configuration

On the Raspberry Pi, run the following commands from a terminal to install and configure the OTBR software:

```
git clone https://github.com/openthread/ot-br-posix
sudo NAT64=1 DNS64=1 WEB_GUI=1 ./script/bootstrap
sudo NAT64=1 DNS64=1 WEB_GUI=1 ./script/setup
```

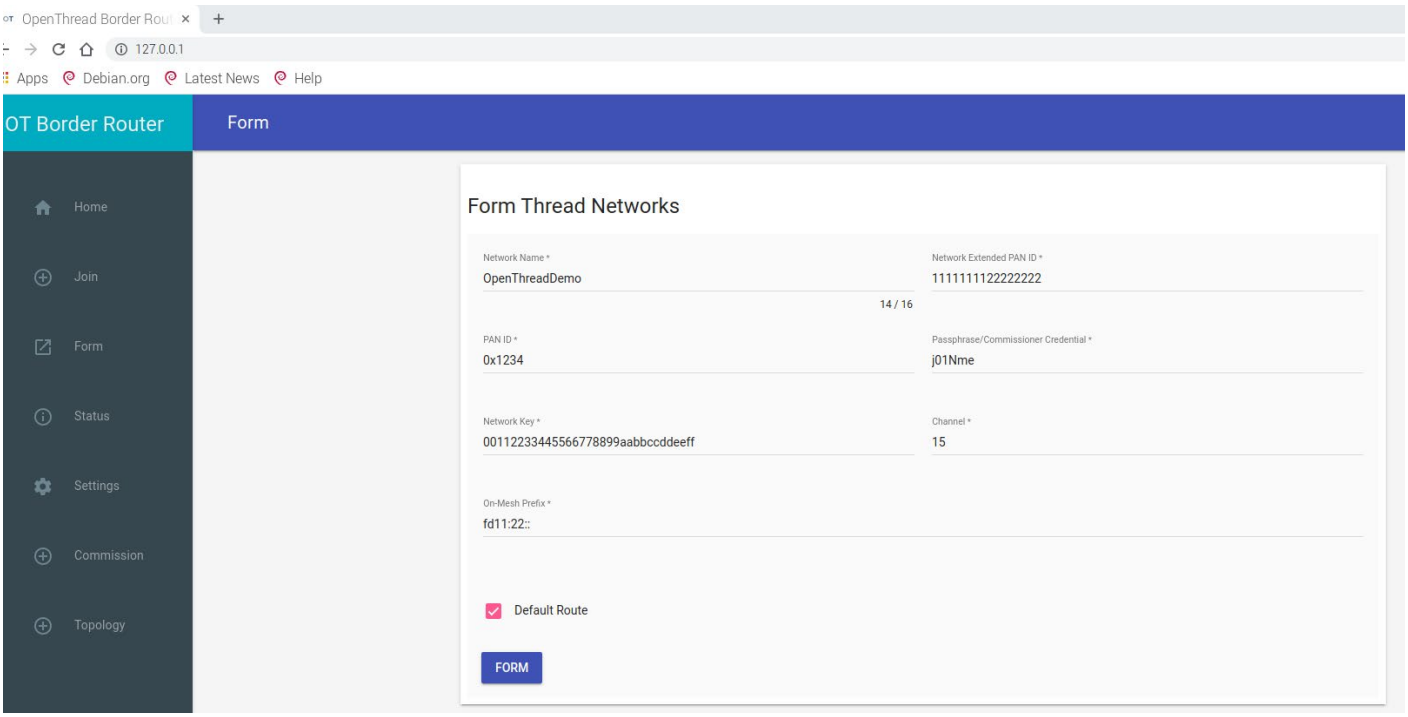
5.1.2 Operation and Demonstration

Once the initial configuration has occurred, the OTBR should be functional and operated through the web GUI.

1. To open the OTBR GUI, enter the following IP in a web browser:

   ```
   127.0.0.1
   ```

2. In the **Form** tab, enter the details for the Thread network being formed. For demonstration purposes, we only updated the credentials field.



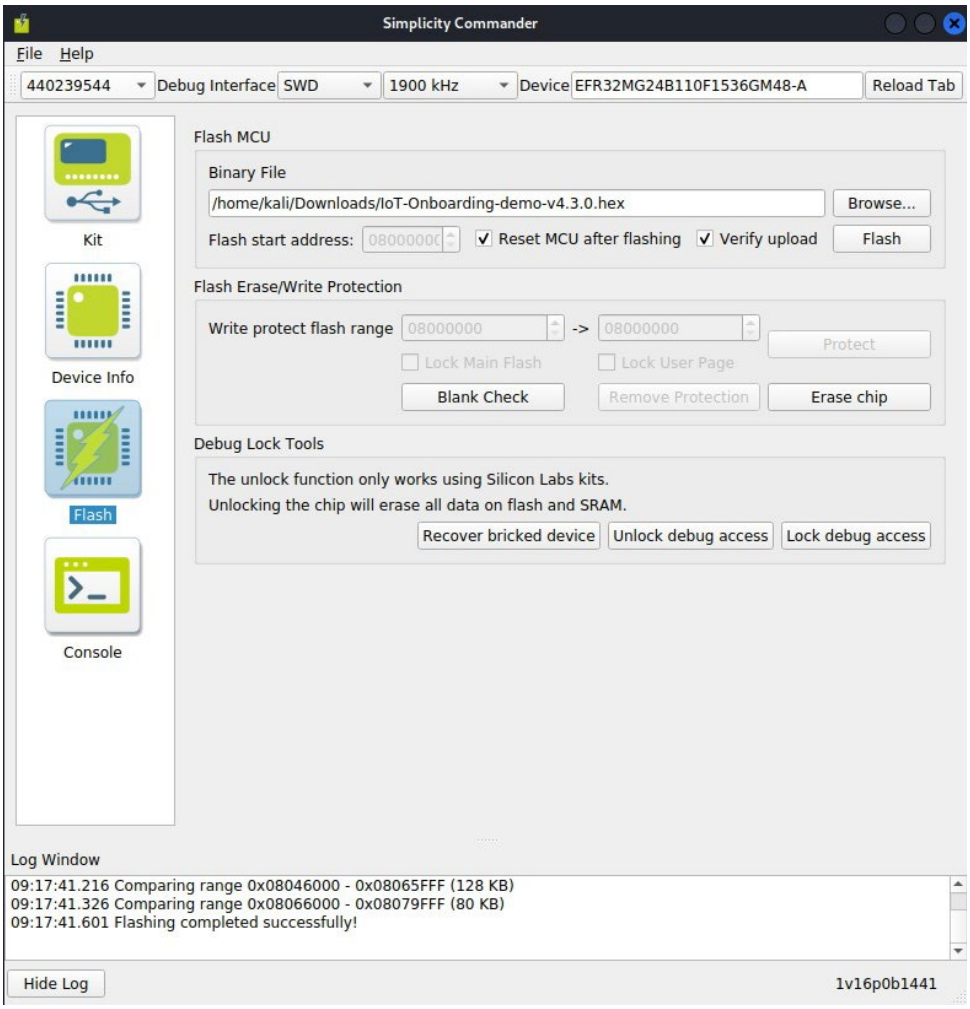
5.2 Silicon Labs Dev Kit (BRD2601A)

The Silicon Labs Dev Kit acts as the IoT device for this build. It is controlled using the Simplicity Studio v5 Software available at the official Simplicity Studio page and connected to a computer running Windows or Linux via USB. Our implementation leveraged a Linux machine running Simplicity Studio. The custom firmware for the Dev Kit leveraged in this use case was made by Silicon Labs.

5.2.1 Setup and Configuration

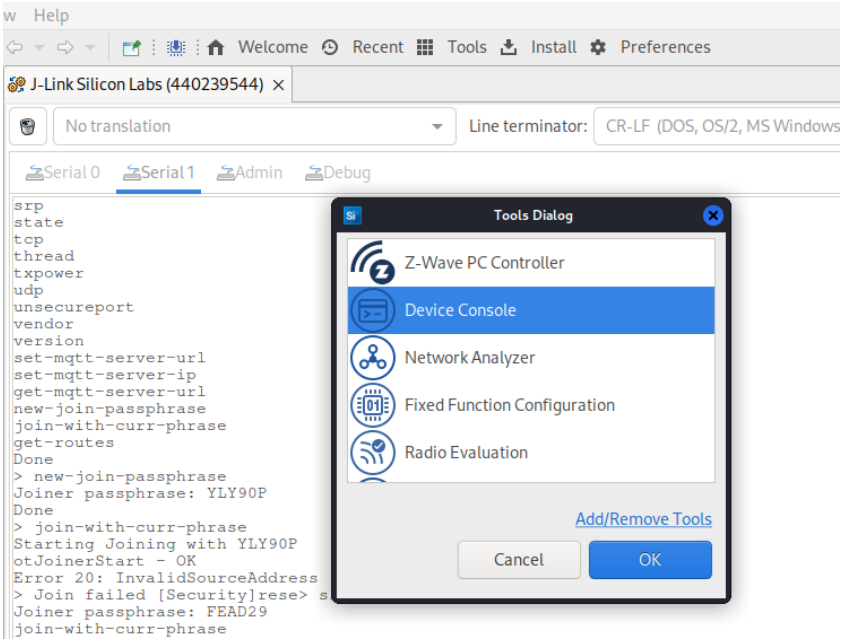
The Dev Kit custom firmware image works in conjunction with the Kudelski keySTREAM service. More information is available by contacting Silicon Labs through their contact form. Once the custom firmware has been acquired, the Dev Kit can be configured using the following steps.

