NIST SPECIAL PUBLICATION 1800-36

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

Enhancing Internet Protocol-Based IoT Device and Network Security

Includes Executive Summary (A); Approach, Architecture, and Security Characteristics (B); How-To Guides (C); Functional Demonstrations (D) and Compliance and Risk Management (E)

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May 2024

DRAFT

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NIST SPECIAL PUBLICATION 1800-36A

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

Enhancing Internet Protocol-Based IoT Device and Network Security

Volume A:
Executive Summary

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Executive Summary

Establishing trust between a network and an Internet of Things (IoT) device (as defined in [NIST Internal Report 8425]) prior to providing the device with the credentials it needs to join the network is crucial for mitigating the risk of potential attacks. There are two possibilities for attack. One happens when a device is convinced to join an unauthorized network, which would take control of the device. The other occurs when a network is infiltrated by a malicious device. Trust is achieved by attesting and verifying the identity and posture of the device and the network before providing the device with its network credentials—a process known as *network-layer onboarding*. In addition, scalable, automated mechanisms are needed to safely manage IoT devices throughout their lifecycles, such as safeguards that verify the security posture of a device before the device is permitted to execute certain operations. In this practice guide, the National Cybersecurity Center of Excellence (NCCoE) applies standards, best practices, and commercially available technology to demonstrate various mechanisms for trusted network-layer onboarding of IoT devices in Internet Protocol based environments. This guide shows how to provide network credentials to IoT devices in a trusted manner and maintain a secure device posture throughout the device lifecycle, thereby enhancing IoT security in alignment with the IoT Cybersecurity Improvement Act of 2020.

CHALLENGE

With 40 billion IoT devices expected to be connected worldwide by 2025, it is unrealistic to onboard or manage these devices by manually interacting with each device. In addition, providing local network credentials at the time of manufacture requires the manufacturer to customize network-layer onboarding on a build-to-order basis, which prevents the manufacturer from taking full advantage of the economies of scale that could result from building identical devices for its customers.

There is a need to have a scalable, automated mechanism to securely manage IoT devices throughout their lifecycles and, in particular, a trusted mechanism for providing IoT devices with their network credentials and access policy at the time of deployment on the network. It is easy for a network to falsely identify itself, yet many IoT devices onboard to networks without verifying the network's identity and ensuring that it is their intended target network. Also, many IoT devices lack user interfaces, making it cumbersome to manually input network credentials. Wi-Fi is sometimes used to provide credentials over an open (i.e., unencrypted) network, but this onboarding method risks credential disclosure. Most home networks use a single password shared among all devices, so access is controlled only by the device's possession of the password and does not consider a unique device identity or whether the device belongs on the network. This method also increases the risk of exposing credentials to unauthorized parties. Providing unique credentials to each device is more secure, but providing unique credentials manually would be resource-intensive and error-prone, would risk credential disclosure, and cannot be performed at scale.

Once a device is connected to the network, if it becomes compromised, it can pose a security risk to both the network and other connected devices. Not keeping such a device current with the most recent software and firmware updates may make it more susceptible to compromise. The device could also be attacked through receipt of malicious payloads. Once compromised, it may be used to attack other devices on the network.

OUTCOME

The outcome of this project is development of example trusted onboarding solutions, demonstration that they support various scenarios, and publication of the findings in this practice guide, a NIST Special Publication (SP) 1800 that is composed of multiple volumes targeting different audiences.

This practice guide can help IoT device users:

Understand how to onboard their IoT devices in a trusted manner to:

- **Ensure that their network is not put at risk** as new IoT devices are added to it
- **Safeguard their IoT devices** from being taken over by unauthorized networks
- **Provide IoT devices with unique credentials** for network access
- **Provide, renew, and replace device network credentials** in a secure manner
- **Support ongoing protection of IoT devices** throughout their lifecycles

This practice guide can help manufacturers and vendors of semiconductors, secure storage components, IoT devices, and network onboarding equipment:

Understand the desired security properties for supporting trusted network-layer onboarding and explore their options with respect to recommended practices for:

- **Providing unique credentials into secure storage on IoT devices at the time of manufacture to mitigate supply chain risks** (i.e., *device credentials*)
- **Installing onboarding software onto IoT devices**
- **Providing IoT device purchasers with information needed to onboard the IoT devices to their networks** (i.e., *device bootstrapping information*)
- **Integrating support for network-layer onboarding with additional security capabilities** to provide ongoing protection throughout the device lifecycle

SOLUTION

The NCCoE recommends the use of trusted network-layer onboarding to provide scalable, automated, trusted ways to provide IoT devices with unique network credentials and manage devices throughout their lifecycles to ensure that they remain secure. The NCCoE is collaborating with technology providers and other stakeholders to implement example trusted network-layer onboarding solutions for IoT devices that:

- provide each device with unique network credentials,
- enable the device and the network to mutually authenticate,
- send devices their credentials over an encrypted channel,
- do not provide any person with access to the credentials, and

- can be performed repeatedly throughout the device lifecycle.

The capabilities demonstrated include:

- trusted network-layer onboarding of IoT devices,
- repeated trusted network-layer onboarding of devices to the same or a different network,
- trusted application-layer onboarding (i.e., automatic establishment of an encrypted connection between an IoT device and a trusted application service after the IoT device has performed trusted network-layer onboarding and used its credentials to connect to the network), and
- software-based methods to provide device credentials in the factory and transfer device bootstrapping information from device manufacturer to device purchaser.

Future capabilities may include demonstrating the integration of trusted network-layer onboarding with zero trust-inspired [Note: See NIST SP 800-207] mechanisms such as ongoing device authorization, renewal of device network credentials, device attestation to ensure that only trusted IoT devices are permitted to be onboarded, device lifecycle management, and enforcement of device communications intent.

This demonstration follows an agile methodology of building implementations (i.e., *builds*) iteratively and incrementally, starting with network-layer onboarding and gradually integrating additional capabilities that improve device and network security throughout a managed device lifecycle. This includes factory builds that simulate activities performed to securely provide device credentials during the manufacturing process, and five network-layer onboarding builds that demonstrate the Wi-Fi Easy Connect, Bootstrapping Remote Secure Key Infrastructure (BRSKI), and Thread Commissioning protocols. These builds also demonstrate both streamlined and independent trusted application-layer onboarding approaches, along with policy-based continuous assurance and authorization. The example implementations use technologies and capabilities from our project collaborators (listed below).

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

While the NCCoE uses a suite of commercial products, services, and proof-of-concept technologies to address this challenge, this guide does not endorse these particular products, services, and technologies, nor does it guarantee compliance with any regulatory initiatives. Your organization's information security experts should identify the products and services that will best integrate with your existing tools, IT and IoT system infrastructure, and operations. Your organization can adopt these solutions 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 solution.

HOW TO USE THIS GUIDE

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

Business decision makers, such as chief information security, product security, and technology officers, can use this part of the guide, *NIST SP 1800-36A: Executive Summary*, to understand the project's challenges and outcomes, as well as our solution approach.

Technology, security, and privacy program managers who are concerned with how to identify, understand, assess, and mitigate risk can use *NIST SP 1800-36B: Approach, Architecture, and Security Characteristics*. This part of the guide describes the architecture and different implementations. Also, *NIST SP 1800-36E: Risk and Compliance Management,* maps components of the trusted onboarding reference architecture to security characteristics in broadly applicable, well-known cybersecurity guidelines and practices.

IT professionals who want to implement an approach like this can make use of *NIST SP 1800-36C: How-To Guides*. It provides product installation, configuration, and integration instructions for building example implementations, allowing them to be replicated in whole or in part. They can also use *NIST SP 1800-36D*: *Functional Demonstrations,* which provides the use cases that have been defined to showcase trusted network-layer onboarding and lifecycle management security capabilities and the results of demonstrating these capabilities with each of the example implementations. These use cases may be helpful when developing requirements for systems being developed.

SHARE YOUR FEEDBACK

You can view or download the preliminary draft guide at https://www.nccoe.nist.gov/projects/building-blocks/iot-network-layer-onboarding. NIST is adopting an agile process to publish this content. Each volume is being made available as soon as possible rather than delaying release until all volumes are completed.

Help the NCCoE make this guide better by sharing your thoughts with us as you read the guide. As example implementations continue to be developed, you can adopt this solution for your own organization. If you do, please share your experience and advice with us. We recognize that technical solutions alone will not fully enable the benefits of our solution, so we encourage organizations to share lessons learned and recommended practices for transforming the processes associated with implementing this guide.

To provide comments, join the community of interest, or learn more by arranging a demonstration of these example implementations, contact the NCCoE at iot-onboarding@nist.gov.

COLLABORATORS

Collaborators participating in this project submitted their capabilities in response to an open call in the Federal Register for all sources of relevant security capabilities from academia and industry (vendors and integrators). Those respondents with relevant capabilities or product components signed a Cooperative Research and Development Agreement (CRADA) to collaborate with NIST in a consortium to build this example solution.

Certain commercial entities, equipment, products, or materials may be identified by name or company logo or other insignia in order to acknowledge their participation in this collaboration or to describe an experimental procedure or concept adequately. Such identification is not intended to imply special status or relationship with NIST or recommendation or endorsement by NIST or the NCCoE; neither is it intended to imply that the entities, equipment, products, or materials are necessarily the best available for the purpose.

NIST SPECIAL PUBLICATION 1800-36B

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

Enhancing Internet Protocol-Based IoT Device and Network Security

Volume B:
Approach, Architecture, and Security Characteristics

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May 2024

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DISCLAIMER

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National Institute of Standards and Technology Special Publication 1800-36B, Natl. Inst. Stand. Technol. Spec. Publ. 1800-36B, 114 pages, May 2024, CODEN: NSPUE2

FEEDBACK

You can improve this guide by contributing feedback regarding which aspects of it you find helpful as well as suggestions on how it might be improved. Should we provide guidance summaries that target specific audiences? What trusted IoT device onboarding protocols and related features are most important to you? Is there some content that is not included in this document that we should cover? Are we missing anything in terms of technologies or use cases? In what areas would it be most helpful for us to focus our future related efforts? For example, should we consider implementing builds that onboard devices supporting Matter and/or the Fast Identity Online (FIDO) Alliance application onboarding protocol? Should we implement builds that integrate security mechanisms such as lifecycle management, supply chain management, attestation, or behavioral analysis? As you review and adopt this solution for your own organization, we ask you and your colleagues to share your experience and advice with us.

Comments on this publication may be submitted to: iot-onboarding@nist.gov.

Public comment period: May 31, 2024 through July 30, 2024

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

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NATIONAL CYBERSECURITY CENTER OF EXCELLENCE

The National Cybersecurity Center of Excellence (NCCoE), a part of the National Institute of Standards and Technology (NIST), is a collaborative hub where industry organizations, government agencies, and academic institutions work together to address businesses' most pressing cybersecurity issues. This public-private partnership enables the creation of practical cybersecurity solutions for specific industries, as well as for broad, cross-sector technology challenges. Through consortia under Cooperative Research and Development Agreements (CRADAs), including technology partners—from Fortune 50 market leaders to smaller companies specializing in information technology security—the NCCoE applies standards and best practices to develop modular, adaptable example cybersecurity solutions using commercially available technology. The NCCoE documents these example solutions in the NIST Special Publication 1800 series, which maps capabilities to the NIST Cybersecurity Framework and details the steps needed for another entity to re-create the example solution. The NCCoE was established in 2012 by NIST in partnership with the State of Maryland and Montgomery County, Maryland.

To learn more about the NCCoE, visit https://www.nccoe.nist.gov/. To learn more about NIST, visit https://www.nist.gov.

NIST CYBERSECURITY PRACTICE GUIDES

NIST Cybersecurity Practice Guides (Special Publication 1800 series) target specific cybersecurity challenges in the public and private sectors. They are practical, user-friendly guides that facilitate the adoption of standards-based approaches to cybersecurity. They show members of the information security community how to implement example solutions that help them align with relevant standards and best practices, and provide users with the materials lists, configuration files, and other information they need to implement a similar approach.

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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Name	Organization
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Toby Ealden	NquiringMinds
John Manslow	NquiringMinds
Antony McCaigue	NquiringMinds
Alexandru Mereacre	NquiringMinds
Loic Cavaille	NXP Semiconductors
Mihai Chelalau	NXP Semiconductors
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Anda-Alexandra Dorneanu	NXP Semiconductors
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Kalvin Yang	SEALSQ, a subsidiary of WISeKey

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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The terms “shall” and “shall not” indicate requirements to be followed strictly to conform to the publication and from which no deviation is permitted. The terms “should” and “should not” indicate that among several possibilities, one is recommended as particularly suitable without mentioning or excluding others, or that a certain course of action is preferred but not necessarily required, or that (in the negative form) a certain possibility or course of action is discouraged but not prohibited. The terms “may” and “need not” indicate a course of action permissible within the limits of the publication. The terms “can” and “cannot” indicate a possibility and capability, whether material, physical, or causal.

CALL FOR PATENT CLAIMS

This public review includes a call for information on essential patent claims (claims whose use would be required for compliance with the guidance or requirements in this Information Technology Laboratory (ITL) draft publication). Such guidance and/or requirements may be directly stated in this ITL Publication or by reference to another publication. This call also includes disclosure, where known, of the existence of pending U.S. or foreign patent applications relating to this ITL draft publication and of any relevant unexpired U.S. or foreign patents.

ITL may require from the patent holder, or a party authorized to make assurances on its behalf, in written or electronic form, either:

a) assurance in the form of a general disclaimer to the effect that such party does not hold and does not currently intend holding any essential patent claim(s); or

b) assurance that a license to such essential patent claim(s) will be made available to applicants desiring to utilize the license for the purpose of complying with the guidance or requirements in this ITL draft publication either:

1. under reasonable terms and conditions that are demonstrably free of any unfair discrimination; or
2. without compensation and under reasonable terms and conditions that are demonstrably free of any unfair discrimination.

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Such statements should be addressed to: iot-onboarding@nist.gov.

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1 Summary

IoT devices are typically connected to a network. As with any other device needing to communicate on a network securely, an IoT device needs credentials that are specific to that network to help ensure that only authorized devices can connect to and use the network. A typical commercially available, mass-produced IoT device cannot be pre-provisioned with local network credentials by the manufacturer during the manufacturing process. Instead, the local network credentials will be provisioned to the device at the time of its deployment. This practice guide is focused on trusted methods of providing IoT devices with the network-layer credentials and policy they need to join a network upon deployment, a process known as *network-layer onboarding.*

Establishing trust between a network and an IoT device (as defined in NIST Internal Report 8425) prior to providing the device with the credentials it needs to join the network is crucial for mitigating the risk of potential attacks. There are two possibilities for attack. One is where a device is convinced to join an unauthorized network, which would take control of the device. The other is where a network is infiltrated by a malicious device. Trust is achieved by attesting and verifying the identity and posture of the device and the network before providing the device with its network credentials—a process known as *network-layer onboarding*. In addition, scalable, automated mechanisms are needed to safely manage IoT devices throughout their lifecycles, such as safeguards that verify the security posture of a device before the device is permitted to execute certain operations.

In this practice guide, the National Cybersecurity Center of Excellence (NCCoE) applies standards, best practices, and commercially available technology to demonstrate various mechanisms for trusted network-layer onboarding of IoT devices. This guide shows how to provide network credentials to IoT devices in a trusted manner and maintain a secure device posture throughout the device lifecycle.

1.1 Challenge

With 40 billion IoT devices expected to be connected worldwide by 2025 [1], it is unrealistic to onboard or manage these devices by visiting each device and performing a manual action. While it is possible for devices to be securely provided with their local network credentials at the time of manufacture, this requires the manufacturer to customize network-layer onboarding on a build-to-order basis, which prevents the manufacturer from taking full advantage of the economies of scale that could result from building identical devices for all its customers.

The industry lacks scalable, automatic mechanisms to safely manage IoT devices throughout their lifecycles and lacks a trusted mechanism for providing IoT devices with their network credentials and policy at the time of deployment on the network. It is easy for a network to falsely identify itself, yet many IoT devices onboard to networks without verifying the network's identity and ensuring that it is their intended target network. Also, many IoT devices lack user interfaces, making it cumbersome to manually input network credentials. Wi-Fi is sometimes used to provide credentials over an open (i.e., unencrypted) network, but this onboarding method risks credential disclosure. Most home networks use a single password shared among all devices, so access is controlled only by the device's possession of the password and does not consider a unique device identity or whether the device belongs on the network. This method also increases the risk of exposing credentials to unauthorized parties. Providing unique credentials to each device is more secure, but doing so manually would be resource-intensive and error-prone, would risk credential disclosure, and cannot be performed at scale.

Once a device is connected to the network, if it becomes compromised, it can pose a security risk to both the network and other connected devices. Not keeping such a device current with the most recent software and firmware updates may make it more susceptible to compromise. The device could also be attacked through the receipt of malicious payloads. Once compromised, it may be used to attack other devices on the network.

1.2 Solution

We need scalable, automated, trusted mechanisms to safely manage IoT devices throughout their lifecycles to ensure that they remain secure, starting with secure ways to provision devices with their network credentials, i.e., beginning with network-layer onboarding. Onboarding is a particularly vulnerable point in the device lifecycle because if it is not performed in a secure manner, then both the device and the network are at risk. Networks are at risk of having unauthorized devices connect to them, and devices are at risk of being taken over by networks that are not authorized to onboard or control them.

The NCCoE has adopted the trusted network-layer onboarding approach to promote automated, trusted ways to provide IoT devices with unique network credentials and manage devices throughout their lifecycles to ensure that they remain secure. The NCCoE is collaborating with CRADA consortium technology providers in a phased approach to develop example implementations of trusted network-layer onboarding solutions. We define a *trusted network-layer onboarding solution* to be a mechanism for provisioning network credentials to a device that:

- provides each device with unique network credentials,
- enables the device and the network to mutually authenticate,
- sends devices their network credentials over an encrypted channel,
- does not provide any person with access to the network credentials, and
- can be performed repeatedly throughout the device lifecycle to enable:
    - the device's network credentials to be securely managed and replaced as needed, and
    - the device to be securely onboarded to other networks after being repurposed or resold.

The use cases designed to be demonstrated by this project's implementations include:

- trusted network-layer onboarding of IoT devices
- repeated trusted network-layer onboarding of devices to the same or a different network
- automatic establishment of an encrypted connection between an IoT device and a trusted application service (i.e., *trusted application-layer onboarding*) after the IoT device has performed trusted network-layer onboarding and used its credentials to connect to the network
- policy-based ongoing device authorization
- software-based methods to provision device birth credentials in the factory

- mechanisms for IoT device manufacturers to provide IoT device purchasers with information needed to onboard the IoT devices to their networks (i.e., *device bootstrapping information*)

1.3 Benefits

This practice guide can benefit both IoT device users and IoT device manufacturers. The guide can help IoT device users understand how to onboard IoT devices to their networks in a trusted manner to:

- Ensure that their network is not put at risk as IoT devices are added to it
- Safeguard their IoT devices from being taken over by unauthorized networks
- Provide IoT devices with unique credentials for network access
- Provide, renew, and replace device network credentials in a secure manner
- Ensure that IoT devices can automatically and securely perform application-layer onboarding after performing trusted network-layer onboarding and connecting to a network
- Support ongoing protection of IoT devices throughout their lifecycles

This guide can help IoT device manufacturers, as well as manufacturers and vendors of semiconductors, secure storage components, and network onboarding equipment, understand the desired security properties for supporting trusted network-layer onboarding and demonstrate mechanisms for:

- Placing unique credentials into secure storage on IoT devices at time of manufacture (i.e., *device birth credentials*)
- Installing onboarding software onto IoT devices
- Providing IoT device purchasers with information needed to onboard the IoT devices to their networks (i.e., *device bootstrapping information*)
- Integrating support for network-layer onboarding with additional security capabilities to provide ongoing protection throughout the device lifecycle

2 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 and 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 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.

NIST is adopting an agile process to publish this content. Each volume is being made available as soon as possible rather than delaying release until all volumes are completed.

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 **(you are here)**
- 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
- 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 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 or security 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 implementations for trusted IoT device network-layer onboarding and lifecycle management.

IT professionals who want to implement similar solutions will find all volumes of the 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 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. Finally, *NIST SP 1800-36E* will be helpful in explaining 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 that 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 welcome your input. Comments, suggestions, and success stories will improve subsequent versions of this guide. Please contribute your thoughts to iot-onboarding@nist.gov.

2.1 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.

3 Approach

This project builds on the document-based research presented in the NIST Draft Cybersecurity White Paper, *Trusted Internet of Things (IoT) Device Network-Layer Onboarding and Lifecycle Management* [2]. That paper describes key security and other characteristics of a trusted network-layer onboarding solution as well as the integration of onboarding with related technologies such as device attestation, device communications intent [3][4], and application-layer onboarding. The security and other attributes of the onboarding process that are cataloged and defined in that paper can provide assurance that the network is not put at risk as new IoT devices are added to it and also that IoT devices are safeguarded from being taken over by unauthorized networks.

To kick off this project, the NCCoE published a Federal Register Notice [5] inviting technology providers to participate in demonstrating approaches to deploying trusted IoT device network-layer onboarding and lifecycle management in home and enterprise networks, with the objective of showing how trusted IoT device network-layer onboarding can practically and effectively enhance the overall security of IoT devices and, by extension, the security of the networks to which they connect. The Federal Register Notice invited technology providers to provide products and/or expertise to compose prototypes. Components sought included network onboarding components and IoT devices that support trusted network-layer onboarding protocols; authorization services; supply chain integration services; access points, routers, or switches; components that support device communications intent management; attestation services; controllers or application services; IoT device lifecycle management services; and asset management services. Cooperative Research and Development Agreements (CRADAs) were established with qualified respondents, and teams of collaborators were assembled to build a variety of implementations.

NIST is following an agile methodology of building implementations iteratively and incrementally, starting with network-layer onboarding and gradually integrating additional capabilities that improve device and network security throughout a managed device lifecycle. The project team began by designing a general, protocol-agnostic reference architecture for trusted network-layer onboarding (see Section 4) and establishing a laboratory infrastructure at the NCCoE to host implementations (see Section 5).

Five build teams were established to implement trusted network-layer onboarding prototypes, and a sixth build team was established to demonstrate multiple builds for factory provisioning activities performed by an IoT device manufacturer to enable devices to support trusted network-layer onboarding. Each of the build teams fleshed out the initial architectures of their example implementations. They then used technologies, capabilities, and components from project collaborators to begin creating the builds:

- Build 1 (Wi-Fi Easy Connect, Aruba/HPE) uses components from Aruba, a Hewlett Packard Enterprise company, to support trusted network-layer onboarding using the Wi-Fi Alliance's Wi-Fi Easy Connect Specification, Version 2.0 [6] and independent (see Section 3.3.2) application-layer onboarding to the Aruba User Experience Insight (UXI) cloud.
- Build 2 (Wi-Fi Easy Connect, CableLabs, OCF) uses components from CableLabs to support trusted network-layer onboarding using the Wi-Fi Easy Connect protocol that allows provisioning of per-device credentials and policy management for each device. Build 2 also uses components from the Open Connectivity Foundation (OCF) to support streamlined (see Section 3.3.2) trusted application-layer onboarding to the OCF security domain.
- Build 3 (BRSKI, Sandelman Software Works) uses components from Sandelman Software Works to support trusted network-layer onboarding using the Bootstrapping Remote Secure Key Infrastructure (BRSKI) [7] protocol and an independent, third-party Manufacturer Authorized Signing Authority (MASA).

- Build 4 (Thread [8], Silicon Labs, Kudelski IoT) uses components from Silicon Labs to support connection to an OpenThread [9] network using pre-shared credentials and components from Kudelski IoT to support trusted application-layer onboarding to the Amazon Web Services (AWS) IoT core.
- Build 5 (BRSKI over Wi-Fi, NquiringMinds) uses components from NquiringMinds to support trusted network-layer onboarding using the BRSKI protocol over 802.11 [10]. Additional components from NquiringMinds support ongoing, policy-based, continuous assurance and authorization, as well as device communications intent enforcement.
- The BRSKI Factory Provisioning Build uses components from NquiringMinds to implement the factory provisioning flows. The build is implemented on Raspberry Pi devices, where the IoT secure element is an integrated Infineon Optiga™ SLB 9670 TPM 2.0. The device certificate authority (CA) is externally hosted on NquiringMinds servers. This build demonstrates activities for provisioning IoT devices with their initial (i.e., birth—see Section 3.3) credentials for use with the BRSKI protocol and for making device bootstrapping information available to device owners.
- The Wi-Fi Easy Connect Factory Provisioning Build uses Raspberry Pi devices and code from Aruba and secure storage elements, code, and a CA from SEALSQ, a subsidiary of WISeKey. This build demonstrates activities for provisioning IoT devices with their birth credentials for use with the Wi-Fi Easy Connect protocol and for making device bootstrapping information available to device owners.

Each build team documented the architecture and design of its build (see Appendix C, Appendix D, Appendix E, Appendix F, Appendix G, and Appendix H). As each build progressed, its team also documented the steps taken to install and configure each component of the build (see NIST SP 1800-36C).

The project team then designed a set of use case scenarios designed to showcase the builds' security capabilities. Each build team conducted a functional demonstration of its build by running the build through the defined scenarios and documenting the results (see NIST SP 1800-36D).

The project team also conducted a risk assessment and a security characteristic analysis and documented the results, including mappings of the security capabilities of the reference solution to both the *Framework for Improving Critical Infrastructure Cybersecurity* (NIST Cybersecurity Framework) [11] and Security and Privacy Controls for Information Systems and Organizations (*NIST SP 800-53 Rev. 5*) (see NIST SP 1800-36E).

Finally, the NCCoE worked with industry and standards-developing organization collaborators to distill their findings and consider potential enhancements to future support for trusted IoT device network-layer onboarding (see Section 6 and Section 7).

3.1 Audience

The intended audience for this practice guide includes:

- IoT device manufacturers, integrators, and vendors
- Semiconductor manufacturers and vendors
- Secure storage manufacturers

- Network equipment manufacturers
- IoT device owners and users
- Owners and administrators of networks (both home and enterprise) to which IoT devices connect
- Service providers (internet service providers/cable operators and application platform providers)

3.2 Scope

This project focuses on the trusted network-layer onboarding of IoT devices in both home and enterprise environments. Enterprise, consumer, and industrial use cases for trusted IoT device network-layer onboarding are all considered to be in scope at this time. The project encompasses trusted network-layer onboarding of IoT devices deployed across different Internet Protocol (IP) based environments using wired, Wi-Fi, and broadband networking technologies. The project addresses the onboarding of IP-based devices in the initial phase and will consider using technologies such as Zigbee or Bluetooth in future phases of this project.

The project's scope also includes security technologies that can be integrated with and enhanced by the trusted network-layer onboarding mechanism to protect the device and its network throughout the device's lifecycle. Examples of these technologies include supply chain management, device attestation, trusted application-layer onboarding, device communications intent enforcement, device lifecycle management, asset management, the dynamic assignment of devices to various network segments, and ongoing device authorization. Aspects of these technologies that are relevant to their integration with network-layer onboarding are within scope. Demonstration of the general capabilities of these technologies independent of onboarding is not within the project's scope. For example, demonstrating a policy that requires device attestation to be performed before the device will be permitted to be onboarded would be within scope. However, the details and general operation of the device attestation mechanism would be out of scope.

3.3 Assumptions and Definitions

This project is guided by a variety of assumptions, which are categorized by subsection below.

3.3.1 Credential Types

There are several different credentials that may be related to any given IoT device, which makes it important to be clear about which credential is being referred to. Two types of IoT device credentials are involved in the network-layer onboarding process: birth credentials and network credentials. Birth credentials are installed onto the device before it is released into the supply chain; trusted network-layer onboarding solutions leverage birth credentials to authenticate devices and securely provision them with their network credentials. If supported by the device and the application service provider, application-layer credentials may be provisioned to the device after the device performs network-layer onboarding and connects to the network, during the application-layer onboarding process. These different types of IoT device credentials are defined as follows:

- **Birth Credential**: In order to participate in trusted network-layer onboarding, devices must be equipped with a birth credential, which is sometimes also referred to as a device *birth identity* or *birth certificate.* A birth credential is a unique, authoritative credential that is generated or installed into secure storage on the IoT device during the pre-market phase of the device's lifecycle, i.e., before the device is released for sale. A manufacturer, integrator, or vendor typically generates or installs the birth credential onto an IoT device in the form of an Initial Device Identifier (IDevID) [12] and/or a public/private key pair.

  Birth credentials:

  - are permanent, and their value is independent of context;
  - enable the trusted network-layer onboarding process while keeping the device manufacturing process efficient; and
  - include a unique identity and a secret and can range from simple raw public and private keys to X.509 certificates that are signed by a trusted authority.

- **Network Credential:** A network credential is the credential that is provisioned to an IoT device during network-layer onboarding. The network credential enables the device to connect to the local network securely. A device's network credential may be changed repeatedly, as needed, by subsequent invocation of the trusted network-layer onboarding process.

Additional types of credentials that may also be associated with an IoT device are:

- **Application-Layer Credential:** An application-layer credential is a credential that is provisioned to an IoT device during application-layer onboarding. After an IoT device has performed network-layer onboarding and connected to a network, it may be provisioned with one or more application-layer credentials during the application-layer onboarding process. Each application-layer credential is specific to a given application and is typically unique to the device, and it may be replaced repeatedly over the course of the device's lifetime.
- **User Credential:** An IoT device that permits authorized users to access it and restricts access only to authorized users will have one or more user credentials associated with it. These credentials are what the users present to the IoT device in order to gain access to it. The user credential is not relevant during network-layer onboarding and is generally not of interest within the scope of this project. We include it in this list only for completeness. Many IoT devices may not even have user credentials associated with them.

In order to perform network- and application-layer onboarding, the device being onboarded must already have been provisioned with birth credentials. A pre-provisioned, unique, authoritative birth credential is essential for enabling the IoT device to be identified and authenticated as part of the trusted network-layer onboarding process, no matter what network the device is being onboarded to or how many times it is onboarded. The value of the birth credential is independent of context, whereas the network credential that is provisioned during network-layer onboarding is significant only with respect to the network to which the IoT device will connect. Each application-layer credential that is provisioned during application-layer onboarding is specific to a given application, and each user credential is specific to a given user. A given IoT device only ever has one birth credential over the course of its lifetime, and the value of this birth credential remains unchanged. However, that IoT device may have any number of network, application-layer, and user credentials at any given point in time, and these credentials may be replaced repeatedly over the course of the device's lifetime.

3.3.2 Integrating Security Enhancements

Integrating trusted network-layer IoT device onboarding with additional security mechanisms and technologies can help increase trust in both the IoT device and the network to which it connects. Examples of such security mechanism integrations demonstrated in this project include:

- **Trusted Application-Layer Onboarding:** When supported, application-layer onboarding can be performed automatically after a device has connected to its local network. Trusted application-layer onboarding enables a device to be securely provisioned with the application-layer credentials it needs to establish a secure association with a trusted application service. In many cases, a network's IoT devices will be so numerous that manually onboarding devices at the application layer would not be practical; in addition, dependence on manual application-layer onboarding would leave the devices vulnerable to accidental or malicious misconfiguration. So, application-layer onboarding, like network-layer onboarding, is fundamental to ensuring the overall security posture of each IoT device.

  As part of the application-layer onboarding process, devices and the application services with which they interact perform mutual authentication and establish an encrypted channel over which the application service can download application-layer credentials and software to the device and the device can provide information to the application service, as appropriate. Application-layer onboarding is useful for ensuring that IoT devices are executing the most up-to-date versions of their intended applications. It can also be used to establish a secure association between a device and a trusted lifecycle management service, which will ensure that the IoT device continues to be patched and updated with the latest firmware and software, thereby enabling the device to remain trusted throughout its lifecycle.

  Network-layer onboarding cannot be performed until after network-layer bootstrapping information has been introduced to the device and the network. This network-layer bootstrapping information enables the device and the network to mutually authenticate and establish a secure channel. Analogously, application-layer onboarding cannot be performed until after application-layer bootstrapping information has been introduced to the device and the application servers with which they will onboard. This application-layer bootstrapping information enables the device and the application server to mutually authenticate and establish a secure channel.

  - *Streamlined Application-Layer Onboarding*—One potential mechanism for introducing this application-layer bootstrapping information to the device and the application server is to use the network-layer onboarding process. The secure channel that is established during network-layer onboarding can serve as the mechanism for exchanging application-layer bootstrapping information between the device and the application server. By safeguarding the integrity and confidentiality of the application-layer bootstrapping information as it is conveyed between the device and the application server, the trusted network-layer onboarding mechanism helps to ensure that information that the device and the application server use to authenticate each other is truly secret and known only to them, thereby establishing a firm foundation for their secure association. In this way, trusted network-layer onboarding can provide a secure foundation for trusted application-layer onboarding. We call an application-layer onboarding process that uses network-layer onboarding to exchange application-layer bootstrapping information *streamlined* application-layer onboarding.

- *Independent Application-Layer Onboarding*—An alternative mechanism for introducing application-layer bootstrapping information to the device is to provide this information to the device during the manufacturing process. During manufacturing, the IoT device can be provisioned with software and associated bootstrapping information that enables the device to mutually authenticate with an application-layer service after it has connected to the network. This mechanism for performing application-layer onboarding does not rely on the network-layer onboarding process to provide application-layer bootstrapping information to the device. All that is required is that the device have connectivity to the application-layer onboarding service after it has connected to the network. We call an application-layer onboarding process that does not rely on network-layer onboarding to exchange application-layer bootstrapping information *independent* application-layer onboarding.

- **Segmentation:** Upon connection to the network, a device may be assigned to a particular local network segment to prevent it from communicating with other network components, as determined by enterprise policy. The device can be protected from other local network components that meet or do not meet certain policy criteria. Similarly, other local network components may be protected from the device if it meets or fails to meet certain policy criteria. A trusted network-layer onboarding mechanism may be used to convey information about the device that can be used to determine to which network segment it should be assigned upon connection. By conveying this information in a manner that protects its integrity and confidentiality, the trusted network-layer onboarding mechanism helps to increase assurance that the device will be assigned to the appropriate network segment. Post-onboarding, if a device becomes untrustworthy, for example because it is found to have software that has a known vulnerability or misconfiguration, or because it is behaving in a suspicious manner, the device may be dynamically assigned to a different network segment as a means of quarantining it, or its network-layer credential can be revoked or deleted.

- **Ongoing Device Authorization:** Once a device has been network-layer onboarded in a trusted manner and has possibly performed application-layer onboarding as well, it is important that as the device continues to operate on the network, it maintains a secure posture throughout its lifecycle. Ensuring the ongoing security of the device is important for keeping the device from being corrupted and for protecting the network from a potentially harmful device. Even though a device is authenticated and authorized prior to being onboarded, it is recommended that the device be subject to ongoing policy-based authentication and authorization as it continues to operate on the network. This may include monitoring device behavior and constraining communications to and from the device as needed in accordance with policy. In this manner, an ongoing device authorization service can ensure that the device and its operations continue to be authorized throughout the device's tenure on the network.

- **Device Communications Intent Enforcement:** Network-layer onboarding protocols can be used to securely transmit device communications intent information from the device to the network (i.e., to transmit this information in encrypted form with integrity protections). After the device has securely connected to the network, the network can use this device communications intent information to ensure that the device sends and receives traffic only from authorized locations. Secure conveyance of device communications intent information, combined with enforcement of it, ensures that IoT devices are constrained to sending and receiving only those communications that are explicitly required for each device to fulfill its purpose.

- **Additional Security Mechanisms:** Although not demonstrated in the implementations that have been built in this project so far, numerous additional security mechanisms can potentially be integrated with network-layer onboarding, beginning at device boot-up and extending through all phases of the device lifecycle. Examples of such mechanisms include integration with supply chain management tools, device attestation, automated lifecycle management, mutual attestation, and centralized asset management. Overall, application of these and other security protections can create a dependency chain of protections. This chain is based on a hardware root of trust as its foundation and extends up to support the security of the trusted network-layer onboarding process. The trusted network-layer onboarding process in turn may enable additional capabilities and provide a foundation that makes them more secure, thereby helping to ensure the ongoing security of the device and, by extension, the network.

3.3.3 Device Limitations

The security capabilities that any onboarding solution will be able to support will depend in part on the hardware, processing power, cryptographic modules, secure storage capacity, battery life, human interface (if any), and other capabilities of the IoT devices themselves, such as whether they support verification of firmware at boot time, attestation, application-layer onboarding, and device communications intent enforcement; what onboarding and other protocols they support; and whether they are supported by supply-chain tools. The more capable the device, the more security capabilities it should be able to support and the more robustly it should be able to support them. Depending on both device and onboarding solution capabilities, different levels of assurance may be provided.

3.3.4 Specifications Are Still Improving

Ideally, trusted network-layer onboarding solutions selected for widespread implementation and use will be openly available and standards-based. Some potential solution specifications are still being improved. In the meantime, their instability may be a limiting factor in deploying operational implementations of the proposed capabilities. For example, the details of running BRSKI over Wi-Fi are not fully specified at this time.

3.4 Collaborators and Their Contributions

Organizations participating in this project submitted their capabilities in response to an open call in the Federal Register for all sources of relevant security capabilities from academia and industry (vendors and integrators). Listed below are the respondents with relevant capabilities or product components (identified as “Technology Partners/Collaborators” herein) who signed a CRADA to collaborate with NIST in a consortium to build example trusted IoT device network-layer onboarding solution.

Technology Collaborators

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

Table 3-1 summarizes the capabilities and components provided, or planned to be provided, by each partner/collaborator.

Table 3-1 Capabilities and Components Provided by Each Technology Partner/Collaborator

Collaborator	Security Capability or Component Provided
Aruba	Infrastructure for trusted network-layer onboarding using the Wi-Fi Easy Connect protocol and application-layer onboarding to the UXI cloud. IoT devices for use with both Wi-Fi Easy Connect network-layer onboarding and application-layer onboarding. The UXI Dashboard provides for an “always-on” remote technician with near real-time data insights into network and application performance.
CableLabs	Infrastructure for trusted network-layer onboarding using the Wi-Fi Easy Connect protocol. IoT devices for use with both Wi-Fi Easy Connect network-layer onboarding and application-layer onboarding to the OCF security domain.
Cisco	Networking components to support various builds.
Foundries.io	Factory software for providing birth credentials into secure storage on IoT devices and for transferring device bootstrapping information from device manufacturer to device purchaser.
Kudelski IoT	Infrastructure for trusted application-layer onboarding of a device to the AWS IoT core. The service comes with a cloud platform and a software agent that enables secure provisioning of AWS credentials into the secure storage of IoT devices.
NquiringMinds	Infrastructure for trusted network-layer onboarding using BRSKI over 802.11. Service that performs ongoing monitoring of connected devices to ensure their continued authorization (i.e., continuous authorization service), as well as device communications intent enforcement.
NXP Semiconductors	IoT devices with secure storage for use with both Wi-Fi Easy Connect and BRSKI network-layer onboarding. Service for provisioning credentials into secure storage of IoT devices.
Open Connectivity Foundation (OCF)	Infrastructure for trusted application-layer onboarding to the OCF security domain using IoTivity, an open-source software framework that implements the OCF specification.
Sandelman Software Works	Infrastructure for trusted network-layer onboarding using BRSKI. IoT devices for use with BRSKI network-layer onboarding.
SEALSQ, a subsidiary of WISeKey	Secure storage elements, code, and software that simulates factory provisioning of birth credentials to those secure elements on IoT devices in support of both Wi-Fi Easy Connect and BRSKI network-layer onboarding; certificate authority for signing device certificates.
Silicon Labs	Infrastructure for connection to a Thread network that has access to other networks for application-layer onboarding. IoT device with secure storage for use with Thread network connection and application-layer onboarding using Kudelski IoT.

Each of these technology partners and collaborators has described the relevant products and capabilities it brings to this trusted onboarding effort in the following subsections. The NCCoE does not certify or validate products or services. We demonstrate the capabilities that can be achieved by using participants' contributed technology.

3.4.1 Aruba, a Hewlett Packard Enterprise Company

Aruba, a Hewlett Packard Enterprise (HPE) company, provides secure, intelligent edge-to-cloud networking solutions that use artificial intelligence (AI) to automate the network, while harnessing data to drive powerful business outcomes. With Aruba ESP (Edge Services Platform) and as-a-service options as part of the HPE GreenLake family, Aruba takes a cloud-native approach to helping customers meet their connectivity, security, and financial requirements across campus, branch, data center, and remote worker environments, covering all aspects of wired, wireless local area networking (LAN), and wide area networking (WAN). Aruba ESP provides unified solutions for connectivity, visibility, and control throughout the IT-IoT workflow, with the objective of helping organizations accelerate IoT-driven digital transformation with greater ease, efficiency, and security. To learn more, visit Aruba at https://www.arubanetworks.com/.

3.4.1.1 Device Provisioning Protocol

Device Provisioning Protocol (DPP), certified under the Wi-Fi Alliance (WFA) as "Easy Connect," is a standard developed by Aruba that allows IoT devices to be easily provisioned onto a secure network. DPP improves security by leveraging Wi-Fi Protected Access 3 (WPA3) to provide device-specific credentials, enhance certificate handling, and support robust, secure, and scalable provisioning of IoT devices in any commercial, industrial, government, or consumer application. Aruba implements DPP through a combination of on-premises hardware and cloud-based services as shown in Table 3-1.

3.4.1.2 Aruba Access Point (AP)

From their unique vantage as ceiling furniture, Aruba Wi-Fi 6 APs have an unobstructed overhead view of all nearby devices. Built-in Bluetooth Low Energy (BLE) and Zigbee 802.15.4 IoT radios, as well as a flexible USB port, provide IoT device connectivity that allows organizations to address a broad range of IoT applications with infrastructure already in place, eliminating the cost of gateways and IoT overlay networks while enhancing IoT security.

Aruba's APs enable a DPP network through an existing Service Set Identifier (SSID) enforcing DPP access control and advertising the Configurator Connectivity Information Element (IE) to attract unprovisioned clients (i.e., clients that have not yet been onboarded). Paired with Aruba's cloud management service "Central", the APs implement the DPP protocol. The AP performs the DPP network introduction protocol (Connector exchange) with provisioned clients and assigns network roles.

3.4.1.3 Aruba Central

Aruba Central is a cloud-based networking solution with AI-powered insights, workflow automation, and edge-to-cloud security that empowers IT teams to manage and optimize campus, branch, remote, data center, and IoT networks from a single point of visibility and control. Built on a cloud-native, microservices architecture, Aruba Central is designed to simplify IT and IoT operations, improve agility, and reduce costs by unifying management of all network infrastructure.

Aruba's "Central" Cloud DPP service exposes and controls many centralized functions to enable a seamless integrated end-to-end solution and act as a DPP service orchestrator. The cloud based DPP service selects an AP to authenticate unprovisioned enrollees (in the event that multiple APs receive the client *chirps*). The DPP cloud service holds the Configurator signing key and generates Connectors for enrollees authenticated through an AP.

3.4.1.4 IoT Operations

Available within Aruba Central, the IoT Operations service extends network administrators' view into IoT devices and applications connected to the network. Organizations can gain critical visibility into previously invisible IoT devices, as well as reduce costs and complexity associated with deploying IoT applications. IoT Operations comprises three core elements:

- IoT Dashboard, which provides a granular view of devices connected to Aruba APs, as well as IoT connectors and applications in use.
- IoT App Store, a repository of click-and-go IoT applications that interface with IoT devices and their data.
- IoT Connector, which provisions multiple applications to be computed at the edge for agile IoT application support.

3.4.1.5 Client Insights

Part of Aruba Central, AI-powered Client Insights automatically identifies each endpoint connecting to the network with up to 99% accuracy. Client Insights discovers and classifies all connected endpoints—including IoT devices—using built-in machine learning and dynamic profiling techniques, helping organizations better understand what's on their networks, automate access privileges, and monitor the behavior of each endpoint's traffic flows to more rapidly spot attacks and act.

3.4.1.6 Cloud Auth

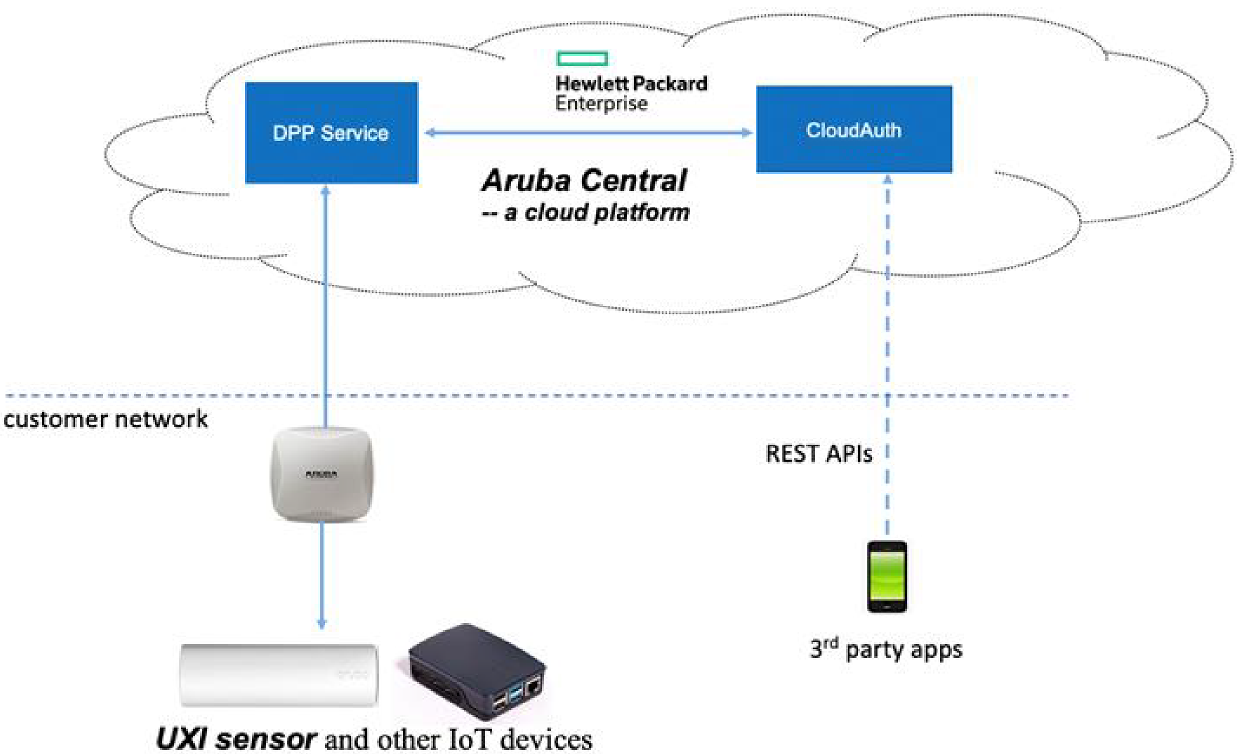
Cloud-native network access control (NAC) solution Cloud Auth delivers time-saving workflows to configure and manage onboarding, authorization, and authentication policies for wired and wireless networks. Cloud Auth integrates with an organization's existing cloud identity store, such as Google Workspace or Azure Active Directory, to authenticate IoT device information and assign the right level of network access.

Cloud Auth operates as the DPP Authorization server and is the repository for trusted DPP Uniform Resource Identifiers (URIs) of unprovisioned enrollees. It maintains role information for each unprovisioned DPP URI and provisioned devices based on unique per-device credential (public key extracted from Connector). Representational State Transfer (RESTful) application programming interfaces (APIs) provide extensible capabilities to support third parties, making an easy path for integration and collaborative deployments.

3.4.1.7 UXI Sensor: DPP Enrollee

User Experience Insight (UXI) sensors continuously monitor end-user experience on customer networks and provide a simple-to-use cloud-based dashboard to assess networks and applications. The UXI sensor is onboarded in a zero-touch experience using DPP. Once network-layer onboarding is complete, the UXI sensor performs application-layer onboarding to the Aruba cloud to download a customer-specific profile. This profile enables the UXI sensor to perform continuous network testing and monitoring, and to troubleshoot network issues that it finds.

Figure 3-1 Aruba/HPE DPP Onboarding Components



3.4.2 CableLabs

CableLabs is an innovation lab for future-forward research and development (R&D)—a global meeting of minds dedicated to building and orchestrating emergent technologies. By convening peers and experts to share knowledge, CableLabs' objective is to energize the industry ecosystem for speed and scale. Its research facilitates solutions with the goal of making connectivity faster, easier, and more secure, and its conferences and events offer neutral meeting points to gain consensus.

As part of this project, CableLabs has provided the reference platform for its Custom Connectivity architecture for the purpose of demonstrating trusted network-layer onboarding of Wi-Fi devices using a variety of credentials. The following components are part of the reference platform.

3.4.2.1 Platform Controller

The controller provides interfaces and messaging for managing 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 integration with third-party systems for the purpose of integrating various business flows (e.g., integration with manufacturing process for device management).

3.4.2.2 Custom Connectivity Gateway Agent

The Gateway Agent is a software component that resides on the Wi-Fi AP and gateway. It connects with the controller to coordinate the Wi-Fi and routing capabilities on the gateway. Specifically, it enforces the policies and configuration from the controller by managing the lifecycle of the Wi-Fi Extended Service Set/Basic Service Set (ESS/BSS) on the AP, authentication and credentials of the client devices that connect to the AP, and service management and routing rules for various devices. It also manages secure onboarding capabilities like Easy Connect, simple onboarding using a per-device pre-shared key (PSK), etc. The Gateway agent is provided in the form of an operational Raspberry Pi-based Gateway that also includes hostapd for Wi-Fi/DPP and open-vswitch for the creation of trust domains and routing.

3.4.2.3 Reference Clients

Three Raspberry Pi-based reference clients are provided. The reference clients have support for WFA Easy Connect-based onboarding as well as support for different Wi-Fi credentials, including per-device PSK and 802.1x certificates. One of the reference clients also has support for OCF-based streamlined application-layer onboarding.

3.4.3 Cisco

Cisco Systems, or Cisco, delivers collaboration, enterprise, and industrial networking and security solutions. The company's cybersecurity team, Cisco Secure, is one of the largest cloud and network security providers in the world. Cisco's Talos Intelligence Group, the largest commercial threat intelligence team in the world, is comprised of world-class threat researchers, analysts, and engineers, and supported by unrivaled telemetry and sophisticated systems. The group feeds rapid and actionable threat intelligence to Cisco customers, products, and services to help identify new threats quickly and defend against them. Cisco solutions are built to work together and integrate into your environment, using the "network as a sensor" and "network as an enforcer" approach to both make your team more efficient and keep your enterprise secure. Learn more about Cisco at https://www.cisco.com/go/secure.

3.4.3.1 Cisco Catalyst Switch

A Cisco Catalyst switch is provided to support network connectivity and network segmentation capabilities.

3.4.4 Foundries.io

Foundries.io helps organizations bring secure IoT and edge devices to market faster. The FoundriesFactory cloud platform offers DevOps teams a secure Linux-based firmware/operating system (OS) platform with device and fleet management services for connected devices, based on a fixed no-royalty subscription model. Product development teams gain enhanced security from boot to cloud while reducing the cost of developing, deploying, and updating devices across their installed lifetime. The open-source platform interfaces to any cloud and offers Foundries.io customers maximum flexibility for hardware configuration, so organizations can focus on their intellectual property, applications, and value add. For more information, please visit https://foundries.io/.

3.4.4.1 FoundriesFactory

FoundriesFactory is a cloud-based software platform provided by Foundries.io that offers a complete development and deployment environment for creating secure IoT devices. It provides a set of tools and services that enable developers to create, test, and deploy custom firmware images, as well as manage the lifecycle of their IoT devices.

Customizable components include open-source secure boot software, the open-source Linux microPlatform (LmP) distribution built with Yocto and designed for secure managed IoT and edge products, secure Over the Air (OTA) update facilities, and a Docker runtime for managing containerized applications and services. The platform is cross architecture (x86, Arm, and RISC-V) and enables secure connections to public and private cloud services.

Leveraging open standards and open software, FoundriesFactory is designed to simplify and accelerate the process of developing, deploying, and managing IoT and edge devices at scale, while also ensuring that they are secure and up to date over the product lifetime.

3.4.5 Kudelski IoT

Kudelski IoT is the Internet of Things division of Kudelski Group and provides end-to-end IoT solutions, IoT product design, and full-lifecycle services to IoT semiconductor and device manufacturers, ecosystem creators, and end-user companies. These solutions and services leverage the group's 30+ years of innovation in digital business model creation; hardware, software, and ecosystem design and testing; state-of-the-art security lifecycle management technologies and services; and managed operation of complex systems.

3.4.5.1 Kudelski IoT keySTREAM™

Kudelski IoT keySTREAM is a device-to-cloud, end-to-end solution for securing all the key assets of an IoT ecosystem during its entire lifecycle. The system provides each device with a unique, immutable, unclonable identity that forms the foundation for critical IoT security functions like in-factory or in-field provisioning, data encryption, authentication, and secure firmware updates, as well as allowing companies to revoke network access for vulnerable devices if necessary. This ensures that the entire lifecycle of the device and its data can be managed.

In this project, keySTREAM is used to enable trusted application-layer onboarding. It manages the attestation of devices, ownership, and provisioning of application credentials.

3.4.6 NquiringMinds

NquiringMinds provides intelligent trusted systems, combining AI-powered analytics with cyber security fundamentals. tdx Volt is the NquiringMinds general-purpose zero-trust services infrastructure platform, upon which it has built Cyber tdx, a cognitively enhanced cyber defense service designed for IoT. Both products are the latest iteration of the TDX product family. NquiringMinds is a UK company. Since 2010, it has been deploying its solutions into smart cities, health care, industrial, agricultural, financial technology, defense, and security sectors.

NquiringMinds collaborates within the open-standards and open-source community. It focuses on the principle of continuous assurance: the ability to continually reassess security risk by intelligently reasoning across the hard and soft information sources available. NquiringMinds' primary contributions to this project, described in the subsections below, are being made available as open source.

3.4.6.1 NquiringMinds' BRSKI Protocol Implementation

NquiringMinds has open sourced their software implementation of IETF's Bootstrapping Remote Secure Key Infrastructure (BRSKI) protocol, which provides a solution for secure zero-touch (automated) bootstrap of new (unconfigured) devices. This implementation includes the necessary adaptations for BRKSI to work with Wi-Fi networks.

The open source BRSKI implementation is available under an Apache 2.0 license at: https://github.com/nqminds/brski

3.4.6.2 TrustNetZ

NquiringMinds has open sourced the TrustNetZ (Zero Trust Networking) software stack which sits on top of their BRSKI implementation. TrustNetZ embodies the network onboarding and lifecycle management concepts into an easy to replicate demonstrator which includes the IoT device, the router, the router onboarding, the registrar, the manufacturer, the manufacturer provisioning, policy enforcement and continuous assurance servers.

This software also encapsulates NquiringMinds' continuous assurance capability, enhancing the security of the network by continually assessing whether connected IoT devices meet the policy requirements of the network. The software also includes a flexible, verifiable credential-based policy framework, which can rapidly be adapted to model different security and business model scenarios. The implementation models networking onboarding flows with EAP-TLS Wi-Fi certificates.

The open source TrustNetZ implementation is available under an Apache 2.0 license at: https://github.com/nqminds/trustnetz

3.4.6.3 edgeSEC

edgeSEC is an open-source, OpenWrt-based implementation of an intelligent secure router. It implements, on an open stack, the key components needed to implement both trusted onboarding and continuous assurance of devices. It contains an implementation of the Internet Engineering Task Force (IETF) BRSKI protocols, with the necessary adaptations for wireless onboarding, fully integrated into an open operational router. It additionally implements device communications intent constraints (IETF Manufacturer Usage Description [MUD]) and behavior monitoring (IoTSF ManySecured) that support some of the more enhanced trusted onboarding use cases. EdgeSEC additionally provides the platform for an asynchronous control plane for the continuous management of multiple routers and a general-purpose policy evaluation point, which can be used to demonstrate the breadth of onboarding and monitoring use cases that can be supported.

EdgeSEC is not directly used in the build that was demonstrated for this project, but it contains critical pieces of code that have been adapted in a simplified manner for the TrustNetZ implementation.

The open source edgeSEC implementation is available under an Apache 2.0 license at: https://github.com/nqminds/edgesec

3.4.6.4 tdx Volt

tdx Volt is NquiringMinds' zero-trust infrastructure platform. It encapsulates identity management, credential management, service discovery, and smart policy evaluation. This platform is designed to simplify the end-to-end demonstration of the trusted onboarding process and provides tools for use on the IoT device, the router, applications, and clouds. Tdx Volt is used by the TrustNetZ demonstrator as a verifiable credential issuer and verifier.

Tdx Volt is an NquiringMinds' product. Documented working implementation are available at: https://docs.tdxvolt.com/en/introduction

3.4.6.5 Reference Hardware

For demonstration purposes the NquiringMinds components can be deployed using the following hardware:

Compute hosts: Raspberry Pi 4

https://www.raspberrypi.com/products/raspberry-pi-4-model-b/. The Raspberry Pis are used to host the IoT client device, the router, and all additional compute services. Other Raspberry Pi models are also likely to work but have not been tested.

TPM/Secure Element

The secure storage for the IoT device (used in network-layer onboarding and factory provisioning) is provided by an Infineon Optiga™ SLB 9670 TPM 2.0, integrated through a Geeek Pi TPM hat. https://www.infineon.com/dgdl/Infineon-OPTIGA_SLx_9670_TPM_2.0_Pi_4-ApplicationNotes-v07_19-EN.pdf?fileId=5546d4626c1f3dc3016c3d19f43972eb.

A working version of the code is also available utilizing the SEALSQ Secure element https://www.sealsq.com/semiconductors/vaultic-secure-elements/vaultic-40x.

3.4.7 NXP Semiconductors

NXP Semiconductors focuses on secure connectivity solutions for embedded applications, NXP is impacting the automotive, industrial, and IoT, mobile, and communication infrastructure markets. Built on more than 60 years of combined experience and expertise, the company has approximately 31,000 employees in more than 30 countries. Find out more at https://www.nxp.com/.

3.4.7.1 EdgeLock SE050 secure element

The EdgeLock SE050 secure element (SE) product family offers strong protection against the latest attack scenarios and an extended feature set for a broad range of IoT use cases. This ready-to-use secure element for IoT devices provides a root of trust at the silicon level and delivers real end-to-end security – from edge to cloud – with a comprehensive software package for integration into any type of device.

3.4.7.2 EdgeLock 2GO

EdgeLock 2GO is the NXP service platform designed for easy and secure deployment and management of IoT devices. This flexible IoT service platform lets the device manufacturers and service providers choose the appropriate options to optimize costs while benefiting from an advanced level of device security. The EdgeLock 2GO service provisions the cryptographic keys and certificates into the hardware root of trust of the IoT devices and simplifies the onboarding of the devices to the cloud.

3.4.7.3 i.MX 8M family

The i.MX 8M family of applications processors based on Arm® Cortex®-A53 and Cortex-M4 cores provide advanced audio, voice, and video processing for applications that scale from consumer home audio to industrial building automation and mobile computers. It includes support for secure boot, secure debug, and lifecycle management, as well as integrated cryptographic accelerators. The development boards and Linux Board Support Package enablement provide out-of-the-box integration with an external SE050 secure element.

3.4.8 Open Connectivity Foundation (OCF)

OCF is a standards-developing organization that has had contributions and participation from over 450+ member organizations representing the full spectrum of the IoT ecosystem, from chip makers to consumer electronics manufacturers, silicon enablement software platform and service providers, and network operators. The OCF specification is an International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) internationally recognized standard that was built in tandem with an open-source reference implementation called IoTivity. Additionally, OCF provides an in-depth testing and certification program.

3.4.8.1 IoTivity

OCF has contributed open-source code from IoTivity that demonstrates the advantage of secure network-layer onboarding and implements the WFA's Easy Connect to power a seamless bootstrapping of secure and trusted application-layer onboarding of IoT devices with minimal user interaction.

This code includes the interaction layer, called the OCF Diplomat, which handles secure communication between the DPP-enabled access point and the OCF application layer. The OCF onboarding tool (OBT) is used to configure and provision devices with operational credentials. The OCF reference implementation of a basic lamp is used to demonstrate both network- and application-layer onboarding and to show that once onboarded and provisioned, the OBT can securely interact with the lamp.

3.4.9 Sandelman Software Works

Sandelman Software Works (SSW) provides consulting and software design services in the areas of systems and network security. A complete stack company, SSW provides consulting and design services from the hardware driver level up to Internet Protocol Security (IPsec), Transport Layer Security (TLS), and cloud database optimization. SSW has been involved with the IETF since the 1990s, now dealing with the difficult problem of providing security for IoT systems. SSW leads standardization efforts through a combination of running code and rough consensus.

3.4.9.1 Minerva Highway IoT Network-Layer Onboarding and Lifecycle Management System

The Highway component is a cloud-native component operated by the device manufacturer (or its authorized designate). It provides the Request for Comments (RFC) 8995 [7] specified Manufacturer Authorized Signing Authority (MASA) for the BRSKI onboarding mechanism.

Highway is an asset manager for IoT devices. In its asset database it maintains an inventory of devices that have been manufactured, what type they are, and who the current owner of the device is (if it has been sold). Highway does this by taking control of the complete identity lifecycle of the device. It can aid in provisioning new device identity certificates (IDevIDs) by collecting Certificate Signing Requests and returning certificates, or by generating the new identities itself. This is consistent with Section 4.1.2.1 (On-device private key generation) and Section 4.1.2.2 (Off-device private key generation) of https://www.ietf.org/archive/id/draft-irtf-t2trg-taxonomy-manufacturer-anchors-00.html.

Highway can act as a standalone three-level private-public key infrastructure (PKI). Integrations with Automatic Certificate Management Environment (RFC 8555) allow it to provision certificates from an external PKI using the DNS-01 challenge in Section 8.4 of https://www.rfc-editor.org/rfc/rfc8555.html#section-8.4. Hardware integrations allow for the private key operations to be moved out of the main CPU. However, the needs of a busy production line in a factory would require continuous access to the hardware offload.

In practice, customers put the subordinate CA into Highway, which it needs to sign new IDevIDs, and put the trust anchor private CA into a hardware security module (HSM).

Highway provides a BRSKI-MASA interface running on a public TCP/HTTPS port (usually 443 or 9443). This service requires access to the private key associated to the anchor that has been "baked into" the Pledge device during manufacturing. The Highway instance that speaks to the world in this way does not have to be the same instance that signs IDevID certificates, and there are significant security advantages to separating them. Both instances do need access to the same database servers, and there are a variety of database replication techniques that can be used to improve resilience and security.

As IDevIDs do not expire, Highway does not presently include any mechanism to revoke IDevIDs, nor does it provide Certificate Revocation Lists (CRLs) or Online Certificate Status Protocol (OCSP). It is unclear how those mechanisms can work in practice.

Highway supports two models. In the Sales Integration model, the intended owner is known in advance. This model requires customer-specific integrations, which often occur at the database level through views or other SQL tools. In the trust on first use (TOFU) model, the first customer to claim a product becomes its owner.

3.4.10 SEALSQ, a subsidiary of WISeKey

WISeKey International Holding Ltd. (WISeKey) is a cybersecurity company that deploys digital identity ecosystems and secures IoT solution platforms. It operates as a Swiss-based holding company through several operational subsidiaries, each dedicated to specific aspects of its technology portfolio.

SEALSQ is the subsidiary of the group that focuses on designing and selling secure microcontrollers, PKI, and identity provisioning services while developing post-quantum technology hardware and software products. SEALSQ products and solutions are used across a variety of applications today, from multi-factor authentication devices, home automation systems, and network infrastructure, to automotive, industrial automation, and control systems.

3.4.11 VaultIC408

The VaultIC408 secure element combines hardware-based key storage with cryptographic accelerators to provide a wide array of cryptographic features including identity, authentication, encryption, key agreement, and data integrity. It protects against hardware attacks such as micro-probing and side channels.

The fundamental cryptography of the VaultIC family includes NIST-recommended algorithms and key lengths. Each of these algorithms, Elliptic Curve Cryptography (ECC), Rivest-Shamir-Adleman (RSA), and Advanced Encryption Standard (AES), is implemented on-chip and uses on-chip storage of the secret key material so the secrets are always protected in the secure hardware.

The secure storage and cryptographic acceleration support use cases like network and IoT end node security, platform security, secure boot, secure firmware download, secure communication or TLS, data confidentiality, encryption key storage, and data integrity.

3.4.11.1 INeS Certificate Management System (CMS)

SEALSQ's portfolio includes INeS, a managed PKI-as-a-service solution. INeS leverages the WISeKey Webtrust-accredited trust services platform, a Matter approved Product Attestation Authority (PAA), and custom CAs. These PKI technologies support large-scale IoT deployments, where IoT endpoints will require certificates to establish their identities. The INeS CMS platform provides a secure, scalable, and manageable trust model.

INeS CMS provides certificate management, CA management, public cloud integration and automation, role-based access control (RBAC), and APIs for custom implementations.

3.4.12 Silicon Labs

Silicon Labs provides products in the area of secure, intelligent wireless technology for a more connected world. Securing IoT is challenging. It's also mission critical. The challenge of protecting connected devices against frequently surfacing IoT security vulnerabilities follows device makers throughout the entire product lifecycle. Protecting products in a connected world is a necessity as customer data and modern online business models are increasingly targets for costly hacks and corporate brand damage. To stay secure, device makers need an underlying security platform in the hardware, software, network, and cloud. Silicon Labs offers security products with features that address escalating IoT threats, with the goal of reducing the risk of IoT ecosystem security breaches and the compromise of intellectual property and revenue loss from counterfeiting.

For this project, Silicon Labs has provided a host platform for the OpenThread border router (OTBR), a Thread radio transceiver, and an IoT device to be onboarded to the AWS cloud service and that communicates using the Thread wireless protocol.

3.4.12.1 OpenThread Border Router Platform

A Raspberry Pi serves as host platform for the OTBR. The OTBR forms a Thread network and acts as a bridge between the Thread network and the public internet, allowing the IoT device that communicates using the Thread wireless protocol and that is to be onboarded communicate with cloud services. The OTBR’s connection to the internet can be made through either Wi-Fi or ethernet. Connection to the SLWSTK6023A (see Section 3.4.12.2) is made through a USB serial port.

3.4.12.2 SLWSTK6023A Thread Radio Transceiver

The SLWSTK6023A (Wireless starter kit) acts as a Thread radio transceiver or radio coprocessor (RCP). This allows the OTBR host platform to form and communicate with a Thread network.

3.4.12.3 xG24-DK2601B Thread “End” Device

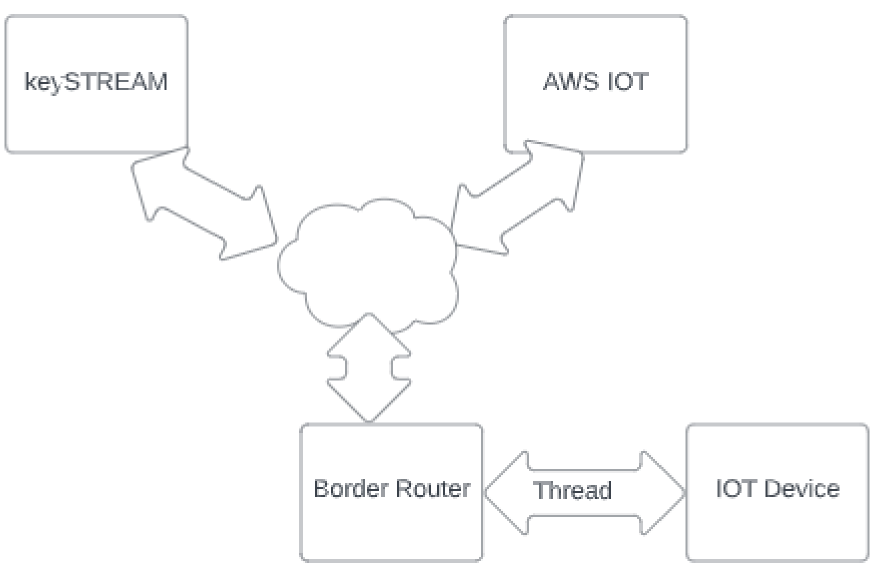
The xG24-DK2601B is the IoT device that is to be onboarded to the cloud service (AWS). It communicates using the Thread wireless protocol. Communication is bridged between the Thread network and the internet by the OTBR.

3.4.12.4 Kudelski IoT keySTREAM™

The Kudelski IoT keySTREAM solution is described more fully in Section 3.4.5.1. It is a cloud service capable of verifying the hardware-based secure identity certificate chain associated with the xG24-DK2601B component described in Section 3.4.12.3 and delivering a new certificate chain that can be refreshed or revoked as needed to assist with lifecycle management. The certificate chain is used to authenticate the xG24-DK2601B device to the cloud service (AWS).

Figure 3-2 shows the relationships among the components provided by Silicon Labs and Kudelski that support the trusted application-layer onboarding of an IoT device that communicates via the Thread protocol to AWS IoT.

Figure 3-2 Components for Onboarding an IoT Device that Communicates Using Thread to AWS IoT

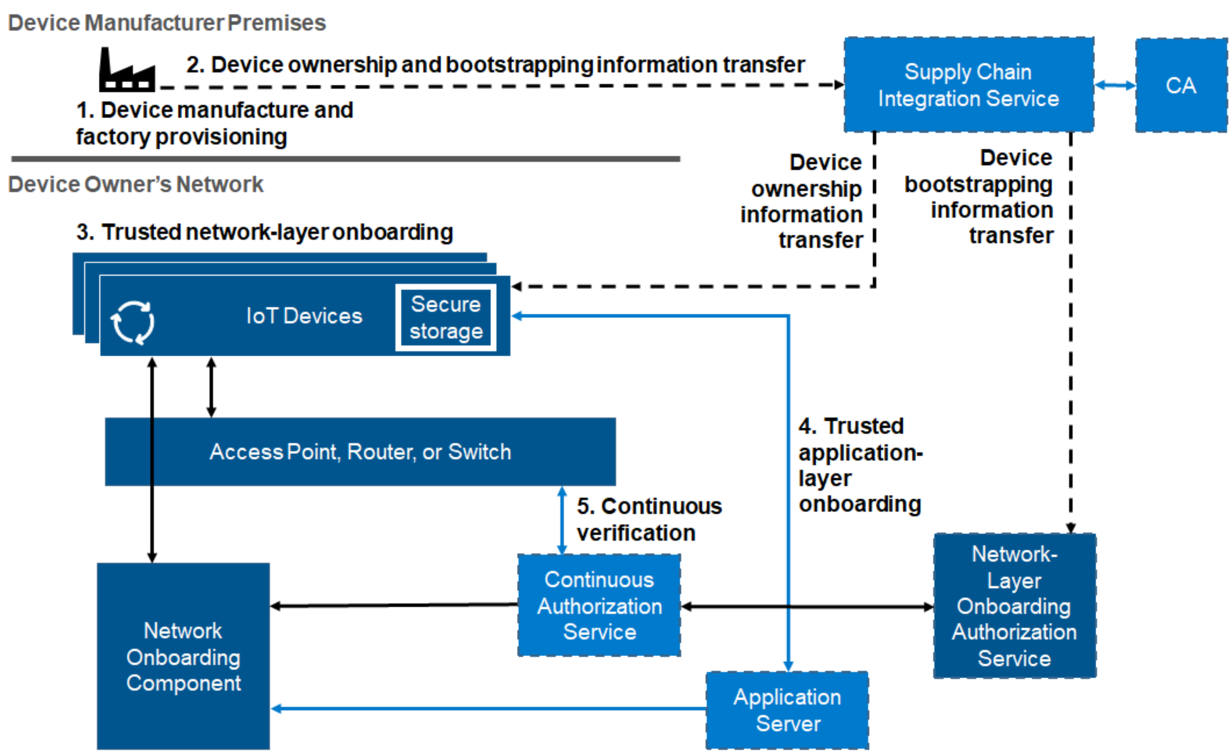


4 Reference Architecture

Figure 4-1 depicts the reference architecture to demonstrate trusted IoT device network-layer onboarding and lifecycle management used throughout this Practice Guide. This architecture shows a high-level, protocol-agnostic, and generic approach to trusted network-layer onboarding. It represents the basic components and processes, regardless of the network-layer onboarding protocol used and the particular device lifecycle management activities supported.

When implementing this architecture, an organization can follow different steps and use different components. The exact steps that are performed may not be in the same order as the steps in the logical reference architecture, and they may use components that do not have a one-to-one correspondence with the logical components in the logical reference architecture. In Appendices C, D, E, F and G we present the architectures for builds 1, 2, 3, 4 and 5, each of which is an instantiation of this logical reference architecture. Those build-specific architectures are more detailed and are described in terms of specific collaborator components and trusted network-layer onboarding protocols.

Figure 4-1 Trusted IoT Device Network-Layer Onboarding and Lifecycle Management Logical Reference Architecture



There are five high-level processes to carry out this architecture, as labeled in Figure 4-1. These five processes are as follows:

1. **Device manufacture and factory provisioning** – the activities that the IoT device manufacturer performs to prepare the IoT device so that it is capable of network- and application-layer onboarding (Figure 4-2, Section 4.1).

2. **Device ownership and bootstrapping information transfer** – the transfer of IoT device ownership and bootstrapping information from the manufacturer to the device and/or the device's owner that enables the owner or an entity authorized by the owner to onboard the device securely. The component in Figure 4-1 labeled "Supply Chain Integration Service" represents the mechanism used to accomplish this information transfer (Figure 4-3, Section 4.2).

3. **Trusted network-layer onboarding** – the interactions that occur between the network-layer onboarding component and the IoT device to mutually authenticate, confirm authorization, establish a secure channel, and provision the device with its network credentials (Figure 4-4, Section 4.3).

4. **Trusted application-layer onboarding** – the interactions that occur between a trusted application server and the IoT device to mutually authenticate, establish a secure channel, and provision the device with application-layer credentials (Figure 4-5, Section 4.4).

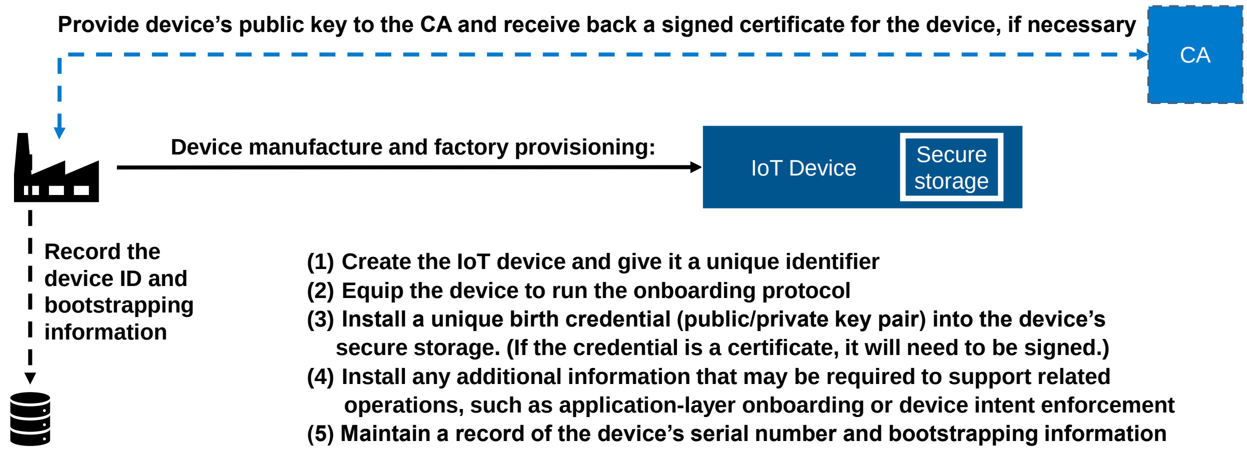
5. **Continuous verification** – ongoing, policy-based verification and authorization checks on the IoT device to support device lifecycle monitoring and control (Figure 4-6, Section 4.5).

Figure 4-1 uses two colors. The dark-blue components are central to supporting trusted network-layer onboarding itself. The light-blue components support the other aspects of the architecture. Each of the five processes is explained in more detail in the subsections below.

4.1 Device Manufacture and Factory Provisioning Process

Figure 4-2 depicts the device manufacture and factory provisioning process in more detail. As shown in Figure 4-2, the manufacturer is responsible for creating the IoT device and provisioning it with the necessary hardware, software, and birth credentials so that it is capable of network-layer onboarding. The IoT device should be manufactured with a secure root of trust as a best practice, possibly as part of a secure manufacturing process, particularly when outsourced. Visibility and control over the provisioning process and manufacturing supply chain, particularly for outsourced manufacturing, is critical in order to mitigate the risk of compromise in the supply chain, which could lead to the introduction of compromised devices. The CA component is shown in light blue in Figure 4-2 because its use is optional and depends on the type of credential that is being provisioned to the device (i.e., whether it is an 802.1AR certificate).

Figure 4-2 IoT Device Manufacture and Factory Provisioning Process



At a high level, the steps that the manufacturer or an integrator performs as part of this preparation process, as shown in Figure 4-2, are as follows:

1. Create the IoT device and assign it a unique identifier (e.g., a serial number). Equip the device with secure storage.
2. Equip the device to run a specific network-layer onboarding protocol (e.g., Wi-Fi Easy Connect, BRSKI, Thread Mesh Commissioning Protocol (MeshCoP) [8]). This step includes ensuring that the device has the software/firmware needed to run the onboarding protocol as well as any additional information that may be required.
3. Generate or install the device's unique birth credential into the device's secure storage. [Note: using a secure element that has the ability to autonomously generate private/public root key pairs is inherently more secure than performing credential injection, which has the potential to expose the private key.] The birth credential includes information that must be kept secret (i.e., the device's private key) because it is what enables the device's identity to be authenticated. The contents of the birth credential will depend on what network-layer onboarding protocol the device supports. For example:
    a. If the device runs the Wi-Fi Easy Connect protocol, its birth credential will take the form of a unique private key, which has an associated DPP URI that includes the corresponding public key and possibly additional information such as Wi-Fi channel and serial number.
    b. If the device runs the BRSKI protocol, its birth credential takes the form of an 802.1AR certificate that gets installed as the device's IDevID and corresponding private key. The IDevID includes the device's public key, the location of the MASA, and trust anchors that can be used to verify vouchers signed by the MASA. The 802.1AR certificate needs to be signed by a trusted signing authority prior to installation, as shown in Figure 4-2.
4. Install any additional information that may be required to support related capabilities that are enabled by network-layer onboarding. The specific contents of the information that gets

installed on the device will vary according to what capabilities it is intended to support. For example, if the device supports:

   a. **streamlined application-layer onboarding** (see Section 3.3.2), then the bootstrapping information that is required to enable the device and a trusted application server to find and mutually authenticate each other and establish a secure association will be stored on the device. This is so it can be sent to the network during network-layer onboarding and used to automatically perform application-layer onboarding after the device has securely connected to the network. The Wi-Fi Easy Connect protocol, for example, can include such application-layer bootstrapping information as third-party information in its protocol exchange with the network, and Build 2 (i.e., the Wi-Fi Easy Connect, CableLabs, OCF build) demonstrates use of this mechanism to support streamlined application-layer onboarding.

      Note, however, that a device may still be capable of performing independent [see Section 3.3.2] application-layer onboarding even if the application-layer onboarding information is not exchanged as part of the network-layer onboarding protocol. The application that is installed on the device, i.e., the application that the device executes to fulfill its purpose, may include application-layer bootstrapping information that enables it to perform application-layer onboarding when it begins executing. Build 1 (i.e., the Wi-Fi Easy Connect, Aruba/HPE build) demonstrates independent application-layer onboarding.

   b. **device communications intent**, then the URI required to enable the network to locate the device's intent information may be stored on the device so that it can be sent to the network during network-layer onboarding. After the device has securely connected to the network, the network can use this device communications intent information to ensure that the device sends and receives traffic only from authorized locations.

5. Maintain a record of the device's serial number (or other uniquely identifying information) and the device's bootstrapping information. The manufacturer will take note of the device's ID and its bootstrapping information and store these. Eventually, when the device is sold, the manufacturer will need to provide the device's owner with its bootstrapping information. The contents of the device's bootstrapping information will depend on what network-layer onboarding protocol the device supports. For example:

   a. If the device runs the Wi-Fi Easy Connect protocol, its bootstrapping information is the DPP URI that is associated with its private key.

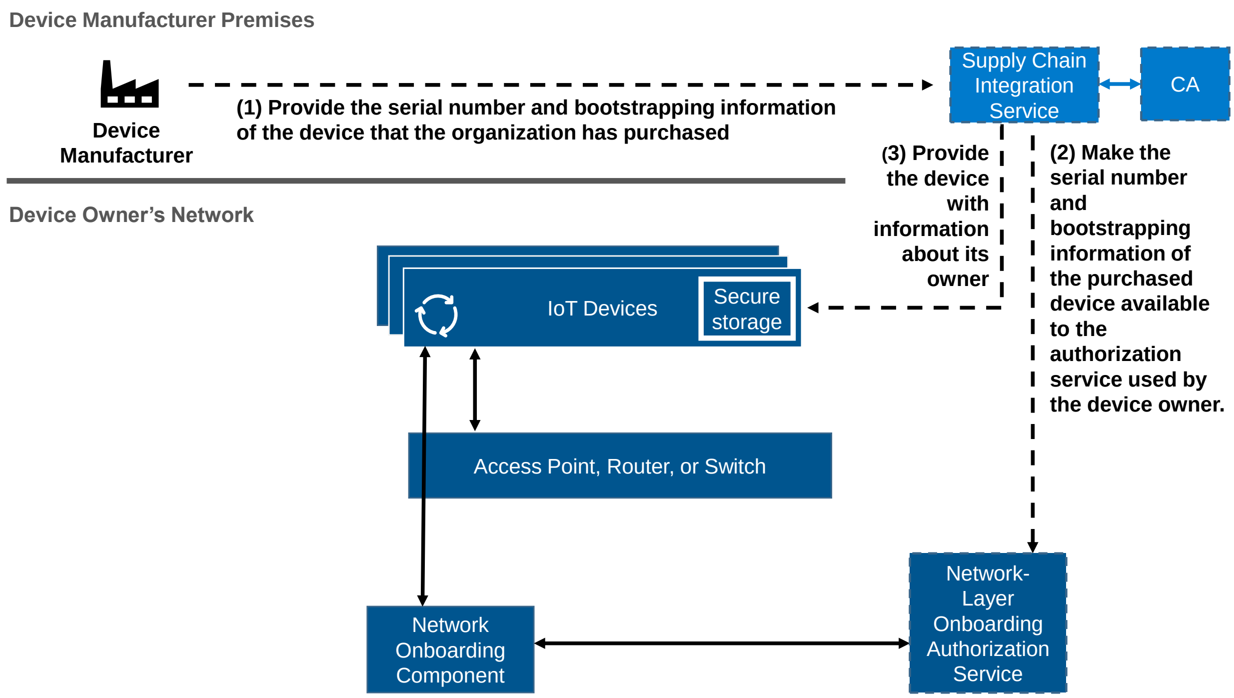
   b. If the device runs the BRSKI protocol, its bootstrapping information is its 802.1AR certificate.

4.2 Device Ownership and Bootstrapping Information Transfer Process

Figure 4-3 depicts the activities that are performed to transfer device bootstrapping information from the device manufacturer to the device owner, as well as to transfer device ownership information to the device itself, if appropriate. A high-level summary of these activities is described in the steps labeled A, B, and C.

The figure uses two colors. The dark-blue components are those used in the network-layer onboarding process. They are the same components as those depicted in the trusted network-layer onboarding process diagram provided in Figure 4-4. The light-blue components and their accompanying steps depict the portion of the diagram that is specific to device ownership and bootstrapping information transfer activities.

Figure 4-3 Device Ownership and Bootstrapping Information Transfer Process



These steps are as follows:

1. The device manufacturer makes the device serial number, bootstrapping information, and ownership information available so that the organization or individual who has purchased the device will have the device's serial number and bootstrapping information, and the device itself can be informed of who its owner is. In Figure 4-3, the manufacturer is shown sending this information to the supply chain integration service, which ensures that the necessary information ultimately reaches the device owner's authorization service as well as the device itself, if appropriate. (This description of the process is deliberately simple in order to enable it to be general enough that it applies to a variety of network-layer onboarding protocols.) In reality, the supply chain integration service mechanism for forwarding this bootstrapping information from the manufacturer to the owner may take many forms. For example, when BRSKI is used, the manufacturer sends the device serial number and bootstrapping information to a MASA that both the device and its owner trust. When other network-layer onboarding protocols are used, the device manufacturer may provide the device owner with this bootstrapping information directly by uploading this information to the owner's portion of a

trusted cloud. Such a mechanism is useful for the case in which the owner is a large enterprise that has made a bulk purchase of many IoT devices. In this case, the manufacturer can upload the information for hundreds or thousands of IoT devices to the supply chain integration service at once. We call this the enterprise use case. Alternatively, the device manufacturer may provide this information to the device owner indirectly by including it on or in the packaging of an IoT device that is sold at retail. We call this the consumer use case.

The contents of the device bootstrapping information will also vary according to the network-layer onboarding protocol that the device supports. For example, if the device supports the Wi-Fi Easy Connect network-layer onboarding protocol, the bootstrapping information will consist of the device's DPP URI. If the device supports the BRSKI network-layer onboarding protocol, bootstrapping information will consist of the device's IDevID (i.e., its 802.1AR certificate).