1. Connect the Dev Kit via USB to the machine running Simplicity Studio.
2. The firmware is installed onto the Dev Kit using the Simplicity Commander tool within Simplicity Studio.



After selecting the firmware file, click **Flash** to flash the firmware of the Dev Kit.

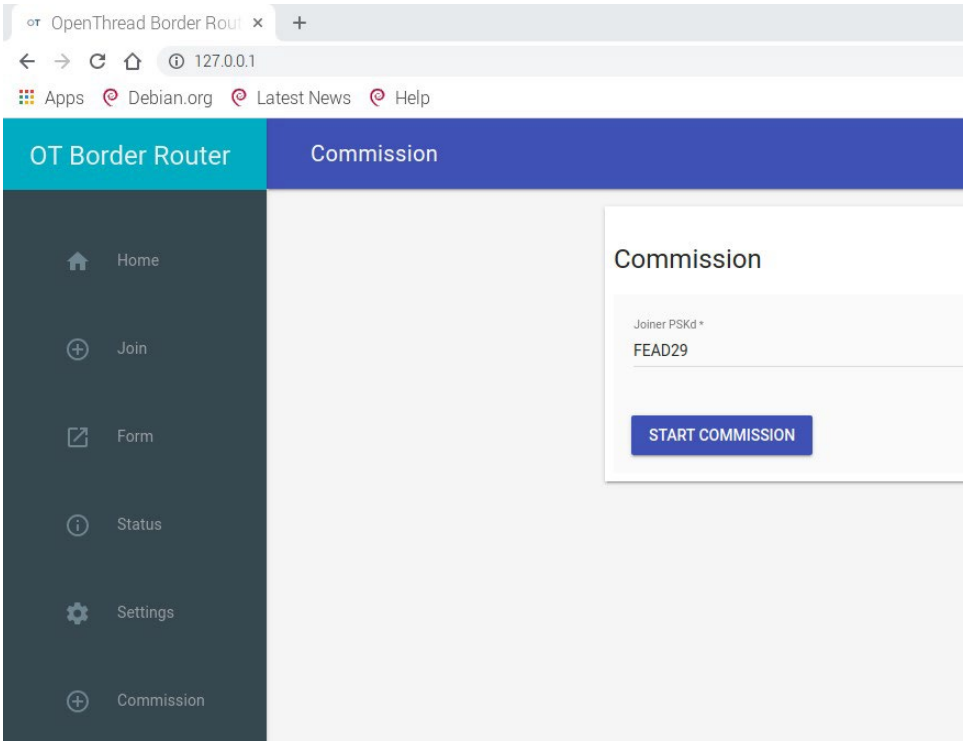
3. Open the device console in the **Tools** tab and select the **Serial 1** tab.



4. Enter the following command to create a new join passphrase in the Serial 1 command line:

   `new-join-passphrase`

5. Enter the output of the previous command in the **Commission** tab in the OTBR GUI and click **Start Commission.**



6. In the Simplicity Commander Device Console, enter the following command to begin the joining process from the Thunderboard:

```
join-with-curr-phrase
```

7. Press the **Reset** button on the Dev Kit and the device will join the thread network and reach out to the Kudelski keySTREAM service. You should see the following output in the Simplicity Commander Device Console:

```
Joiner passphrase: FEAD29
join-with-curr-phrase
Starting Joining with FEAD29
otJoinerStart - OK
Error 20: InvalidSourceAddress
> Join successgot valid ext route
role changed to 2
coap start complete

kta_app start

Calling ktaInitialize
ktaInitialize Succeeded

Calling ktaStartup
ktaStartup Succeeded
KTA life cycle state --> INIT

Calling ktaSetDeviceInformation
ktaSetDeviceInformation Succeeded
KTA life cycle state --> SEALED

Calling ktaExchangeMessage
ktaExchangeMessage Succeeded
```

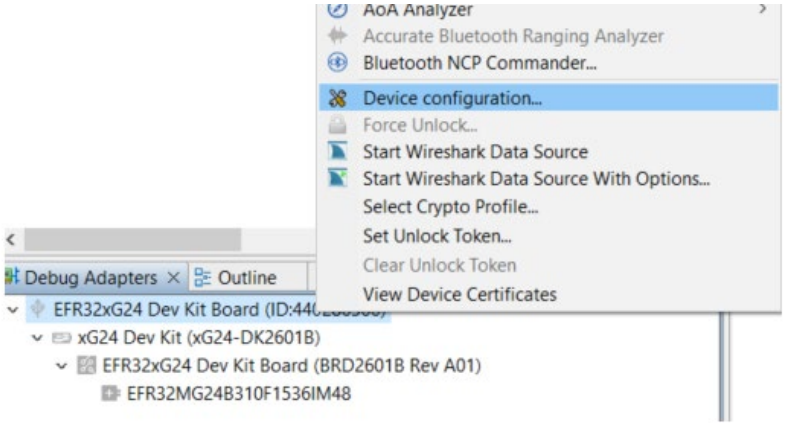
5.3 Kudelski keySTREAM Service

This section describes the Kudelski keySTREAM service that this build utilizes to provision certificates for connecting to the AWS IoT core. More information on keySTREAM is available on the keySTREAM page.

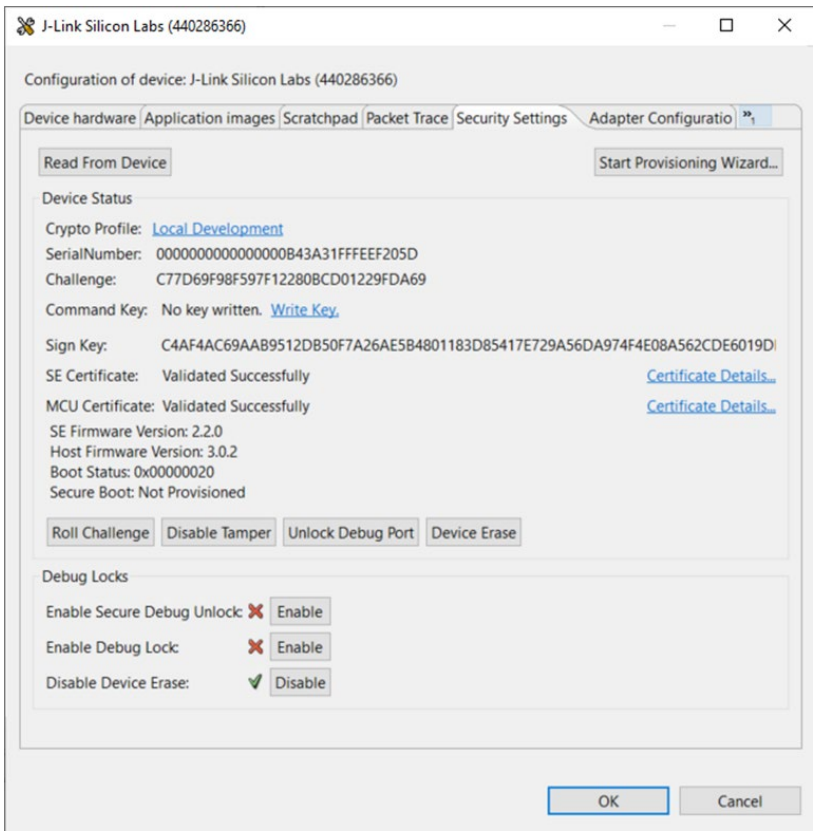
5.3.1 Setup and Configuration

The Kudelski keySTREAM service provides two certificates for the device: a CA certificate and a Proof of Possession (POP) certificate generated using a code from the AWS server. This section describes the steps to download these certificates.

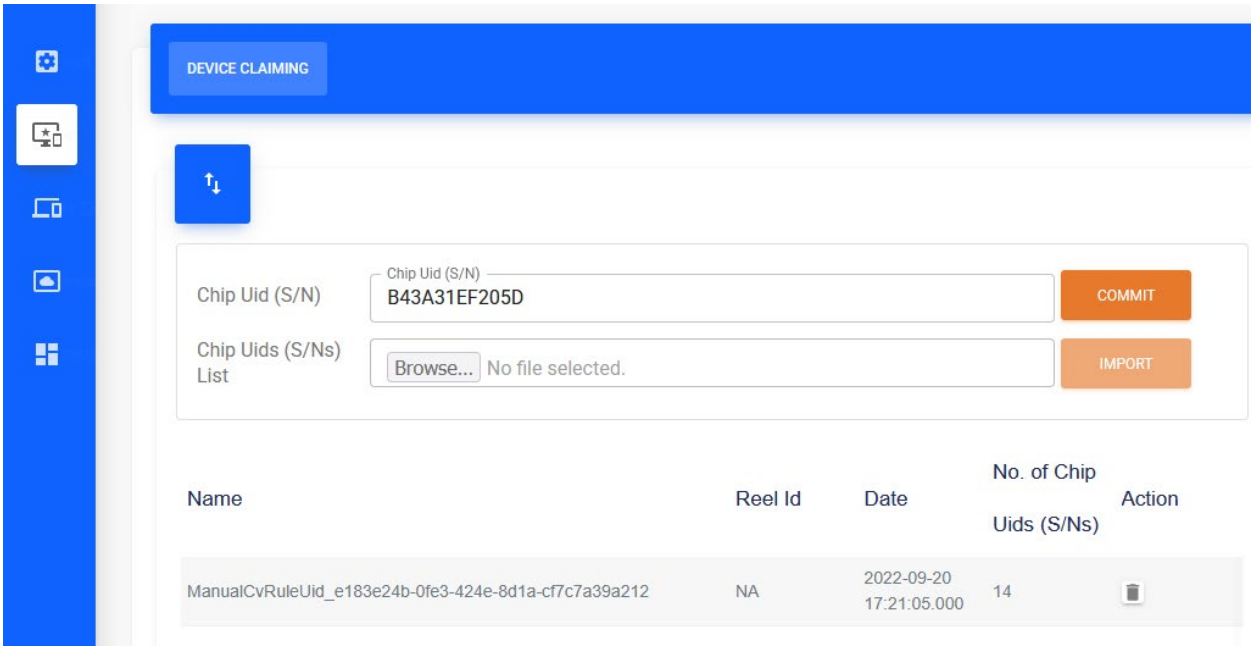
1. Locate the Chip unique identifier (UID) for the Silicon Labs Dev Kit in Simplicity Studio by right-clicking on the **Device Adapters** tab at the bottom and selecting **Device Configuration**.