2. The supply chain integration service forwards the device serial number and bootstrapping information to an authorization service that has connectivity to the network-layer onboarding component that will onboard the device (i.e., to a network-layer onboarding component that belongs either to the device owner or to an entity that the device owner has authorized to onboard the device). The network-layer onboarding component will use the device's bootstrapping information to authenticate the device and verify that it is expected and authorized to be onboarded to the network. Again, this forwarding may take many forms, e.g., enterprise use case or consumer use case, and use a variety of different mechanisms within each use case type, e.g., information moved from one location to another in the device owner's portion of a trusted cloud, information transferred via a standardized protocol operating between the MASA and the onboarding network's domain registrar, or information scanned from a QR code on device packaging using a mobile app. In the case in which BRSKI is used, a certificate authority is consulted to help validate the signature of the 802.1AR certificate that comprises the device bootstrapping information.

3. The supply chain integration service may also provide the device with information about who its owner is. Knowing who its owner is enables the device to ensure that the network that is trying to onboard it is authorized to do so, because it is assumed that if a network owns a device, it is authorized to onboard it. The mechanisms for providing the device with assurance that the network that is trying to onboard it is authorized to do so can take a variety of forms, depending on the network-layer onboarding protocol being used. For example, if the Wi-Fi Easy Connect protocol is being used, then if an entity is in possession of the device's public key, that entity is assumed to be authorized to onboard the device. If BRSKI is being used, the device will be provided with a signed voucher verifying that the network that is trying to onboard the device is authorized to do so. The voucher is signed by the MASA. Because the device manufacturer has installed trust anchors for the MASA onto the device, the device trusts the MASA. It is also able to verify the MASA's signature.

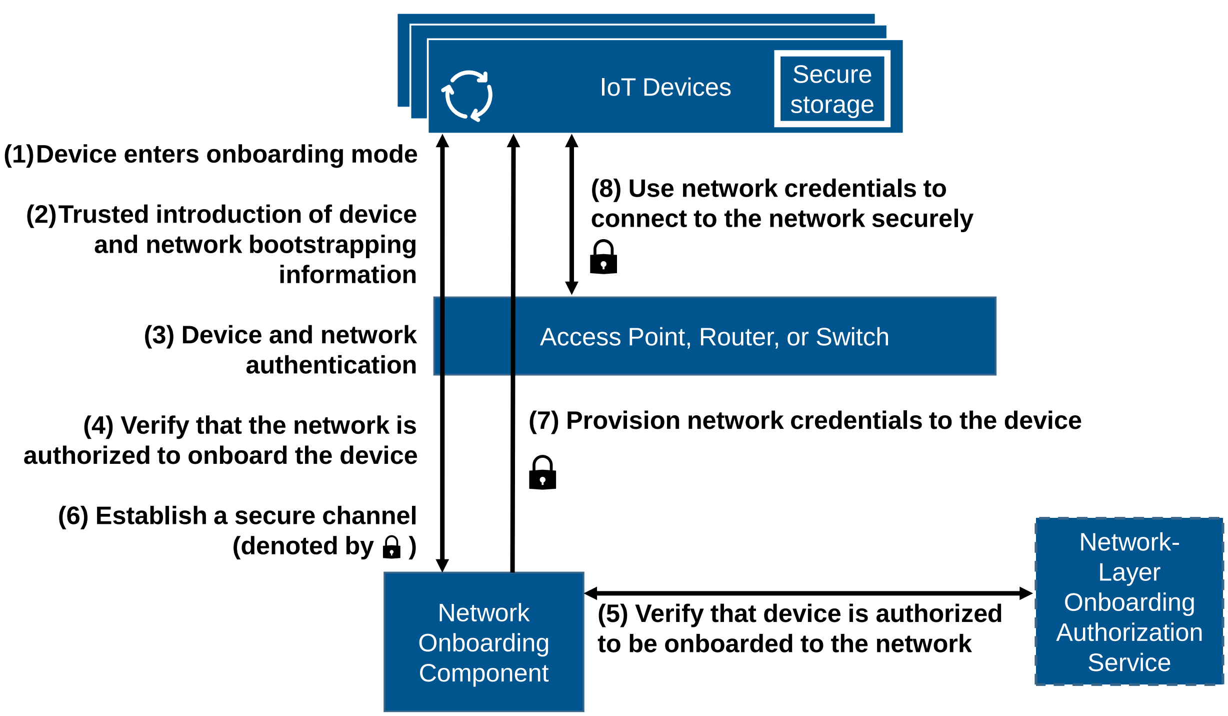
(Note: In this document, for the sake of simplicity, we often refer to the network that is authorized to onboard a device as the device owner's network. In reality, it may not always be the case that the device's owner also owns the network to which the device is being onboarded. While it is assumed that a network that owns a device is authorized to onboard it, and the device and the onboarding network are often owned by the same entity, common ownership is not a requirement. The network that is onboarding a device does not have to be the owner of that device. The network owner may permit devices that it does not own to be onboarded to the network. In order for such a device to be onboarded, the network owner must be in possession of the device's bootstrapping information. By accepting the bootstrapping information, the network owner is implicitly authorizing the device to be onboarded to its network. Conversely, a device may permit itself to be onboarded to a network that is not owned by the device's owner. A device owner that wants to authorize a network to onboard the device needs to ensure that the device trusts the onboarding network. The specific mechanism for accomplishing this will vary according to the network-layer onboarding protocol being used. When the Wi-Fi Easy Connect protocol is being used, simply providing the network with the device's public key is sufficient to authorize the network to onboard the device. When BRSKI is being used, the voucher that the MASA provides to the device must authorize the network to onboard it.)

Authentication of the network by the device may also take a variety of forms. These may range from simply trusting the person who is onboarding the device to onboard it to the correct network, to providing the IoT device with the network's public key.

4.3 Trusted Network-Layer Onboarding Process

Figure 4-4 depicts the trusted network-layer onboarding process in more detail. It shows the interactions that occur between the network-layer onboarding component and the IoT device to mutually authenticate, confirm that the device is authorized to be onboarded to the network, confirm that the network is authorized to onboard the device, establish a secure channel, and provision the device with its network credentials.

Figure 4-4 Trusted Network-Layer Onboarding Process



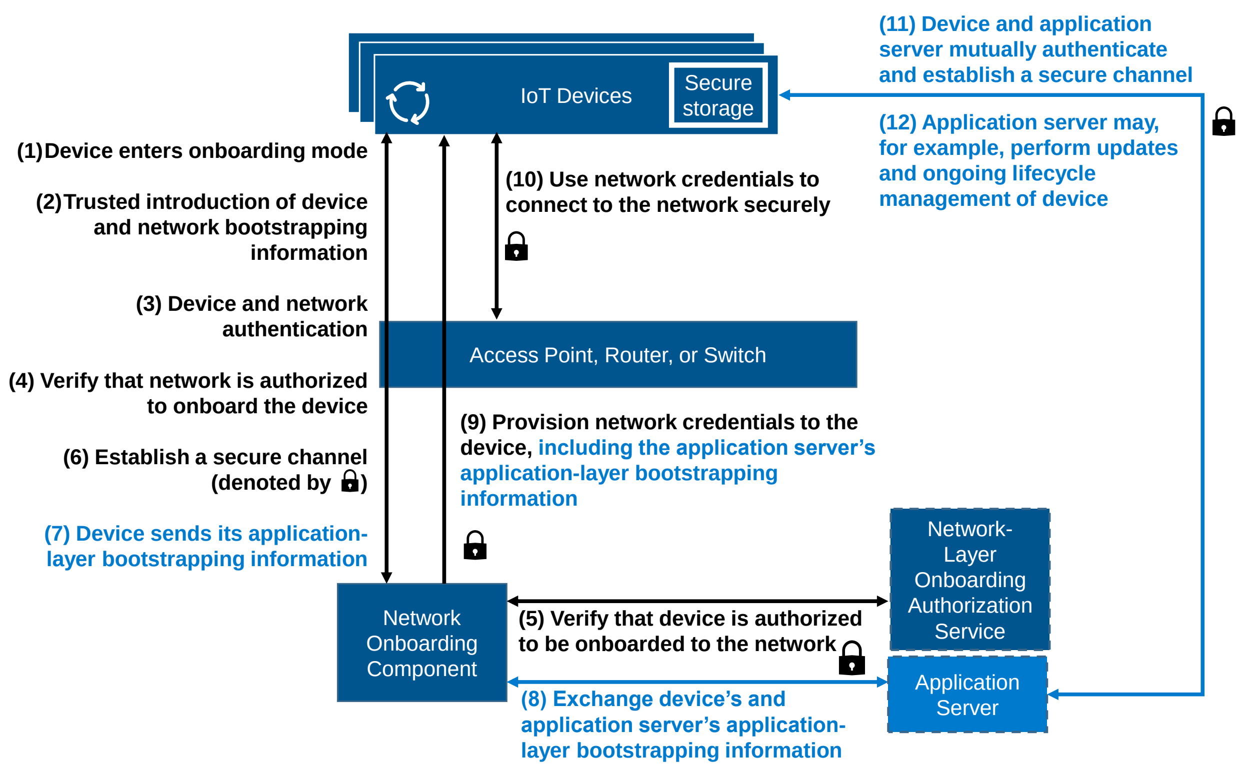
The numbered arrows in the diagram are intended to provide a high-level summary of the network-layer onboarding steps. These steps are assumed to occur after any device bootstrapping information and ownership transfer activities (as described in the previous section) that may need to be performed. The steps of the trusted network-layer onboarding process are as follows:

1. The IoT device to be onboarded is placed in onboarding mode, i.e., it is put into a state such that it is actively listening for and/or sending initial onboarding protocol messages.
2. Any required device bootstrapping information that has not already been provided to the network and any required network bootstrapping information that has not already been provided to the device are introduced in a trusted manner.
3. Using the device and network bootstrapping information that has been provided, the network authenticates the identity of the IoT device (e.g., by ensuring that the IoT device is in possession of the private key that corresponds with the public key for the device that was provided as part of the device's bootstrapping information), and the IoT device authenticates the identity of the network (e.g., by ensuring that the network is in possession of the private key that corresponds with the public key for the network that was provided as part of the network's bootstrapping information).
4. The device verifies that the network is authorized to onboard it. For example, the device may verify that it and the network are owned by the same entity, and therefore, assume that the network is authorized to onboard it.
5. The network onboarding component consults the network-layer onboarding authorization service to verify that the device is authorized to be onboarded to the network. For example, the network-layer authorization service can confirm that the device is owned by the network and is on the list of devices authorized to be onboarded.
6. A secure (i.e., encrypted) channel is established between the network onboarding component and the device.
7. The network onboarding component uses the secure channel that it has established with the device to confidentially send the device its unique network credentials.
8. The device uses its newly provisioned network credentials to establish secure connectivity to the network. The access point, router, or switch validates the device's credentials in this step. The mechanism it uses to do so varies depending on the implementation and is not depicted in Figure 4-4.

4.4 Trusted Application-Layer Onboarding Process

Figure 4-5 depicts the trusted application-layer onboarding process as enabled by the streamlined application-layer onboarding mechanism. As defined in Section 3.3.2, streamlined application-layer onboarding occurs after network-layer onboarding and depends upon and is enabled by it. The figure uses two colors. The dark-blue components are those used in the network-layer onboarding process. They and their accompanying steps (written in black font) are identical to those found in the trusted network-layer onboarding process diagram provided in Figure 4-4. The light-blue component and its accompanying steps (written in light-blue font) depict the portion of the diagram that is specific to streamlined application-layer onboarding.

Figure 4-5 Trusted Streamlined Application-Layer Onboarding Process



As is the case with Figure 4-4, the steps in this diagram are assumed to occur after any device ownership and bootstrapping information transfer activities that may need to be performed. Steps 1-6 in this figure are identical to Steps 1-6 in the trusted network-layer onboarding diagram of Figure 4-4, but steps 7 and 8 are different. With the completion of steps 1-6 in Figure 4-5, a secure channel has been established between the IoT device and the network-layer onboarding component. However, the device does not get provisioned with its network-layer credentials until step 9. To support streamlined application-layer onboarding, additional steps are required. Steps 1-12 are as follows:

1. The IoT device to be onboarded is placed in onboarding mode, i.e., it is put into a state such that it is actively listening for and/or sending initial onboarding protocol messages.
2. Any required device bootstrapping information that has not already been provided to the network and any required network bootstrapping information that has not already been provided to the device are introduced in a trusted manner.
3. Using the device and network bootstrapping information that has been provided, the network authenticates the identity of the IoT device (e.g., by ensuring that the IoT device is in possession of the private key that corresponds with the public key for the device that was provided as part of the device's bootstrapping information), and the IoT device authenticates the identity of the network (e.g., by ensuring that the network is in possession of the private key that corresponds

with the public key for the network that was provided as part of the network's bootstrapping information).

4. The device verifies that the network is authorized to onboard it. For example, the device may verify that it and the network are owned by the same entity, and therefore, assume that the network is authorized to onboard it.

5. The network onboarding component consults the network-layer onboarding authorization service to verify that the device is authorized to be onboarded to the network. For example, the network-layer authorization service can confirm that the device is owned by the network and is on the list of devices authorized to be onboarded.

6. A secure (i.e., encrypted) channel is established between the network onboarding component and the device.

7. The device sends its application-layer bootstrapping information to the network onboarding component. Just as the network required the trusted introduction of device network-layer bootstrapping information in order to enable the network to authenticate the device and ensure that the device was authorized to be network-layer onboarded, the application server requires the trusted introduction of device application-layer bootstrapping information to enable the application server to authenticate the device at the application layer and ensure that the device is authorized to be application-layer onboarded. Because this application-layer bootstrapping information is being sent over a secure channel, its integrity and confidentiality are ensured.

8. The network onboarding component forwards the device's application-layer bootstrapping information to the application server. In response, the application server provides its application-layer bootstrapping information to the network-layer onboarding component for eventual forwarding to the IoT device. The IoT device needs the application server's bootstrapping information to enable the device to authenticate the application server and ensure that it is authorized to application-layer onboard the device.

9. The network onboarding component uses the secure channel that it has established with the IoT device to confidentially send the device its unique network credentials. Along with these network credentials, the network onboarding component also sends the IoT device the application server's bootstrapping information. Because the application server's bootstrapping information is being sent over a secure channel, its integrity and confidentiality are ensured.z

10. The device uses its newly provisioned network credentials to establish secure connectivity to the network.

11. Using the device and application server application-layer bootstrapping information that has already been exchanged in a trusted manner, the application server authenticates the identity of the IoT device and the IoT device authenticates the identity of the application server. Then they establish a secure (i.e., encrypted) channel.

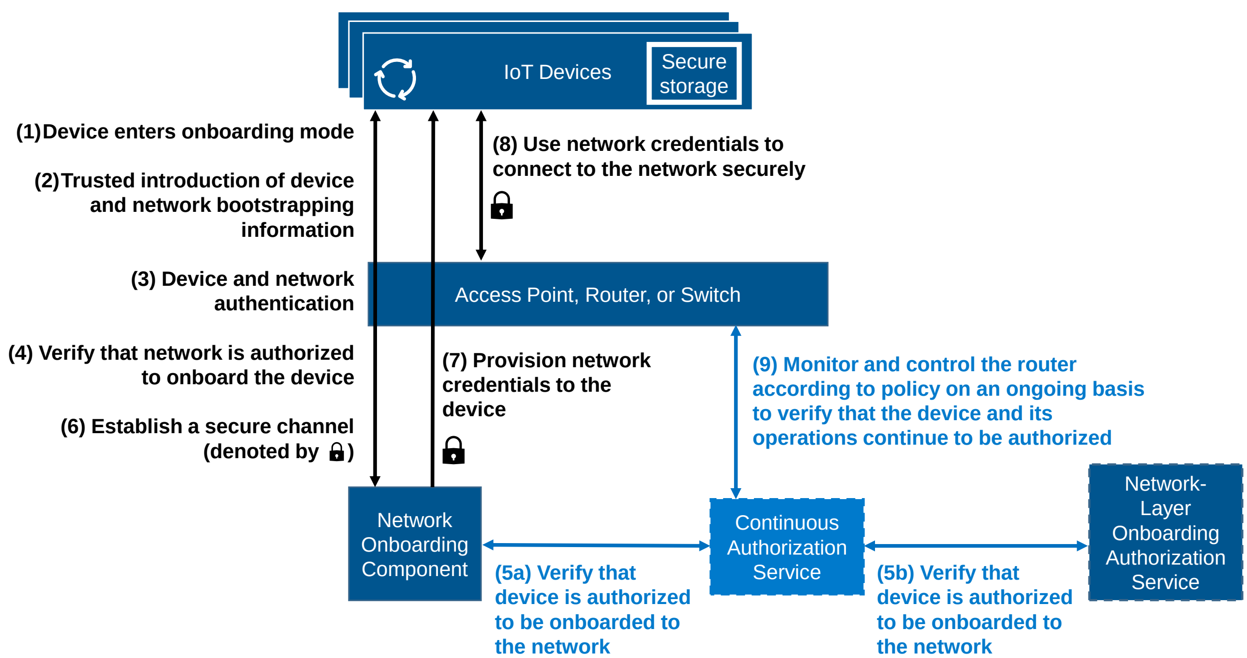
12. The application server application layer onboards the IoT device. This application-layer onboarding process may take a variety of forms. For example, the application server may download an application to the device for the device to execute. It may associate the device

with a trusted lifecycle management service that performs ongoing updates of the IoT device to patch it as needed to ensure that the device remains compliant with policy.

4.5 Continuous Verification

[Figure](#)4-6 depicts the steps that are performed to support continuous verification. The figure uses two colors. The light-blue component and its accompanying steps (written in light-blue font) depict the portion of the diagram that is specific to continuous authorization. The dark-blue components are those used in the network-layer onboarding process. They and their accompanying steps (written in black font) are identical to those found in the trusted network-layer onboarding process diagram provided in [Figure](#)4-4, except for step 5, *Verify that device is authorized to be onboarded to the network*.

Figure 4-6 Continuous Verification



When continuous verification is being supported, step 5 is broken into two separate steps, as shown in Figure 4-6. Instead of the network onboarding component directly contacting the network-layer onboarding authorization service to see if the device is owned by the network and on the list of devices authorized to be onboarded (as shown in the trusted network-layer onboarding architecture depicted in [Figure](#)4-4), a set of other enterprise policies may also be applied to determine if the device is authorized to be onboarded. The application of these policies is represented by the insertion of the Continuous Authorization Service (CAS) component in the middle of the exchange between the network onboarding component and the network-layer onboarding authorization service.

For example, the CAS may have received external threat information indicating that certain device types have a vulnerability. If so, when the CAS receives a request from the network-layer onboarding component to verify that a device of this type is authorized to be onboarded to the network (Step 5a), it would immediately respond to the network-layer onboarding component that the device is not authorized to be onboarded to the network. If the CAS has not received any such threat information about the device and it checks all its policies and determines that the device should be permitted to be onboarded, it will forward the request to the network-layer onboarding authorization service (Step 5b) and receive a response (Step 5b) that it will forward to the network onboarding component (Step 5a).

As depicted by Step 9, the CAS also continues to operate after the device connects to the network and executes its application. The CAS performs asynchronous calls to the network router to monitor the device on an ongoing basis, providing policy-based verification and authorization checks on the device throughout its lifecycle.

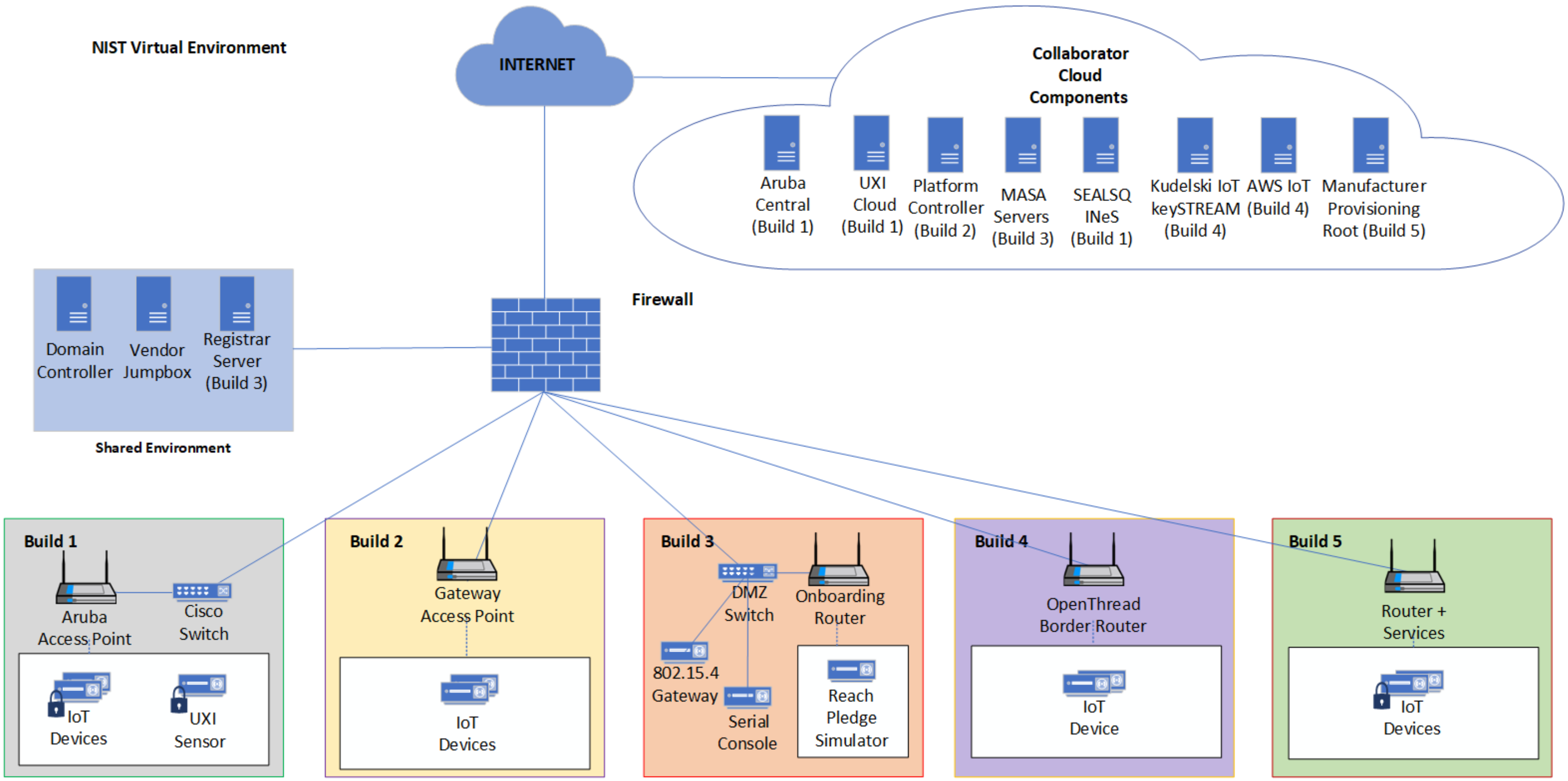
5 Laboratory Physical Architecture

Figure 5-1 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 factory provisioning builds are being 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.

Access to and from the IoT Onboarding lab is protected by a pfSense firewall, represented by the brick box icon in Figure 5-1. 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 LANs, 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 MASA server (Build 3), Kudelski IoT keySTREAM application-layer onboarding service and AWS IoT (Build 4), and a Manufacturer Provisioning Root (Build 5).

1435 **Figure 5-1 NCCoE IoT Onboarding Laboratory Physical Architecture**



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

- The 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 that are onboarded using Build 1 include the UXI Sensor and the Raspberry Pi.
- The 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.
- The 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 which is accessed via the internet. In addition, a Raspberry Pi 3 provides an ethernet/802.15.4 gateway, as well as a test platform.
- The Build 4 (i.e., the Thread, Silicon Labs, Kudelski IoT build) network infrastructure components within the NCCoE lab include an Open Thread Border Router, 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 that is 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.
- The 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 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 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 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.

Information regarding the physical architecture of all builds, their related collaborators' cloud components, and the shared environment, as well as the baseline software running on these physical architectures, are described in the subsections below. Table 5-1 summarizes the builds that were implemented and provides links to the appendices where each is described in detail.

Table 5-1 Build 1 Products and Technologies

Build	Network-Layer Protocols	Build Champions	Link to Details
Onboarding Builds			
Build 1	Wi-Fi Easy Connect	Aruba/HPE	Appendix C
Build 2	Wi-Fi Easy Connect	CableLabs and OCF	Appendix D
Build 3	BRSKI	Sandelman Software Works	Appendix E
Build 4	Thread	Silicon Labs and Kudelski IoT	Appendix F
Build 5	BRSKI over Wi-Fi	NquiringMinds	Appendix G
Factory Provisioning Builds			
BRSKI with Build 5	BRSKI over WIFI	SEALSQ and NquiringMinds	Appendix H.3
Wi-Fi Easy Connect with Build 1	Wi-Fi Easy Connect	SEALSQ and Aruba/HPE	Appendix H.4

5.1 Shared Environment

The NCCoE IoT Onboarding laboratory contains a shared environment to host several baseline services in support of the builds. These baseline services supported configuration and integration work in each of the builds and allowed collaborators to work together throughout the build process. This shared environment is contained in its own network segment, with access to/from the rest of the lab environment closely controlled. In addition, each of the systems in the shared environment is hardened with baseline configurations.

5.1.1 Domain Controller

The Domain Controller provides Active Directory and Domain Name System (DNS) services supporting network access and access control in the lab. It runs on Windows Server 2019.

5.1.2 Jumpbox

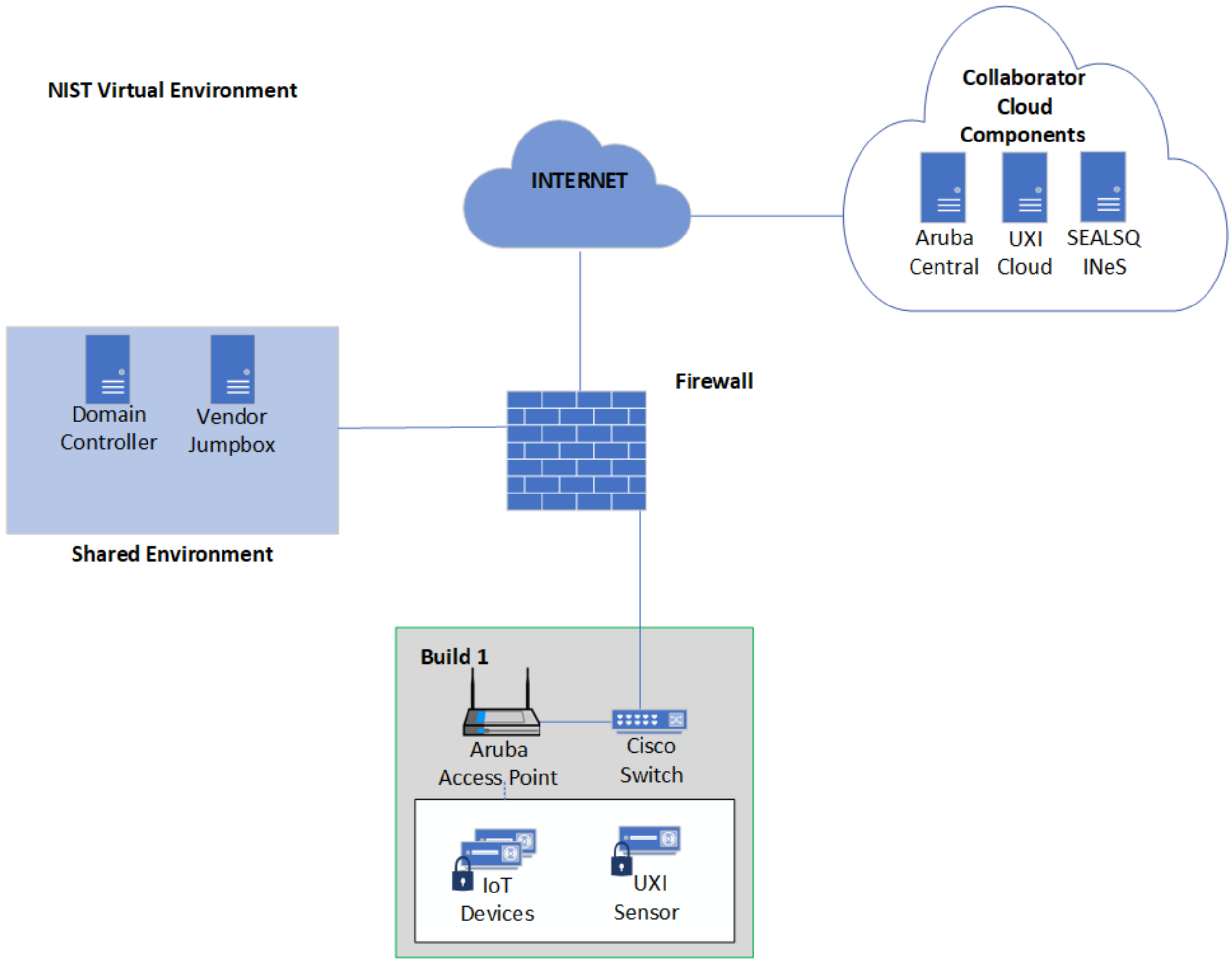
The jumpbox provides secure remote access and management to authorized collaborators on each of the builds. It runs on Windows Server 2019.

5.2 Build 1 (Wi-Fi Easy Connect, Aruba/HPE) Physical Architecture

Figure 5-2 is a view of the high-level physical architecture of Build 1 in the NCCoE IoT Onboarding laboratory. The build components include an Aruba Wireless Access Point, Aruba Central, UXI Cloud, a Cisco Catalyst switch, a SEALSQ INeS CMS CA, and the IoT devices to be onboarded, which include both a Raspberry Pi and a UXI sensor. Most of these components are described in Section 3.4.1 and Section 3.4.3.

- The Aruba Access Point acts as the DPP Configurator and relies on the Aruba Central cloud service for authentication and management purposes.
- Aruba Central ties together the IoT Operations, Client Insights, and Cloud Auth services to support the network-layer onboarding operations of the build. It also provides an API to support the device ownership and bootstrapping information transfer process.
- The Cisco Catalyst Switch provides Power-over-Ethernet and network connectivity to the Aruba Access Point.
- The UXI Sensor acts as an IoT device and onboards to the network via Wi-Fi Easy Connect. After network-layer onboarding, it performs independent (see Section 3.3.2) application-layer onboarding. Once it has application-layer onboarded and is operational on the network, it does passive and active monitoring of applications and services and will report outages, disruptions, and quality of service issues.
- UXI Cloud is an HPE cloud service that the UXI sensor contacts as part of the application-layer onboarding process. The UXI sensor downloads a customer-specific configuration from the UXI Cloud so that the UXI sensor can learn about the customer networks and services it needs to monitor.
- The Raspberry Pi acts as an IoT device and onboards to the network via Wi-Fi Easy Connect.
- SEALSQ Certificate Authority has been integrated with Build 1 to sign network credentials that are issued to IoT devices.

Figure 5-2 Physical Architecture of Build 1

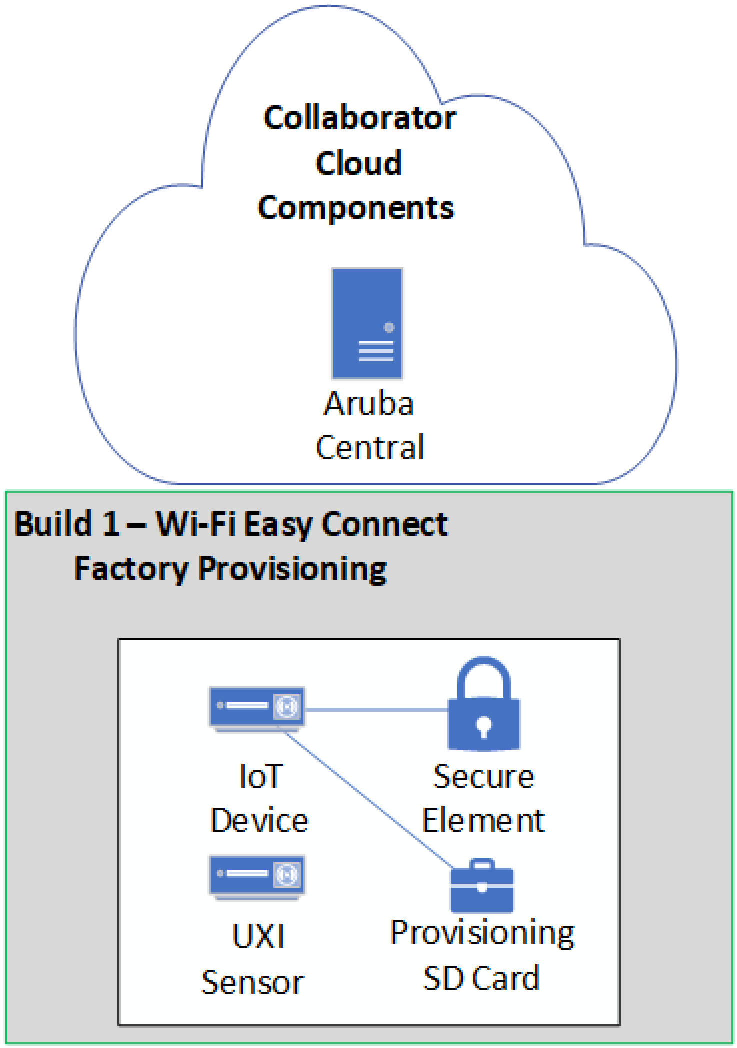


5.2.1 Wi-Fi Easy Connect Factory Provisioning Build Physical Architecture

Figure 5-3 is a view of the high-level physical architecture of the Wi-Fi Easy Connect Factory Provisioning Build in the NCCoE IoT Onboarding laboratory. The build components include the IoT device, an SD card with factory provisioning code on it, and a Secure Element. See Appendix H.4 for additional details on the Wi-Fi Easy Connect Factory Provisioning Build.

- A UXI sensor.
- The IoT Device is a Raspberry Pi.
- The Secure Element is a SEALSQ VaultIC Secure Element and is interfaced with the Raspberry Pi. The Secure Element both generates and stores the key material necessary to support the DPP URI during the Factory Provisioning Process.
- An SD card with factory provisioning code.
- Aruba Central provides an API to ingest the DPP URI in support of the device ownership and bootstrapping information transfer process.

Figure 5-3 Physical Architecture of Wi-Fi Easy Connect Factory Provisioning Build

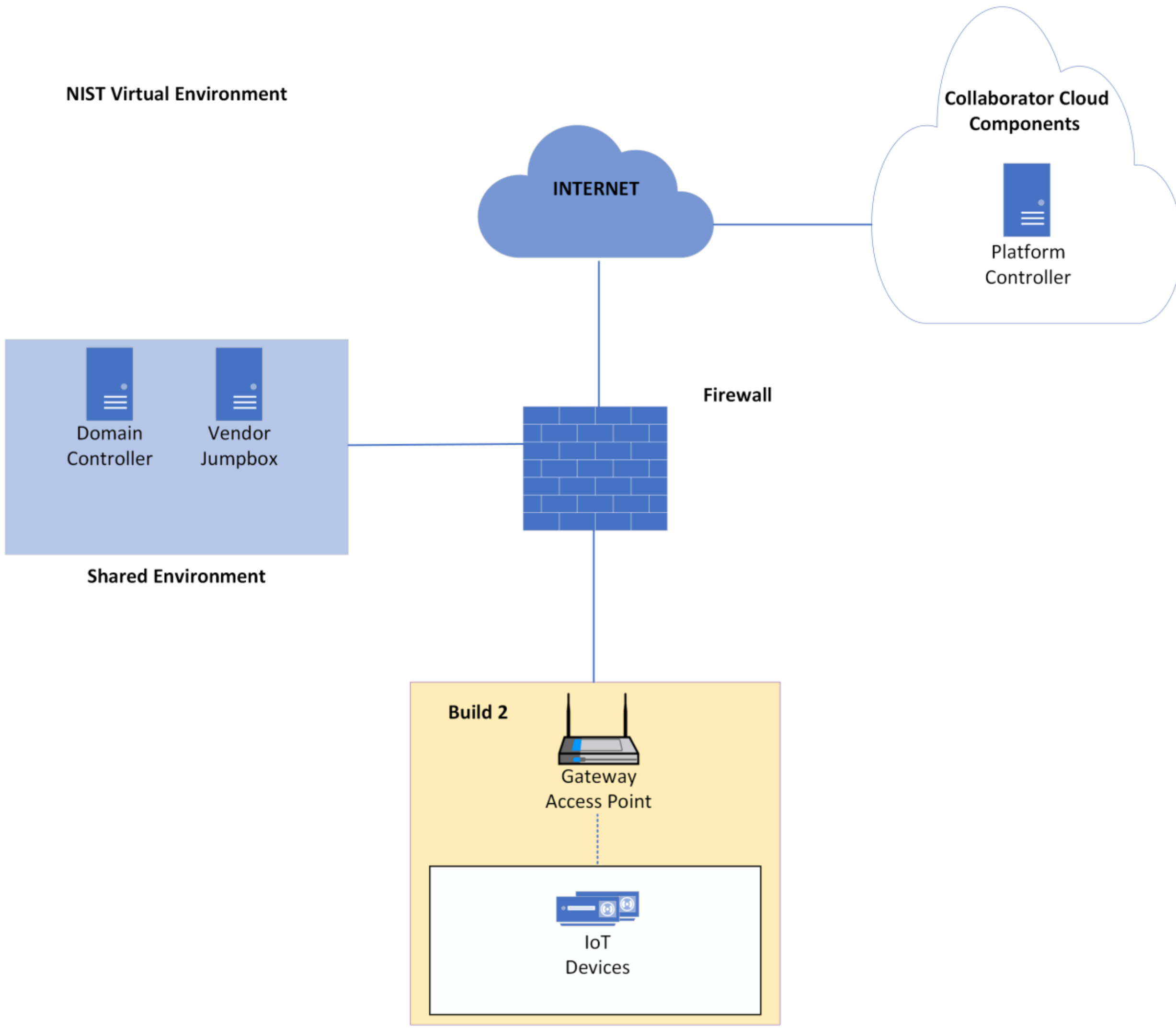


5.3 Build 2 (Wi-Fi Easy Connect, CableLabs, OCF) Physical Architecture

Figure 5-3 is a view of the high-level physical architecture of Build 2 in the NCCoE IoT Onboarding laboratory. The Build 2 components include the Gateway Access Point, three IoT devices, and the Platform Controller, which hosts the application-layer IoTivity service.

- The Gateway Access Point acts as the Custom Connectivity Gateway Agent described in Section 3.4.2.2 and controls all network-layer onboarding activity within the network. It also hosts OCF IoTivity functions, such as the OCF OBT and the OCF Diplomat.
- The Platform Controller described in Section 3.4.2.1 provides management capabilities for the Custom Connectivity Gateway Agent. It also hosts the application-layer IoTivity service for the IoT devices as described in Section 3.4.8.1.
- The IoT devices serve as reference clients, as described in Section 3.4.2.3. They run OCF reference implementations. The IoT devices are onboarded to the network and complete both application-layer and network-layer onboarding.

Figure 5-4 Physical Architecture of Build 2



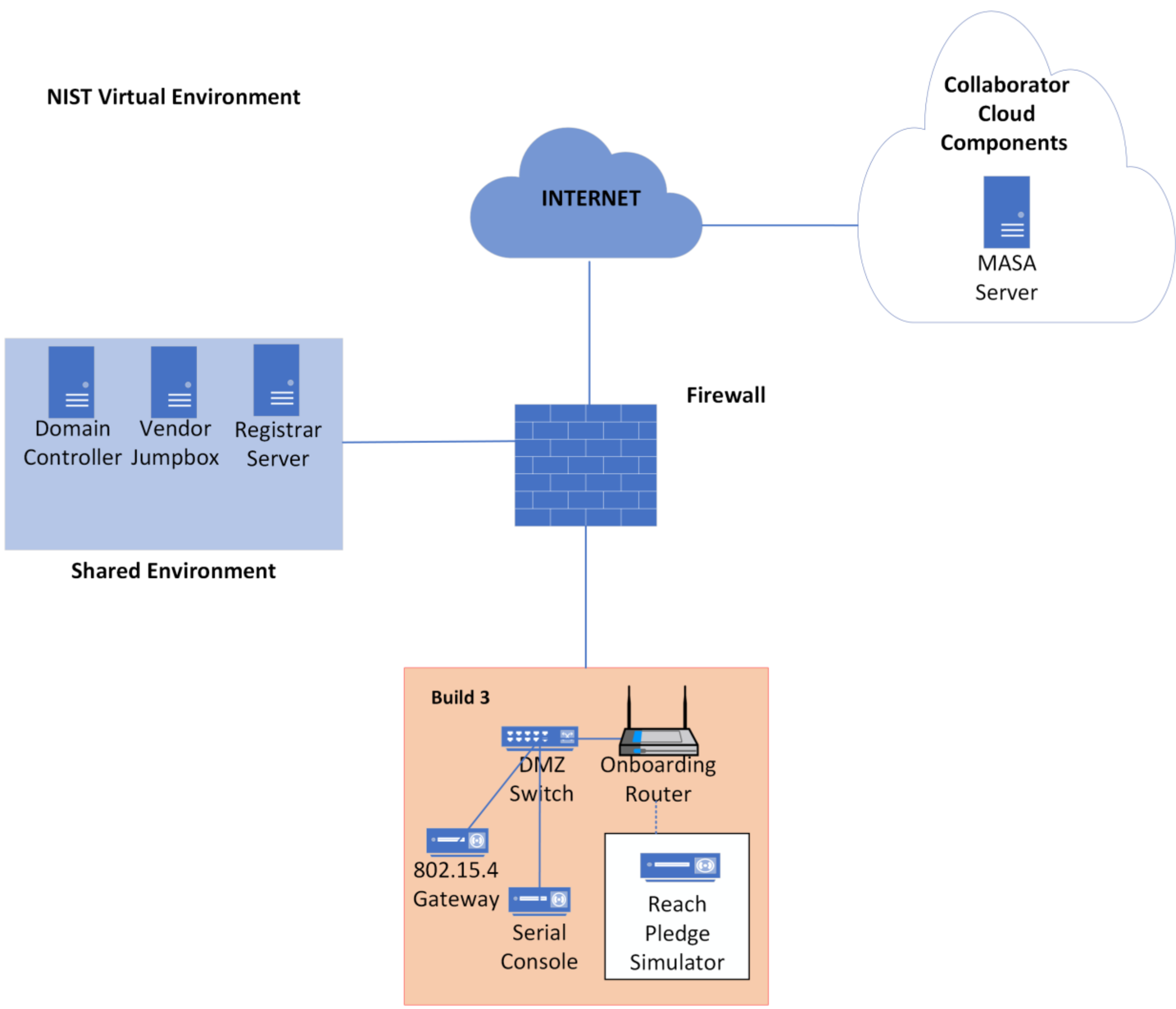
5.4 Build 3 (BRSKI, Sandelman Software Works) Physical Architecture

Figure 5-4 is a view of the high-level physical architecture of Build 3 in the NCCoE IoT Onboarding laboratory. The Build 3 components include the onboarding router, a Registrar Server, a MASA server, a DMZ switch, IoT devices, a serial console, and an 802.15.4 gateway.

- The onboarding router is a Turris MOX router running OpenWRT. The onboarding router quarantines the IoT devices until they complete the BRSKI onboarding process.
- The owner's Registrar Server hosts the Minerva Fountain Join Registrar Coordinator application running in a virtual machine. The Registrar Server determines whether or not a device meets the criteria to join the network.
- The MASA server for this build is a Minerva Highway MASA server as outlined in Section 3.4.9.1. The role of the MASA server is to receive the voucher-request from the Registrar Server and confirm that the Registrar Server has the right to own the device.

- The DMZ switch is a basic Netgear switch that segments the build from the rest of the lab.
- The IoT devices include an ESP32 Xtensa device with Wi-Fi that will be tested with FreeRTOS and RIOT-OS, a Raspberry Pi 3 running Raspbian 11, and an nRF52840 with an 802.15.4 radio that is running RIOT-OS. The IoT devices are currently not used in the build but will serve as clients to be onboarded onto the network in a future implementation of the build.
- The Sandelman Software Works Reach Pledge Simulator is the device that is onboarded to the network in the current build.
- The serial console is a BeagleBone Green with an attached USB hub. The serial console is used to access the IoT devices for diagnostic purposes. It also provides power and power control for USB-powered devices.
- The 802.15.4 gateway is integrated into the Raspberry Pi 3 via an OpenMote daughter card. This gateway will serve to onboard one of the IoT devices in a future implementation of this build.

Figure 5-5 Physical Architecture of Build 3

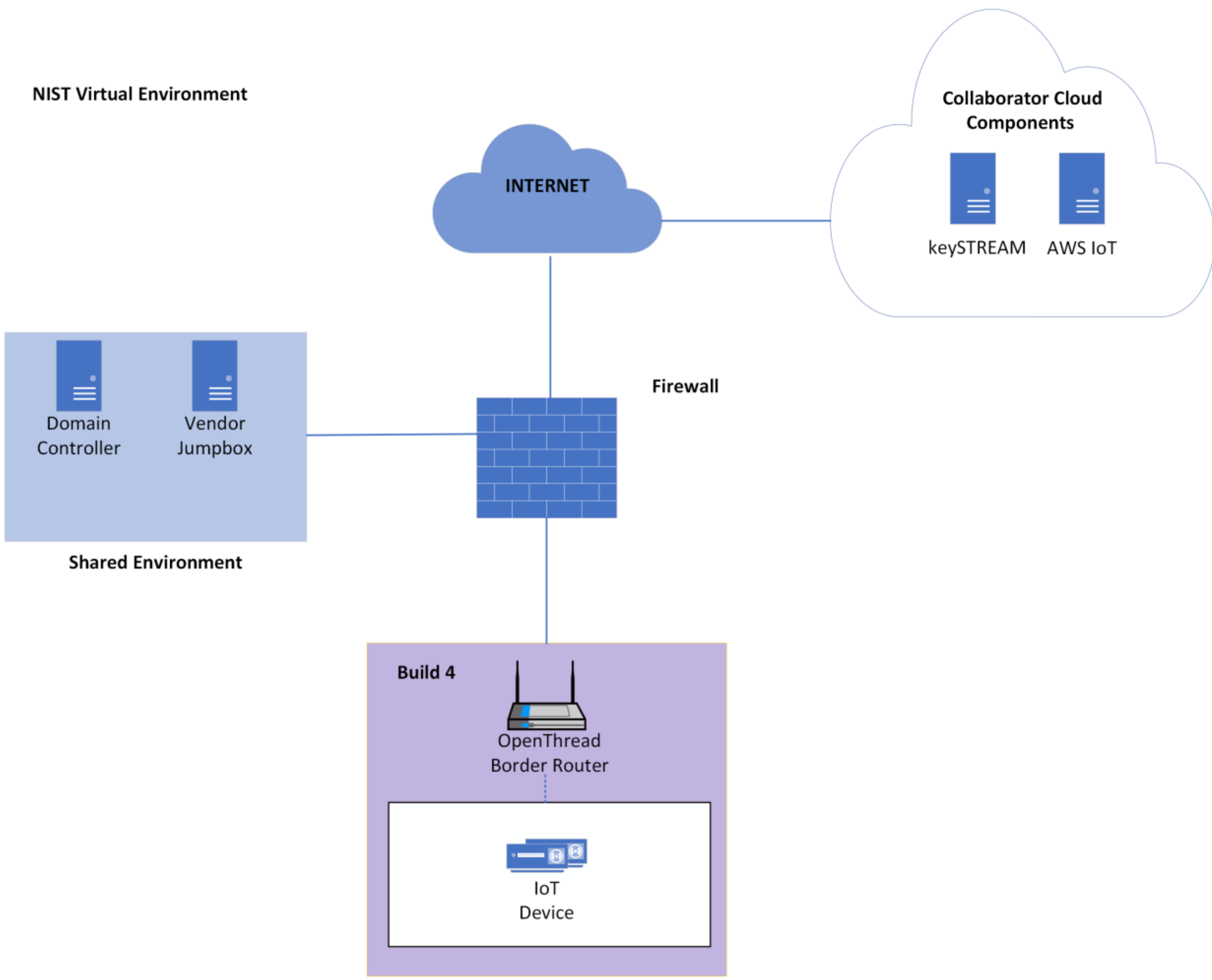


5.5 Build 4 (Thread, Silicon Labs, Kudelski IoT) Physical Architecture

Figure 5-6 is a view of the high-level physical architecture of Build 4 in the NCCoE IoT Onboarding laboratory. The Build 4 components include a keySTREAM server, an AWS IoT server, an OpenThread Border Router, and a Thread IoT device.

- The keySTREAM server described in Section 3.4.5.1 is the application layer onboarding service provided by Kudelski IoT. The IoT device will authenticate to keySTREAM using a Silicon Labs chip birth certificate and private key and leveraging Silicon Labs' Secure Engine in the EFR32MG24 chipset ("Secure Vault(TM) High" which is security certified Platform Security Architecture (PSA)/Security Evaluation Standard for IoT Platforms (SESIP) Level 3 to protect that birth identity with Secure Boot, Secure Debug, and physically unclonable function (PUF) wrapped key storage and hardware tamper protection).
- The AWS IoT server provides the MQTT test client for the trusted application-layer onboarding. The Proof of Possession Certificate is provisioned for the device using a registration code from the AWS server.
- The OpenThread Border Router is run on a Raspberry Pi 3B and serves as the Thread Commissioner and Leader. It communicates with the IoT device by means of a Silicon Labs Gecko Wireless Devkit which serves as the 802.15.4 antenna for the build.
- The IoT Device in this build is a Silicon Labs Thunderboard (BRD2601A) containing the EFR32MG24Bx 15.4 SoC with Secure Vault (TM) High running the Thread protocol. It serves as the child node on the Thread network and is onboarded onto AWS IoT Core using credentials provisioned from the Kudelski keySTREAM service.

Figure 5-6 Physical Architecture of Build 4



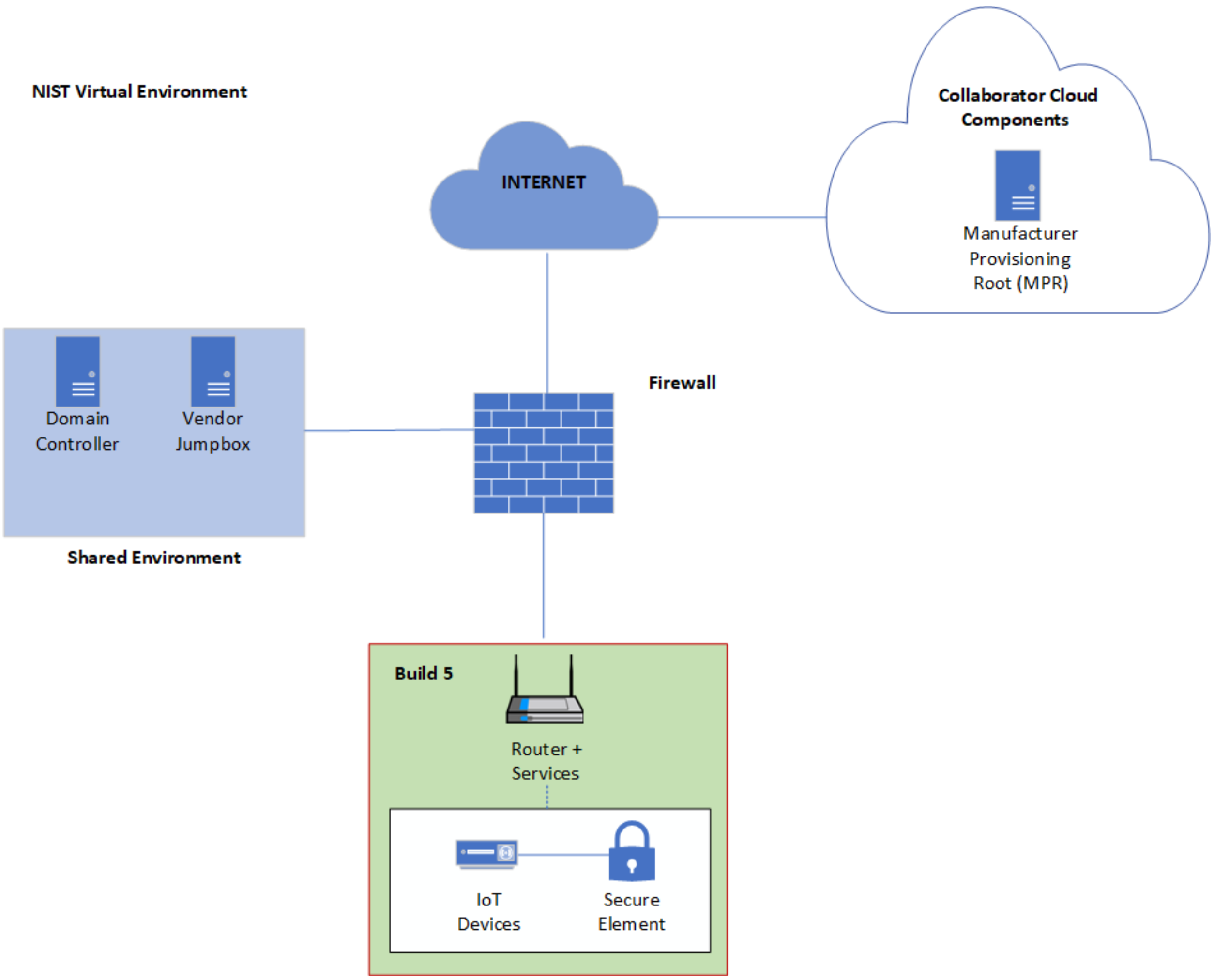
5.6 Build 5 (BRSKI, NquiringMinds) Physical Architecture

Figure 5-6 is a view of the high-level physical architecture of Build 5 in the NCCoE IoT Onboarding laboratory. The Build 5 components include a MASA, Registrar, Router Access Point, an IoT Device, and a Secure Element:

- A Raspberry Pi 4B serves as the MASA, Registrar and Router Access Point for the local network. The role of the MASA is to receive the voucher-request from the Registrar and confirm that the Registrar has the right to own the device. The registrar self-signs credentials, namely the Local Device Identifier (LDevID), issued to the IoT devices. The pledge (IoT device) gets its IDevID certificate for device identity from the Manufacturer Provisioning Root (MPR) server during the factory provisioning process, it can be assumed to be present on the device at the point of onboarding. The Registrar determines whether or not a device meets the criteria to join the network. The router access point runs an open and closed BRSKI network, the closed BRSKI network may only be accessed through secure onboarding, which is performed via the open network. The registrar leverages a local tdx Volt instance to sign and verify verifiable credentials.
- Raspberry Pi 4Bs act as IoT Devices (pledges) for this build.

- The Secure Element is an Infineon Optiga SLB 9670 TPM 2.0 Secure Element, and both generates and stores the key material necessary to support the IDevID certificate during the Factory Provisioning Process, as well as the onboarding process to request the voucher from the MASA via the registrar and the request to the registrar to sign the LDevID. The system can also be configured to use a SEALSQ VaultIC408 secure element. See Appendix H.3 for additional details on the BRSKI factory provisioning builds.

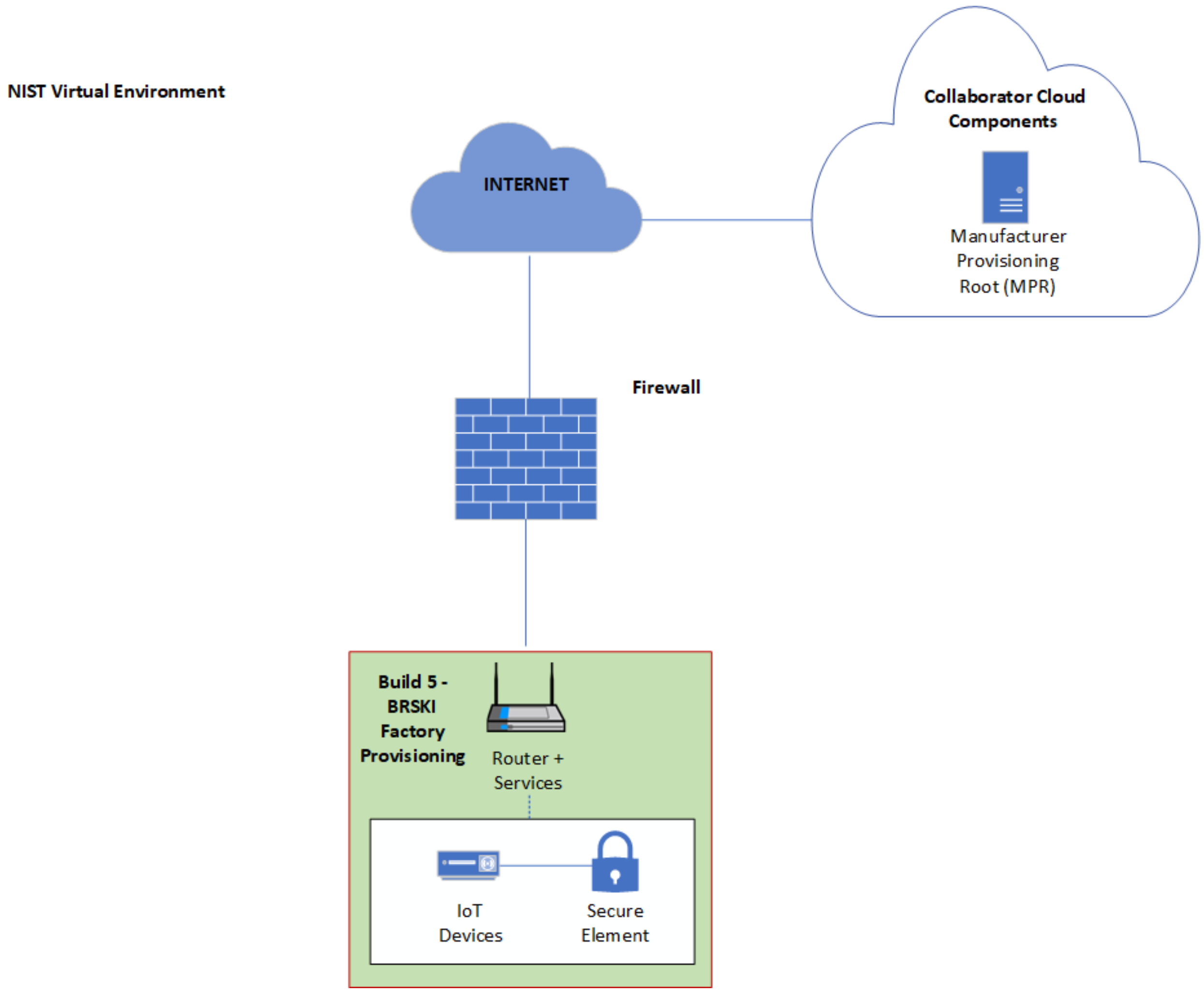
Figure 5-7 Physical Architecture of Build 5



5.6.1 BRSKI Factory Provisioning Build Physical Architecture

Figure 5-8 is a view of the high-level physical architecture of the BRSKI Factory Provisioning Build in the NCCoE IoT Onboarding laboratory. This build uses the same IoT device as Build 5: a Raspberry Pi integrated with an Infineon Optiga SLB 9670 TPM 2.0 Secure Element. The factory provisioning code is hosted on an SD card. When a provisioning event is triggered the IoT device will attempt a connection to a Manufacturer Provisioning Root (MPR) server that sits in the cloud and acts as the certification authority. It signs the IDevID (X.509) certificate, which is then passed back to the IoT device for installation. As in Build 5, the Router + Services hosts a MASA, which is given device identity information in order to verify voucher requests during the BRKSI process. See Appendix H.3 for additional details on the BRSKI factory provisioning builds.

Figure 5-8 Physical Architecture of BRSKI Factory Provisioning Build



6 General Findings

6.1 Wi-Fi Easy Connect

The Wi-Fi Easy Connect solution that was demonstrated in Build 1 and Build 2 supports trusted network-layer onboarding in a manner that is secure, efficient, and flexible enough to meet the needs of various use cases. It is simple enough to be used by consumers, who typically do not have specialized technical knowledge. In addition, to meet the needs of enterprises, it may be used to onboard a large number of devices quickly. Builds 1 and 2 are implementations of this protocol, and they are interoperable: IoT devices that were provisioned for use with Build 1 were able to be onboarded onto the network using Build 2, and IoT devices that were provisioned for use with Build 2 were able to be onboarded onto the network using Build 1.

6.1.1 Mutual Authentication

Although DPP is designed to support authentication of the network by the IoT device as well as authentication of the device by the network, the Wi-Fi Easy Connect solutions that were demonstrated in builds 1 and 2 do not demonstrate mutual authentication at the network layer. They only support authentication of the device. In order to authenticate the network, the device needs to be provided with the DPP URI for the network configurator, which means that the device has to have a functional user interface so that the DPP URI can be input into it. The devices being used in builds 1 and 2 do not have user interfaces.

6.1.2 Mutual Authorization

When using DPP, device authorization is based on possession of the device's DPP URI. When the device is acquired, its DPP URI is provided to the device owner. A trusted administrator of the owner's network is assumed to approve addition of the device's DPP URI to the database or cloud service where the DPP URIs of authorized devices are stored. During the onboarding process, the fact that the owning network is in possession of the device's DPP URI indicates to the network that the device is authorized to join it.

DPP supports network authorization using the Resurrecting Duckling security model [13]. Although the device cannot cryptographically verify that the network is authorized to onboard it, the fact that the network possesses the device's public key is understood by the device to implicitly authorize the network to onboard the device. The assumption is that an unauthorized network would not have possession of the device and so would not be able to obtain the device's public key. While this assurance of authorization is not cryptographic, it does provide some level of assurance that the "wrong" network won't onboard it.

6.1.3 Secure Storage

The UXI sensor used in Build 1 has a TPM where the device's birth credential and private key are stored, providing a secure root of trust. However, the lack of secure storage on some of the other IoT devices (e.g., the Raspberry Pis) used to demonstrate onboarding in Build 2 is a current weakness. Ensuring that the confidentiality of a device's birth, network, and other credentials is protected while stored on the device is an essential aspect of ensuring the security of the network-layer onboarding process, the device, and the network itself. To fully demonstrate trusted network-layer onboarding, devices with secure storage should be used in the future whenever possible.

6.2 BRSKI

The BRSKI solution that is demonstrated in Build 3 supports trusted network-layer onboarding in a manner that is secure, efficient, and able to meet the needs of enterprises. It may be used to onboard a large number of devices quickly onto a wired network. This BRSKI build is based on IETF RFC 8995 [7]. The build has a reliance on the manufacturer to provision keys for the onboarding device and has a reliance on a cloud-based service for the MASA server. The BRSKI solution that is demonstrated in Build 5 provides similar trusted functionality for onboarding devices onto a Wi-Fi network. This BRSKI build is based on an IETF individual draft describing how to run BRSKI over IEEE 802.11 [10].

6.2.1 Reliance on the Device Manufacturer

Organizations implementing BRSKI (whether wired or over Wi-Fi) should be aware of the reliance that they will have on the IoT device manufacturer in properly and securely provisioning their devices. If keys become compromised, attackers may be able to onboard their own devices to the network, revoke certificates to prevent legitimate devices from being onboarded, or onboard devices belonging to others onto the attacker's network using the attacker's MASA. These concerns are addressed in depth in RFC 8995 section 11.6. If a device manufacturer goes out of business or otherwise shuts down their MASA servers, the onboarding services for their devices will no longer function.

During operation, onboarding services may become temporarily unavailable for a number of reasons. In the case of a DoS attack on the MASA, server maintenance, or other outage on the part of the manufacturer, an organization will not be able to access the MASA. These concerns are addressed in depth in RFC 8995 section 11.1.

6.2.2 Mutual Authentication

BRSKI supports authentication of the IoT device by the network as well as authentication of the network by the IoT device. The Registrar authenticates the device when it receives the IDevID from the device. The MASA confirms that the Registrar is the legitimate owner or authorized onboarder of the device and issues a voucher. The device is able to authenticate the network using the voucher that it receives back from the MASA. This process is explained in depth in RFC 8995 section 11.5.

6.2.3 Mutual Authorization

BRSKI authorization for the IoT device is done via the voucher that is returned to the Registrar from the MASA. The voucher states which network the IoT device is authorized to join. The Registrar determines the level of access the IoT device has to the network.

6.2.4 Secure Storage

Build 5 uses a Secure Element attached to the IoT devices (e.g., Raspberry Pi devices) to store the IDevID after it is generated during the factory provisioning process (see Appendix H.3 for more details), however the LDevID is not stored on the Secure Element after network-layer onboarding is completed. The lack of secure storage on the IoT devices (e.g., the Raspberry Pi devices) used to demonstrate onboarding in Build 3 is a current weakness. Ensuring that the confidentiality of a device's birth, network, and other credentials is protected while stored on the device is an essential aspect of ensuring the security of the network-layer onboarding process, the device, and the network itself. To fully demonstrate trusted network-layer onboarding, devices with secure storage should be used in the future whenever possible.

6.3 Thread

We do not have any findings with respect to trusted network-layer onboarding using the Thread commissioning protocol. Build 4 demonstrated the connection of an IoT device to a Thread network, but not trusted onboarding of the Thread network credentials to the device. In Build 4, a passphrase is generated on the IoT device and then a person is required to enter this passphrase into the OpenThread

Border Router's (OTBR) web interface. This passphrase serves as a pre-shared key that the device uses to join the Thread network. Due to the fact that a person must be privy to this passphrase in order to provide it to the OTBR, this network-layer onboarding process is not considered to be trusted, according to the definition of trusted network-layer onboarding that we provided in Section 1.2.

After connecting to the Thread network using the passphrase, the Build 4 device was successfully able to gain access to the public IP network via a border router. This enabled the IoT device that was communicating using the Thread wireless protocol to communicate with cloud services and use them to successfully perform trusted application-layer onboarding to the AWS IoT Core.

6.4 Application-Layer Onboarding

We successfully demonstrated both:

- streamlined application-layer onboarding (to the OCF security domain in Build 2) and
- independent application-layer onboarding (to the UXI cloud in Build 1 and to the AWS IoT Core using the Kudelski keySTREAM service in Build 4).

6.4.1 Independent Application-Layer Onboarding

Support for independent application-layer onboarding requires the device manufacturer to pre-provision the device with software to support application-layer onboarding to the specific application service (e.g., the UXI cloud or the AWS IoT Core) desired. The Kudelski keySTREAM service supports the application-layer onboarding provided in Build 4. KeySTREAM is a device security management service that runs as a SaaS platform on the Amazon cloud. Build 4 relies on an integration that has been performed between Silicon Labs and Kudelski keySTREAM. KeySTREAM has integrated software libraries with the Silicon Lab EFR32MG24 (MG24) IoT device's secure vault to enable the private signing key that is associated with an application-layer certificate to be stored into the secure vault using security controls that are available on the MG24. This integration ensures that application-layer credentials can be provisioned into the vault securely such that no key material is misused or exposed.

Because the device is prepared for application-layer onboarding on behalf of a specific, pre-defined customer in Build 4 and this ownership information is sealed into device firmware, the device is permanently identified as being owned by that customer.

6.4.2 Streamline Application-Layer Onboarding

Support for streamlined application-layer onboarding does not necessarily present such a burden on the device manufacturer to provision application-layer onboarding software and/or credentials to the device at manufacturing time. If desired, the manufacturer could pre-install application-layer bootstrapping information onto the device at manufacturing time, as must be done in the independent application-layer onboarding case. Alternatively, the device manufacturer may simply ensure that the device has the capability to generate one-time application-layer bootstrapping information at runtime and use the secure exchanges inherent in trusted network-layer onboarding to support application-layer onboarding.

7 Additional Build Considerations

The Trusted Internet of Things (IoT) Device Network-Layer Onboarding and Lifecycle Management project is now complete, so no additions or changes to the existing builds are planned as part of this project effort. As trusted network-layer onboarding is increasingly adopted, however, others may wish to continue implementation efforts to develop new build capabilities or enhance existing ones, so it is worth noting potential areas of further work. Various ways in which individual builds could be enhanced are noted in the appendices that detail each build's technologies and architectures. For example, some builds could be enhanced by the addition of architectural components that they have not yet implemented, such as secure device storage; the use of an independent, third-party certificate signing authority; support for network-layer onboarding using Thread MeshCoP; support for application-layer onboarding; and support (or enhanced support) for ongoing device authorization. In addition to adding components to support these capabilities, future work could potentially involve demonstration of application-layer onboarding using the FIDO Alliance's FIDO Device Onboard (FDO) specification and/or the Connectivity Standards Alliance (CSA) MATTER specification. Other future work could involve integrating additional security mechanisms with network-layer onboarding, beginning at device boot-up and extending through all phases of the device lifecycle, to further protect the device and, by extension, the network. For example, future builds could include the capability to demonstrate the integration of trusted network-layer onboarding with zero trust-inspired capabilities such as those described in the following subsections. In addition, the scope of implementation efforts could potentially be expanded beyond the current focus on IP-based networks. While this project's goal has been to tackle what is currently implementable, the subsections that follow briefly discuss areas that could potentially be addressed by others in the future.

7.1 Network Authentication

Future builds could be designed to demonstrate network authentication in addition to device authentication as part of the network-layer onboarding process. Network authentication enables the device to verify the identity of the network that will be taking control of it prior to permitting itself to be onboarded.

7.2 Device Communications Intent

Future builds could be designed to demonstrate the use of network-layer onboarding protocols to securely transmit device communications intent information from the device to the network (i.e., to transmit this information in encrypted form with integrity protections). Secure conveyance of device communications intent information, combined with enforcement of it, would enable the build 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. Build 5 currently enforces device communications intent as part of its continuous assurance process. Build 5 determines device communications intent information (e.g., the device's MUD file URL) based on device type rather than conveying this information from the device to the network during onboarding.

7.3 Network Segmentation

Future builds could demonstrate the ability of the onboarding network to dynamically assign each new device that is permitted to join the network to a specific subnetwork. The router may have multiple network segments configured to which an onboarded device may be dynamically assigned. The decision regarding which segment (subnetwork) to which to assign the device could potentially be based on the device's DHCP fingerprint, other markers of the device's type, or some indication of the device's trustworthiness, subject to organizational policy.

7.4 Integration with a Lifecycle Management Service

Future builds could demonstrate trusted network-layer onboarding of a device, followed by streamlined trusted application-layer onboarding of that device to a lifecycle management application service. Such a capability would ensure that, once connected to the local network, the IoT device would automatically and securely establish an association with a trusted lifecycle management service that is designed to keep the device updated and patched on an ongoing basis.

7.5 Network Credential Renewal

Some devices may be provisioned with network credentials that are X.509 certificates and that will, therefore, eventually expire. Future build efforts could explore and demonstrate potential ways of renewing such credentials without having to reprovision the credentials to the devices.

7.6 Integration with Supply Chain Management Tools

Future work could include definition of an open, scalable supply chain integration service that can provide additional assurance of device provenance and trustworthiness automatically as part of the onboarding process. The supply chain integration service could be integrated with the authorization service to ensure that only devices whose provenance meets specific criteria and that reach a threshold level of trustworthiness will be onboarded or authorized.

7.7 Attestation

Future builds could integrate device attestation capabilities with network-layer onboarding to ensure that only IoT devices that meet specific attestation criteria are permitted to be onboarded. In addition to considering the attestation of each device as a whole, future attestation work could also focus on attestation of individual device components, so that detailed attestation could be performed for each board, integrated circuit, and software program that comprises a device.

7.8 Mutual Attestation

Future builds could implement mutual attestation of the device and its application services. In one direction, device attestation could be used to enable a high-value application service to determine whether a device should be given permission to access it. In the other direction, attestation of the application service could be used to enable the device to determine whether it should give the application service permission to access and update the device.

7.9 Behavioral Analysis

Future builds could integrate artificial intelligence (AI) and machine learning (ML)-based tools that are designed to analyze device behavior to spot anomalies or other potential signs of compromise. Any device that is flagged as a potential threat by these tools could have its network credentials invalidated to effectively evict it from the network, be quarantined, or have its interaction with other devices restricted in some way.

7.10 Device Trustworthiness Scale

Future efforts could incorporate the concept of a device trustworthiness scale in which information regarding device capabilities, secure firmware updates, the existence (or not) of a secure element for private key protection, type and version of each of the software components that comprise the device, etc., would be used as input parameters to calculate each device’s trustworthiness value. Calculating such a value would essentially provide the equivalent of a background check. A history for the device could be maintained, including information about whether it has ever been compromised, if it has a known vulnerability, etc. Such a trustworthiness value could be provided as an onboarding token or integrated into the authorization service so permission to onboard to the network, or to access certain resources once joined, could be granted or denied based on historical data and trustworthiness measures.

7.11 Resource Constrained Systems

At present, onboarding solutions for technologies such as Zigbee, Z-Wave, and BLE use their own proprietary mechanisms or depend on gateways. In the future, efforts could be expanded to include onboarding in highly resource-constrained systems and non-IP systems without using gateways. Future work could include trying to perform trusted onboarding in these smaller microcontroller-constrained spaces in a standardized way with the goal of bringing more commonality across various solutions without having to rely on IP gateways.

1848 # Appendix A List of Acronyms

AAA	Authentication, Authorization, and Accounting
ACL	Access Control List
AES	Advanced Encryption Standard
AI	Artificial Intelligence
AP	Access Point
API	Application Programming Interface
AWS	Amazon Web Services
BLE	Bluetooth Low Energy
BRSKI	Bootstrapping Remote Secure Key Infrastructure
BSS	Basic Service Set
CA	Certificate Authority
CAS	Continuous Authorization Service
CMS	Certificate Management System
CPU	Central Processing Unit
CRADA	Cooperative Research and Development Agreement
CRL	Certificate Revocation List
DHCP	Dynamic Host Configuration Protocol
DMZ	Demilitarized Zone
DNS	Domain Name System
DPP	Device Provisioning Protocol
DTLS	Datagram Transport Layer Security
ECC	Elliptic Curve Cryptography
ESP	(Aruba) Edge Services Platform
ESS	Extended Service Set
EST	Enrollment over Secure Transport
HPE	Hewlett Packard Enterprise
HSM	Hardware Security Module
HTTPS	Hypertext Transfer Protocol Secure

IDevID	Initial Device Identifier
IE	Information Element
IEC	International Electrotechnical Commission
IETF	Internet Engineering Task Force
IoT	Internet of Things
IP	Internet Protocol
IPsec	Internet Protocol Security
ISO	International Organization for Standardization
LAN	Local Area Network, Local Area Networking
LDevID	Local Device Identifier
LmP	Linux microPlatform
MASA	Manufacturer Authorized Signing Authority
MeshCoP	Thread Mesh Commissioning Protocol
ML	Machine Learning
mPKI	Managed Public Key Infrastructure
MUD	Manufacturer Usage Description
NAC	Network Access Control
NCCoE	National Cybersecurity Center of Excellence
NIST	National Institute of Standards and Technology
OBT	Onboarding Tool
OCF	Open Connectivity Foundation
OCSP	Online Certificate Status Protocol
OS	Operating System
OTA	Over the Air
OTBR	OpenThread Border Router
PKI	Public Key Infrastructure
PSK	Pre-Shared Key
R&D	Research & Development
RBAC	Role-Based Access Control

RCP	Radio Coprocessor
RESTful	Representational State Transfer
RFC	Request for Comments
RoT	Root of Trust
RSA	Rivest-Shamir-Adleman (public-key cryptosystem)
SaaS	Software as a Service
SE	Secure Element
SEF	Secure Element Factory
SoC	System-on-Chip
SP	Special Publication
SSID	Service Set Identifier
SSW	Sandelman Software Works
TCP	Transmission Control Protocol
TLS	Transport Layer Security
TOFU	Trust On First Use
TPM	Trusted Platform Module
URI	Uniform Resource Identifier
UXI	(Aruba) User Experience Insight
VM	Virtual Machine
WAN	Wide Area Network, Wide Area Networking
WFA	Wi-Fi Alliance
WPA2	Wi-Fi Protected Access 2
WPA3	Wi-Fi Protected Access 3

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Appendix B Glossary

Application-Layer Bootstrapping Information	Information that the device and an application-layer service must have in order for them to mutually authenticate and use a trusted application-layer onboarding protocol to onboard a device at the application layer. There is application-layer bootstrapping information about the device that the network must be in possession of, and application-layer bootstrapping information about the application service that the device must be in possession of. A typical example of application-layer bootstrapping information that the device must have is the public key that corresponds to the trusted application service's private key.
Application-Layer Onboarding	The process of providing IoT devices with the application-layer credentials they need to establish a secure (i.e., encrypted) association with a trusted application service. This document defines two types of application-layer onboarding: independent and streamlined.
Independent Application-Layer Onboarding	An application-layer onboarding process that does not rely on use of the network-layer onboarding process to transfer application-layer bootstrapping information between the device and the application service.
Network-Layer Bootstrapping Information	Information that the device and the network must have in order for them to use a trusted network-layer onboarding protocol to onboard a device. There is network-layer bootstrapping information about the device that the network must be in possession of, and network-layer bootstrapping information about the network that the device must be in possession of. A typical example of device bootstrapping information that the network must have is the public key that corresponds with the device's private key.
Network-Layer Onboarding	The process of providing IoT devices with the network-layer credentials and policy they need to join a network upon deployment.
Streamlined Application-Layer Onboarding	An application-layer onboarding process that uses the network-layer onboarding protocol to securely transfer application-layer bootstrapping information between the device and the application service.

Trusted Network-Layer Onboarding	A network-layer onboarding process that meets the following criteria:
	• provides each device with unique network credentials,
	• enables the device and the network to mutually authenticate,
	• sends devices their network credentials over an encrypted channel,
	• does not provide any person with access to the network credentials, and
	• can be performed repeatedly throughout the device lifecycle to enable:
	    ◦ the device's network credentials to be securely managed and replaced as needed, and
	    ◦ the device to be securely onboarded to other networks after being repurposed or resold.

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

C.1 Technologies

Build 1 is an implementation of network-layer onboarding that uses the Wi-Fi Easy Connect protocol. The onboarding infrastructure and related technology components for Build 1 have been provided by Aruba/HPE. IoT devices that were onboarded using Build 1 were provided by Aruba/HPE and CableLabs. The CA used for signing credentials issued to IoT devices was provided by SEALSQ, a subsidiary of WISeKey. For more information on these collaborators and the products and technologies that they contributed to this project overall, see Section 3.4.

Build 1 network onboarding infrastructure components within the NCCoE lab consist of the Aruba Access Point. Build 1 also requires support from Aruba Central and the UXI Cloud, which are accessed via the internet. IoT devices that can be network-layer onboarded using Build 1 include the Aruba/HPE UXI sensor and CableLabs Raspberry Pi. The UXI sensor also includes the Aruba UXI Application, which enables it to use independent (see Section 3.3.2) application-layer onboarding to be onboarded at the application layer as well, providing that the network to which the UXI sensor is onboarded has connectivity to the UXI Cloud via the internet. The Build 1 implementation supports the provisioning of all three types of network credentials defined in DPP:

- Connector for DPP-based network access
- Password/passphrase/PSK for WPA3/WPA2 network access
- X.509 certificates for 802.1X network access

Build 1 has been integrated with the SEALSQ CA on SEALSQ INeS CMS to enable Build 1 to obtain signed certificates from this CA when Build 1 is onboarding devices and issuing credentials for 802.1X network access. When issuing credentials for DPP and WPA3/WPA2-based network access, the configurator does not need to use a CA.

Table C-1 lists the technologies used in Build 1. It lists the products used to instantiate each component of the reference architecture and describes the security function that the component provides. The components listed are logical. They may be combined in physical form, e.g., a single piece of hardware may house a network onboarding component, a router, and a wireless access point.

Table C-1 Build 1 Products and Technologies

Component	Product	Function
Network-Layer Onboarding Component (Wi-Fi Easy Connect Configurator)	Aruba Access Point with support from Aruba Central	Runs the Wi-Fi Easy Connect network-layer onboarding protocol to interact with the IoT device to perform one-way or mutual authentication, establish a secure channel, and securely provide local network credentials to the device. If the network credential that is being provided to the device is a certificate, the onboarding component will interact with a certificate authority to sign the certificate. The configurator deployed in Build 1 supports DPP 2.0, but it is also backward compatible with DPP 1.0.

Component	Product	Function
Access Point, Router, or Switch	Aruba Access Point	Wireless access point that also serves as a router. It may get configured with per-device access control lists (ACLs) and policy when devices are onboarded.
Supply Chain Integration Service	Aruba Central	The device manufacturer provides device bootstrapping information to the HPE Cloud via the REST API that is documented in the DPP specification. Once the device is transferred to an owner, the HPE Cloud provides the device bootstrapping information (i.e., the device's DPP URI) to the device owner's private tenancy within the HPE Cloud.
Authorization Service	Cloud Auth (on Aruba Central)	The authorization service provides the configurator and router with the information needed to determine if the device is authorized to be onboarded to the network and, if so, whether it should be assigned any special roles or be subject to any specific access controls. It provides device authorization, role-based access control, and policy enforcement.
Build-Specific IoT Device	Aruba UXI Sensor	The IoT device that is used to demonstrate both trusted network-layer onboarding and trusted application-layer onboarding. It runs the Wi-Fi Easy Connect network-layer onboarding protocol supported by the build to securely receive its network credentials. It also has an application that enables it to perform independent (see Section 3.3.2) application-layer onboarding.
Generic IoT Device	Raspberry Pi	The IoT device that is used to demonstrate only trusted network-layer onboarding.
Secure Storage	Aruba UXI Sensor Trusted Platform Module (TPM)	Storage on the IoT device that is designed to be protected from unauthorized access and capable of detecting attempts to hack or modify its contents. Used to store and process private keys, credentials, and other information that must be kept confidential.
Certificate Authority (CA)	SEALSQ INeS CMS CA	Issues and signs certificates as needed. These certificates can be used by the device to connect to any 802.1a-based network.
Application-Layer Onboarding Service	UXI Application and UXI Cloud	After connecting to the network, the device downloads its application-layer credentials from the UXI cloud and uses them to authenticate to the UXI application, with which it interacts.

Component	Product	Function
Ongoing Device Authorization	N/A – Not intended for inclusion in this build	Performs activities designed to provide an ongoing assessment of the device's trustworthiness and authorization to access network resources. For example, it may perform behavioral analysis or device attestation and use the results to determine whether the device should be granted access to certain high-value resources, assigned to a particular network segment, or other action taken.
Manufacturer Factory Provisioning Process	N/A (Not implemented at the time of publication)	Manufactures the IoT device. Creates, signs, and installs the device's unique identity and other birth credentials into secure storage. Installs information the device requires for application-layer onboarding (if applicable). May populate a manufacturer database with information regarding devices that are created and, when the devices are sold, may record what entity owns them.

C.2 Build 1 Architecture

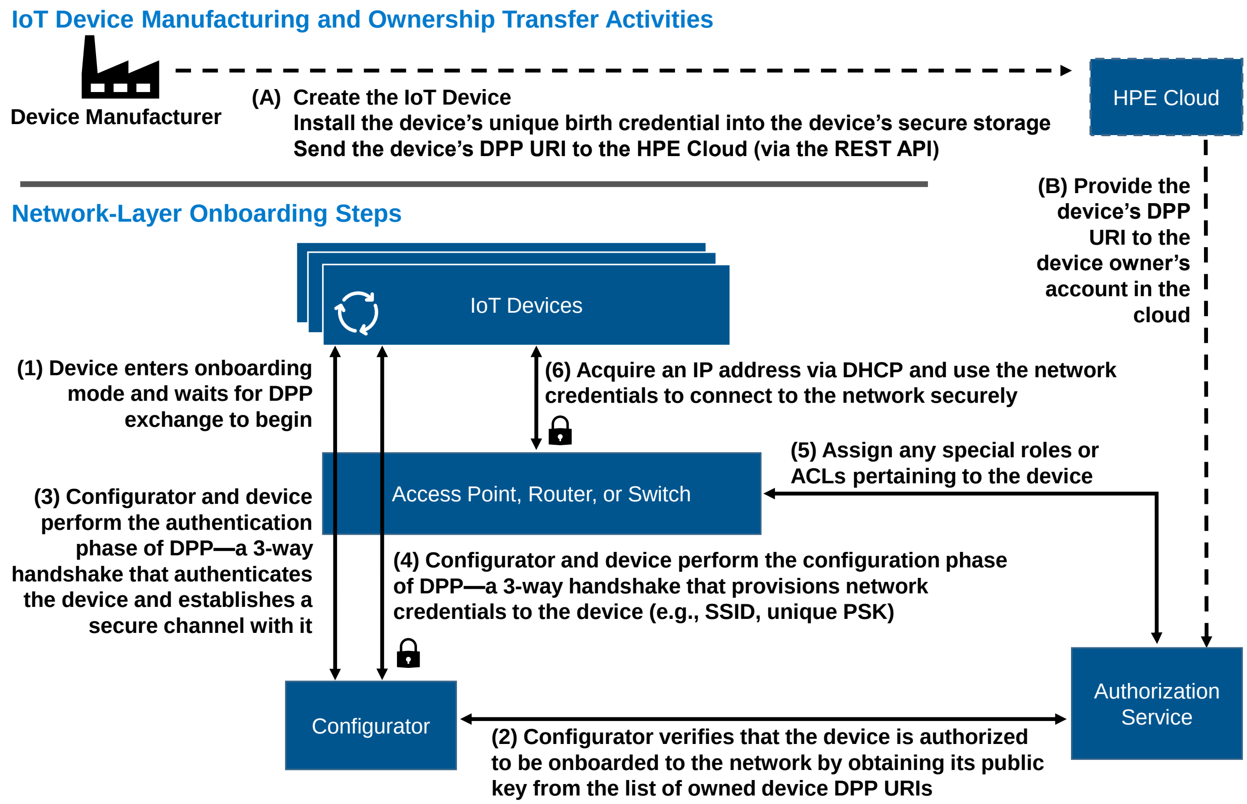
C.2.1 Build 1 Logical Architecture

The network-layer onboarding steps that are performed in Build 1 are depicted in Figure C-1. These steps are broken into two main parts: those required to transfer device bootstrapping information from the device manufacturer to the device owner's authorization service (labeled with letters) and those required to perform network-layer onboarding of the device (labeled with numbers).