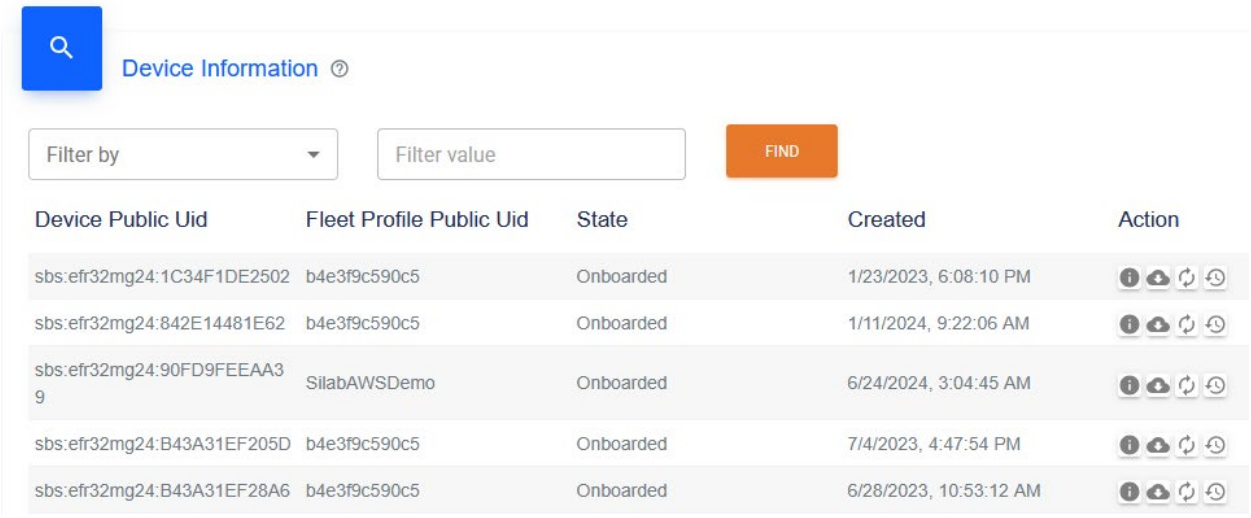
2. On the **Security Settings** tab, take the last 16 characters of the serial number and remove the 'FFFE' characters from the 7th – 11th positions.



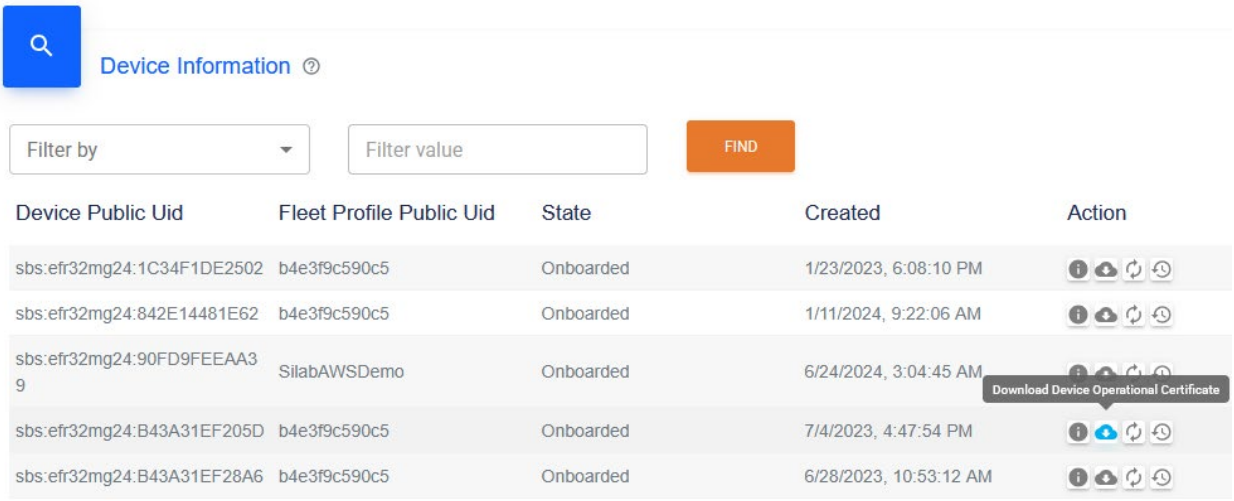
3. In the Kudelski keySTREAM service, claim your device by entering the chip UID from Simplicity Studio and clicking **Commit**.



4. The device will now be visible in the **My Devices** tab. A device can be removed from the key-STREAM service by scrolling to the right and clicking the **Refurbish** button.



5. Click the cloud icon to download the CA Certificate and the POP certificate. The POP certificate will require a code obtained from the AWS IoT Core, which will be generated in Section 5.4.1.



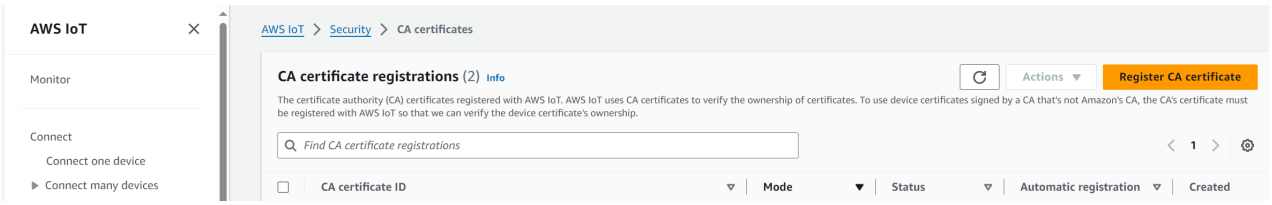
5.4 AWS IoT Core

The Silicon Labs Dev Kit will connect to the AWS MQ Telemetry Transport (MQTT) test client using the certificates provisioned from the Kudelski keySTREAM service.

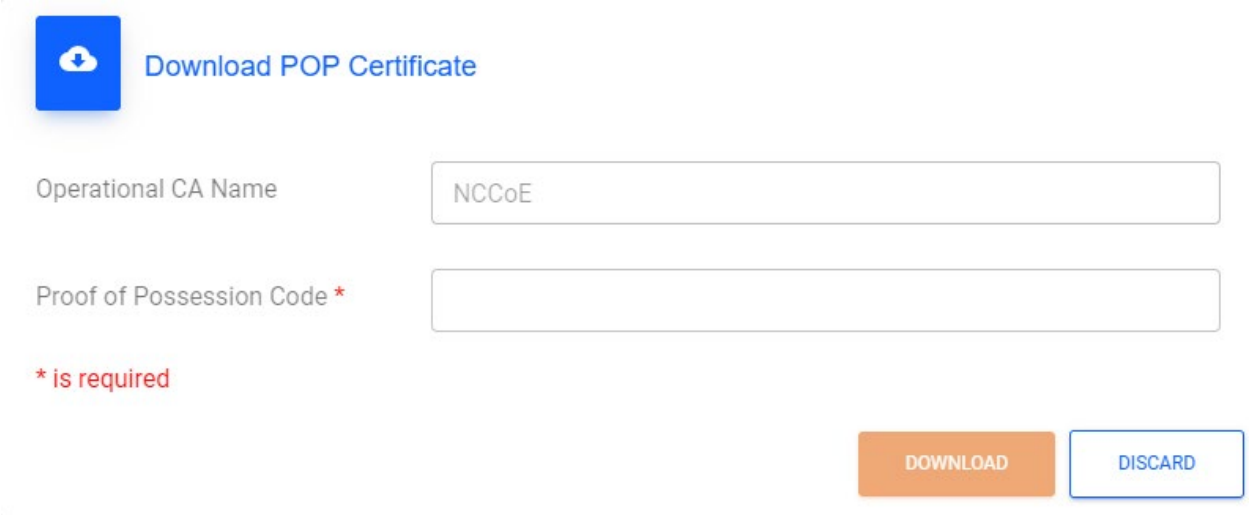
5.4.1 Setup and Configuration

Application-layer onboarding for this build is performed using the AWS MQTT test client. Certificates provisioned from the Kudelski keySTREAM service are uploaded to an AWS instance, allowing the device to demonstrate its ability to successfully send a message to AWS.