The device manufacturer:

1. Creates the device and installs a unique birth credential into secure storage on the device. Then the manufacturer sends the device's bootstrapping information, which takes the form of a DPP URI, to Aruba Central in the HPE cloud. The device manufacturer interfaces with the HPE cloud via a REST API.
2. When the device is purchased, the device's DPP URI is sent to the HPE cloud account of the device's owner. The device owner's cloud account contains the DPP URIs for all devices that it owns.

Figure C-1 Logical Architecture of Build 1



After obtaining the device, the device owner provisions the device with its network credentials by performing the following network-layer onboarding steps:

1. The owner puts the device into onboarding mode. The device waits for the DPP exchange to begin. This exchange includes the device issuing a discovery message, which the owner's configurator hears. The discovery message is secured such that it can only be decoded by an entity that possesses the device's DPP URI.
2. The configurator consults the list of DPP URIs of all owned devices to decode the discovery message and verify that the device is owned by the network owner and is therefore assumed to be authorized to be onboarded to the network.
3. Assuming the configurator finds the device's DPP URI, the configurator and the device perform the authentication phase of DPP, which is a three-way handshake that authenticates the device and establishes a secure (encrypted) channel with it.
4. The configurator and the device use this secure channel to perform the configuration phase of DPP, which is a three-way handshake that provisions network credentials to the device, along with any other information that may be needed, such as the network SSID.
5. The router or switch consults the owner's authentication, authorization, and accounting (AAA) service to determine if the device should be assigned any special roles or if any special ACL entries should be made for the device. If so, these are configured on the router or switch.

6. The device uses Dynamic Host Configuration Protocol (DHCP) to acquire an IP address and then uses its newly provisioned network credentials to connect to the network securely.

This completes the network-layer onboarding process.

After the device is network-layer onboarded and connects to the network, it automatically performs independent (see Section 3.3.2) application-layer onboarding. The application-layer onboarding steps are not depicted in Figure C-1. During the application-layer onboarding process, the IoT device, which is a UXI sensor, authenticates itself to the UXI cloud using its manufacturing certificate and pulls its application-layer credentials from the UXI cloud. In addition, if a firmware update is relevant, this also happens. The UXI sensor contacts the UXI cloud service to download a customer-specific configuration that tells it what to monitor on the customer's network. The UXI sensor then conducts the network performance monitoring functions it is designed to perform and uploads the data it collects to the UXI application dashboard.

C.2.2 Build 1 Physical Architecture

Section 5.2 describes the physical architecture of Build 1.

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

D.1 Technologies

Build 2 is an implementation of network-layer onboarding that uses the Wi-Fi Easy Connect protocol. Build 2 also supports streamlined (see Section 3.3.2) application-layer onboarding to the OCF security domain. The network-layer onboarding infrastructure for Build 2 is provided by CableLabs and the application-layer onboarding infrastructure is provided by OCF. IoT devices that were network-layer onboarded using Build 2 were provided by Aruba/HPE and OCF. Only the IoT devices provided by OCF were capable of being both network-layer onboarded and streamlined application-layer onboarded. For more information on these collaborators and the products and technologies that they contributed to this project overall, see Section 3.4.

Build 2 onboarding infrastructure components consist of the CableLabs Custom Connectivity Gateway Agent, which runs on the Gateway Access Point, and the Platform Controller. IoT devices onboarded by Build 2 include the Aruba UXI Sensor and CableLabs Raspberry Pi.

Table D-1 lists the technologies used in Build 2. It lists the products used to instantiate each logical build component and the security function that the component provides. The components listed are logical. They may be combined in physical form, e.g., a single piece of hardware may house a network onboarding component, a router, and a wireless access point.

Table D-1 Build 2 Products and Technologies

Component	Product	Function
Network-Layer Onboarding Component (Configurator)	CableLabs Custom Connectivity Gateway Agent with support from CableLabs Platform Controller	Runs the Wi-Fi Easy Connect network-layer onboarding protocol to interact with the IoT device to perform one-way or mutual authentication, establish a secure channel, and securely provide local network credentials to the device. It also securely conveys application-layer bootstrapping information to the device as part of the Wi-Fi Easy Connect protocol to support application-layer onboarding. The network-layer onboarding component deployed in Build 2 supports DPP 2.0, but it is also backward compatible with DPP 1.0.
Access Point, Router, or Switch	Raspberry Pi (running Custom Connectivity Gateway Agent)	The access point includes a configurator that runs the Wi-Fi Easy Connect Protocol. It also serves as a router that: 1) routes all traffic exchanged between IoT devices and the rest of the network, and 2) assigns each IoT device to a local network segment appropriate to the device's trust level (optional).

Component	Product	Function
Supply Chain Integration Service	CableLabs Platform Controller/IoTivity Cloud Service	The device manufacturer provides device bootstrapping information (i.e., the DPP URI) to the CableLabs Web Server. There are several potential mechanisms for sending the DPP URI to the CableLabs Web Server. The manufacturer can send the device's DPP URI to the Web Server directly, via an API. The API used is not the REST API that is documented in the DPP specification. However, the API is published and was made available to manufacturers wanting to onboard their IoT devices using Build 2. Once the device is transferred to an owner, the CableLabs Web Server provides the device's DPP URI to the device owner's authorization service, which is part of the owner's configurator.
Authorization Service	CableLabs Platform Controller	The authorization service provides the configurator and router with the information needed to determine if the device is authorized to be onboarded to the network and, if so, whether it should be assigned any special roles, assigned to any specific network segments, or be subject to any specific access controls.
Build-Specific IoT Device	Raspberry Pi (Bulb) Raspberry Pi (switch)	The IoT devices that are used to demonstrate both trusted network-layer onboarding and trusted application-layer onboarding. They run the Wi-Fi Easy Connect network-layer onboarding protocol to securely receive their network credentials. They also support application-layer onboarding of the device to the OCF environment by conveying the device's application-layer bootstrapping information as part of the network-layer onboarding protocol.
Generic IoT Device	Aruba UXI Sensor	The IoT device that is used to demonstrate only trusted network-layer onboarding.
Secure Storage	N/A (IoT device is not equipped with secure storage)	Storage designed to be protected from unauthorized access and capable of detecting attempts to hack or modify its contents. Used to store and process private keys and other information that must be kept confidential.
Certificate Authority	N/A (Not implemented at the time of publication)	Issues and signs certificates as needed.
Application-Layer Onboarding Service	OCF Diplomat and OCF OBT within IoTivity	After connecting to the network, the OCF Diplomat authenticates the devices, establishes secure channels with them, and sends them access control lists that control which bulbs each switch is authorized to turn on and off.

Component	Product	Function
Ongoing Device Authorization	N/A – Not intended for inclusion in this build	Performs activities designed to provide ongoing assessment of the device's trustworthiness and authorization to access network resources. For example, it may perform behavioral analysis or device attestation and use the results to determine whether the device should be granted access to certain high-value resources, assigned to a particular network segment, or other action taken.
Manufacturer Factory Provisioning Process	N/A (Not yet implemented)	Manufactures the IoT device. Creates, signs, and installs the device's unique identity and other birth credentials into secure storage. Installs information the device requires for application-layer onboarding (if applicable). May populate a manufacturer database with information regarding devices that are created and, when the devices are sold, may record what entity owns them.

D.2 Build 2 Architecture

D.2.1 Build 2 Logical Architecture

The network-layer onboarding steps that are performed in Build 2 are depicted in Figure D-1. These steps are broken into two main parts: those required to transfer device bootstrapping information from the device manufacturer to the device owner's authorization service (labeled with letters) and those required to perform network-layer onboarding of the device (labeled with numbers).

The device manufacturer:

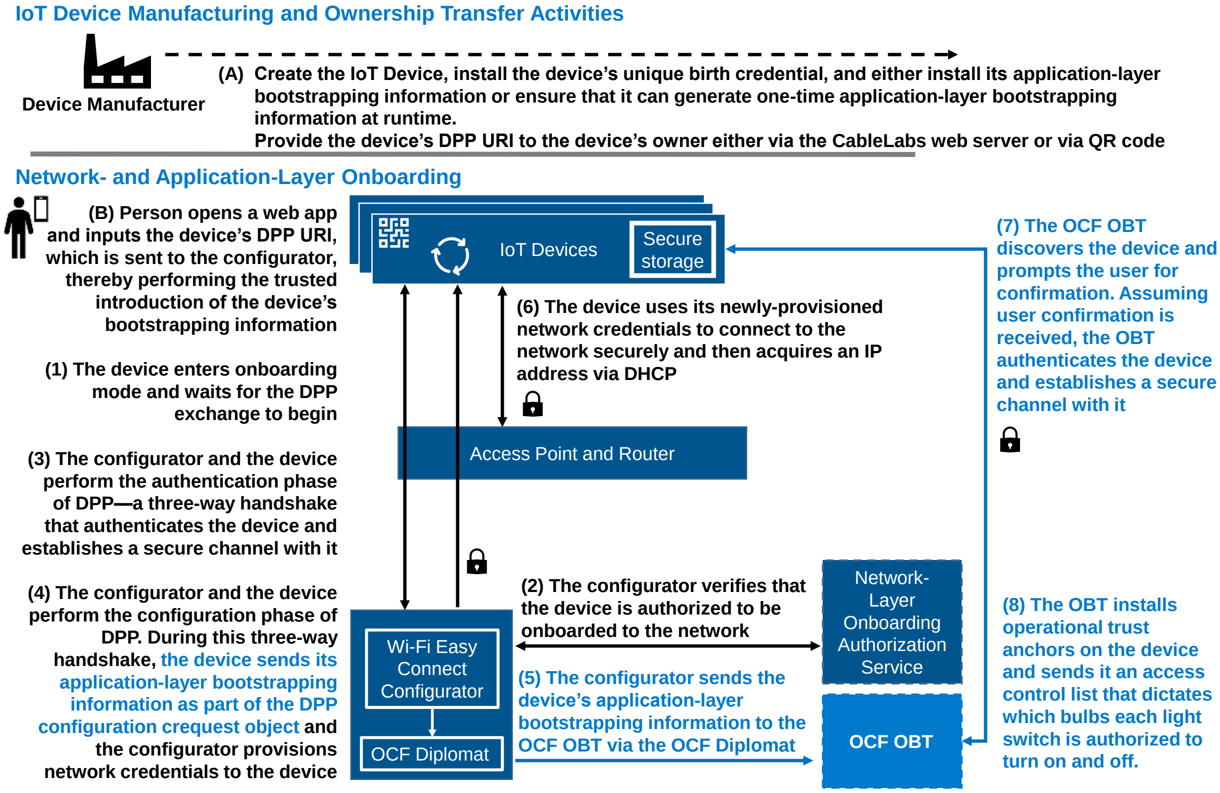
1. Creates the device and installs a unique birth credential into secure storage on the device. Because the device created for use in Build 2 will also perform application-layer onboarding into the OCF security domain, as part of the manufacturing process the manufacturer also either installs application-layer bootstrapping information onto the device or ensures that the device has the capability to generate one-time application-layer bootstrapping information at runtime. Then the manufacturer makes the device's network-layer bootstrapping information, which takes the form of a DPP URI, available to the device's owner.

   Build 2 supports several mechanisms whereby the manufacturer can make the device's network-layer bootstrapping information (i.e., its DPP URI) available to the device owner. The device's DPP URI can be uploaded directly to a device owner's cloud account or web server via API (as might come in handy when onboarding many enterprise devices at one time). Alternatively, the DPP URI can be manually entered into a local web portal that runs a configuration webpage that a device on the same Wi-Fi network can connect to for purposes of scanning a QR code or typing in the DPP URI. A DPP URI that is to be entered manually could, for example, be emailed to the owner or encoded into a QR code and printed on the device chassis, in device documentation, or on device packaging. Table D-1 depicts the case in which the manufacturer provides the device's DPP URI to the owner for manual entry. When the owner receives the device's DPP URI, the owner may optionally add the device's DPP URI to a list of

DPP URIs for devices that it owns that is maintained as part of the owner's authorization service. Such a list would enable the owner's network to determine if a device is authorized to be onboarded to it.

2. The person onboarding the device opens a web application and enters the device's DPP URI. The web application then sends the DPP URI to the Wi-Fi Easy Connect configurator, e.g., through a web request. (Note: Although the laboratory implementation of Build 2 requires the user to enter the DPP URI via a web page, an implementation designed for operational use would typically require the user to provide the DPP URI by scanning a QR code into a network operator-provided app that is logged into the user's account.)

Figure D-1 Logical Architecture of Build 2



After ensuring that the device's network-layer bootstrapping information (i.e., its DPP URI) has been uploaded to the configurator, the device owner performs both trusted network-layer onboarding and streamlined application-layer onboarding to the OCF security domain by performing the steps depicted in Figure D-1. In this diagram, the components that relate to network-layer onboarding are depicted in dark blue and their associated steps are written in black font. The components and steps that are related to application-layer onboarding are depicted in light blue. The steps are as follows:

1. The owner puts the device into onboarding mode. The device waits for the DPP exchange to begin. This exchange includes the device issuing a discovery message, which the owner's configurator hears. The discovery message is secured such that it can only be decoded by an entity that possesses the device's DPP URI.

2. Optionally, if such a list is being maintained, the configurator consults the list of DPP URIs of all owned devices to verify that the device is owned by the network owner and is, therefore, assumed to be authorized to be onboarded to the network. (If the device is being onboarded by an enterprise, the enterprise would likely maintain such a list; however, if the device is being onboarded to a home network, this step might be omitted.)

3. Assuming the configurator finds the device's DPP URI, the configurator and the device perform the authentication phase of DPP, which is a three-way handshake that authenticates the device and establishes a secure (encrypted) channel with it.

4. The configurator and the device use this secure channel to perform the configuration phase of DPP, which is a three-way handshake that provisions network credentials to the device, along with any other information that may be needed, such as the network SSID. In particular, as part of the three-way handshake in the Build 2 demonstration, the device sends its application-layer bootstrapping information to the configurator as part of the DPP configuration request object.

5. The configurator receives the device's application-layer bootstrapping information and forwards it to the OCF Diplomat. The purpose of the OCF Diplomat is to provide a bridge between the network and application layers. It accomplishes this by parsing the org.openconnectivity fields of the DPP request object, which contains the UUID of the device and the application-layer bootstrapping credentials, and sending these to the OCF OBT as part of a notification that the OBT has a new device to onboard. The Diplomat and the OBT use a subscribe and notify mechanism to ensure that the OBT will receive the onboarding request even if the OBT is unreachable for a period of time (e.g., the OBT is out of the home).

6. The device uses its newly provisioned network credentials to connect to the network securely and then uses DHCP to acquire an IP address. This completes the network-layer onboarding process.

7. The OBT implements a filtered discovery mechanism using the UUID provided from the OCF Diplomat to discover the new device on the network. Once it discovers the device, before proceeding, the OBT may optionally prompt the user for confirmation that they want to perform application-layer onboarding to the OCF security domain. This prompting may be accomplished, for example, by sending a confirmation request to an OCF app on the user's mobile device. Assuming the user responds affirmatively, the OBT uses the application-layer bootstrapping information to authenticate the device and take ownership of it by setting up a Datagram Transport Layer Security (DTLS) connection with the device.

8. The OBT then installs operational trust anchors and access control lists onto the device. For example, in the access control list, each light bulb may have an access control entry dictating which light switches are authorized to turn it on and off. This completes the application-layer onboarding process.

Note that, at this time, the application-layer bootstrapping information is provided unilaterally in the Build 2 application-layer onboarding demonstration. The application-layer bootstrapping information of the device is provided to the OCF Diplomat, enabling the OBT to authenticate the device. In a future version of this process, the application-layer bootstrapping information could be provided bidirectionally, meaning that the OCF Diplomat could also send the OCF operational root of trust to the IoT device as part of the DPP configuration response frame. Exchanging application-layer bootstrapping information bilaterally in this way would enable the secure channel set up as part of the network-layer onboarding process to support establishment of a mutually authenticated session between the device and the OBT.

In the Build 2 demonstration, two IoT devices, a switch and a light bulb, are onboarded at both the network and application layers. Each of these devices sends the OCF Diplomat its application-layer bootstrapping information over the secure network-layer onboarding channel during the network-layer onboarding process. Immediately after they complete the network-layer onboarding process and connect to the network, the OCF Diplomat provides their application-layer bootstrapping information to the OBT. The OBT then uses the provided application-layer bootstrapping information to discover, authenticate, and onboard each device. Because the devices have no way to authenticate the identity of the OBT in the current implementation, the devices are configured to trust the OBT upon first use.

After the OBT authenticates the devices, it establishes secure channels with them and provisions them access control lists that control which bulbs each switch is authorized to turn on and off. To demonstrate that the application onboarding was successful, Build 2 demonstrates that the switch is able to control only those bulbs that the OCF OBT has authorized it to.

D.2.2 Build 2 Physical Architecture

Section 5.3 describes the physical architecture of Build 2.

Appendix E Build 3 (BRSKI, Sandelman Software Works)

E.1 Technologies

Build 3 is an implementation of network-layer onboarding that uses the BRSKI protocol. Build 3 does not support application-layer onboarding. The network-layer onboarding infrastructure and related technology components for Build 3 were provided by Sandelman Software Works. The Raspberry Pi, ESP32, and Nordic NRF IoT devices that will be onboarded in a future implementation of Build 3 were also provided by Sandelman Software Works, as was the Sandelman Software Works Reach Pledge Simulator, which is the device that is onboarded in the current build. The IoT devices do not have secure storage, but future plans are to integrate them with secure storage elements. Build 3 issues private PKI certificates as network credentials at this time, but future plans are to integrate Build 3 with a third-party private CA from which it can obtain signed certificates. For more information on Sandelman Software Works and the products and technologies that it contributed to this project overall, see Section 3.4.

Onboarding Build 3 infrastructure components consist of Raspberry Pi, Nordic NRF, ESP32, Sandelman Software Works Minerva Fountain Join Registrar/Coordinator, Sandelman Software Works Minerva. Highway, Sandelman Software Works Reach Pledge Simulator, and a Minerva Fountain internal CA.

Table E-1 lists the technologies used in Build 3. It lists the products used to instantiate each logical build component and the security function that the component provides. The components are logical. They may be combined in physical form, e.g., a single piece of hardware may house both a network onboarding component and a router and/or wireless access point.

Table E-1 Build 3 Products and Technologies

Component	Product	Function
Network-Layer Onboarding Component (BRSKI Domain Registrar)	Sandelman Software Works Minerva Fountain Registrar	Runs the BRSKI protocol. It authenticates the IoT device, receives a voucher-request from the IoT device, and passes the request to the MASA. It also receives a voucher from the MASA, verifies it, and passes it to the IoT device. Assuming the IoT device finds the voucher to be valid and determines that the network is authorized to onboard it, the Domain Registrar provisions network credentials to the IoT device using EST.
Access Point, Router, or Switch	Turris MOX router running OpenWRT	The Onboarding Router segments the onboarding device from the rest of the network until the BRSKI onboarding is complete

Component	Product	Function
Supply Chain Integration Service (Manufacturer Authorized Signing Authority—MASA)	Minerva Highway, which is a MASA provided by Sandelman Software Works	The device manufacturer provides device bootstrapping information (e.g., the device's X.509 certificate) and device ownership information to the MASA. The MASA creates and signs a voucher saying who the owner of the device is and provides this voucher to the IoT device via the Domain Registrar so that the device can verify that the network that is trying to onboard it is authorized to do so.
Authorization Service	Minerva Highway, which is a MASA provided by Sandelman Software Works	As described in the previous row.
IoT Device (Pledge)	Sandelman Software Works Reach Pledge Simulator	The device that is used to demonstrate trusted network-layer onboarding by joining the network.
Secure Storage	N/A (The IoT devices and the Sandelman Software Works Reach Pledge Simulator do not include secure storage)	Storage on the IoT device that is designed to be protected from unauthorized access and capable of detecting attempts to hack or modify its contents. Used to store and process private keys, credentials, and other information that must be kept confidential.
Certificate Authority	N/A (self-signed certificates were used)	Issues and signs certificates as needed.
Application-Layer Onboarding Service	None. Not supported in this build.	After connecting to the network, the device mutually authenticates with a trusted application service and interacts with it at the application layer.
Ongoing Device Authorization	N/A – Not intended for inclusion in this build	Performs activities designed to provide an ongoing assessment of the device's trustworthiness and authorization to access network resources. For example, it may perform behavioral analysis or device attestation and use the results to determine whether the device should be granted access to certain high-value resources, assigned to a particular network segment, or other action taken.
Manufacturer Factory Provisioning Process	N/A (Not implemented at the time of publication)	Manufactures the IoT device. Creates, signs, and installs the device's unique identity and other birth credentials into secure storage. Installs information the device requires for application-layer onboarding (if applicable). May populate a manufacturer database with information regarding devices that are created and, when the devices are sold, may record what entity owns them.

E.2 Build 3 Architecture

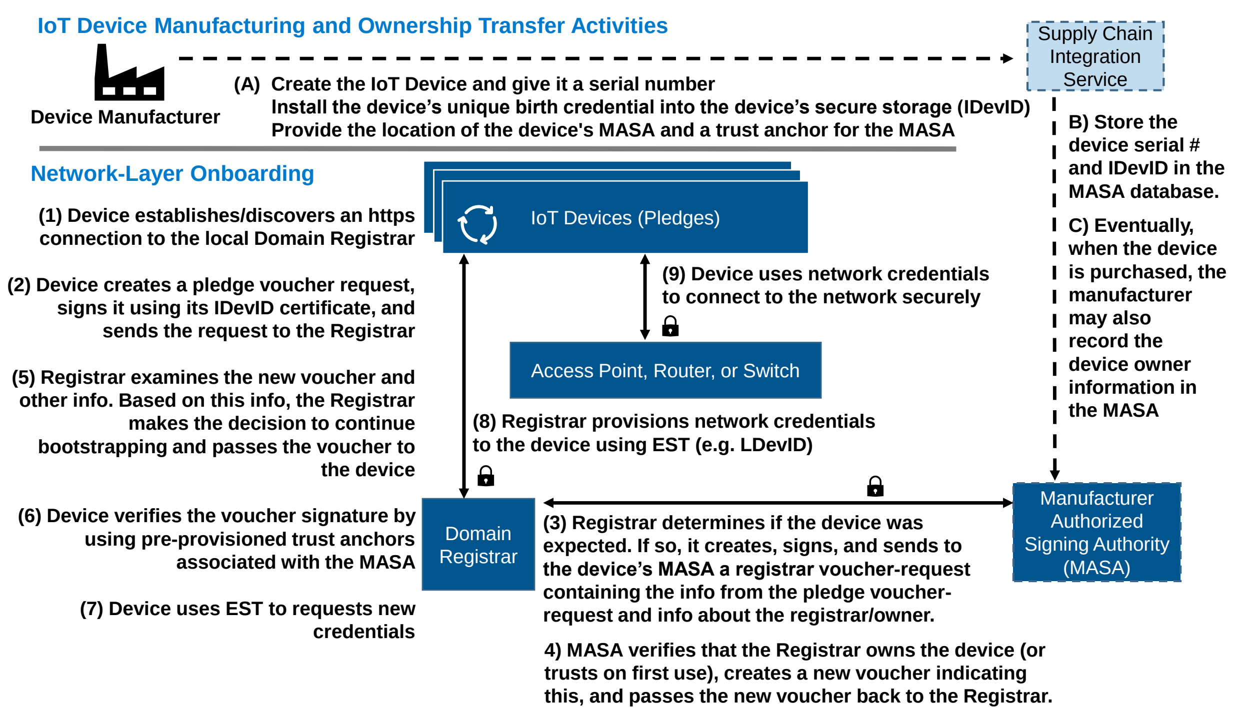
E.2.1 Build 3 Logical Architecture

The network-layer onboarding steps that are performed in Build 3 are depicted in Figure E-1. These steps are broken into two main parts: those required to transfer device bootstrapping information from the device manufacturer to the device owner's authorization service (labeled with letters) and those required to perform network-layer onboarding of the device (labeled with numbers). These steps are described in greater detail in IETF RFC 8995.

The device manufacturer:

1. Creates the device and installs a unique serial number and birth credential into secure storage on the device. This unique birth credential takes the form of a private key and its associated 802.1AR certificate, e.g., the device's IDevID. As part of this factory-installed certificate process, the location of the device's MASA is provided in an extension to the IDevID. The device is also provided with trust anchors for the MASA entity that will sign the returned vouchers.
2. Stores information about the device, such as its serial number and its IDevID, in the MASA's database.
3. Eventually, when the device is sold, the MASA may also record the device ownership information in its database.

Figure E-1 Logical Architecture of Build 3



After obtaining the device, the device owner provisions the device with its network credentials by performing the following network-layer onboarding steps:

1. The owner puts the device into onboarding mode. The device establishes an https connection to the local Domain Registrar. Trust in the Domain Registrar is provisional. (In a standard implementation, the device would use link-local network connectivity to locate a join proxy, and the join proxy would provide the device with https connectivity to the local Domain Registrar. The Build 3 implementation, however, does not support discovery at this time. To overcome this code limitation, the IoT device has been pre-provided with the address of the local Domain Registrar, to which it connects directly.)
2. The device creates a pledge voucher-request that includes the device serial number, signs this request with its IDevID certificate (i.e., its birth credential), and sends this signed request to the Registrar.
3. The Registrar receives the pledge voucher-request and considers whether the manufacturer is known to it and whether devices of that type are welcome. If so, the Registrar forms a registrar voucher-request that includes all the information from the pledge voucher-request along with information about the registrar/owner. The Registrar signs this registrar voucher-request. It locates the MASA that the IoT device is known to trust (e.g., the MASA that is identified in the device's IDevID extension) and sends the registrar voucher-request to the MASA.
4. The MASA consults the information that it has stored and applies policy to determine whether or not to approve the Registrar's claim that it owns and/or is authorized to onboard the device. (For example, the MASA may consult sales records for the device to verify device ownership, or it may be configured to trust that the first registrar that contacts it on behalf of a given device is in fact the device owner.) Assuming the MASA decides to approve the Registrar's claim to own and/or be authorized to onboard the device, the MASA creates a voucher that directs the device to accept its new owner/authorized network, signs this voucher, and sends it back to the Registrar.
5. The Registrar receives this voucher, examines it along with other related information (such as security posture, remote attestation results, and/or expected device serial numbers), and determines whether it trusts the voucher. Assuming it trusts the voucher, the Registrar passes the voucher to the device.
6. The device uses its factory-provisioned MASA trust anchors to verify the voucher signature, thereby ensuring that the voucher can be trusted. The voucher also validates the Registrar and represents the intended owner, ending the provisional aspect of the EST connection.
7. The device uses Enrollment over Secure Transport (EST) to request new credentials.
8. The Registrar provisions network credentials to the device using EST. These network credentials get stored into secure storage on the device, e.g., as an LDevID.
9. The device uses its newly provisioned network credentials to connect to the network securely.

This completes the trusted network-layer onboarding process for Build 3.

2124
E.2.2 Build 3 Physical Architecture

2125 Section 5.4 describes the physical architecture of Build 3.

Appendix F Build 4 (Thread, Silicon Labs-Thread, Kudelski KeySTREAM)

F.1 Technologies

Build 4 is an implementation of network-layer connection to an OpenThread network, followed by use of the Kudelski IoT keySTREAM Service to perform independent (see Section 3.3.2) application-layer onboarding of the device to a particular customer's tenancy in the AWS IoT Core. To join the network, the joining device generates and displays a pre-shared key that the owner enters on the commissioner, through a web interface, for authentication. The network-layer infrastructure for Build 4 was provided by Silicon Labs. The application-layer onboarding infrastructure for Build 4 was provided by Kudelski IoT. IoT devices that were onboarded using Build 4 were provided by Silicon Labs. For more information on these collaborators and the products and technologies that they contributed to this project overall, see Section 3.4.

Build 4 network infrastructure components within the NCCoE lab consist of a Thread border router (which is implemented using a Raspberry Pi) and a Silicon Labs Gecko Wireless Starter Kit. Build 4 also requires support from the Kudelski IoT keySTREAM service to perform application-layer onboarding. The keySTREAM service comes as a SaaS platform that is running in the cloud (accessible via the internet), and a software library (KTA – Kudelski Trusted Agent) that is integrated in the IoT device software stack. The KTA integrates with the Silicon Labs' Hardware Root of Trust (Secure Vault). The IoT device that is connected to the network and application-layer onboarded using Build 4 is the Silicon Labs Thunderboard (BRD2601A) with EFR32MG24x with Secure Vault(TM) High which is security certified to PSA/SESIP Level 3.

Table F-1 lists the technologies used in Build 4. It lists the products used to instantiate each logical build component and the security function that the component provides. The components are logical. They may be combined in physical form, e.g., a single piece of hardware may house a network onboarding component, a router, and a wireless access point.

Table F-1 Build 4 Products and Technologies

Component	Product	Function
Network-Layer Onboarding Component (Thread Protocol Component)	SLWSTK6023A Thread Radio Transceiver (Wireless starter kit);	The SLWSTK6023A acts as a Thread radio transceiver or radio coprocessor (RCP), allowing the open thread boarder router host platform to form and communicate with a Thread network. If the Thread MeshCoP were running on this device, it would provision the IoT device with credentials for the Thread network.
Access Point, Router, or Switch	OpenThread Border Router (OTBR) hosted on a Raspberry Pi	Router that has interfaces both on the Thread network and on the IP network to act as a bridge between the Thread network and the public internet. This allows the IoT device that communicates using the Thread wireless protocol to communicate with cloud services.

Component	Product	Function
Supply Chain Integration Service	Silicon Labs Custom Parts Manufacturer Service (CPMS)	To support network-layer onboarding, the device manufacturer provides device bootstrapping information to the to the device owner.
Authorization Service	Not implemented	Enables the network to verify that the device that is trying to onboard to it is authorized to do so.
IoT Device	Silicon Labs Thunderboard (BRD2601A)	The IoT device that is used to demonstrate trusted network- and application-layer onboarding.
Secure Storage	Secure Vault ™ High on Silicon Labs IoT device	Storage designed to be protected from unauthorized access and capable of detecting attempts to hack or modify its contents. Used to store and process private keys and other information that must be kept confidential.
Certificate Authority	Each tenant in the Kudelski keySTREAM service cloud has its own certificate signing authority	Issues and signs certificates as needed. For application-layer onboarding, the device owner has its own certificate signing authority in its portion of the Kudelski keySTREAM service cloud.
Application-Layer Onboarding Service	Kudelski keySTREAM Service	After connecting to the Thread network, the device performs application-layer onboarding by accessing the Kudelski keySTREAM service. The device and the keySTREAM service mutually authenticate; the keySTREAM service verifies the device's owner, generates an application-layer credential (i.e., an AWS certificate that is based on the device's chipset identity and owner) for the device, and provisions the device with this X.509 credential that will enable the device to access the owner's tenancy in the AWS IoT Core cloud.
Ongoing Device Authorization	N/A – Not intended for inclusion in this build	Performs activities designed to provide an ongoing assessment of the device's trustworthiness and authorization to access network resources. For example, it may perform behavioral analysis or device attestation and use the results to determine whether the device should be granted access to certain high-value resources, assign the device to a particular network segment, or take other action.

Component	Product	Function
Manufacturer Factory Provisioning Process	Silicon Labs Custom Parts Manufacturing Service (CPMS)	Manufactures the IoT device. Creates, signs, and installs the device's unique identity and other birth credentials into secure storage. Installs software and information the device requires for application-layer onboarding. May populate a manufacturer database with information regarding devices that are created and, when the devices are sold, may record what entity owns them. The MG24 "B" version comes pre-loaded with a Silicon Labs Birth certificate. The "A" or "B" version birth certificate can be modified via their Custom Part Manufacturing Service (CPMS) to be unique per end device manufacturer and signed into their Root CA if desired.

F.2 Build 4 Architecture

F.2.1 Build 4 Logical Architecture

Build 4 demonstrates a device connecting to an OpenThread network. IoT devices generate and use a pre-shared key to connect to the OpenThread network of Build 4 using the Thread MeshCoP service. Once a device is connected to the OpenThread network of Build 4, it gets access to an IP network via a border router, and then performs application-layer onboarding using the Kudelski keySTREAM Service. Kudelski keySTREAM is a device security management service that runs as a SaaS platform on the Amazon cloud. Build 4 relies on an integration that has been performed between Silicon Labs and Kudelski keySTREAM. KeySTREAM has integrated software libraries with the Silicon Lab EFR32MG24 (MG24) IoT device's secure vault to enable the private signing key that is associated with an application-layer certificate to be stored into the secure vault using security controls that are available on the MG24. This integration ensures that application-layer credentials can be provisioned into the vault securely such that no key material is misused or exposed.

At a high level, the steps required to enable demonstration of Build 4's network connection and application-layer onboarding capabilities can be broken into the following three main parts:

- <u>Device Preparation</u>: The IoT device is prepared for network connection and application-layer onboarding by the device manufacturer.
    - The device comes from the manufacturer ready to be provisioned onto a Thread network. No additional preparation is required.
    - The device is prepared for application-layer onboarding on behalf of a specific, pre-defined customer who will become its owner. The device is assigned ownership to this customer (e.g., customer A) and this ownership information is sealed into device firmware, permanently identifying the device as being owned by customer A. The device owner, customer A, has a tenancy on the Kudelski keySTREAM Service and is also an Amazon Web Services (AWS) customer. After the device has been prepared, the device is provided to its owner (customer A).

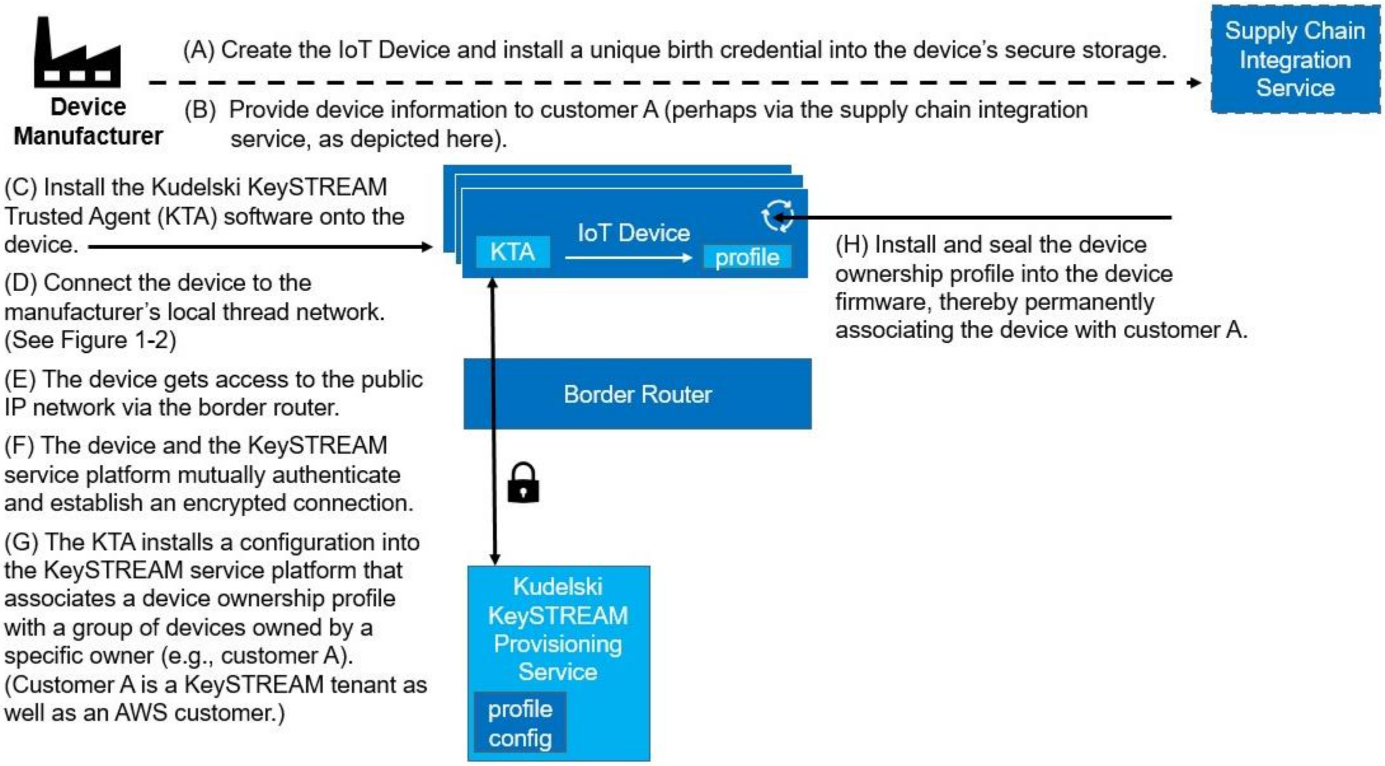
- Network Connection: Customer A connects the device to Customer A's OpenThread network by entering the pre-shared key displayed on the device's serial terminal in the OpenThread Border Router's (OTBR) web interface. This allows the network's radio channel, PAN ID, extended PAN ID and network name to be discovered, avoiding the need to preconfigure any of these parameters. Once on customer A's OpenThread network, the device has access to the public IP network via the border router.
- Application-Layer Onboarding: The device and the keySTREAM service mutually authenticate, keySTREAM confirms that customer A owns the device, and keySTREAM provisions the device with an AWS certificate that is specific to the device and to customer A, enabling the device to authenticate to customer A's tenancy in the AWS IoT Core.

Each of these three aspects of the demonstration are illustrated in its own figure and described in more detail in the three subsections below.

F.2.1.1 Device Preparation

Figure F-1 depicts the steps that are performed by the device manufacturer, which in this case is Silicon Labs, to prepare the device for network- and application-layer onboarding by a particular customer, Customer A. Each step is described in more detail below. Because these steps are performed to prepare the device for onboarding rather than as part of onboarding itself, they are labeled with letters instead of numbers in keeping with the conventions used in other build descriptions.

Figure F-1 Logical Architecture of Build 4: Device Preparation



The following steps are performed to prepare the device for network connection and application-layer onboarding:

1. The manufacturer creates the device, which in this case is a Silicon Labs MG24, and prepares it for network connection by installing the device's unique birth credential into the device's chipset. This chipset identity is a hardware root of trust. The MG24 "B" version comes pre-loaded with a Silicon Labs Birth certificate. The "A" or "B" version birth certificate can be modified via their Custom Part Manufacturing Service (CPMS) to be unique per end device manufacturer and signed into their Root CA if desired.

2. The manufacturer provides information about the device to customer A (perhaps via the supply chain service, as depicted in Figure 1-1) so customer A can be aware that the device is expected on its network.

3. The manufacturer prepares the device for application-layer onboarding by installing the Kudelski keySTREAM Trusted Agent (KTA) software onto the device.

4. The manufacturer connects the device to the manufacturer's local OpenThread network. (See Figure 1-2 for details of the network connection steps.) Note that in this case, which is the first time that the device is being connected to a network, the device is being connected to the manufacturer's network rather than to the network of the device's eventual owner.

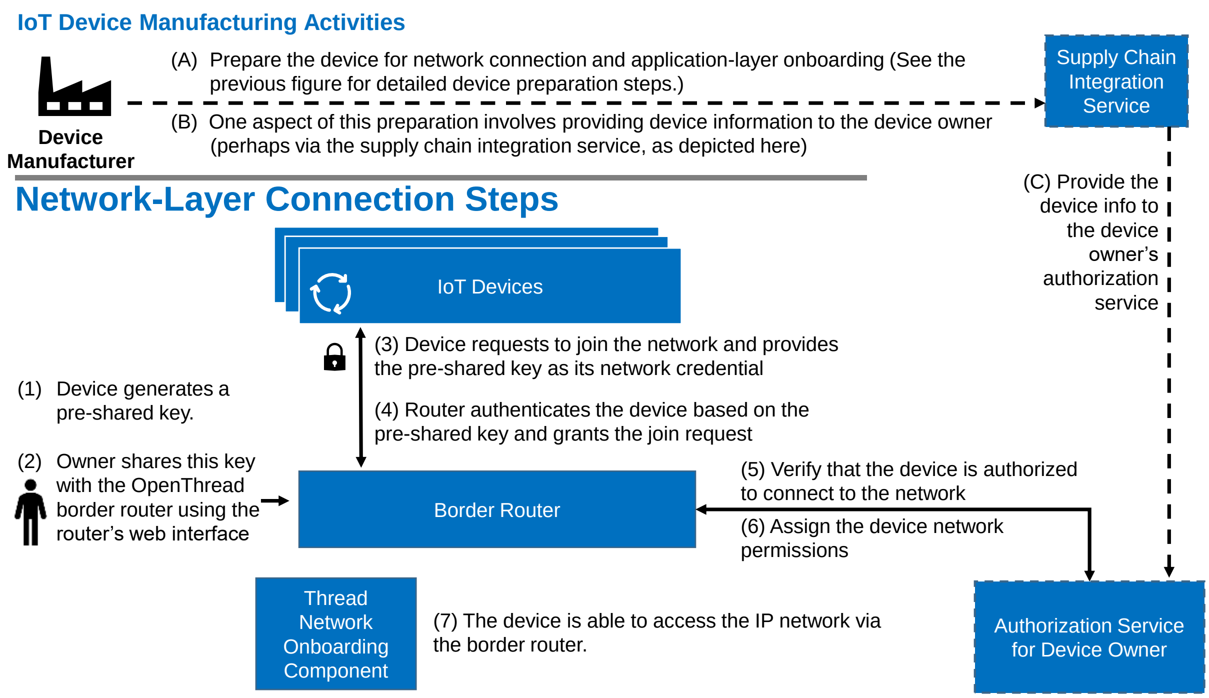
5. After the device connects to the manufacturer's OpenThread network, the device has access to the public IP network via the border router.

6. The device and the Kudelski keySTREAM service mutually authenticate and establish an encrypted connection.
7. The KTA installs a configuration into the keySTREAM service platform that builds up a group of devices that belong to a certain end user and associates the group with a device ownership profile. This device ownership profile is associated with a particular customer (e.g., customer A). The same device profile is used by all devices in a group of devices that are owned by this owner. The profile is not specific to individual devices. The owner of these devices (customer A) has a keySTREAM tenancy, which includes a dedicated certificate signing CA. Customer A is also an AWS customer.
8. The device manufacturer installs and seals this device ownership profile into the device firmware. This profile permanently identifies the device as being owned by customer A.

F.2.1.2 Network-Layer Connection

Figure F-2 depicts the steps of an IoT device connecting to that thread network using a pre-shared key that the device generates and shares with the OpenThread boarder router. Each step is described in more detail below.

Figure F-2 Logical Architecture of Build 4: Connection to the OpenThread Network



The device connects to the OpenThread network using the following steps:

1. The device generates a pre-shared key.
2. The owner starts the commissioning process by entering this pre-shared key on the OpenThread border router.

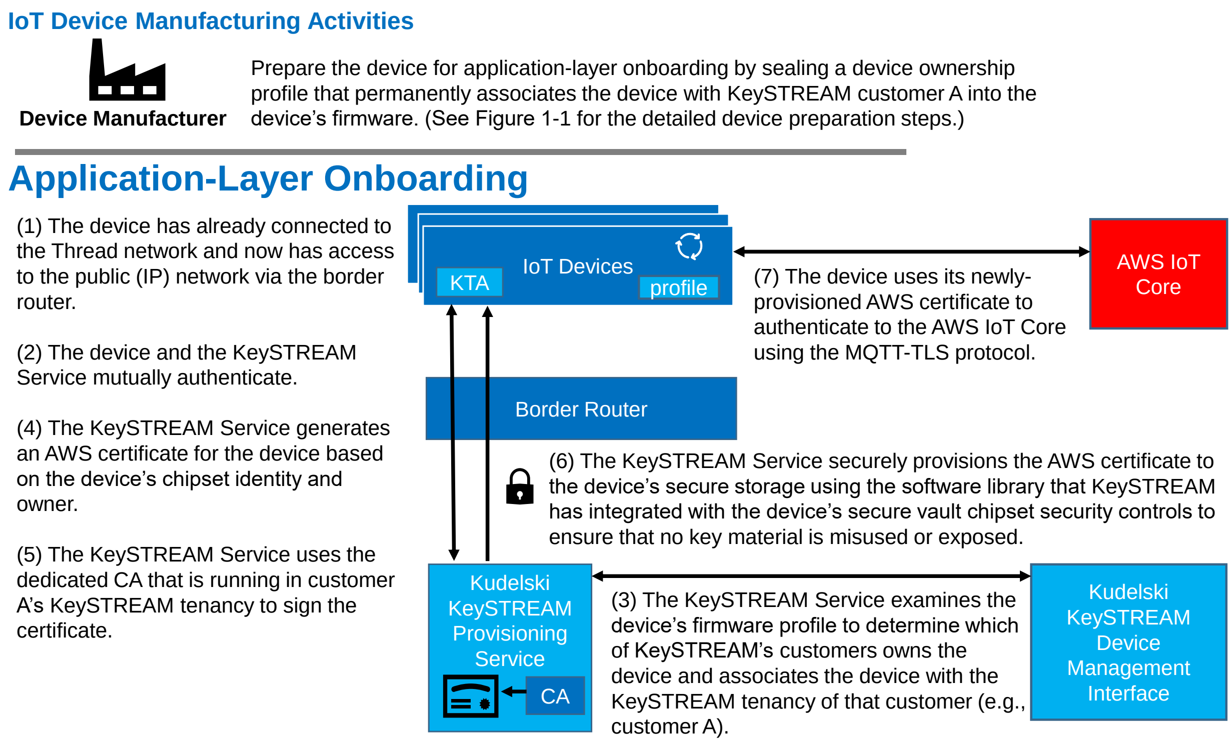
3. The device requests to join the network and provides the pre-shared key as its network credential.
4. The network authenticates the device based on the pre-shared key and grants the join request.
5. The network verifies that the device is authorized to connect to the network.
6. The network assigns the device network permissions and configures these as policies on the border router.
7. The device is able to access the IP network (and the internet) via the border router.

This completes the network-layer connection process.

F.2.1.3 Application-Layer Onboarding

Figure F-3 depicts the steps of the application-layer onboarding process using the Kudelski keySTREAM service. Each step is described in more detail below.

Figure F-3 Logical Architecture of Build 4: Application-Layer Onboarding using the Kudelski keySTREAM Service



The application-layer onboarding steps performed to provision the device with its application-layer credentials (e.g., its AWS certificate) are as follows:

1. The device, which is already connected to the OpenThread network, accesses the IP network via the border router.
2. The device and the keySTREAM service mutually authenticate.

3. The keySTREAM Service examines the device's firmware profile to determine which of keySTREAM's customers owns the device. In this case, customer A is identified as the device owner. The keySTREAM service associates the device with customer A's keySTREAM tenancy.
4. The keySTREAM Service generates an AWS IoT Core certificate for the device based on both the device's ownership information and the secure hardware root of trust that is in the device's chipset.
5. The keySTREAM Service uses the dedicated CA that is running in customer A's keySTREAM tenancy to sign the AWS certificate.
6. The keySTREAM Service securely provisions the AWS certificate to the device's secure storage using the software library that keySTREAM has integrated with the device's secure vault chipset security controls to ensure that no key material is misused or exposed.
7. The device uses its newly provisioned application-layer credentials (i.e., the AWS certificate) to authenticate to customer A's tenancy in the AWS IoT Core using the MQTT-TLS protocol.

F.2.2 Build 4 Physical Architecture

Section 5.5 describes the physical architecture of Build 4.

Appendix G Build 5 (BRSKI over Wi-Fi, NquiringMinds)

G.1 Technologies

Build 5 is an implementation of network-layer onboarding that uses a version of the BRSKI Protocol that has been modified to work over Wi-Fi. After the IoT device has joined the network, Build 5 also demonstrates a number of mechanisms that are performed on an ongoing basis to provide continuous, policy-based authorization and assurance. Both the network-layer onboarding infrastructure and the continuous assurance service for Build 5 were provided by NquiringMinds. This entire build can be replicated using the open sourced TrustNetZ code base.

For more information on NquiringMinds and the products and technologies that they contributed to this project overall, see Section 3.4.

Build 5 network onboarding infrastructure components within the NCCoE lab consist of a Linux based Raspberry Pi 4B router (which also runs the registrar service and MASA service), and a USB hub. The Build 5 components used to support the continuous assurance service include TrustNetZ Authorization interfaces, TrustNetZ information provider, and TrustNetZ policy engine. The IoT devices that are onboarded using Build 5 are a Raspberry Pi device. These IoT devices do not have secure storage, but use the Infineon Optiga SLB 9670 TPM 2.0 as an external secure element. Build 5 depends on an IDevID (X.509 Certificate) having been provisioned to the secure element of the IoT device (pledge) prior to onboarding, as part of the factory provisioning process (see Section H.1). For Build 5, this factory provisioning process was accomplished by the BRSKI Factory Provisioning Build, which is described in Appendix H.3.

Table G-1 lists the technologies used in Build 5. It lists the products used to instantiate each logical build component and the security function that the component provides. The components are logical. They may be combined in physical form, e.g., a single piece of hardware may house a network onboarding component, a router, and a wireless access point.

Table G-1 Build 5 Products and Technologies

Component	Product	Function
Network-Layer Onboarding Component (BRSKI Domain Registrar)	Stateful, non-persistent Linux app that has two functional interfaces for both BRSKI and for the Authentication Service. (TrustNetZ onboarding)	Runs the BRSKI protocol modified to work over Wi-Fi and acts as a BRSKI Domain Registrar. It authenticates the IoT device, receives a voucher request from the IoT device, and passes the request to the MASA. It also receives a voucher from the MASA, verifies it, and passes it to the IoT device. Assuming the IoT device finds the voucher to be valid and determines that the network is authorized to onboard it, the Domain Registrar provisions network credentials to the IoT device using EST.

Component	Product	Function
Access Point, Router, or Switch	Raspberry Pi 4B equipped with USB Wi-Fi dongle, running TrustNetZ AP code.	Router, providing an open Wi-Fi network and closed Wi-Fi network. Physical access control is mediated through the RADUIS interface (which is part of the TrustNetZ AP configuration) The AP also receives network commands from the continuous assurance service.
Supply Chain Integration Service (Manufacturer Authorized Signing Authority—MASA)	TrustNetZ MASA	The MASA creates and signs a voucher and provides this voucher to the IoT device via the Registrar so that the device can verify that the network that is trying to onboard it is authorized to do so.
Authorization Service	Linux application which contains an encapsulated policy engine (TrustNetZ policy engine)	Determines whether the device is authorized to be onboarded to the network. The application features a REST API which accepts verifiable credential claims to feed data on entities and their relationships into its SQL database. The policy engine itself is based on verifiable credentials presentation, (persisted to SQL database), making it easily configurable and extensible.
IoT Device	Raspberry Pi devices (running TrustNetZ pledge agent)	The IoT device that is used to demonstrate trusted network- and application-layer onboarding. Handles the client side BRSKI protocols, the integration with the secure storage, with factory provisioning and TLS connections.
Secure Storage	Infineon Optiga SLB 9670 TPM 2.0	Storage on the IoT device that is designed to be protected from unauthorized access and capable of detecting attempts to hack or modify its contents. Used to store and process private keys and other information that must be kept confidential.
Certificate Authority	TrustNetZ demo manufacturer CA (MPR – manufacture provisioning root) TrustNetZ Domain CA	Two CA are used in Build 5 Domain CA issues certificates and provides signing and attestation functions that model network owner relationships (e.g. sign the LDevID certificate) Manufacturer CA issues the IDevID certificates; proving the device has been created by the manufacturer.
Application-Layer Onboarding Service	TrustNetZ Demo application sever	After connecting to the network, the device mutually authenticates with a trusted application service and interacts with it at the application layer. The IDevID and TPM private key are used to establish a TLS session with the demonstration application server and send data to it from the device. This demonstrates the concept of secure connection to a third-party application server using the cryptographic artifacts from the onboarding process.

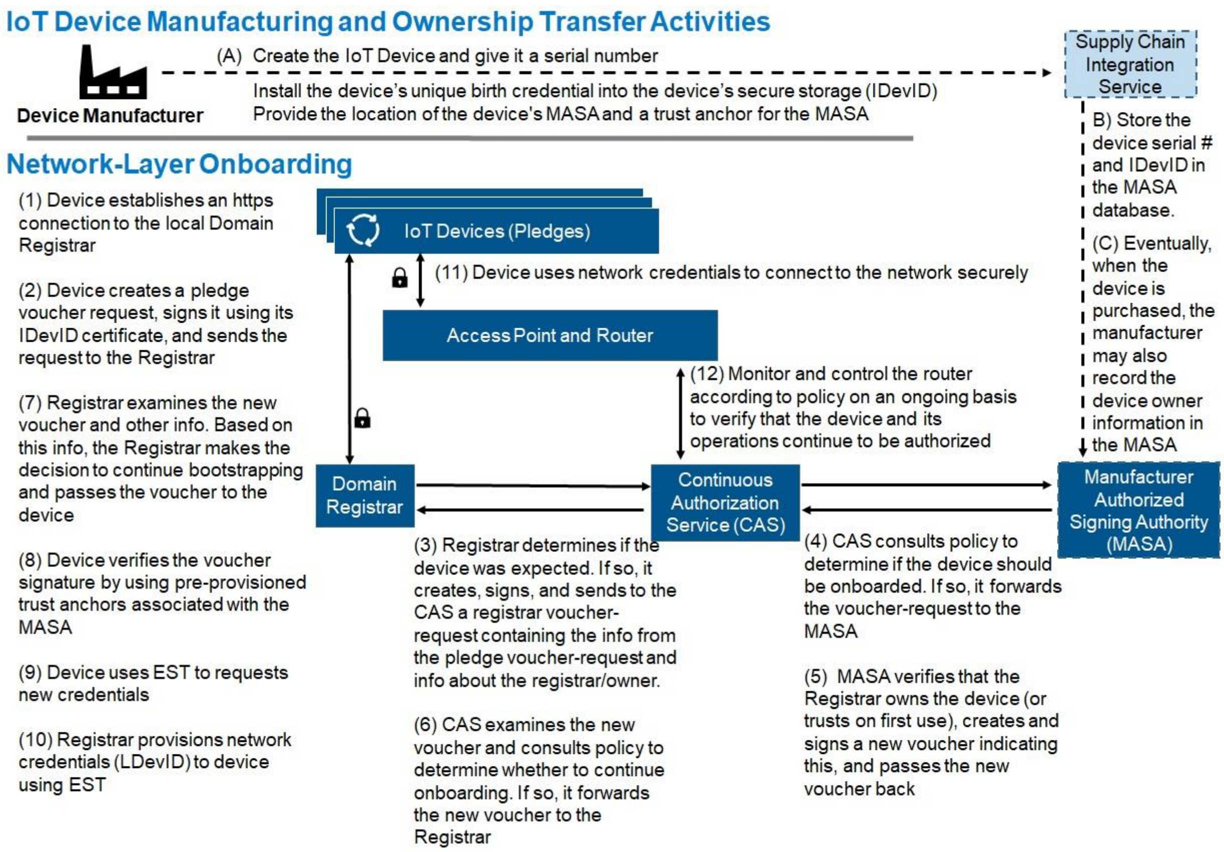
Component	Product	Function
Ongoing Device Authorization	Continuous Authorization Service, which calls into the in the TrustNetZ policy engine	Designed to perform a set of ongoing, policy-based continuous assurance and authorization checks on the device after it has connected to the network. As of this publication, the following ongoing checks have been implemented: ▪ The manufacturer of the device must be trusted by the network owner ▪ The device must be trusted by a user with appropriate privileges ▪ The device must have an associated device type ▪ The vulnerability score of the software bill of materials (SBOM) for the device type must be lower than a set threshold ▪ The device must not have contacted an IP address that is on a deny list If it fails any of these periodic checks, its voucher is revoked, which removes the device from the network.
Manufacturer Factory Provisioning Process	BRSKI Factory Provisioning Process used to provision the Infineon TPM with its private key and IDevID (See Appendix H.3)	Manufactures the IoT device. Creates, signs, and installs the device's unique identity (i.e., its IDevID, which is an X.509 certificate) into secure storage. Installs information the device requires for application-layer onboarding. Populates the MASA with information regarding devices that are created and, when the devices are sold, may record what entity owns them.

G.2 Build 5 Architecture

G.2.1 Build 5 Logical Architecture

The network-layer onboarding steps that are performed in Build 5 are depicted in Figure G-1. These steps are broken into two main parts: those required to transfer device bootstrapping information from the device manufacturer to the MASA (labeled with letters) and those required to perform network-layer onboarding of the device and establish the operation of the continuous authorization service (labeled with numbers).

Figure G-1 Logical Architecture of Build 5



The device manufacturer:

1. Creates the device and installs a unique serial number and birth credential into secure storage on the device. This unique birth credential takes the form of a private key and its associated 802.1AR certificate, e.g., the device's IDevID. As part of this factory-installed certificate process, the location of the device's manufacturer authorized signing authority (MASA) is provided in an extension to the IDevID. The device is also provided with trust anchors for the MASA entity that will sign the returned vouchers.

2. Stores information about the device, such as its serial number and its IDevID, in the MASA's database.

3. Eventually, when the device is sold, the MASA may also record the device ownership information in its database.

After obtaining the device, the device owner provisions the device with its network credentials by performing the following network-layer onboarding steps:

1. The owner puts the device (i.e., the pledge) into onboarding mode. The device establishes an https connection to the local Domain Registrar. (In a standard BRSKI implementation, the device would have wired network connectivity. The device would use its link-local network connectivity to locate a join proxy, and the join proxy would provide the device with https connectivity to the

local Domain Registrar.) The Build 5 implementation, however, relies on wireless connectivity and initially uses the unauthenticated EAP-TLS protocol. The pledge discovers potential onboarding networks by searching for public Wi-Fi networks that either match a particular SSID wildcard name or that advertise a particular realm. When the device finds a potential onboarding network, it connects to it and attempts to discover the registrar. The pledge will connect to the open Wi-Fi network and will receive either an IPv4 or IPv6 address. Subsequently, the pledge will listen to mDNS packets and will obtain the list of join proxies (IP addresses). Finally, the pledge will subsequently connect to each join proxy using the BRSKI-EST protocol.

2. The device creates a pledge voucher-request that includes the device serial number, signs this request with its IDevID certificate (i.e., its birth credential), and sends this signed request to the Registrar.
3. The Registrar receives the pledge voucher-request and considers whether the manufacturer is known to it and whether devices of that type are welcome. If so, the Registrar forms a registrar voucher-request that includes all the information from the pledge voucher request along with information about the registrar/owner. The Registrar sends this registrar voucher-request to the Continuous Authorization Service.
4. The Continuous Authorization Service consults policy to determine if this device should be permitted to be onboarded and what other conditions should be enforced. An example of policy that might be used is that the network owner wants to disable MASA validation. Assuming the device is permitted to be onboarded, the Continuous Authorization Service locates the MASA that the IoT device is known to trust (i.e., the MASA that is identified in the device's IDevID extension) and sends the registrar voucher-request to the MASA.
5. The MASA consults the information that it has stored and applies policy to determine whether to approve the Registrar's claim that it owns the device. (For example, the MASA may consult sales records for the device to verify device ownership, or it may be configured to trust that the first registrar that contacts it on behalf of a given device is in fact the device owner). Assuming the MASA decides to approve the Registrar's claim to own the device, the MASA creates a new voucher that directs the device to accept its new owner, signs this voucher, and sends it back to the Continuous Authorization Service.
6. The Continuous Authorization Service receives this new voucher and examines it in consultation with policy to determine whether to continue onboarding. Some examples of policies that might be used include: permit onboarding only if no current critical vulnerabilities have been disclosed against the declared device type, the device instance has successfully passed a site-specific test process, or a test compliance certificate has been found for the declared device type. Assuming the device is permitted to be onboarded, the Continuous Authorization Service sends the new voucher to the Domain Registrar.
7. The Domain Registrar receives and examines the new voucher along with other related information and determines whether it trusts the voucher. Assuming it trusts the voucher, the Registrar passes the voucher to the device.

8. The device uses its factory-provisioned MASA trust anchors to verify the voucher signature, thereby ensuring that the voucher can be trusted.
9. The device uses Enrollment over Secure Transport (EST) to request new credentials.
10. The Registrar provisions network credentials to the device using EST. These network credentials get stored into secure storage on the device, e.g., as an LDevID.
11. The device uses its newly provisioned network credentials to connect to the network securely.
12. After the device is connected and begins operating on the network, the Continuous Authorization Service and the router make periodic asynchronous calls to each other that enable the Continuous Authorization Service to monitor device behavior and constrain communications to and from the device as needed in accordance with policy. In this manner, the Continuous Authorization Service interacts with the router on an ongoing basis to verify that the device and its operations continue to be authorized throughout the device's tenure on the network.

This completes the network-layer onboarding process for Build 5 as well as the initialization of the Build 5 continuous authorization service. More details regarding the Build 5 implementation can be found at https://trustnetz.nqm.ai/docs/.

G.2.2 Build 5 Physical Architecture

Section 5.6 describes the physical architecture of Build 5.

Appendix H Factory Provisioning Process

H.1 Factory Provisioning Process

The Factory Provisioning Process creates and provisions a private key into the device's secure storage; generates and signs the device's certificate (when BRSKI is supported), generates the device's DPP URI (when Wi-Fi Easy Connect is supported), or generates other bootstrapping information (when other trusted network-layer onboarding protocols are supported); provisions the device's certificate, DPP URI, or other bootstrapping information onto the device; and sends the device's certificate, DPP URI, or other bootstrapping information to the manufacturer's database, which will eventually make this information available to the device owner to use during network-layer onboarding.

H.1.1 Device Birth Credential Provisioning Methods

There are various methods by which a device can be provisioned with its private key and bootstrapping information (e.g., its certificate, DPP URI, etc.) depending on how, where, and by what entity the public/private key pairs are generated [14]. Additional methods are also possible depending on how the device's certificate is provided to the manufacturer's database. The following are high-level descriptions of five potential methods for provisioning device birth credentials during various points in the device lifecycle. These methods are not intended to be exhaustive:

1. **Method 1: Key Pair Generated on IoT Device**
   Summary: Generate the private key on the device; device sends the device's bootstrapping information (e.g., the device's certificate or DPP URI) to the manufacturer's database. The steps for Method 1 are:
   a. The public/private key pair is generated on the device and stored in secure storage.
   b. The device generates and signs a CSR structure and sends the CSR to the manufacturer's IDevID CA, which sends a signed certificate (IDevID) back to the device.
   c. If BRSKI is being supported, the device loads the certificate (IDevID) into its secure storage; if Wi-Fi Easy Connect is being supported, the device creates a DPP URI and loads that into secure storage.
   d. The device sends the certificate or DPP URI to the manufacturer's database.

   One disadvantage of this method is that the device's random number generator is being relied upon to generate the key pair, and it is possible that a device's random number generator will not be as robust as the random number generator that would be included in an SE, for example. An advantage of this method is that the device's private key is not vulnerable to disclosure, assuming the device is equipped with a strong random number generator that is used for key generation and the private key is put into secure storage immediately upon generation.

2. **Method 2: Key Pair Generated in Secure Element**
   Summary: Generate the private key in a secure element on the device; IDevID CA provides the device certificate to the manufacturer's database. The steps for Method 2 are:
   a. The public/private key pair is generated within the device's SE.

   b. The device generates a CSR structure, the SE signs it, and the device sends the CSR to the manufacturer's IDevID CA, which sends a signed certificate (IDevID) back to the device.
   c. If BRSKI is being supported, the device loads the certificate (IDevID) into its secure storage; if Wi-Fi Easy Connect is being supported, the device creates a DPP URI and loads that into secure storage.
   d. The IDevID CA provides the certificate to the manufacturer's database. The manufacturer stores either the certificate (i.e., if BRSKI is being supported), or creates and stores a DPP URI (i.e., if Wi-Fi Easy Connect is being supported).

Method 2 is similar to Method 1 except that in method 2, the key pair is generated and stored in a secure element and the manufacturer's database receives the signed certificate directly from the CA (either via a push or a pull) rather than via the device. An advantage of method 2 is that the device's private key is not vulnerable to disclosure because secure elements are normally equipped with a strong random number generator and tamper-proof storage.

3. Method 3: Key Pair Loaded into IoT Device

Summary: Generate the private key in the device factory and load it onto the device. The steps for Method 3 are:

   a. The public/private key pairs and certificates are generated in advance at the device factory and recorded in the manufacturer's database.
   b. The public/private key pair and certificate are loaded onto the device at the device factory.

One advantage of this method is that there is no need to trust the random number generator on the device to generate strong public/private key pairs. However, the private keys may be vulnerable to disclosure during the period of time before they are provisioned into secure storage on the devices (and afterwards if they are not deleted once they have been copied into secure storage).

4. Method 4: Key Pair Pre-Provisioned onto Secure Element

Summary: Generate the private key in the SE and load the certificate on the device at the SE factory (SEF). The steps for Method 4 are:

   a. The public/private key pair and certificate are generated in advance in the SE at the SEF and the public key is recorded.
   b. The certificate is loaded onto the devices at the SEF.
   c. The certificates and the serial numbers of their corresponding devices are provided to the device manufacturer, and the device manufacturer can put them into the manufacturer database.
   d. The CA that signs the certificates that are generated and loaded onto the SEs may come from either the SEF or the device manufacturer. (Note: the CA is likely not located at the factory, which may be offshore.)

Additional trust anchors can also be loaded into the SE at the SEF (e.g., code signing keys, server public keys for TLS connections, etc.) As with methods 2 and 3, one advantage of this method (method 4) is that there is no need to trust the random number generator on the device to generate strong public/private key pairs because the random number generator on the SE is used instead. With this method, the security level of the manufacturer's factory does not need to be as high as that of the SEF because all key generation and certificate signing is performed at the SEF; the manufacturer can rely on the security of the SEF, which can be advantageous to the device manufacturer, assuming that the SEF is in fact secure.

5. **Method 5: Private Key Derived from Shared Seed**

Summary: The device's private key is derived from a shared seed. The steps for Method 5 are:

   a. The chip vendor embeds a random number into each IoT device (e.g., this may be burned into fuses on the IoT device, inside the Trusted Execution Environment (TEE)).
   b. The IoT device manufacturer gets a copy of this seed securely (e.g., on a USB device that is transported via trusted courier).
   c. On first boot, the IoT device generates a private key from this seed.
   d. The manufacturer uses the same seed to generate a public key and signs a certificate.

As with method 4, with this option (method 5), there is no need for the IoT device manufacturer to have a secure factory because the IoT device manufacturer may rely on the security of the chip manufacturer. However, the IoT device manufacturer must also rely on the security of the courier or other mechanism that is delivering the seed, and the IoT device manufacturer must ensure that the value of this seed is not disclosed.

H.2 Factory Provisioning Builds – General Provisioning Process

The Factory Provisioning Builds implemented as part of this project simulate activities performed during the IoT device manufacturing process to securely provision the device's birth credentials (i.e., its private key) into secure storage on the device and make the device's network-layer bootstrapping information available by enrolling the device's public key into a database that will make this public key accessible to the device owner in a form such as a certificate or DPP URI. The method used in the factory provisioning builds most closely resembles *Method 2: Key Pair Generated on IoT Devic*e, as described in Section H.1.1.

There are several different potential versions of the factory provisioning build architecture depending on whether the credentials being generated are designed to support BRSKI, Wi-Fi Easy Connect, Thread, or some other trusted network-layer onboarding protocol. For example, when BRSKI is being supported, the device bootstrapping information that is created takes the form of an 802.1AR certificate (IDevID); if DPP is supported, it takes the form of a DPP URI.

Because this project does not have access to a real factory or the tools necessary to provision birth credentials directly into device firmware, the factory builds simulate the firmware loading process by loading factory provisioning code into the IoT device (e.g., a Raspberry Pi device). This code plays the role of the factory in the builds by instructing the SE that is attached to the IoT device to generate the device's private key and bootstrapping information. Once the IoT device has been provisioned with its birth credentials in this manner, it can, in theory, be network-layer onboarded to one of the project build networks.

H.3 BRSKI Factory Provisioning Builds (NquiringMinds and SEALSQ)

Two variants of the BRSKI Factory Provisioning Build were implemented:

- **NquiringMinds and SEALSQ implementation** (first version): SEALSQ, a subsidiary of WISeKey, and NquiringMinds collaborated to implement one version of the BRSKI Factory Provisioning Build. This build is designed to provision birth credentials to a Raspberry Pi device that has an attached secure element provided by SEALSQ.
- **NquiringMinds and Infineon implementation** (second version): NquiringMinds implemented a second version of the BRSKI Factory Provisioning Build using an Infineon SE. This build is designed to provision birth credentials to a Raspberry Pi device that has an attached Infineon Optiga SLB 9670 TPM 2.0.

H.3.1 BRSKI Factory Provisioning Build Technologies

The general infrastructure for the first version of the BRSKI Factory Provisioning Build (i.e., the NquiringMinds and SEALSQ implementation) is provided by SEALSQ. The first version of the BRSKI Factory Provisioning Build infrastructure consists of:

- A SEALSQ VaultIC SE that is attached to the Raspberry Pi
- SEALSQ Factory Provisioning Code that is located on an SD card and that communicates with the chip in the SE to
  - create a P-256 Elliptic Curve public/private key pair within the SE,
  - construct a certificate signing request, and
  - store the certificate in the SE as well as send it to the manufacturer's database
- SEALSQ INeS CMS CA, a certificate authority for signing the device's birth certificate

As mentioned earlier, separate factory provisioning builds are required for each network-layer onboarding protocol being supported. A small amount of factory provisioning code is required to be customized for each build, depending on the onboarding protocol that is supported and how the bootstrapping information will be provided to the manufacturer. In this build, NquiringMinds provided this code and made it available to the Raspberry Pi IoT device by placing it on an SD card. (This could be either in a partition of the SD card that holds the device's BRSKI onboarding software or on a separate SD card altogether).

Table H-1 lists the technologies used in the first version of the BRSKI Factory Provisioning Build. It lists the products used to instantiate each logical build component and the security function that the component provides. The components listed are logical. They may be combined in physical form, e.g., a single piece of hardware may both generate key pairs and provide secure storage.

Table H-1 First Version of the BRSKI Factory Provisioning Build Products and Technologies

Component	Product	Function
Key Pair Generation Component	SEALSQ VaultIC and associated provisioning code	Generates and installs the public/private key pair into secure storage. The VaultIC has a SP800-90B certified random number generator for key pair generation.

Component	Product	Function
		[15][16][17] Signs the certificate signing request that is sent to the CA.
Secure Storage	SEALSQ VaultIC	Storage on the IoT device that is designed to be protected from unauthorized access and capable of detecting attempts to hack or modify its contents. Used to generate, store, and process private keys, credentials, and other information that must be kept confidential.
General Factory Provisioning Instructions	SEALSQ Factory Provisioning Code	Creates a CSR associated with the key pair, installs the signed certificate into secure storage. Creates a record of devices that it has created and their certificates.
Build-specific Factory Provisioning Instructions	NquiringMinds Factory Provisioning Code	Sends device ownership information and the certificate received by the General Factory Provisioning code to the MASA.
Manufacturer Database	MASA	When devices are manufactured, device identity and bootstrapping information is stored here by the manufacturer. Eventually, this database makes the device's bootstrapping information available to the device owner. Device bootstrapping information is information that the device owner requires to perform trusted network-layer onboarding; for BRSKI, the bootstrapping information is a signed certificate that is sent to the MASA, along with information regarding the device's owner.
Certificate Authority (CA)	SEALSQ INeS CMS CA	Issues and signs certificates as needed.

The second version of the BRSKI Factory Provisioning Build (i.e., the NquiringMinds implementation with an Infineon SE) infrastructure consists of:

- An Infineon Optiga SLB 9670 TPM 2.0. that is attached to the Raspberry Pi
- Factory Provisioning Code written by NquiringMinds that is located on an SD card and that communicates with the chip in SE to
    - create a P-256 Elliptic Curve public/private key pair within the SE,
    - construct a certificate signing request, and
    - store the certificate in the SE as well as send it to the manufacturer's database
- NquiringMinds Manufacturer Provisioning Root (MPR) server, which signs the device's IDevID birth certificate. It sits in the cloud and is securely contacted using the keys in the Infineon Optiga secure element.

In this build, NquiringMinds provided all of the factory provisioning code and made it available to the Raspberry Pi IoT device by placing it on an SD card. (This could be either in a partition of the SD card that holds the device's BRSKI onboarding software or on a separate SD card altogether).

Table H-2 lists the technologies used in the second version of the BRSKI Factory Provisioning Build. It lists the products used to instantiate each logical build component and the security function that the component provides. The components listed are logical. They may be combined in physical form, e.g., a single piece of hardware may both generate key pairs and provide secure storage.

Table H-2 Second Version of the BRSKI Factory Provisioning Build Products and Technologies

Component	Product	Function
Key Pair Generation Component	Infineon TPM and associated provisioning code	Generates and installs the public/private key pair into secure storage. Signs the certificate signing request that is sent to the CA.
Secure Storage	Infineon TPM	Storage on the IoT device that is designed to be protected from unauthorized access and capable of detecting attempts to hack or modify its contents. Used to generate, store, and process private keys, credentials, and other information that must be kept confidential.
General Factory Provisioning Instructions	Infineon TPM-specific Factory Provisioning Code	Creates a CSR associated with the key pair, installs the signed certificate into secure storage. Creates a record of devices that it has created and their certificates.
Build-specific Factory Provisioning Instructions	Build-specific Factory Provisioning Code	Sends device ownership information and the signed certificate to the MASA.
Manufacturer Database	MASA	When devices are manufactured, device identity and bootstrapping information is stored here by the manufacturer. Eventually, this database makes the device's bootstrapping information available to the device owner. Device bootstrapping information is information that the device owner requires to perform trusted network-layer onboarding; for BRSKI, the bootstrapping information is a signed certificate that is sent to the MASA, along with information regarding the device's owner.
Certificate Authority (CA)	SEALSQ INeS CMS CA NquiringMinds On-premises CA	Issues and signs certificates as needed.

H.3.2 BRSKI Factory Provisioning Build Logical Architectures

Figure H-1 depicts the logical architecture of the first version of the BRSKI factory provisioning build (i.e., the NquiringMinds and SEALSQ implementation) and is annotated with the steps that are performed in this build to prepare IoT devices for network-layer onboarding using the BRSKI protocol. Figure H-1 shows a Raspberry Pi device with a SEALSQ VaultIC SE attached. An SD card that contains factory provisioning code provided by SEALSQ and NquiringMinds is also required. To perform factory provisioning using this build, insert the SD card into the Raspberry Pi, as depicted (or activate the code in the factory provisioning partition of the SD card that is already in the Raspberry Pi). The SEALSQ software will boot up and perform the following steps to simulate the activities of a factory:

1. Instruct the SE to generate and store a private/public key pair
2. Create a certificate signing request for this key pair and have the SE sign it
3. Send the signed CSR to the IDevID CA (i.e., to the INeS CA that is operated by SEALSQ)
4. Receive back the signed certificate from the CA
5. Load the certificate into the SE
6. Send the certificate (along with device ownership information) to the manufacturer's database, which in this case is the MASA that is trusted by the owner

This completes the steps performed as part of the first version of the BRSKI Factory Provisioning Build. Once complete, shipment of the device to its owner can be simulated by walking the device across the room in the NCCoE laboratory to the Build 5 (NquiringMinds) implementation and replacing the SD card that has the factory provisioning code on it with and SD card that has the BRSKI onboarding code on it. (Alternatively, if the factory provisioning code and the BRSKI onboarding code are stored in separate partitions of the same SD card, shipment of the device to its owner can be simulated by booting up the code in the onboarding partition.) Build 5 is designed to execute this BRSKI onboarding software, which onboards the device to the device owner's network by provisioning the device with an LDevID that will serve as its network-layer credential. Such successful network-layer onboarding of the newly provisioned device using the BRSKI protocol by Build 5 would serve to confirm that the first version of the BRSKI factory provisioning process successfully provisioned the device with its birth credentials. At the time of this writing, however, this confirmation process was not able to be performed. In order to securely network-layer onboard the newly provisioned Raspberry Pi using the BRSKI protocol, the Raspberry Pi's onboarding software would need to be written to use the private key stored in the SEALSQ secure element when running the BRSKI protocol. Such software was not yet available at the time of this publication. The BRSKI onboarding code on the Raspberry Pi does not currently use the private key stored in the SEALSQ SE. As a result, Build 5 was not able to onboard this factory Pi as a way of confirming that the first version of the BRSKI factory build process completed successfully. The repository that hosts the code for this implementation can be found here at the [trustnetz-se Github repository].

Figure H-1 Logical Architecture of the First Version of the BRSKI Factory Provisioning Build

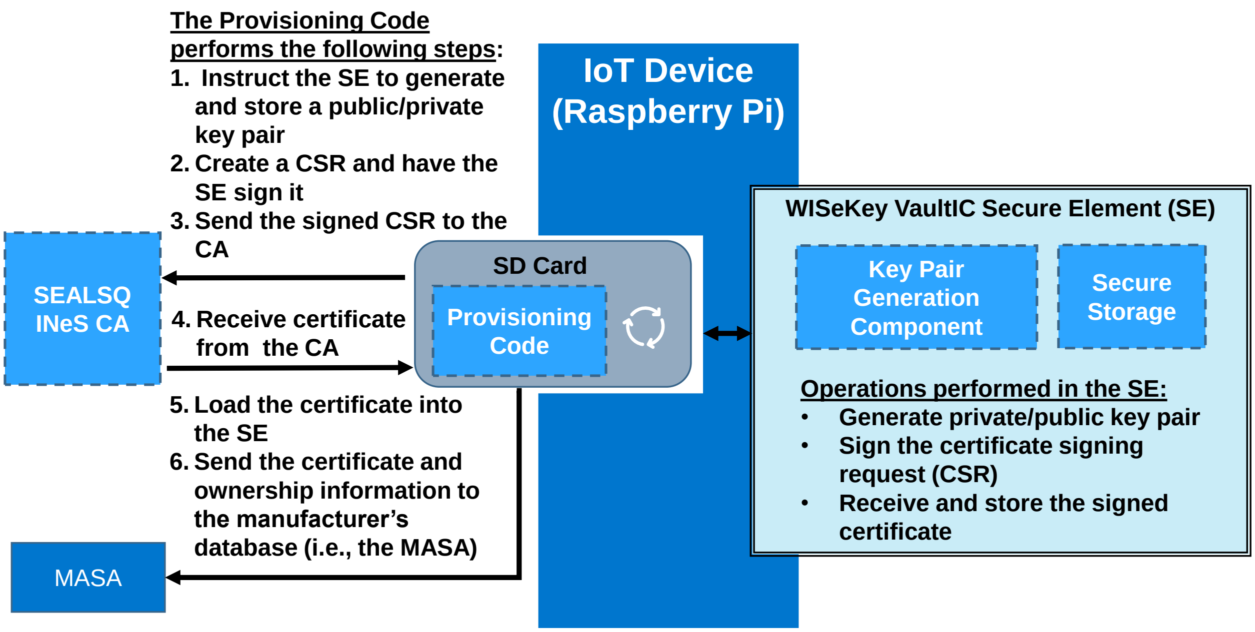
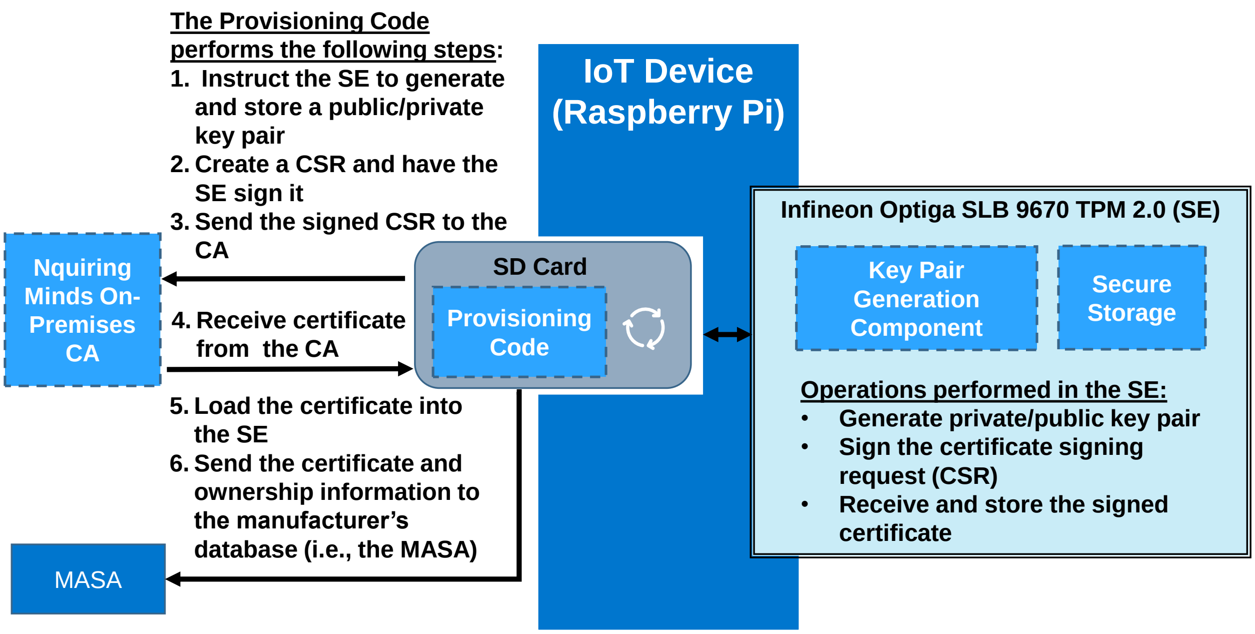


Figure H-2 depicts the logical architecture of the second version of the BRSKI factory provisioning build and is annotated with the steps that are performed in this build to prepare IoT devices for network-layer onboarding using the BRSKI protocol. Figure H-2 shows a Raspberry Pi device with an Infineon Optiga SLB 9670 TPM 2.0 SE attached. An SD card that contains factory provisioning code provided by NquiringMinds is also required. To perform factory provisioning using this build, insert the SD card into the Raspberry Pi, as depicted (or activate the code in the factory provisioning partition of the SD card that is already in the Raspberry Pi). The factory provisioning code software will boot up and perform the following steps to simulate the activities of a factory:

1. Instruct the Infineon SE to generate and store a private/public key pair
2. Create a certificate signing request for this key pair and have the SE sign it
3. Send the signed CSR to the IDevID CA (i.e., to the NquiringMinds on-premises CA/Manufacturer Provisioning Root)
4. Receive back the signed certificate from the CA
5. Load the certificate into the SE
6. Send the certificate (along with device ownership information) to the manufacturer's database, which in this case is the MASA that is trusted by the owner

This completes the steps performed as part of the second version of the BRSKI Factory Provisioning Build. Once complete, shipment of the device to its owner can be simulated by walking the device across the room in the NCCoE laboratory to the Build 5 (NquiringMinds) implementation and replacing the SD card that has the factory provisioning code on it with and SD card that has the BRSKI onboarding code on it. (Alternatively, if the factory provisioning code and the BRSKI onboarding code are stored in separate partitions of the same SD card, shipment of the device to its owner can be simulated by booting up the code in the onboarding partition.) Build 5 executes a modification of the BRSKI onboarding software that has been modified to use the IDevID resident on the Infineon TPM throughout the protocol flow, ensuring the device's IDevID's private key is never made public and never leaves the secure element. Specifically, the critical signing operations and the TLS negotiation steps are fully secured by the SE. The full BRSKI onboarding flow provisions a new LDevID onto the device. This LDevID provides the secure method for the device to connect to the domain owner's network. This successful network-layer onboarding of the IoT device by Build 5 serves as confirmation that the second version of the BRSKI factory provisioning process successfully provisioned the device with its birth credentials.

Figure H-2 Logical Architecture of the Second Version of the BRSKI Factory Provisioning Build



H.3.3 BRSKI Factory Provisioning Build Physical Architectures

Section 5.6.1 describes the physical architecture of the BRSKI Factory Provisioning Builds.

H.4 Wi-Fi Easy Connect Factory Provisioning Build (SEALSQ and Aruba/HPE)

SEALSQ, a subsidiary of WISeKey, and Aruba/HPE implemented a Wi-Fi Easy Connect Factory Provisioning Build. This build is designed to provision birth credentials to a Raspberry Pi device that has an attached secure element provided by SEALSQ.