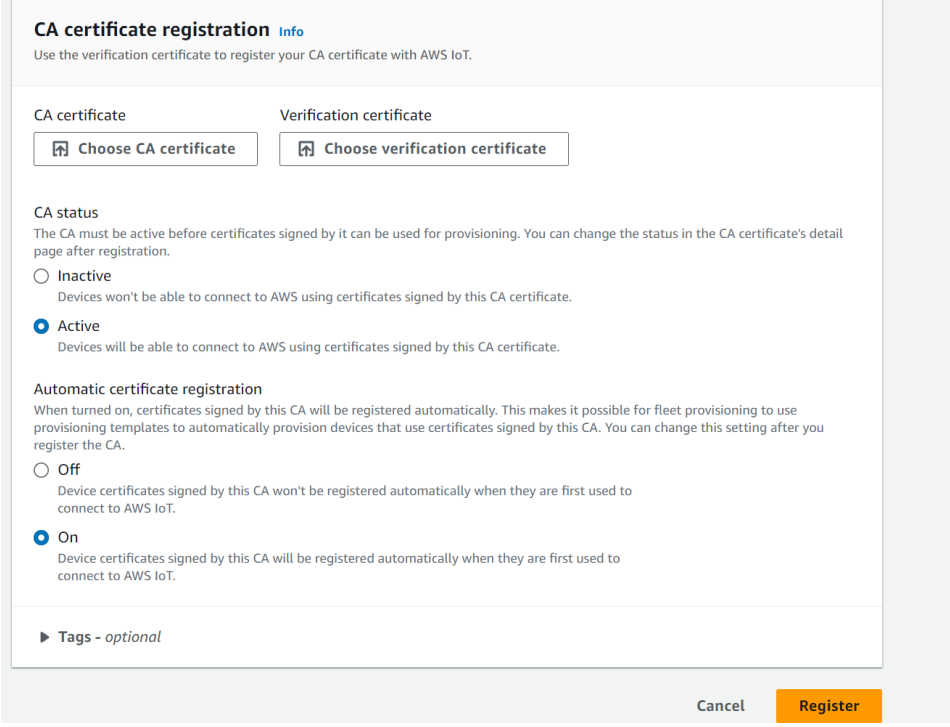
1. Within the AWS IoT Core, open the **Security** drop-down menu, click on **Certificate authorities**, and click the **Register CA certificate** button on the right.



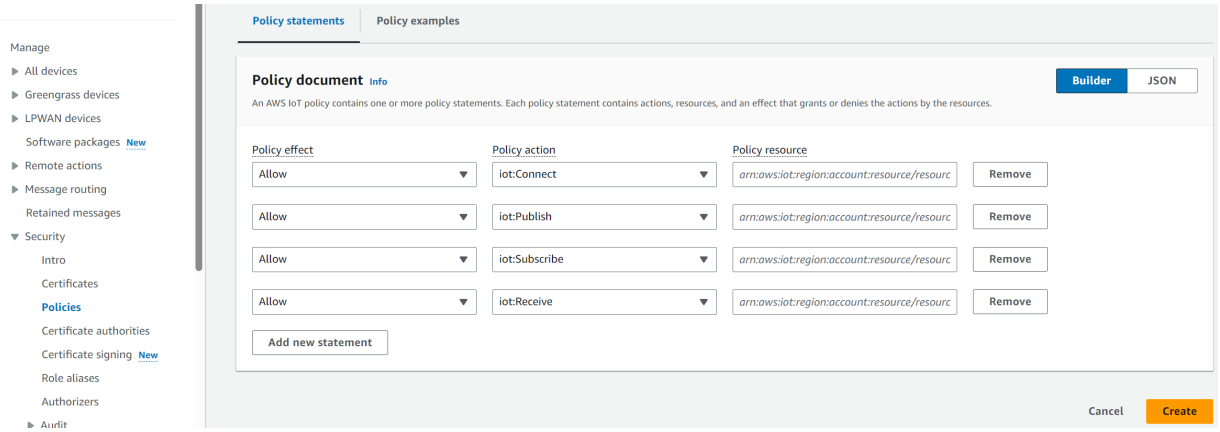
2. Select the radio button for **Register CA in Single-account mode,** copy the registration code to use as the **Proof of Possession Code** in the Kudelski keySTREAM service, and download the POP certificate.



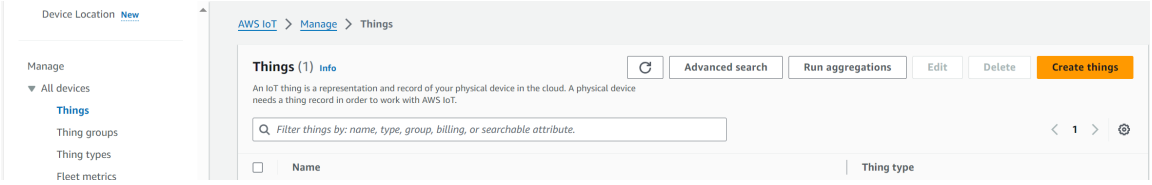
3. After downloading the POP certificate, upload the CA certificate and the POP (verification) certificate, and select the radio buttons for **Active** under **CA Status** and **On** under **Automatic Certificate Registration**. Then click **Register**.



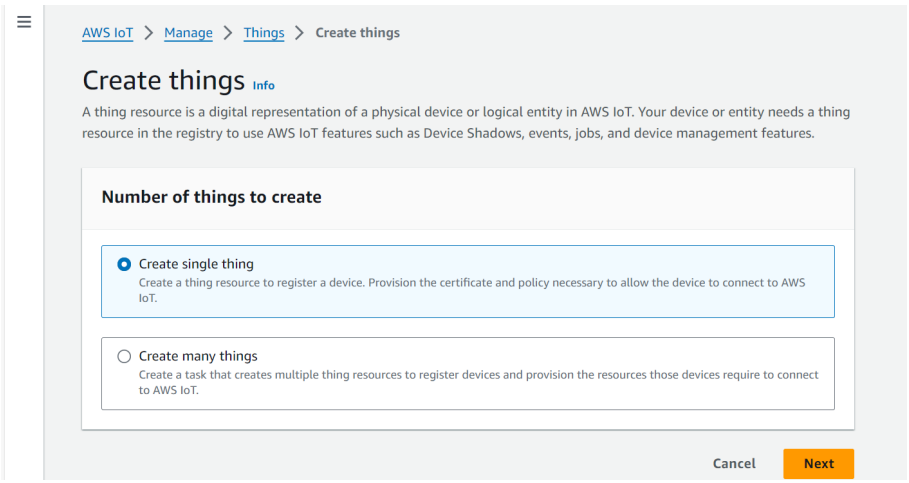
4. In the **Security** drop-down menu, click on **Policies** and add the policies shown below. Then, click **Create**.



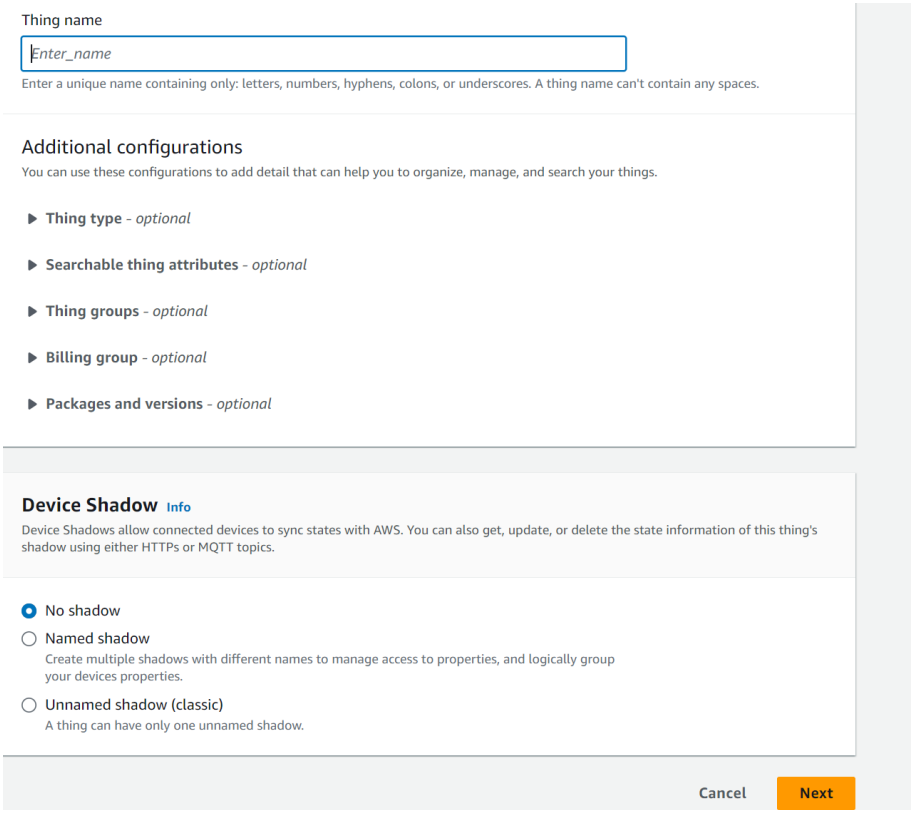
5. In the **All devices** drop-down menu, click on **Things** and click **Create things**.



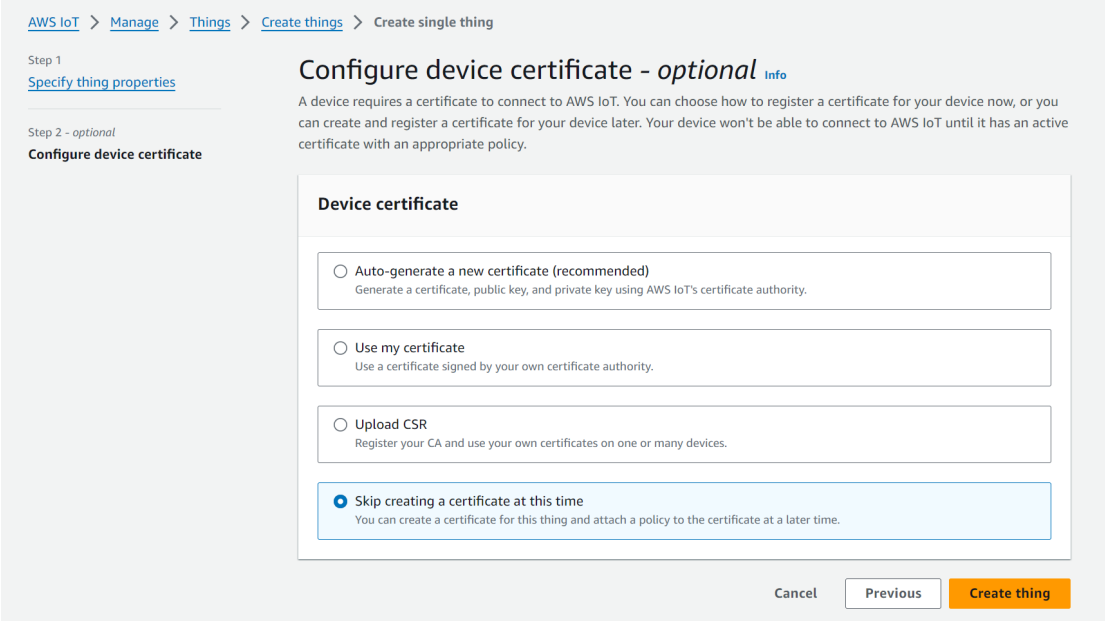
6. Click the **Create single thing** radio button and click **Next**.



7. Enter a **Thing name** and click **Next.**

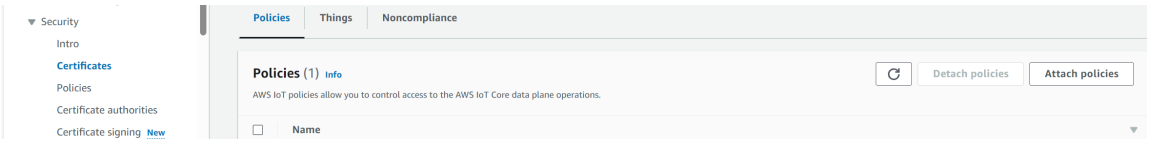


8. Select the **Skip creating a certificate at this time** radio button and click **Create thing**.

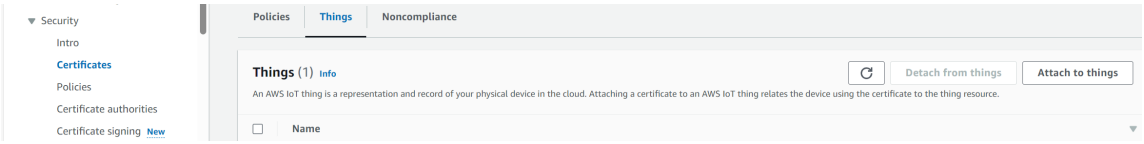


9. In the **Security** drop-down menu, click on **Certificates** and click the Certificate ID of the certificate that you created.

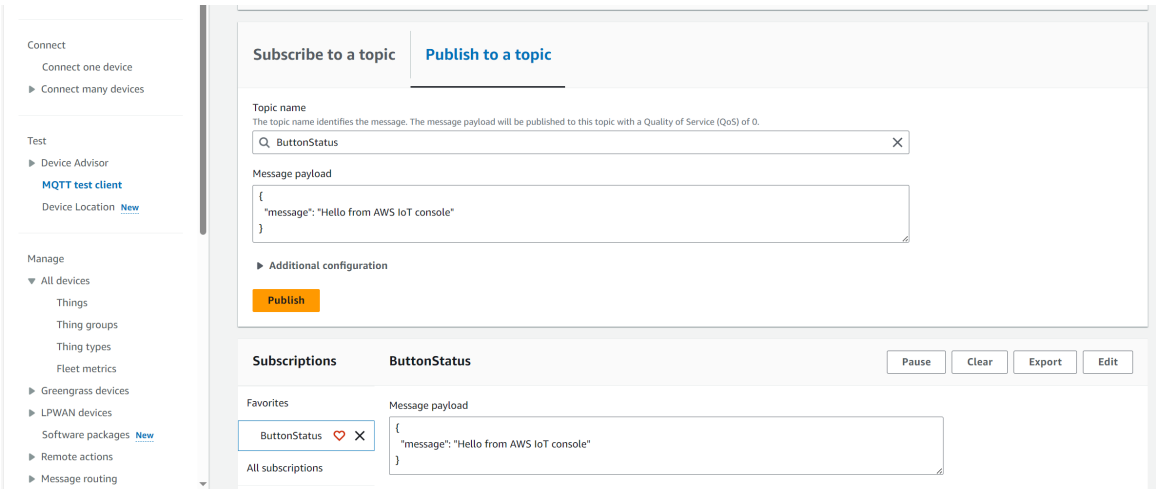
10. In the **Policies** tab at the bottom, click **Attach policies** and add the policy that you created.



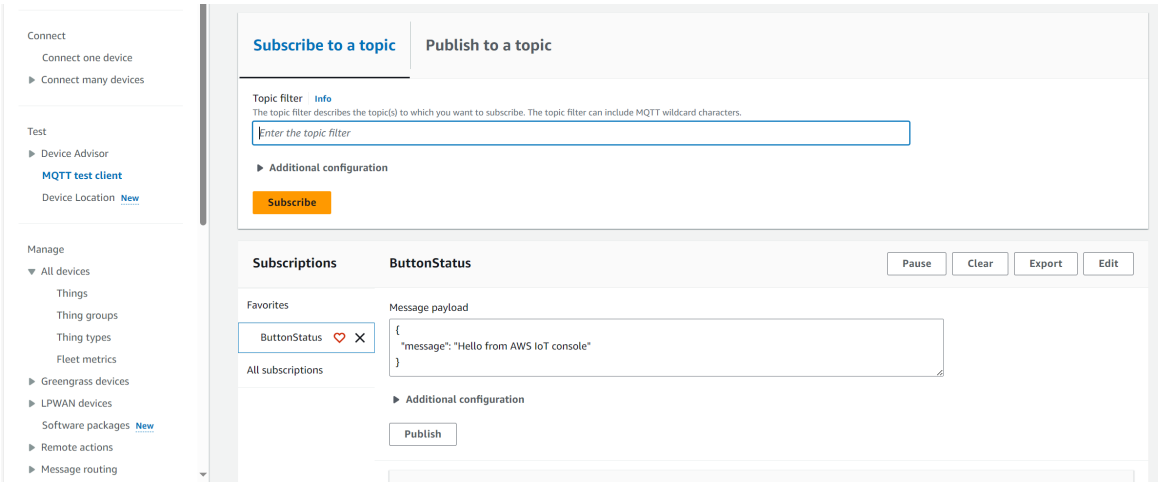
11. In the **Things** tab, click **Attach to things** and add the thing that you created.