H.4.1 Wi-Fi Easy Connect Factory Provisioning Build Technologies

The general infrastructure for the Wi-Fi Easy Connect Factory Provisioning Build is provided by SEALSQ. The Wi-Fi Easy Connect Factory Provisioning Build infrastructure consists of:

- A SEALSQ VaultIC SE that is attached to the Raspberry Pi

- SEALSQ Factory Provisioning Code that is located on an SD card and that communicates with the chip in the SE to:
  - create a P-256 Elliptic Curve public/private key pair within the SE,
  - use the public key to construct a DPP URI
  - export the DPP URI and convert it into a QR code

Table H-3 lists the technologies used in the Wi-Fi Easy Connect Factory Provisioning Build. It lists the products used to instantiate each logical build component and the security function that the component provides. The components listed are logical. They may be combined in physical form, e.g., a single piece of hardware may both generate key pairs and provide secure storage.

Table H-3 Wi-Fi Easy Connect Factory Provisioning Build Products and Technologies

Component	Product	Function
Key Pair Generation Component	SEALSQ VaultIC and associated provisioning code	Generates and installs the public/private key pair into secure storage. The VaultIC has a SP800-90B certified random number generator for key pair generation. [17]
Secure Storage	SEALSQ VaultIC	Storage on the IoT device that is designed to be protected from unauthorized access and capable of detecting attempts to hack or modify its contents. Used to generate, store, and process private keys, credentials, and other information that must be kept confidential.
General Factory Provisioning Instructions	SEALSQ Factory Provisioning Code	Creates a public/private key pair.
Build-specific Factory Provisioning Instructions	Aruba/HPE Factory Provisioning Code	Uses the public key to create a DPP URI. Exports the DPP URI and converts it into a QR code.
Manufacturer Database	Manufacturer cloud or imprint on device	The DPP URI information is stored in the QR code and is the mechanism for conveying the device's bootstrapping information to the device owner.

H.4.2 Wi-Fi Easy Connect Factory Provisioning Build Logical Architecture

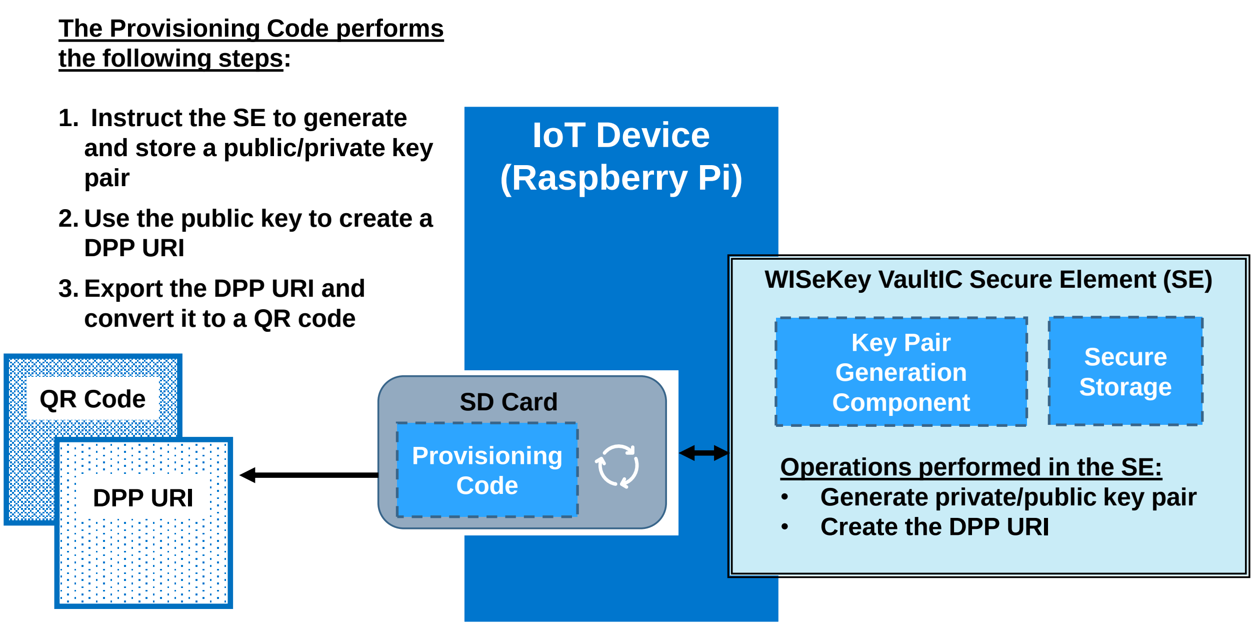
Figure H-3 depicts the logical architecture of the Wi-Fi Easy Connect factory provisioning build and is annotated with the steps that are performed in this build to prepare Raspberry Pi IoT devices for network-layer onboarding using the Wi-Fi Easy Connect protocol. Figure H-3 shows a Raspberry Pi device with a SEALSQ VaultIC SE attached. Factory provisioning code provided by SEALSQ and Aruba/HPE must also be loaded. In Figure H-3, this code is shown as being on an SD card. The factory provisioning software will boot up and perform the following steps to simulate the activities of a factory:

1. Instruct the SE to generate and store a private/public key pair
2. Use the public key to create a DPP URI

3. Export the DPP URI and convert it into a QR code

This completes the steps performed as part of the Wi-Fi Easy Connect Factory Provisioning Build. Once complete, shipment of the device to its owner can be simulated by walking the device across the room in the NCCoE laboratory to the Build 1 (Aruba/HPE) implementation. Build 1 uses the Wi-Fi Easy Connect protocol to network-layer onboard the device to the device owner's network by provisioning the device with connector that will serve as its network-layer credential. Successful network-layer onboarding of the newly provisioned device using the Wi-Fi Easy Connect protocol by Build 1 would serve to confirm that the Wi-Fi Easy Connect factory provisioning process correctly provisioned the device with its birth credentials. At the time of this writing, however, this confirmation process was not able to be performed. In order to securely network-layer onboard the newly provisioned Raspberry Pi using the Wi-Fi Easy Connect protocol, the Raspberry Pi would need to be equipped with a firmware image that uses the private key stored in the secure element when running the Wi-Fi Easy Connect protocol. Such firmware was not yet available at the time of this publication. The Wi-Fi Easy Connect code on the Raspberry Pi does not use the private key stored in the SE at this time. Confirmation that the factory build process completed successfully is limited to inspection of the .PNG file and .URI file that were created to display the QR Code and the device's DPP URI, respectively.

Figure H-3 Logical Architecture of the Wi-Fi Easy Connect Factory Provisioning Build



H.4.3 Wi-Fi Easy Connect Factory Provisioning Build Physical Architecture

Section 5.2.1 describes the physical architecture of the Factory Provisioning Build.

Appendix I References

[1] L. S. Vailshery, "Number of Internet of Things (IoT) connected devices worldwide from 2019 to 2023, with forecasts from 2022 to 2030," Statista, July 2023. Available: https://www.statista.com/statistics/1183457/iot-connected-devices-worldwide/.

[2] S. Symington, W. Polk, and M. Souppaya, *Trusted Internet of Things (IoT) Device Network-Layer Onboarding and Lifecycle Management (Draft)*, National Institute of Standards and Technology (NIST) Draft Cybersecurity White Paper, Gaithersburg, MD, Sept. 2020, 88 pp. https://doi.org/10.6028/NIST.CSWP.09082020-draft.

[3] E. Lear, R. Droms, and D. Romascanu, *Manufacturer Usage Description Specification,* IETF Request for Comments (RFC) 8520, March 2019. Available: https://tools.ietf.org/html/rfc8520.

[4] M. Souppaya et al, *Securing Small-Business and Home Internet of Things (IoT) Devices: Mitigating Network-Based Attacks Using Manufacturer Usage Description (MUD)*, National Institute of Standards and Technology (NIST) Special Publication (SP) 1800-15, Gaithersburg, Md., May 2021, 438 pp. Available: https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1800-15.pdf.

[5] "National Cybersecurity Center of Excellence (NCCoE) Trusted Internet of Things (IoT) Device Network-Layer Onboarding and Lifecycle Management," Federal Register Vol. 86, No. 204, October 26, 2021, pp. 59149-59152. Available: https://www.federalregister.gov/documents/2021/10/26/2021-23293/national-cybersecurity-center-of-excellence-nccoe-trusted-internet-of-things-iot-device.

[6] Wi-Fi Alliance, *Wi-Fi Easy Connect™ Specification Version 3.0*, 2022. Available: https://www.wi-fi.org/system/files/Wi-Fi_Easy_Connect_Specification_v3.0.pdf.

[7] M. Pritikin, M. Richardson, T.T.E. Eckert, M.H. Behringer, and K.W. Watsen, *Bootstrapping Remote Secure Key Infrastructure (BRSKI)*, IETF Request for Comments (RFC) 8995, October 2021. Available: https://datatracker.ietf.org/doc/rfc8995/.

[8] Thread 1.1.1 Specification, February 13, 2017.

[9] OpenThread Released by Google. Available: https://openthread.io/.

[10] O. Friel, E. Lear, M. Pritikin, and M. Richardson, *BRSKI over IEEE 802.11*, IETF Internet-Draft (Individual), July 2018. Available: https://datatracker.ietf.org/doc/draft-friel-brski-over-802dot11/01/.

[11] NIST. *The NIST Cybersecurity Framework (CSF) 2.0*. Available: https://doi.org/10.6028/NIST.CSWP.29.

[12] *IEEE Standard for Local and Metropolitan Area Networks - Secure Device Identity*, IEEE Std 802.1AR-2018 (Revision of IEEE Std 802.1AR-2009), 2 Aug. 2018, 73 pp. Available: https://ieeexplore.ieee.org/document/8423794.

[13] F. Stajano and R. Anderson, *The Resurrecting Duckling: Security Issues for Ad-hoc Wireless Networks*, B. Christianson, B. Crispo and M. Roe (Eds.). Security Protocols, 7th International Workshop Proceedings, Lecture Notes in Computer Science, 1999. Springer-Verlag Berlin Heidelberg 1999. Available: https://www.cl.cam.ac.uk/~fms27/papers/1999-StajanoAnd-duckling.pdf.

[14] M. Richardson, *A Taxonomy of operational security considerations for manufacturer installed keys and Trust Anchors*, IETF Internet-Draft (Individual), November 2022. Available: https://datatracker.ietf.org/doc/draft-richardson-t2trg-idevid-considerations/.

[15] Certificate #4302, Cryptographic Module Validation Program, NIST Computer Security Resource Center. Available: https://csrc.nist.gov/projects/cryptographic-module-validation-program/certificate/4302.

[16] Certificate #4303, Cryptographic Module Validation Program, NIST Computer Security Resource Center. Available: https://csrc.nist.gov/projects/cryptographic-module-validation-program/certificate/4303.

[17] Entropy Certificate #E2, Cryptographic Module Validation Program, NIST Computer Security Resource Center. Available: https://csrc.nist.gov/projects/cryptographic-module-validation-program/entropy-validations/certificate/2.

NIST SPECIAL PUBLICATION 1800-36C

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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May 2024

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The National Cybersecurity Center of Excellence (NCCoE), a part of the National Institute of Standards and Technology (NIST), is a collaborative hub where industry organizations, government agencies, and academic institutions work together to address businesses' most pressing cybersecurity issues. This public-private partnership enables the creation of practical cybersecurity solutions for specific industries, as well as for broad, cross-sector technology challenges. Through consortia under Cooperative Research and Development Agreements (CRADAs), including technology partners—from Fortune 50 market leaders to smaller companies specializing in information technology security—the NCCoE applies standards and best practices to develop modular, adaptable example cybersecurity solutions using commercially available technology. The NCCoE documents these example solutions in the NIST Special Publication 1800 series, which maps capabilities to the NIST Cybersecurity Framework and details the steps needed for another entity to re-create the example solution. The NCCoE was established in 2012 by NIST in partnership with the State of Maryland and Montgomery County, Maryland.

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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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Mike Dow	Silicon Labs
Steve Egerter	Silicon Labs

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
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Contents

List of Figures

1 Introduction

The following volumes of this guide 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. Rather, these 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 and 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.

NIST is adopting an agile process to publish this content. Each volume is being made available as soon as possible rather than delaying release until all volumes are completed.

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 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 or security 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 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. Finally, *NIST SP 1800-36E* will be helpful in explaining 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 that 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 welcome your input. Comments, suggestions, and success stories will improve subsequent versions of this guide. 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 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 that will serve as examples of how to onboard IoT devices using the protocols described in NIST SP 1800-36B, as well as the factory provisioning builds, are being implemented and will be demonstrated as part of this project. 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 that is 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*.

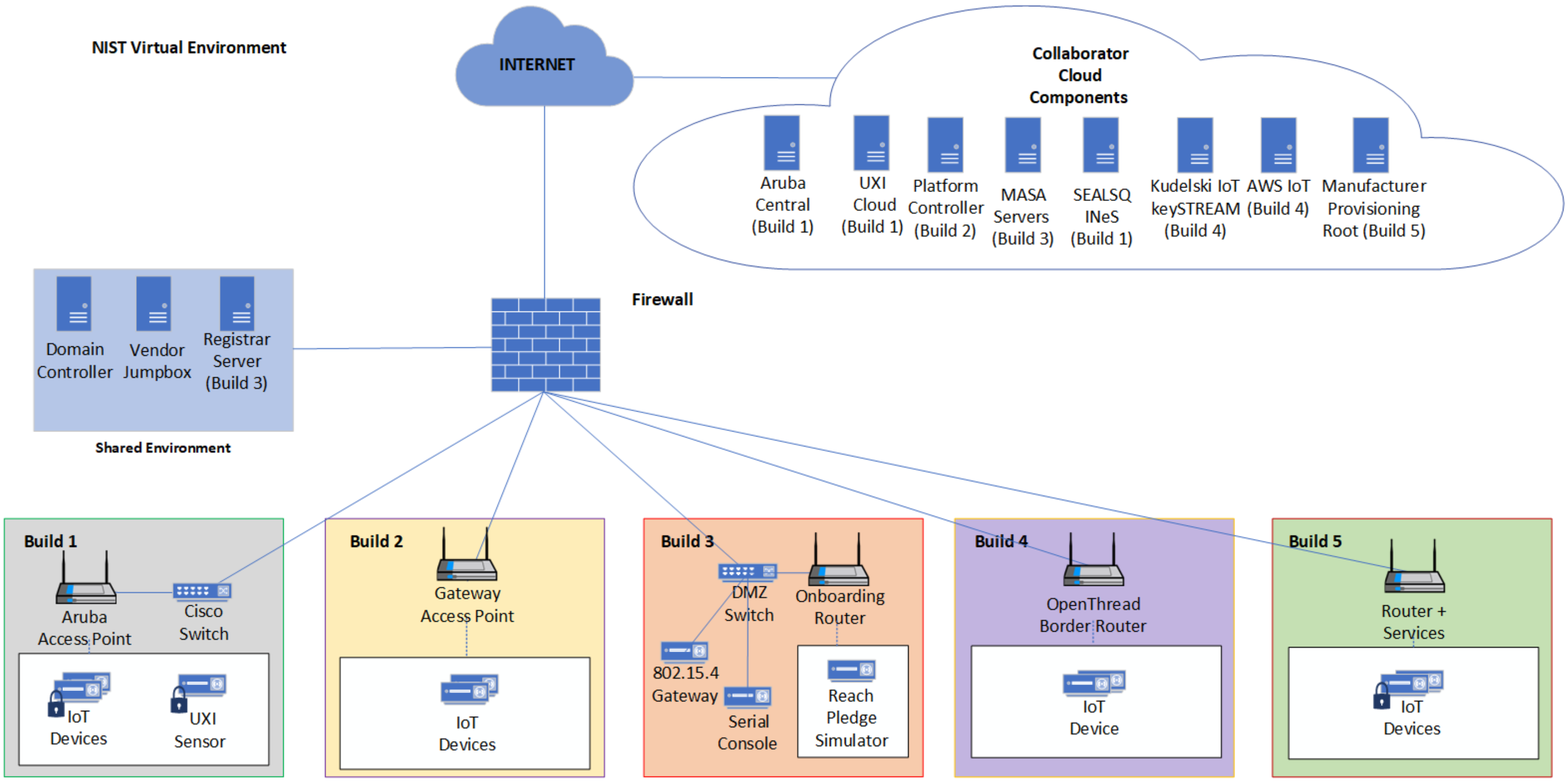
1.2.2 Physical Architecture Summary

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 are being 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.

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 MASA server (Build 3), Kudelski IoT keySTREAM application-layer onboarding service and AWS IoT (Build 4), and a Manufacturer Provisioning Root (Build 5).

300 **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 that are 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 which 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, 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 that is onboarded in Build 4 is the Silicon Labs Dev Kit (BRD2601A) with an EFR32MG24 System-on-Chip. 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 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 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 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. As AP only, referred to as an *underlay deployment,* where traffic is bridged locally from the APs.

2. An *overlay deployment,* where all data is securely tunneled to an on-prem gateway where advanced services can route, inspect, and analyze the data before it's either bridged locally or routed to its next hop.

3. A *mixed-mode deployment,* which is a combination of the two where a returned 'role/label' is used to determine how the data is processed and forwarded.

At the time of this publication, a user can leverage any 3xx, 5xx, or 6xx APs to support a DPP deployment, with a view that all future series APs will implicitly include support. For an existing or new user there is a prerequisite of the creation of a Service Set Identifier (SSID). Note that DPP today is not supported under Wi-Fi Protected Access 3 (WPA3); this is a roadmap item with no published timeline.

Assuming there is an existing SSID or a new one is created based upon the above security restrictions, the next step is to enable DPP (as detailed below in Section 2.2.1) such that the SSID can support multiple authentication and key managements (AKMs) 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.

Within this document, we do not cover the specifics of radio frequency (RF) design and placement of APs. Guidance and assistance is available within the Aruba community site, https://community.arubanetworks.com or the Aruba Support Portal, https://asp.arubanetworks.com. Additionally, we do not cover 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), it will default on the slide-bar 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**, and 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. It's expected you'll see a **default** radio-profile. If a custom one has been created, you'll 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. Support for DPP on 6.0 GHz is a roadmap item at this time and is not yet available.

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. This switch utilized a minimal configuration 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 network-layer onboarding process is automatically initiated by the device 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. This public/private keypair for each device is created as part of the manufacturing process. The public key effectively identifiers the sensor to the network and as 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 onboard with the Aruba AP.

2.5.1 Configuration

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

1. Set the management IP for the Raspberry Pi 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

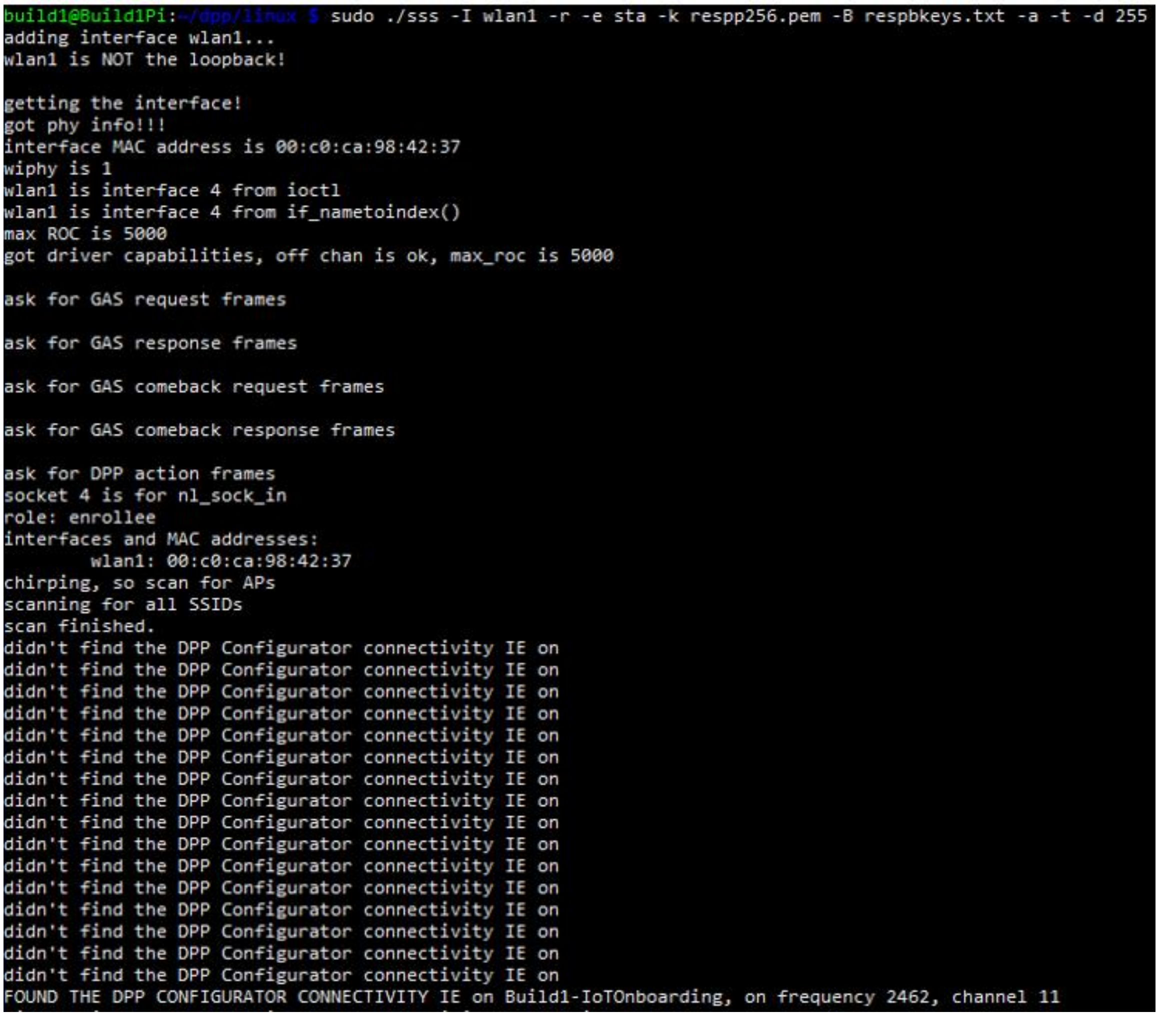
This section describes the steps for using the Raspberry Pi as a DPP enrollee. The Pi uses a DPP utility to send out chirps to make its presence known to available DPP configurators. Once the Pi is discovered, the DPP configurator (Aruba Wireless AP) initiates the DPP authentication protocol. During 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 which 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
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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.

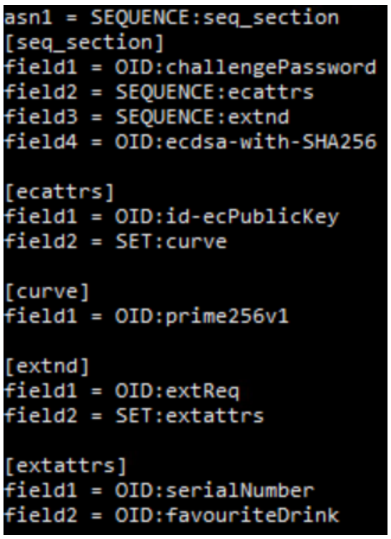
3. Configure the file *configakm* located in *~/dpp/linux/*. This file instructs the configurator on how to deploy a DPP connector (network credential) from the configurator to the enrollee. As shown below, the *configakm* file is filled with the following fields:
   `dpp unused Build1-IoTOnboarding`.

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
```



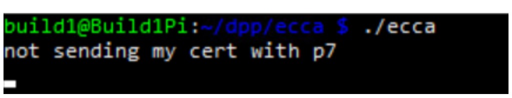
```
asn1 = SEQUENCE:seq_section
[seq_section]
field1 = OID:challengePassword
field2 = SEQUENCE:ecattrs
field3 = SEQUENCE:extnd
field4 = OID:ecdsa-with-SHA256

[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:

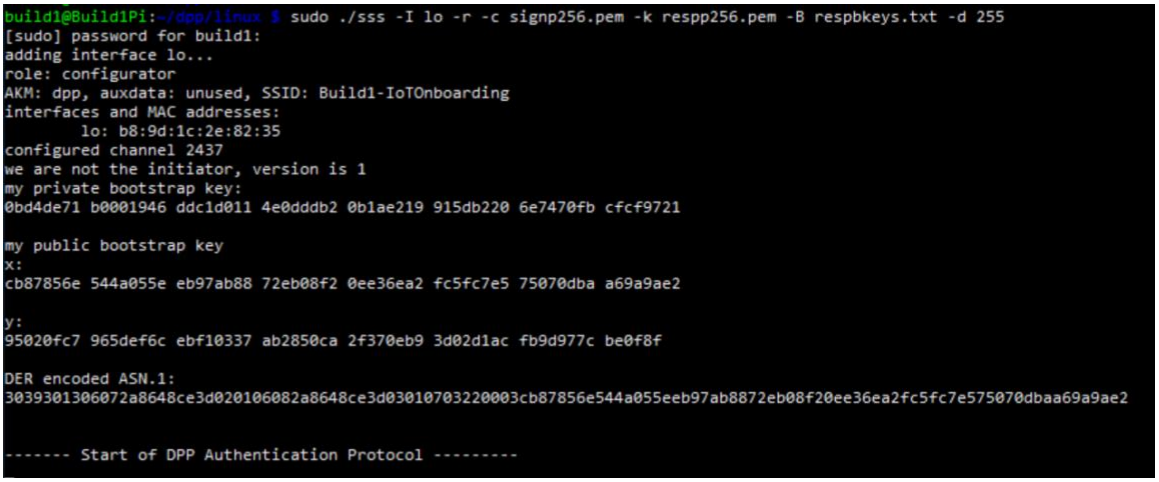
   ```
   ./ecca.
   ```

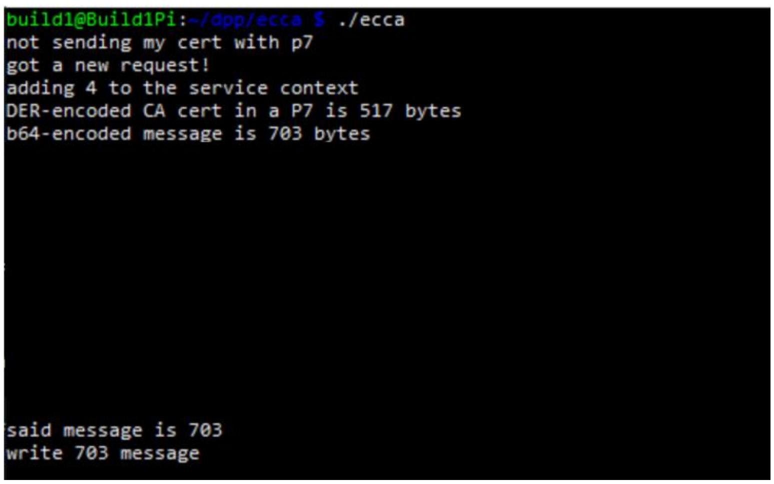
   ```
   build1@Build1Pi:~/dpp/ecca $ ./ecca
   not sending my cert with p7
   ```

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
   ```



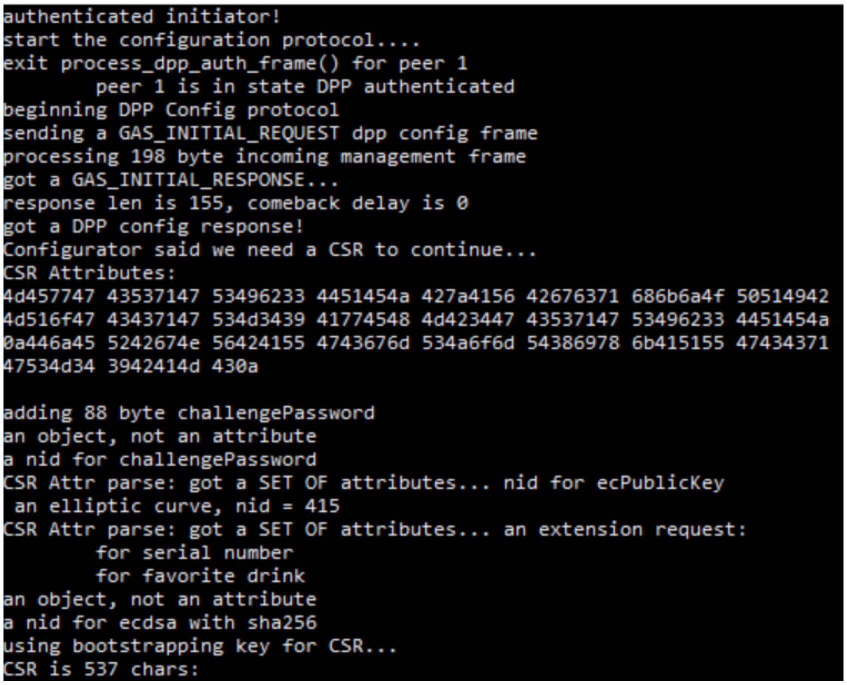
As shown in the terminal where the ecca program is running, the configurator contacts the CA and asks for the certificate.



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

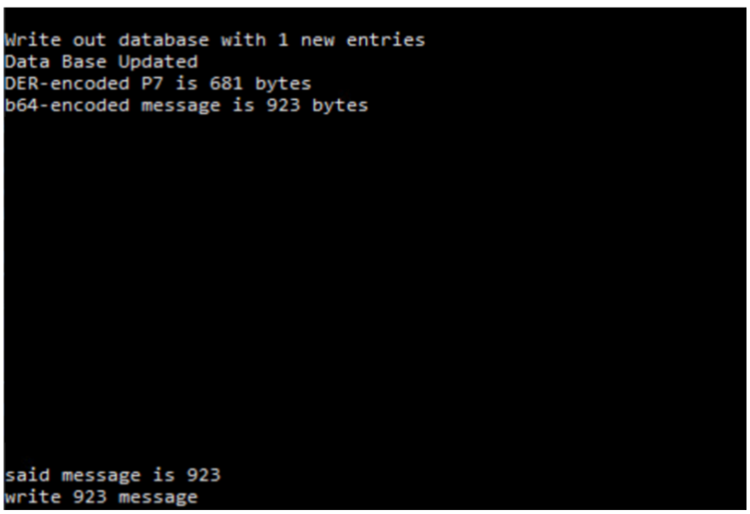
```
sudo ./sss -I lo -r -e sta -k initp256.pem -B initbkeys.txt -t -a -q -d 255
```

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 performance monitoring that the UXI sensor conducts. 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 application-layer onboarding was completed and the application configuration had been 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 keypair 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 at 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 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 with 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 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.

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 integration with third-party systems for the purpose of integrating various business flows (e.g., integration with 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 web interface. Additional information for this deployment can be accessed at the official CableLabs repository.

3.1.1 Operation and Demonstration

Once configuration of the Platform Controller, Gateway, and Reference Client has been completed, full operation can commence. Instructions for this are located at the official CableLabs repository.

3.2 CableLabs Custom Connectivity Gateway

In this deployment, the gateway software is running 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 configuration and functions of the gateway. 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 initial configuration has occurred, the gateway can be integrated with the CableLabs Platform Controller. Instructions can be found at the official CableLabs repository.

3.2.3 Operation and Demonstration

Once configuration of the Platform Controller, Gateway, and Reference Client has been completed, full operation can commence. 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

Once configuration of the Platform Controller, Gateway, and Reference Client has been completed, full operation can commence. 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 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 to function 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 purpose of the Join Registrar is to determine 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 at the Minerva fountain page. Further setup and configuration instructions are available on the Sandelman website on the configuration page.

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 https interface
- Configure certificates for use with the Bucardo database replication system
- Configure certificates for 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 upon the PID of the script).

4.3 Reach Pledge Simulator

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

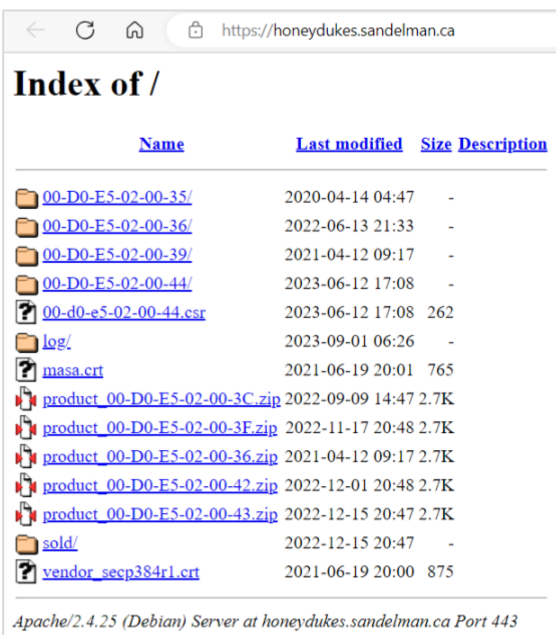
4.3.1 Setup and Configuration

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

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

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
```

```
nccoe@satine:~$ ls
bin  minerva  reach
nccoe@satine:~$ cd reach
nccoe@satine:~/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 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 implementation of the build, the MASA server provides the Reach Pledge Simulator with an IDevID Certificate and a public/private keypair 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 at the Highway configuration page. Additional configuration details are available at the Highway development page.

Availability of VMs and containers is described at the following 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

The Open Thread Border Router forms the Thread network and acts as the router on this build. The Open Thread Border Router 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 Open Thread Border Router 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
```

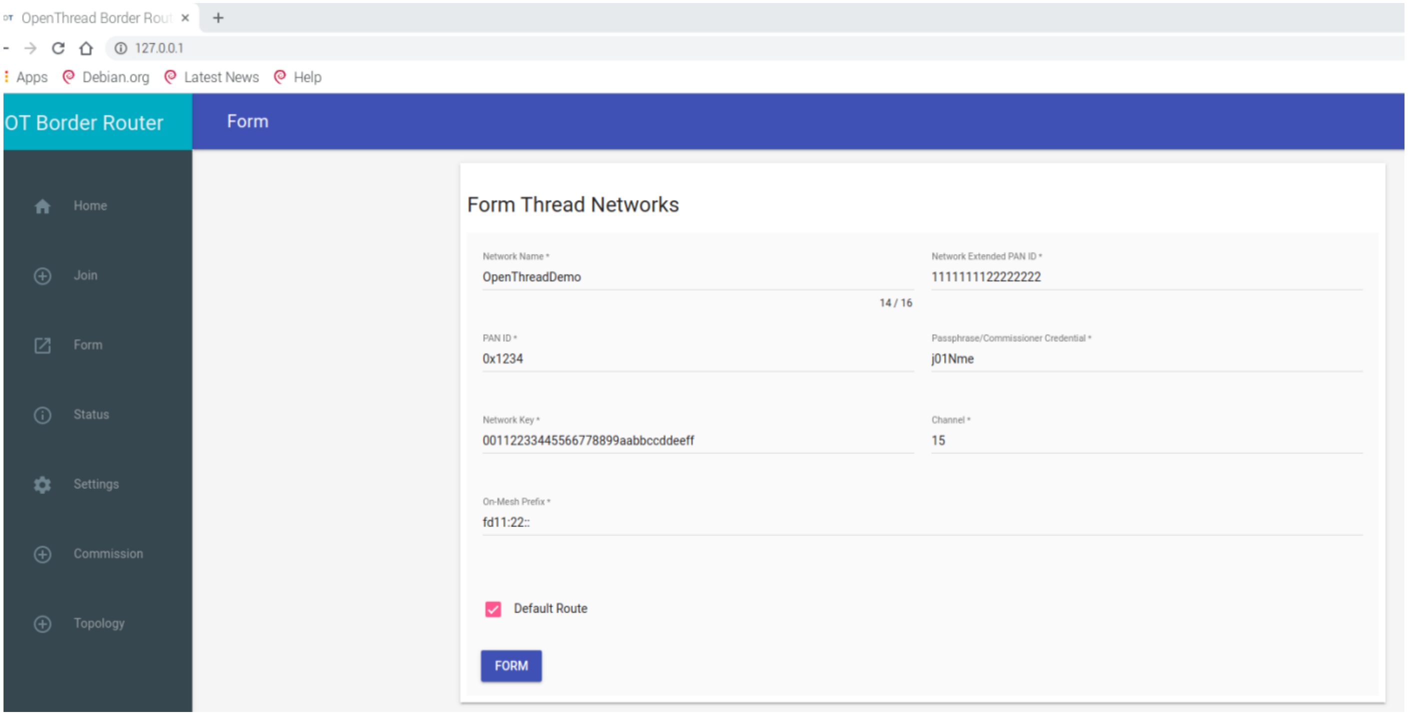
5.1.2 Operation and Demonstration

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

1. To open the OpenThread Border Router 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.



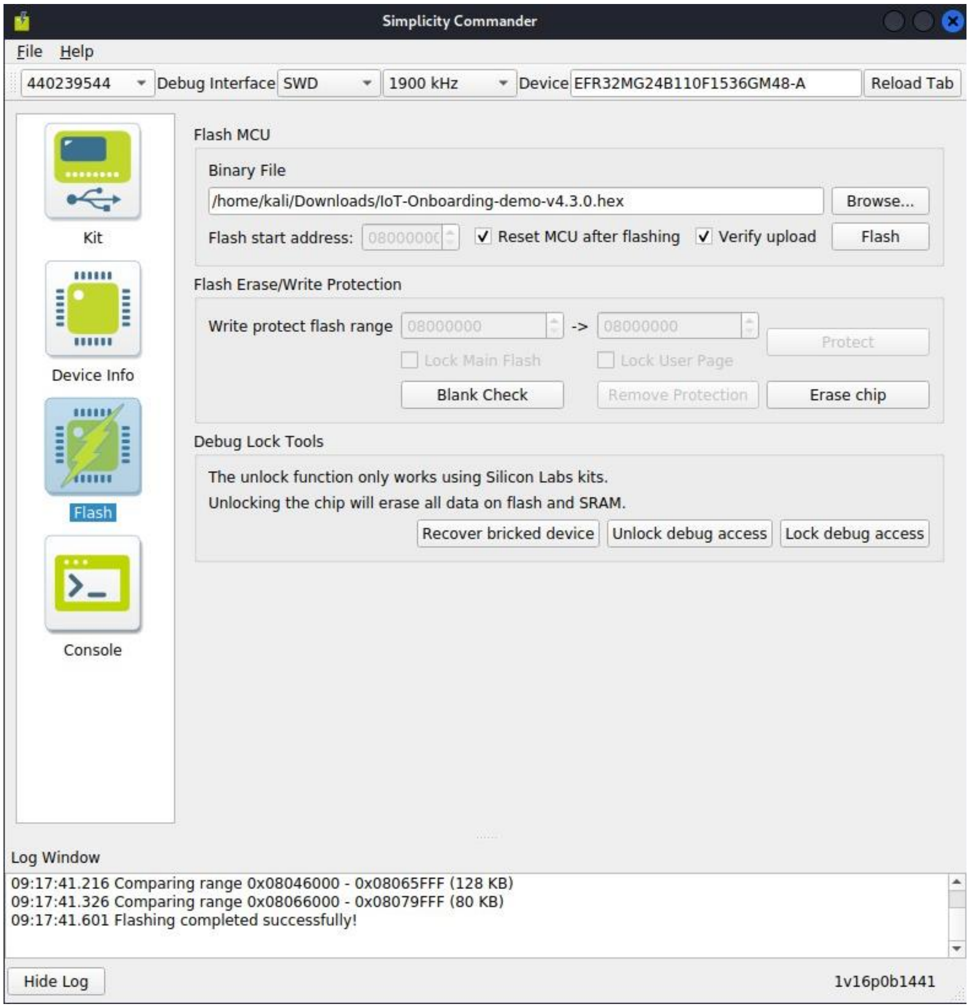
5.2 Silicon Labs Dev Kit (BRD2601A)

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. Custom firmware for the Dev Kit leveraged in this use case was made by Silicon Labs.

5.2.1 Setup and Configuration

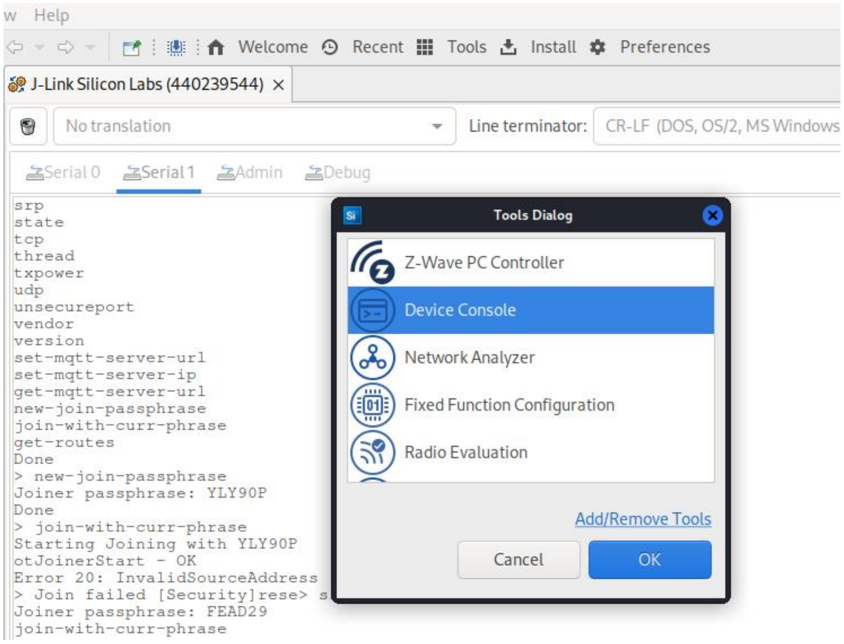
The Dev Kit custom firmware image works in conjunction with the Kudelski keySTREAM service. More information is available by contacting Silicon Labs through their contact form. Once the custom firmware has been acquired the Dev Kit can be configured using the following steps.

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 the Dev Kit.