12. Click the **MQTT test client** on the left side of the page and click the **Publish to a topic** tab.



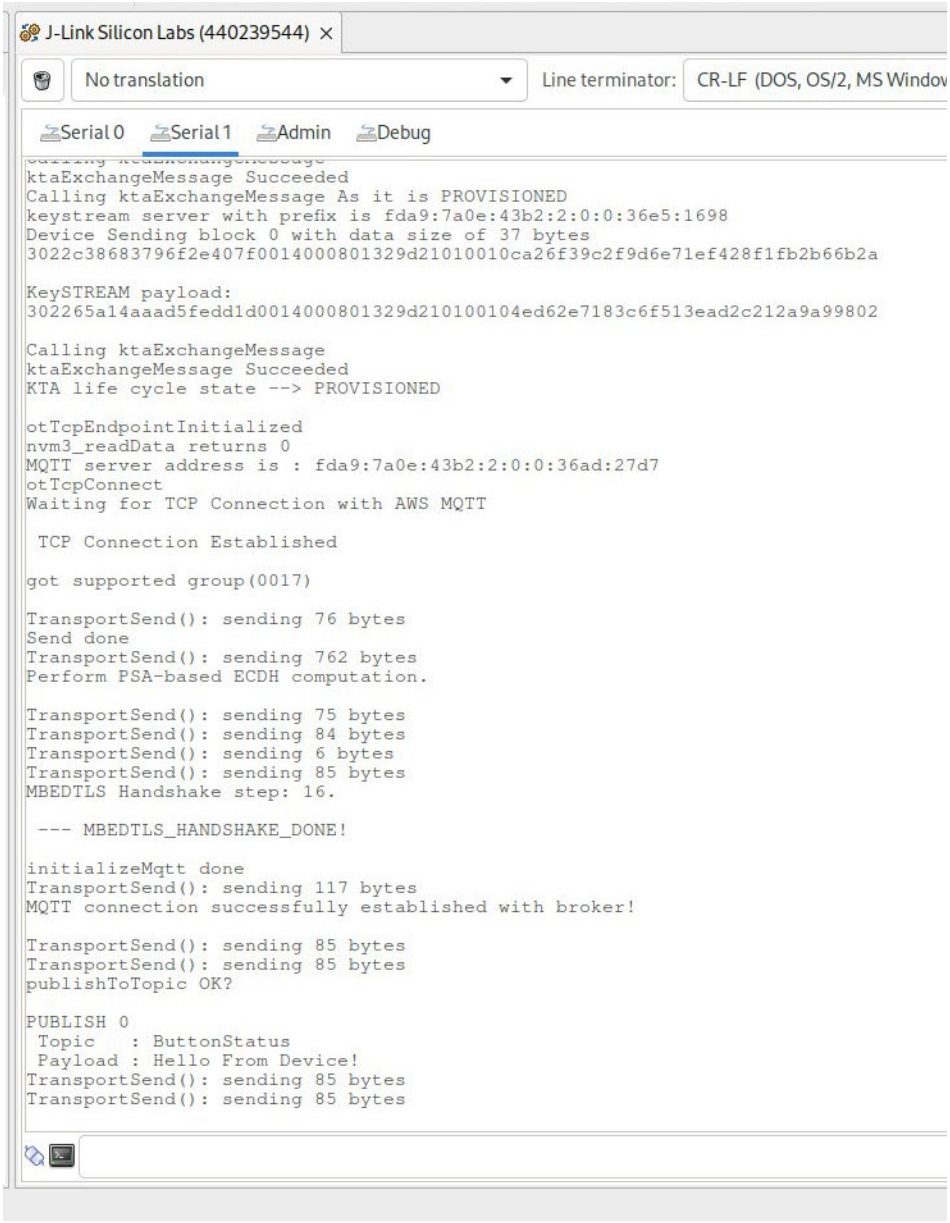
13. Create a message of your choosing and click **Publish**. On the **Subscribe to a topic** tab, make sure that you are subscribed to the topic that you just created.



5.4.2 Testing

Information sent and received by the Silicon Labs Dev Kit to the MQTT test client will be displayed in the device console in Simplicity Commander. This section describes testing the communication between the MQTT test client and the device.

1. On the Thunderboard, press **Button 0**. This will begin the connection to the MQTT test client.


J-Link Silicon Labs (440239544)
No translation
Line terminator:
CR-LF (DOS, OS/2, MS Windov
Serial 0
Serial 1
Admin
Debug
ktaExchangeMessage Succeeded
Calling ktaExchangeMessage As it is PROVISIONED
keystream server with prefix is fda9:7a0e:43b2:2:0:0:36e5:1698
Device Sending block 0 with data size of 37 bytes
3022c38683796f2e407f0014000801329d21010010ca26f39c2f9d6e71ef428f1fb2b66b2a
KeySTREAM payload:
302265a14aaad5fedd1d0014000801329d210100104ed62e7183c6f513ead2c212a9a99802
Calling ktaExchangeMessage
ktaExchangeMessage Succeeded
KTA life cycle state --> PROVISIONED
otTcpEndpointInitialized
nvm3_readData returns 0
MQTT server address is : fda9:7a0e:43b2:2:0:0:36ad:27d7
otTcpConnect
Waiting for TCP Connection with AWS MQTT
TCP Connection Established
got supported group(0017)
TransportSend(): sending 76 bytes
Send done
TransportSend(): sending 762 bytes
Perform PSA-based ECDH computation.
TransportSend(): sending 75 bytes
TransportSend(): sending 84 bytes
TransportSend(): sending 6 bytes
TransportSend(): sending 85 bytes
MBEDTLS Handshake step: 16.
--- MBEDTLS_HANDSHAKE_DONE!
initializeMqtt done
TransportSend(): sending 117 bytes
MQTT connection successfully established with broker!
TransportSend(): sending 85 bytes
TransportSend(): sending 85 bytes
publishToTopic OK?
PUBLISH 0
Topic : ButtonStatus
Payload : Hello From Device!
TransportSend(): sending 85 bytes
TransportSend(): sending 85 bytes

6 Build 5 (BRSKI over Wi-Fi, NquiringMinds)

This section of the practice guide contains detailed instructions for installing and configuring all of the products used to build an instance of the example solution. For additional details on Build 5's logical and physical architectures, see NIST SP 1800-36B: *Approach, Architecture, and Security Characteristics*.

The network-layer onboarding component of Build 5 utilizes the BRSKI protocol.

6.1 Pledge

The pledge acts as the IoT device attempting to onboard onto the secure network. It implements the pledge functionality as per the IETF BRSKI specification. It consists of software provided by NquiringMinds running on a Raspberry Pi Model 4B.

6.1.1 Installation and Configuration

Hardware requirements, pre-installation steps, installation steps, and configuration instructions for the pledge device can be found at the official NquiringMinds repository.

6.1.2 Operation and Demonstration

To demonstrate the onboarding and offboarding functionality, NquiringMinds has provided a web application that runs on the pledge device. It features a button to manually run the onboarding script and display the output of the onboarding process, as well as a button for offboarding. It also features a button to ping an IP address via the wireless network interface.

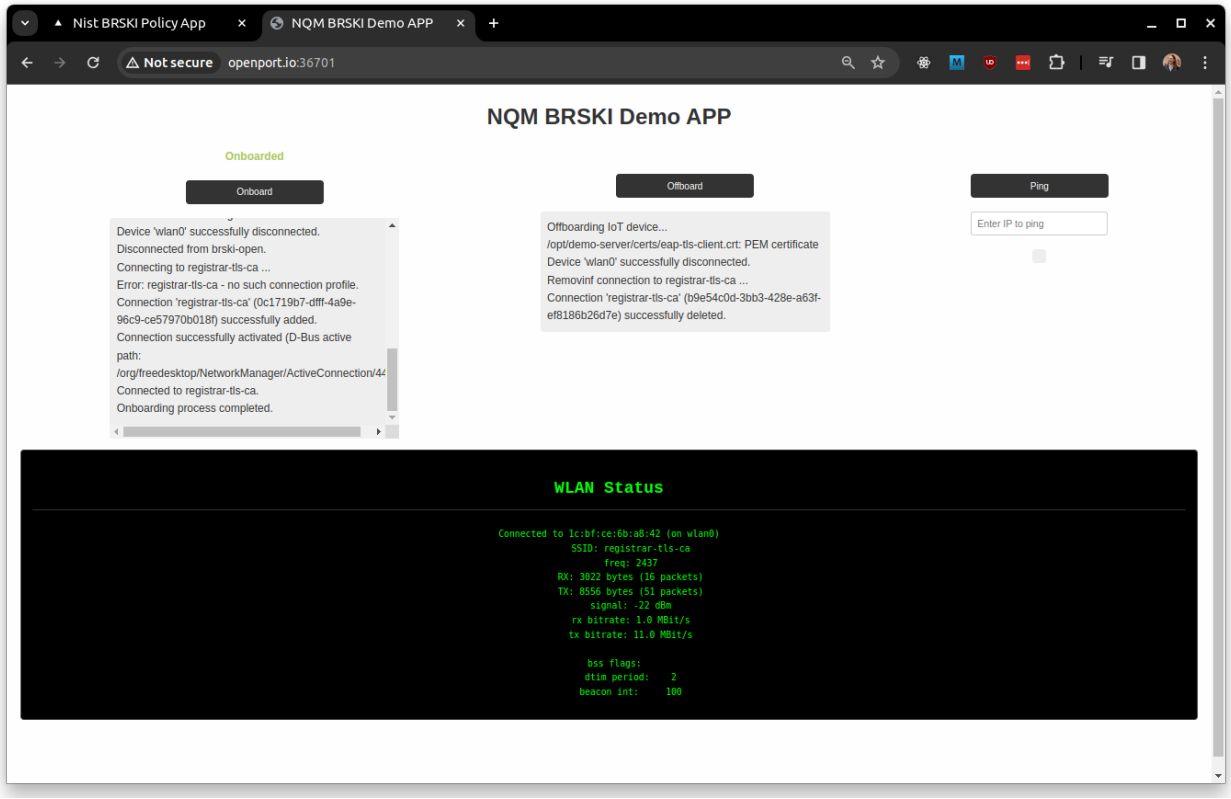


Figure 6-1 NQM BRSKI Demo App Web Interface

6.2 Router and Logical Services

The router and logical services were hosted on a Raspberry Pi Model 4B equipped with two external Wi-Fi adapters. These additional Wi-Fi adapters are needed to support VLAN tagging, which is a hardware-dependent feature. The details of the physical setup and all connections are provided in the official NquiringMinds documentation.

6.2.1 Installation and Configuration

All of the services described in the next section can be installed on a Raspberry Pi using the installer provided by NquiringMinds.

The demonstration services can also be built from source code if needed. The following links provide the instructions for building each of those services:

- BRSKI Demo Setup
- EAP Config
- MDNS publishing services

6.2.2 Logical Services

The following logical services are installed on the registrar and services device. Their implementations can be found at the following repository links: NIST BRSKI implementation and BRSKI.

Figure 6-2 below describes how these entities and logical services fit together to perform the BRSKI flow and a top-level view of how information is transmitted throughout the services to onboard the pledge.

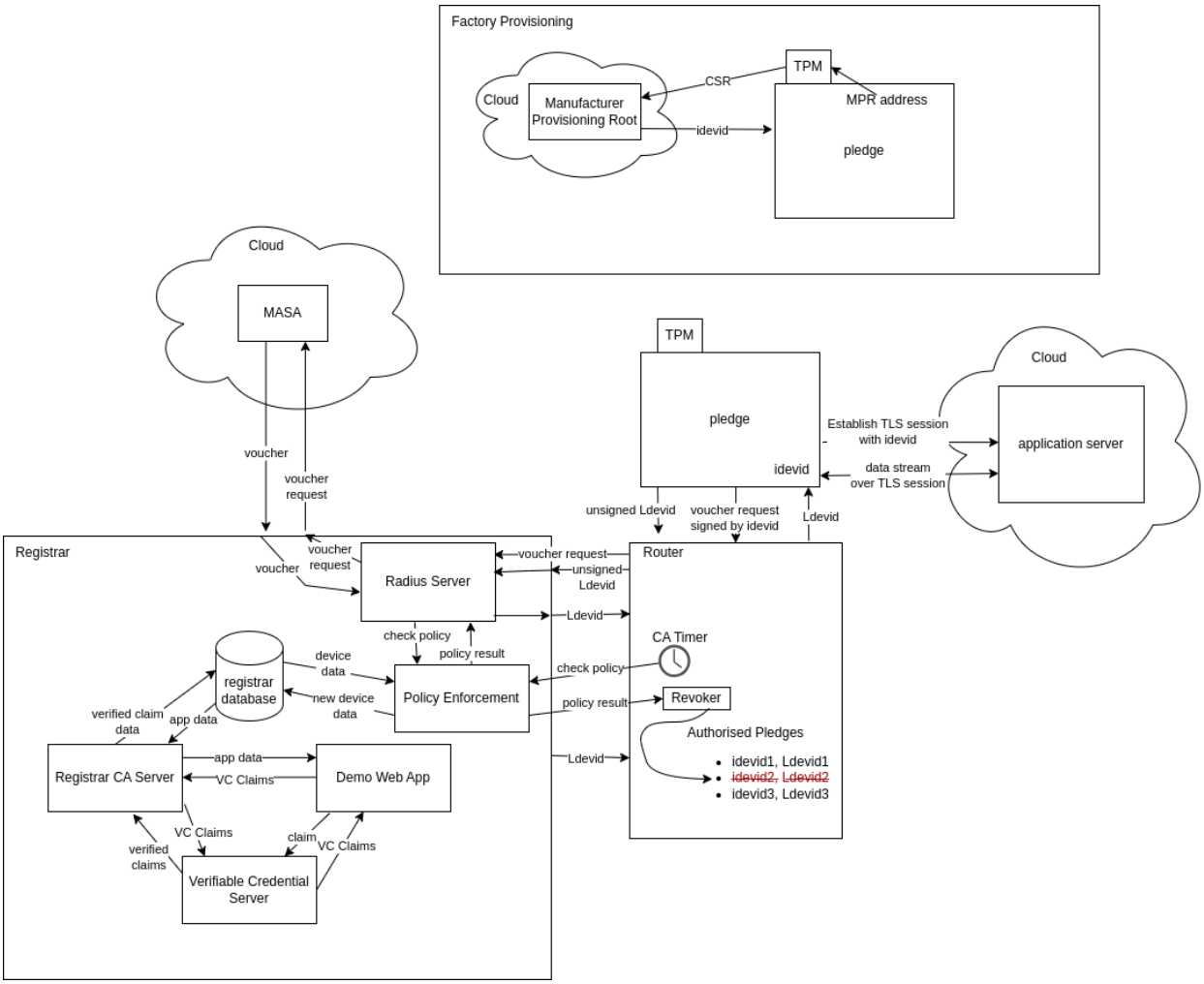


Figure 6-2 Logical Services for Build 5

6.2.2.1 MASA

The MASA currently resides as a local service on the registrar. In practice, this service would be located on an external server managed by the manufacturer. The MASA verifies that the IDevID is authentic and that the manufacturer's MPR produced the IDevID.

6.2.2.2 Manufacturer Provisioning Root (MPR)

The MPR sits on an external server and provides the IDevID (X.509 Certificate) for the device to initialize after production and notarize with a unique identity. The address of the MPR is built into the device's firmware at build time.

6.2.2.3 Registrar

Build 5's BRSKI Domain Registrar runs the BRSKI protocol modified to work over Wi-Fi and functions as the Domain Registrar to authenticate the IoT devices, receive and transfer voucher requests and

responses to and from the MASA, and ultimately determines whether network-layer onboarding of the device is authorized to take place on the respective network. NquiringMinds has developed a stateful, non-persistent Linux app for Android that serves this purpose.

The registrar is responsible for verifying if the IDevID certificate provided by the pledge is authentic by verifying it with the MASA and verifying that the policy for a pledge to be allowed onto the closed, secure network has been met. It also runs continuous assurance periodically to ensure that the device still meets the policy requirements, revoking the pledge's access if, at a later time, it doesn't meet the policy requirements. Signed verifiable credential claims may be submitted to the registrar to communicate information about entities, which it uses to update the database used to determine if the policy is met. The tdx Volt facilitates the signing and verification of verifiable credentials. The MASA and router are integrated into the same physical device in the demonstrator system.

6.2.2.3.1 Radius server (Continuous Assurance Client)

The registrar includes a Radius server that integrates with the Continuous Assurance Server to provide continuous assurance capabilities for connected IoT devices.

The continuous assurance policy is enforced by a script that periodically runs to ensure the policy conditions are met. It accomplishes this by querying the Registrar's SQLite database. For the demonstration, the defined policy is:

- The manufacturer and device must be trusted by a user with appropriate privileges.
- The device must have a device type associated with it.
- The vulnerability score of the Software Bill of Materials (SBOM) for the device type must be lower than six.
- The device must not have contacted a denylisted IP address within the last two minutes.

If the device fails any of these checks, the device will be offboarded.

6.2.2.4 Continuous Assurance Server

The registrar runs several services used to power the continuous assurance flow.

6.2.2.4.1 Verifiable Credential Server

The verifiable credential server is used to sign credentials submitted through the Demo web app and verify the credentials submitted to the registrar. The web app is powered by a local instance of the tdx Volt running on the registrar.

The code for the Verifiable Credential Server is hosted at the GitHub repository.

6.2.2.4.2 Registrar Continuous Assurance Server

The registrar hosts a REST API that is used to interface with the registrar's SQLite database; the database stores information about the entities the registrar knows of. This server utilizes the verifiable credential server to validate the verifiable credential claims submitted.

The code for the Registrar Continuous Assurance Server is hosted at the GitHub repository.

6.2.2.4.3 Demo Web Application

The demo web application is used as an interactive, user-friendly way to administer the registrar. Users can view the list of verifiable credentials submitted to the registrar. The application also displays the state of the manufacturers, devices, device types, and Manufacturer Usage Description (MUD). There are buttons provided that allow you to trust or distrust a manufacturer, trust or distrust a device, set the device type for a device, set if a device type is vulnerable, and set the MUD file associated with the device type. These operations are performed by generating a verifiable credential containing the claim being made, which is then submitted to the verifiable credential server to sign the credential. The signed verifiable credential is then sent to the Registrar Continuous Assurance Server to be verified and used to update the SQLite database on the registrar.

The code for the Demo Web Application is hosted at the GitHub repository.

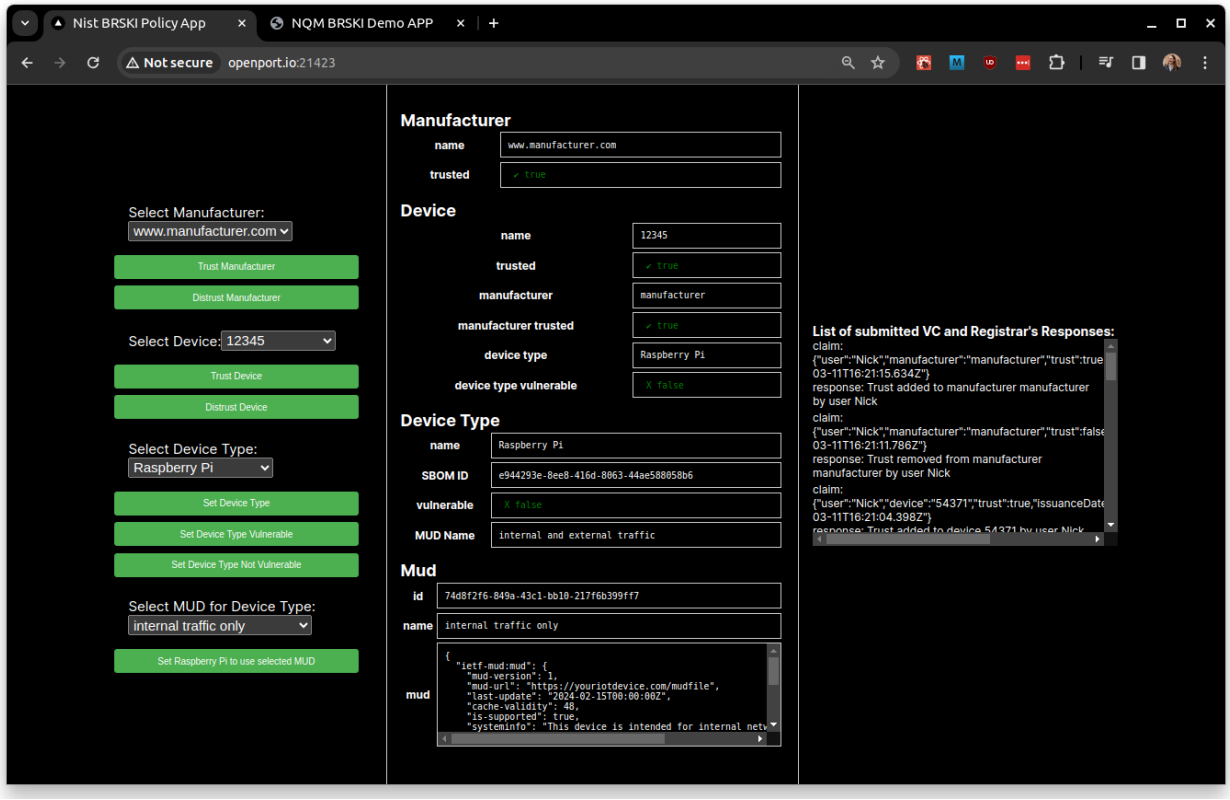


Figure 6-3 NQM BRSKI Policy App Web Interface

6.2.2.5 *Application server*

The application server is hosted on a remote server and is the destination for data consumed from the pledge device. To onboard onto the application server, the pledge device establishes a secure TLS connection using its IDevID certificate. Currently, the pledge uses OpenSSL's s_client to initiate the TLS session with the application server, which runs off-site. As a proof of concept, the pledge device sends data—such as the current date and CPU temperature—to be logged on the application server.

6.2.2.5.1 Installation/Configuration

Hardware requirements, pre-installation steps, installation steps, and configuration instructions for the router can be found at the official NquiringMinds repository.

6.2.2.5.2 Operation/Demonstration

The instructions for using this factory use case code to provision an IDevID onto your pledge are also located at the official NquiringMinds repository in the above section.

6.3 Onboarding Demonstration

6.3.1 Prerequisites

Prior to beginning the demonstration, the router and pledge devices must be connected to power and the network via their Ethernet port. Both devices should start the services required to demonstrate the BRSKI flow on boot.

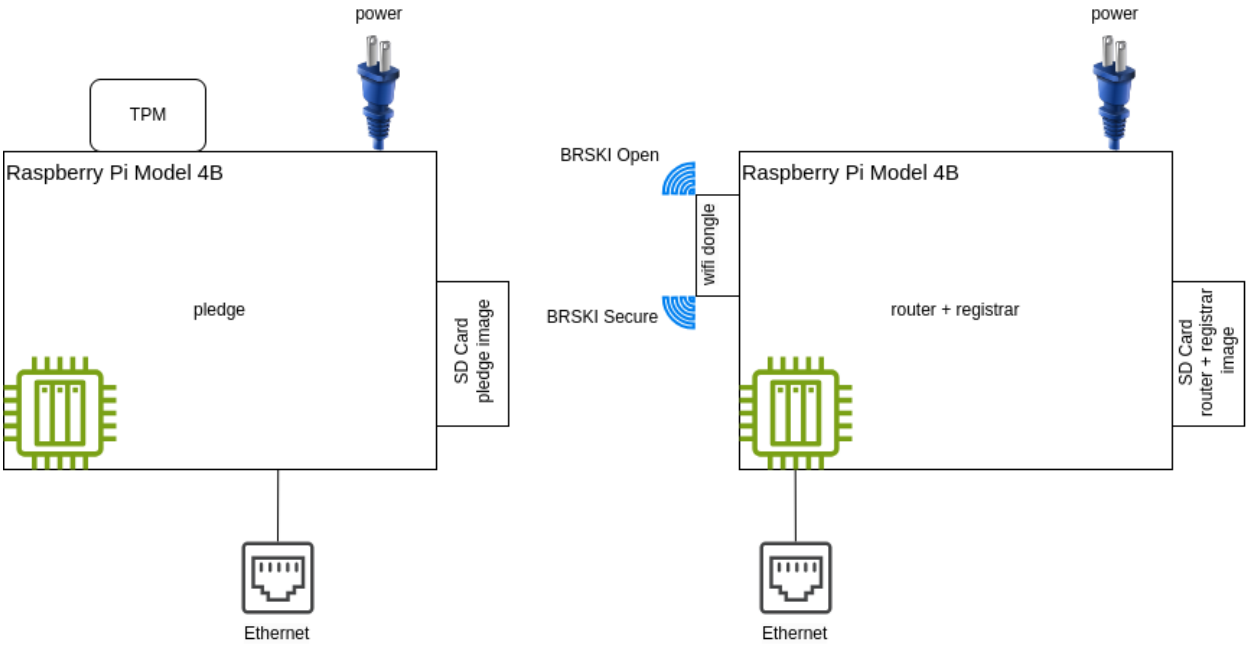


Figure 6-4 Diagram of Physical/Logical Components Used to Demonstrate BRSKI Flow

To support the demo and debug features, the pledge and the registrar need to be connected to physical Ethernet, ideally with internet access. They should still function without an internet connection, but the SBOMs' vulnerability scores will not be updated, and the demo web apps will only be accessible on the local network.

The details of the networking setup are available in the NquiringMinds NIST Trusted Onboarding Build-5.

6.3.2 Onboarding Demonstration

Once the devices have been configured and the prerequisite conditions have been achieved, the onboarding demonstration can be executed following the NquiringMinds Demo Continuous Assurance Workflow.

6.3.3 Continuous Assurance Demonstration

The instructions to demonstrate the continuous assurance workflow are contained in the official NquiringMinds documentation.

6.4 BRSKI Factory Provisioning Build

This Factory Provisioning Build includes many of the components listed in Section 6.2, including the Pledge, Registrar, and other services. An Infineon Secure Element was also included in the build and provides secure generation and storage of the key material and certificates provisioned to the device.

6.4.1 Pledge

The pledge acts as the IoT device attempting to onboard onto the secure network. It implements the pledge functionality as per the IETF BRSKI specification. It consists of a Raspberry Pi Model 4B equipped with an Infineon Optiga SLB 9670 TPM 2.0 Secure Element, which was connected to the Raspberry Pi via the built-in GPIO pins.

6.4.1.1 Factory Use Case - IDevID provisioning

NquiringMinds provided demonstration code that generates a public/private key pair within the secure element, creates a CSR, and uses that CSR to obtain an IDevID certificate from tdx Volt. The demonstration process can be found in the official NquiringMinds documentation.

Initially, it generates a CSR using the TPM secure element to sign it, then sends the CSR to the MPR server (the manufacturer's IDevID Certificate Authority) and bootstraps the vanilla firmware on the pledge's creation in the factory. The MPR sends back a unique IDevID for the pledge, which it stores in its secure element.

The code for this is hosted at the official NquiringMinds repository.

6.4.2 Installation and Configuration

Hardware requirements, pre-installation steps, installation steps, and configuration instructions for the pledge can be found in the official NquiringMinds repository referenced above.

6.4.3 Operation and Demonstration

The instructions for using this factory provisioning use case code to provision an IDevID onto the pledge are also in the official NquiringMinds repository referenced above.

Appendix A List of Acronyms

AKM	Authentication and Key Management
AOS	ArubaOS
AP	Access Point
API	Application Programming Interface
ASN.1	Abstract Syntax Notation One
AWS	Amazon Web Services
BRSKI	Bootstrapping Remote Secure Key Infrastructure
BSS	Basic Service Set
CA	Certificate Authority
CRADA	Cooperative Research and Development Agreement
CSR	Certificate Signing Request
DPP	Device Provisioning Protocol (Wi-Fi Easy Connect)
EAP	Extensible Authentication Protocol
GPIO	General Purpose Input/Output
GUI	Graphical User Interface
HPE	Hewlett Packard Enterprise
IaaS	Infrastructure as a Service
IDevID	Initial Device Identifier
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IPv4	Internet Protocol Version 4
IPv6	Internet Protocol Version 6
ITL	Information Technology Laboratory
LDevID	Locally Significant Device Identifier
MASA	Manufacturer Authorized Signing Authority
MPR	Manufacturer Provisioning Root
MUD	Manufacturer Usage Description
MQTT	MQ Telemetry Transport

NCCoE	National Cybersecurity Center of Excellence
NIST	National Institute of Standards and Technology
OCF	Open Connectivity Foundation
OS	Operating System
OTBR	Open Thread Border Router
PNG	Portable Network Graphics
POP	Proof of Possession
QR	Quick-Response
RF	Radio Frequency
SBOM	Software Bill of Materials
SP	Special Publication
SoC	System-on-Chip
SSID	Service Set Identifier
TPM	Trusted Platform Module
UID	Unique Identifier
URI	Uniform Resource Identifier
USB	Universal Serial Bus
UXI	User Experience Insight
VLAN	Virtual Local Area Network
VM	Virtual Machine
WLAN	Wireless Local Area Network
WPA2	Wi-Fi Protected Access 2
WPA3	Wi-Fi Protected Access 3

Appendix B References

[1] Wi-Fi Alliance. *Wi-Fi Easy Connect*. Available: https://www.wi-fi.org/discover-wi-fi/wi-fi-easy-connect.