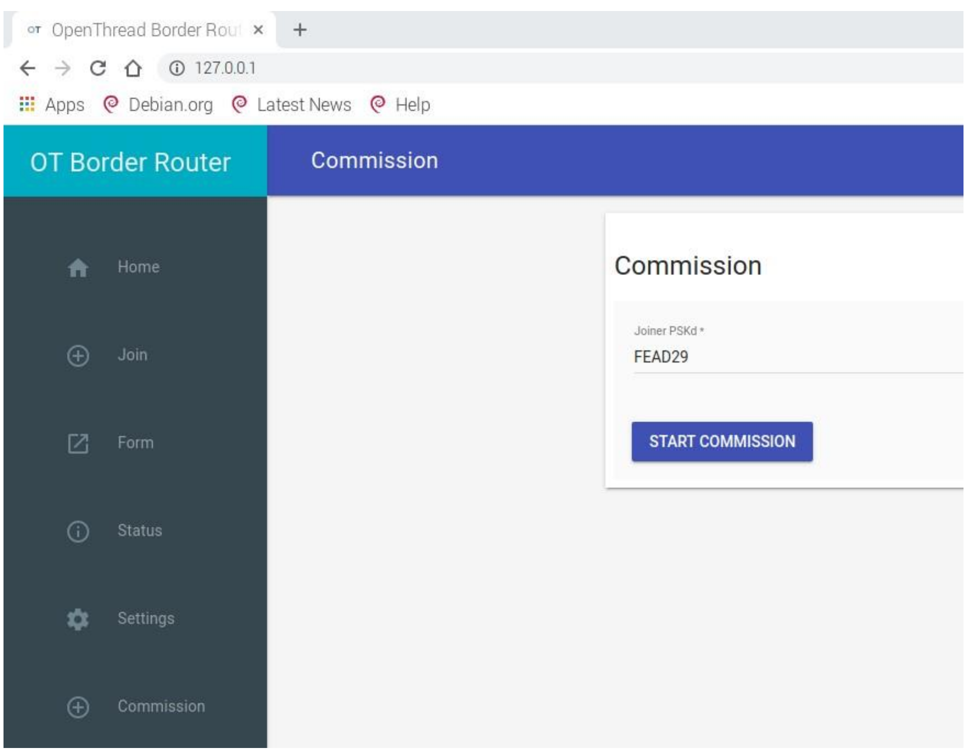
3. Open the device console in the **Tools** tab and then select the **Serial 1** tab.



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 OpenThread Border Router 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
```

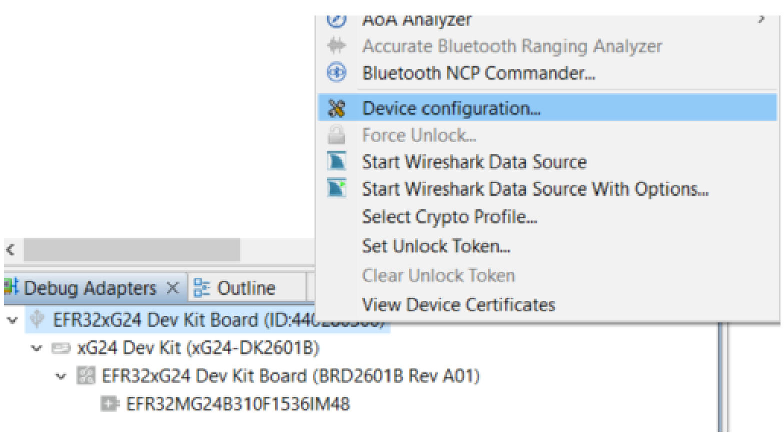
5.3 Kudelski keySTREAM Service

In this section we describe the Kudelski keySTREAM service which this build utilizes to provision certificates for connecting to the AWS IoT core. More information on keySTREAM is available at the keySTREAM page.

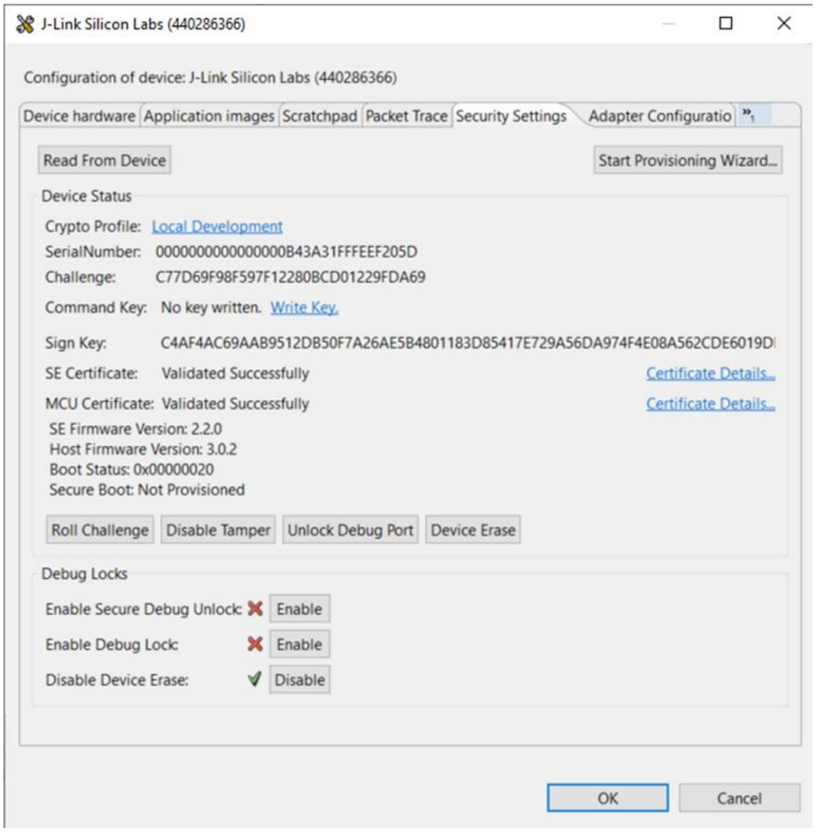
5.3.1 Setup and Configuration

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

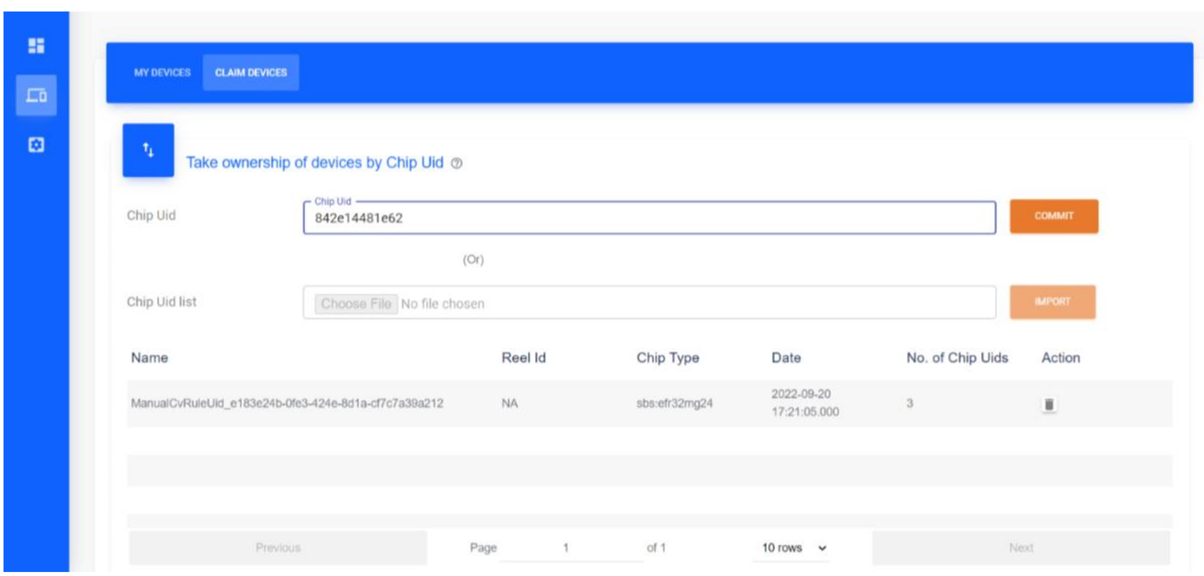
1. Locate the Chip UID for the Silicon Labs Dev Kit in Simplicity Studio by right clicking on the **Device Adapters** tab at the bottom and selecting **Device Configuration**.



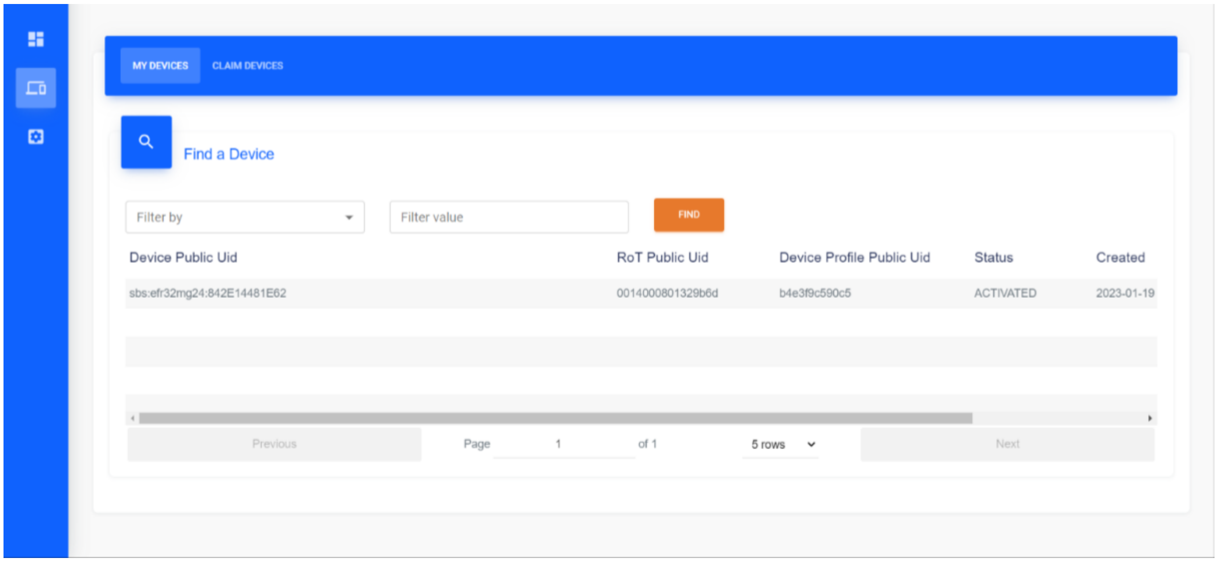
2. On the **Security Settings** tab, take the last 16 characters of the serial number and remove the 'FFFE' characters from the 7th – 11th positions.



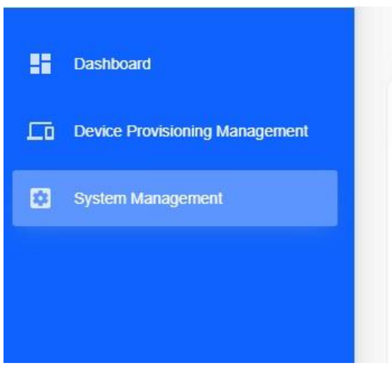
3. In the Kudelski keySTREAM service, claim your device by entering the chip UID from Simplicity Studio and clicking **Commit**.



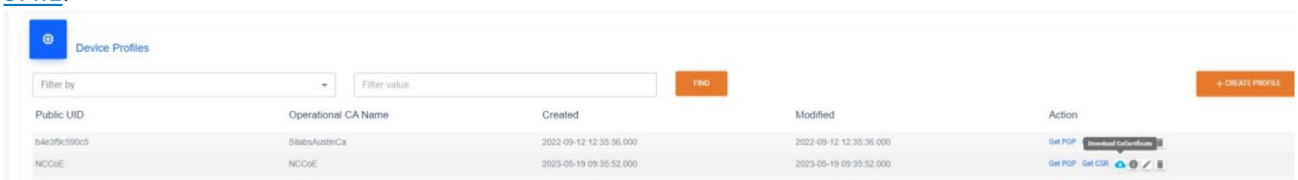
4. The device will now be visible in the **My Devices** tab. A device can be removed from the keySTREAM service by scrolling to the right and clicking the **Refurbish** button.



5. Open the **System Management** tab on the left side:



6. Click the cloud icon to download the CA Certificate and the POP certificate, the POP certificate will require a code that is obtained from the AWS IoT Core which will be generated in [Section 5.4.1](#).



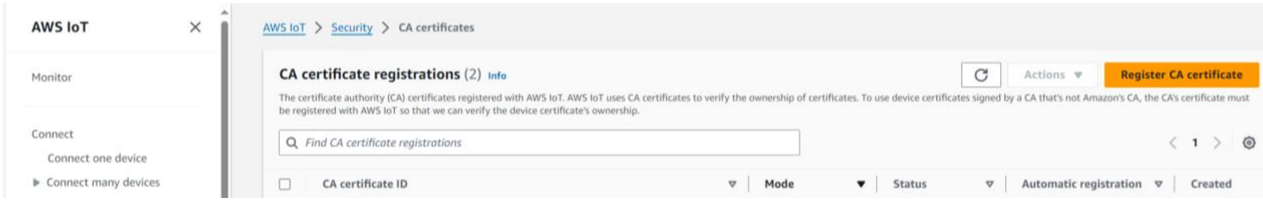
5.4 AWS IoT Core

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

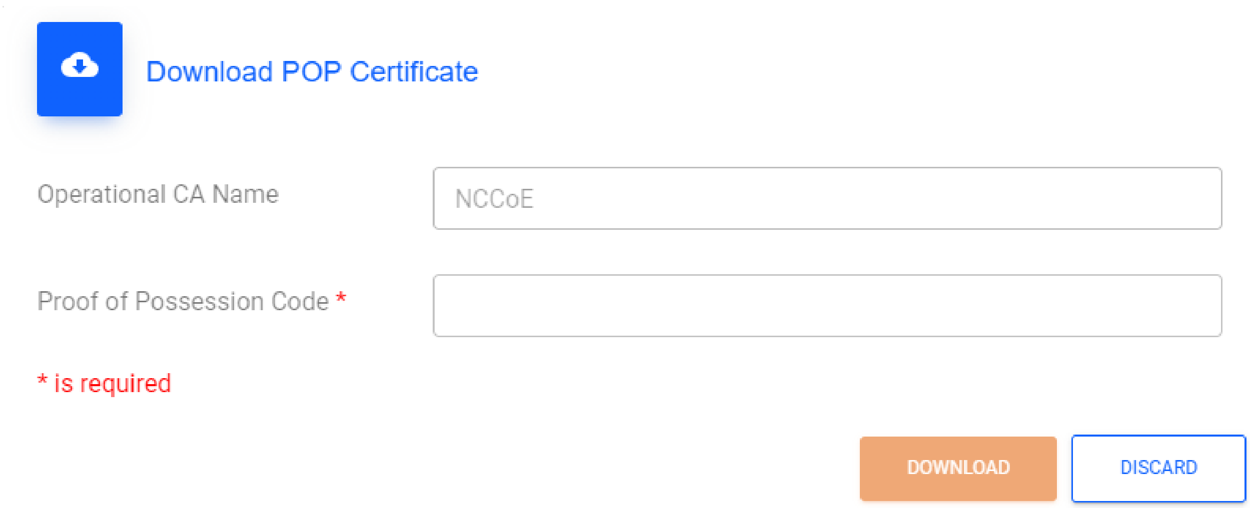
5.4.1 Setup and Configuration

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 and the device will demonstrate its ability to successfully send a message to AWS.

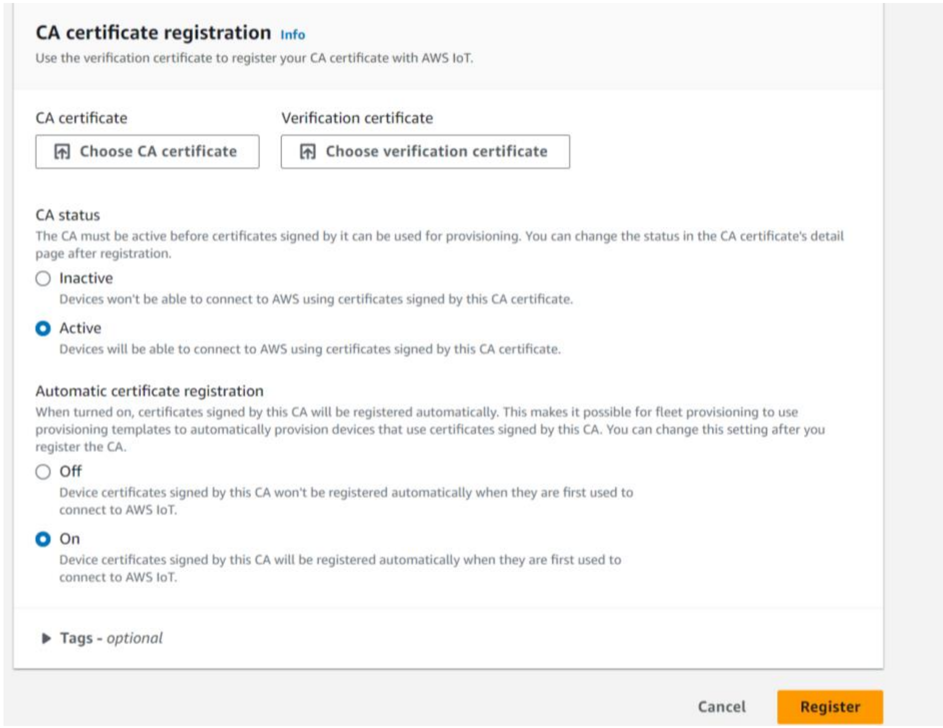
1. Within the AWS IoT Core, open the **Security** drop-down menu, click on **Certificate authorities**, and click the **Register CA certificate** button on the right.



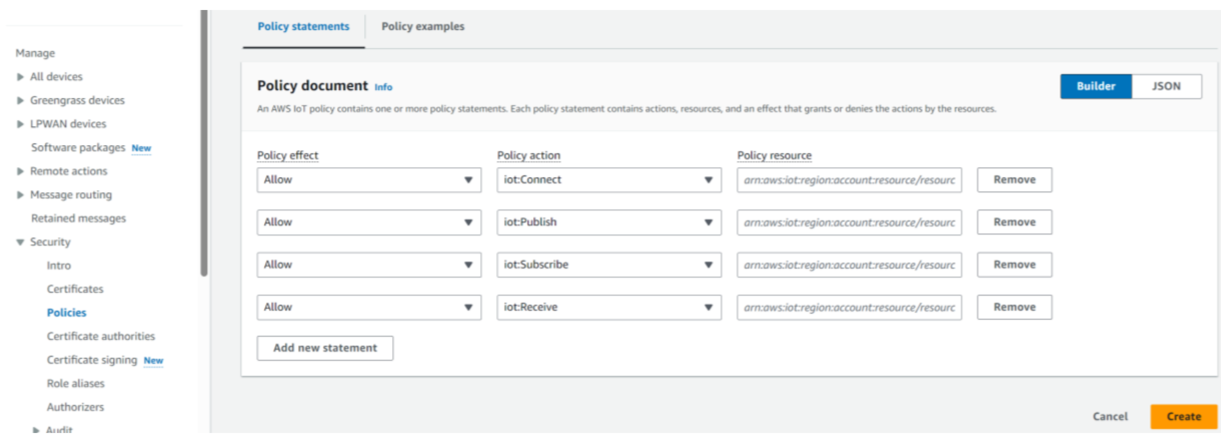
2. Select the radio button for **Register CA in Single-account mode** and copy the registration code to use as the **Proof of Possession Code** in the Kudelski keySTREAM service and download the POP certificate.



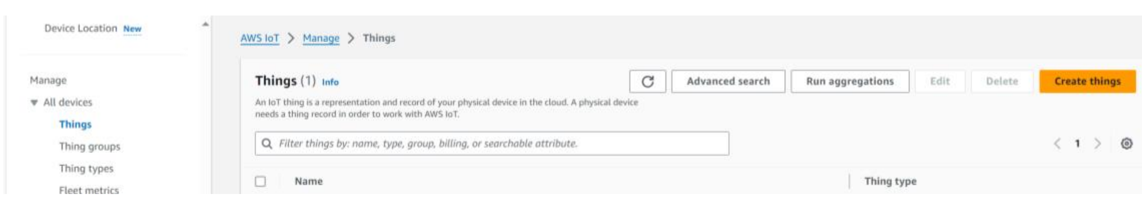
3. After downloading the POP certificate, upload the CA certificate and the POP (verification) certificate, and select the radio buttons for **Active** under **CA Status** and **On** under **Automatic Certificate Registration**. Then click **Register**.



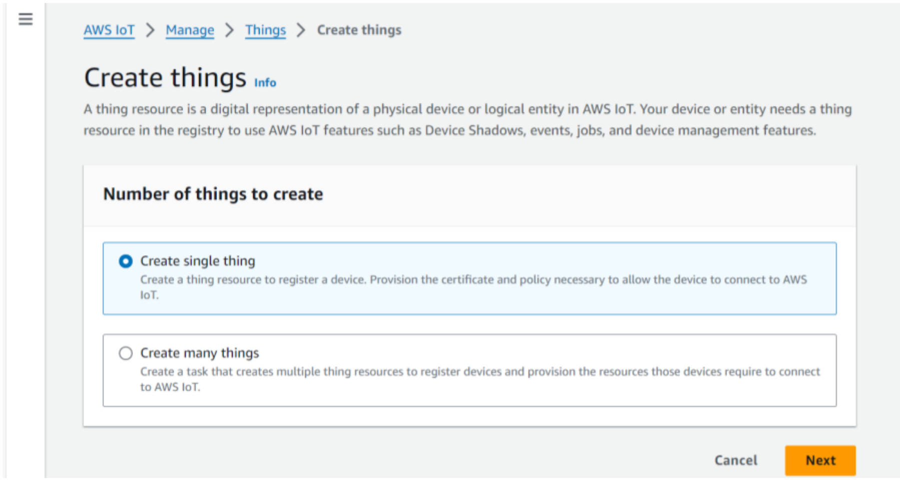
4. In the **Security** drop down menu, click on **Policies** and add the policies shown below. Then, click **Create**.



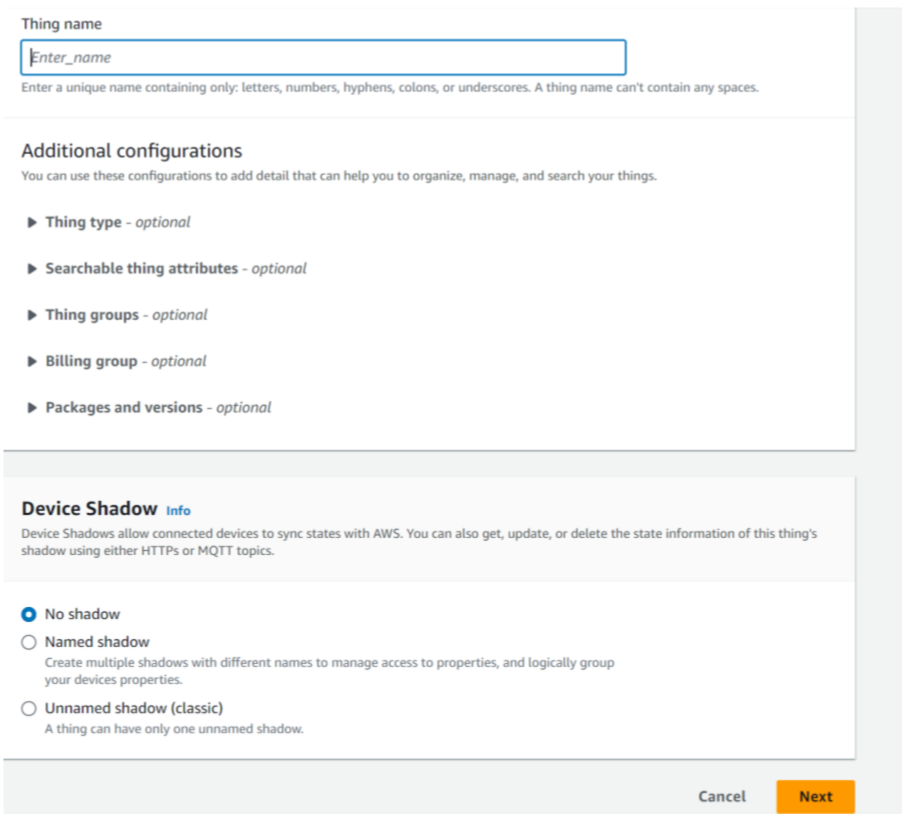
5. In the **All devices** drop-down menu, click on **Things** and click **Create things**.



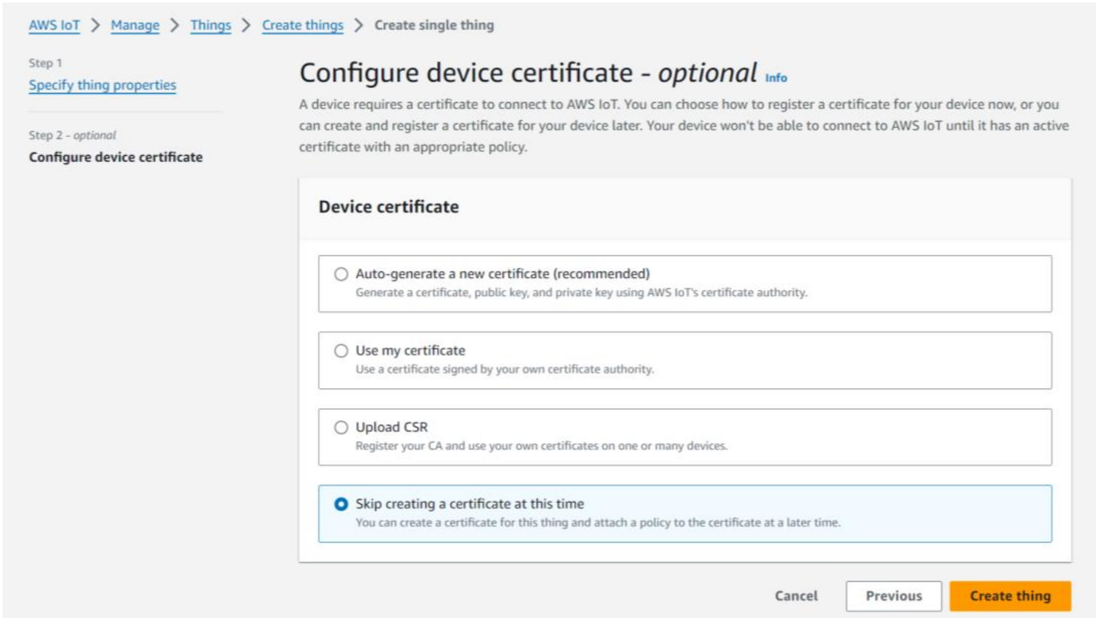
6. Click the **Create single thing** radio button and click **Next**.



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

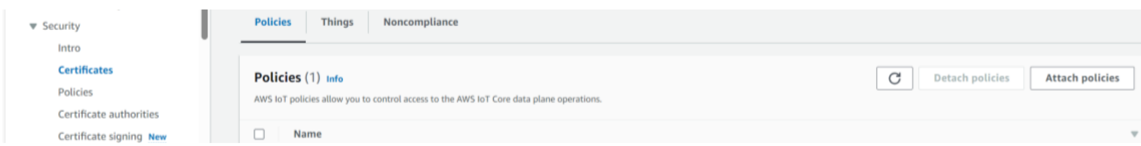


8. Select the **Skip creating a certificate at this time** radio button and click **Create thing**.

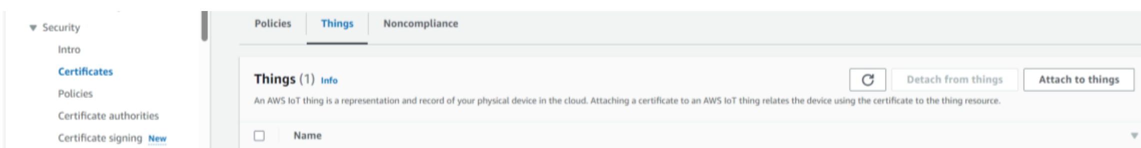


9. In the **Security** drop-down menu, click on **Certificates** and click the Certificate ID of the certificate that you created.

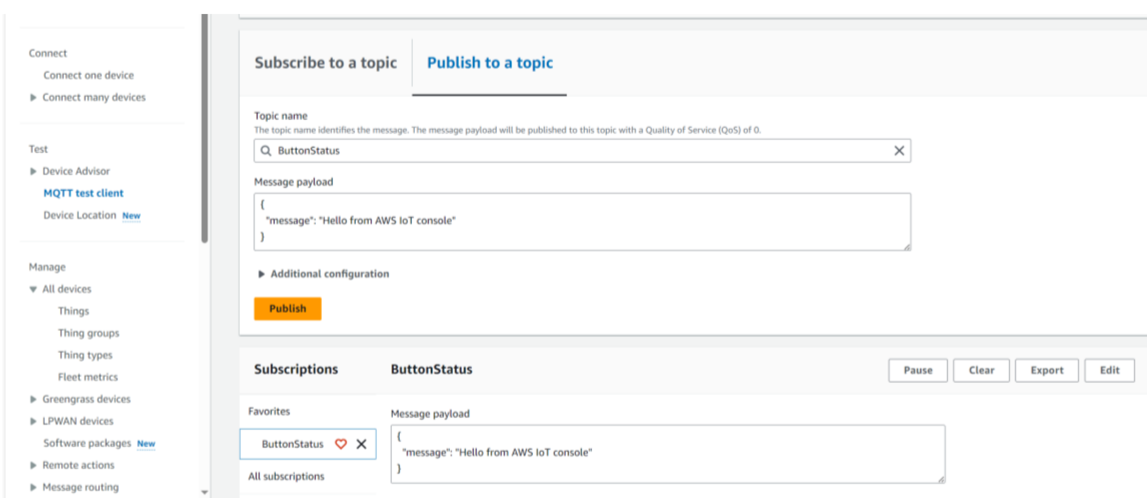
10. In the **Policies** tab at the bottom, click **Attach policies** and add the policy that you created.



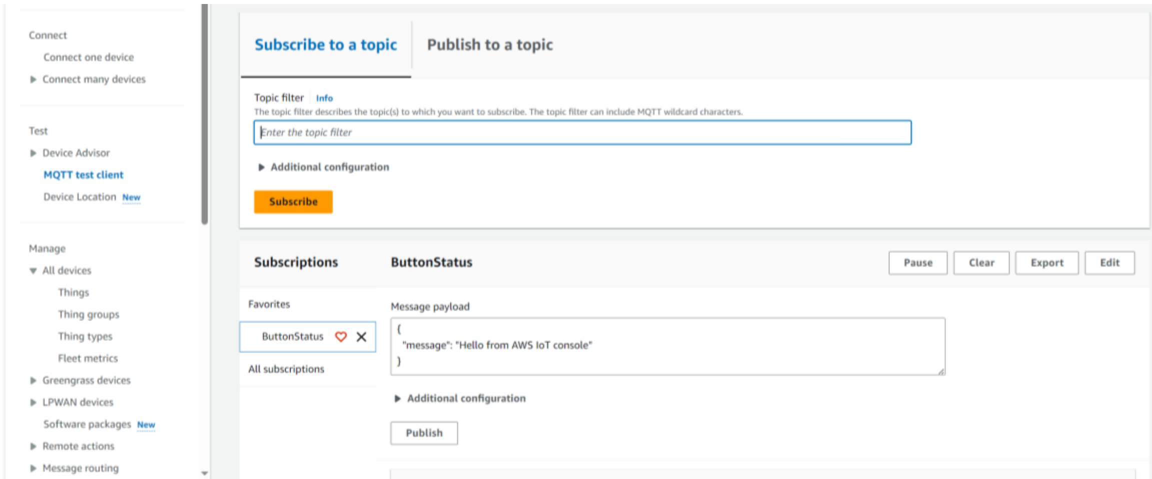
11. In the **Things** tab, click **Attach to things** and add the thing that you created.



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



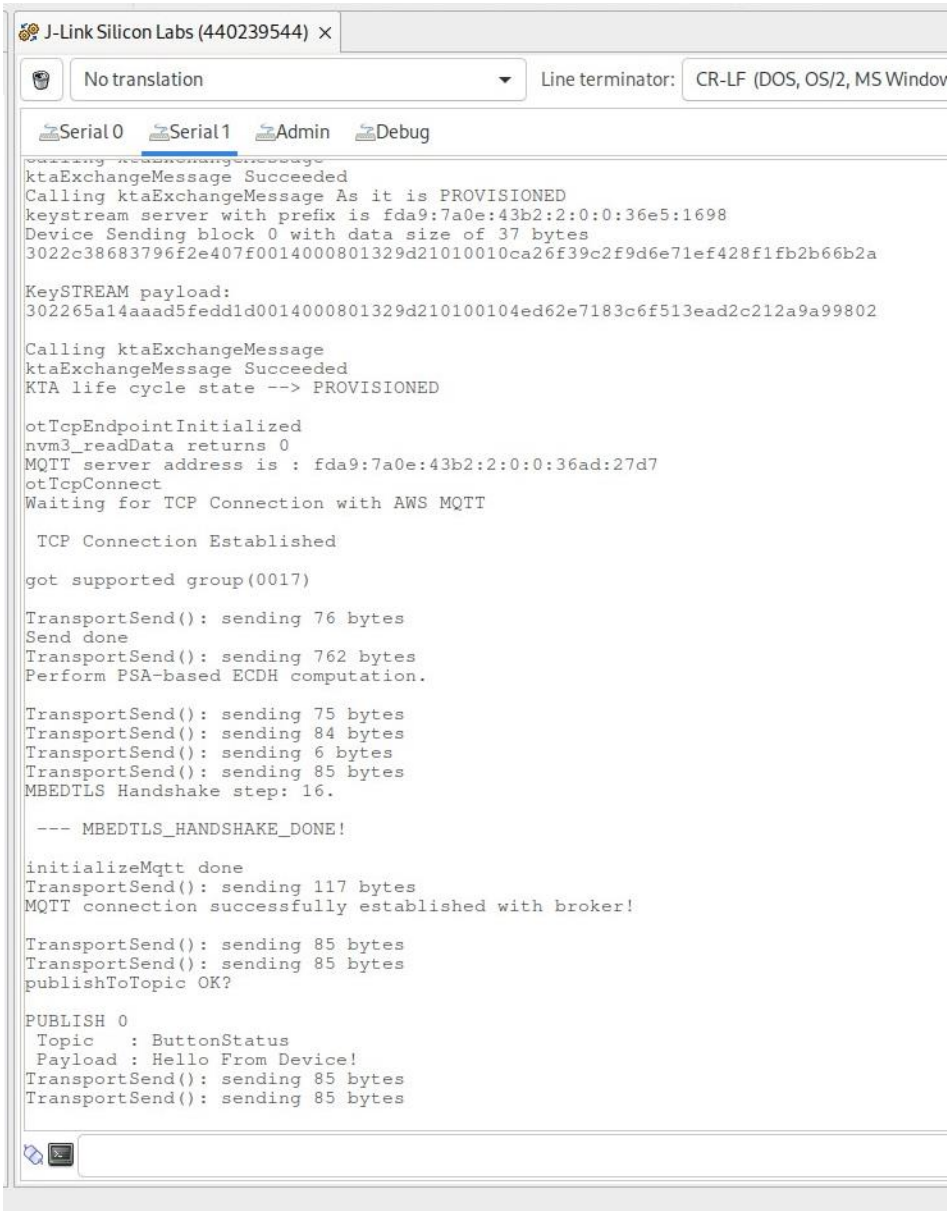
13. Create a message of your choosing and click **Publish**. On the **Subscribe to a topic** tab, make sure that you are subscribed to the topic that you just created.



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.



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

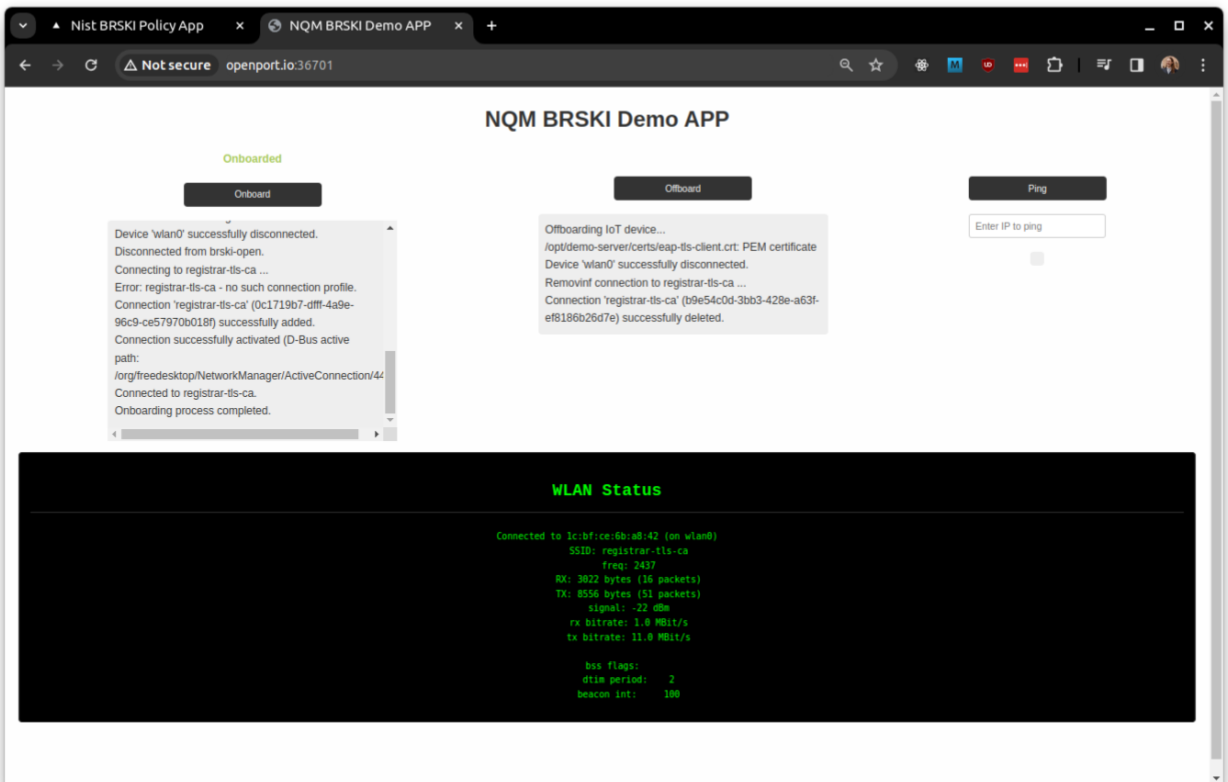
The Pledge acts as the IoT device which is attempted to onboard onto the secure network. It implements the pledge functionality as per the IETF BRSKI specification. It consists of software provided by NquiringMinds running on a Raspberry Pi Model 4B.

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 which runs on the pledge device. It features a button one can use 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, which is configured to ping the designated address via the wireless network interface.



6.2 Router and Logical Services

The router and logical services were hosted on a Raspberry Pi Model 4B equipped with 2 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:

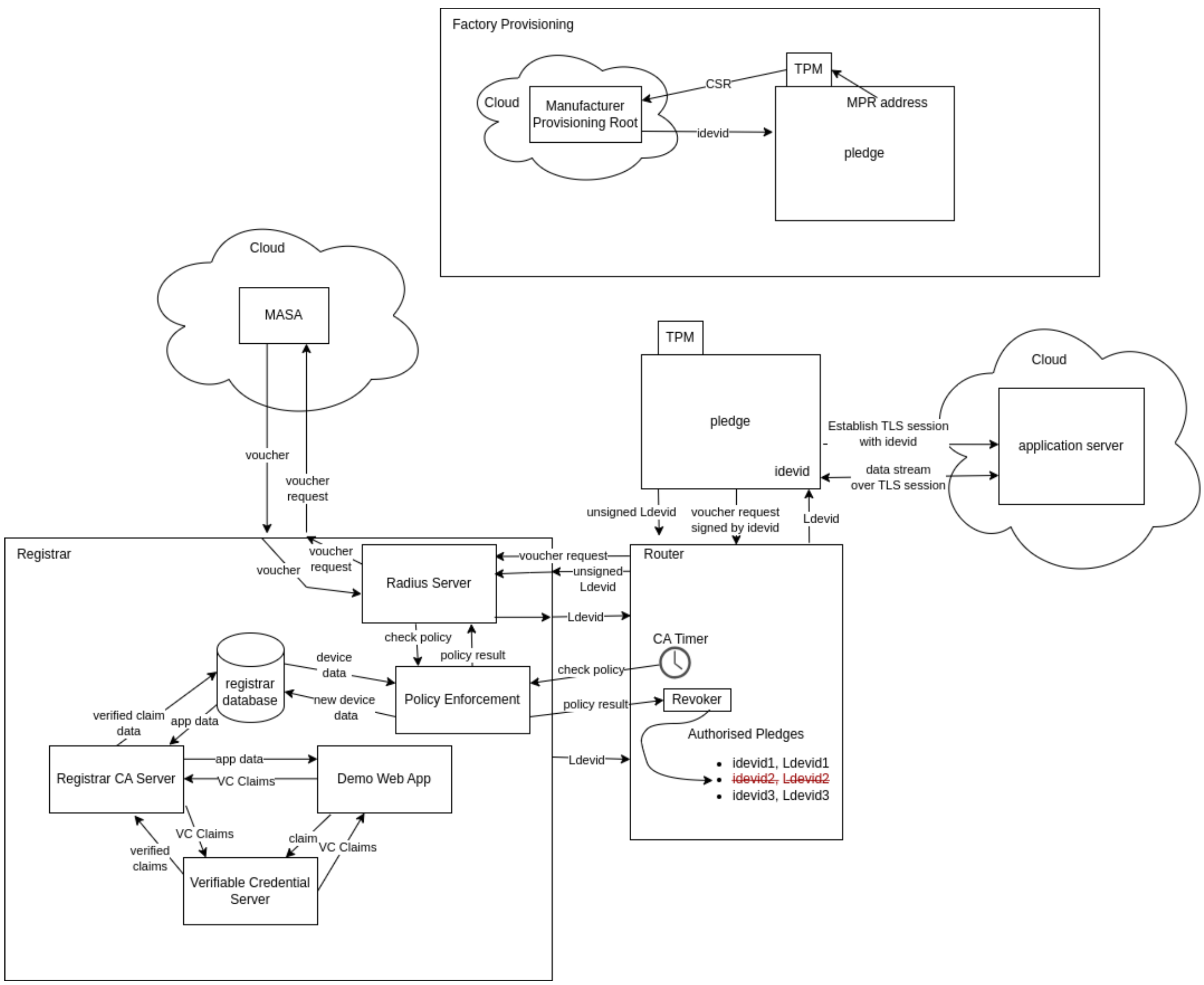
- BRSKI Demo Setup
- EAP Config
- MDNS publishing services

6.2.2 Logical services

The following logical services are installed on the Registrar and services device. The implementation of these services are to be found at the following repository links: NIST BRSKI implementation and BRSKI.

Figure 6-1 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 6-1 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 IDevID was produced by the manufacturer's MPR.

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 it after production and notarize it with a unique identity. The address of the MPR is built into the firmware of the device 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 its database used to determine if the policy is met, the tdx Volt is used to facilitate signing and verification of verifiable credentials. In the demonstrator system the MASA and router are integrated into the same physical device.

6.2.2.3.1 Radius server (Continuous Assurance Client)

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

The continuous assurance policy is enforced by a script which periodically runs to check that 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
- The vulnerability score of the SBOM for the device type must be lower than 6
- The device must not have contacted a denylisted IP address within the last 2 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 verifiable credentials submitted through the Demo web app and verify verifiable credentials submitted to the registrar, it is powered by the functionality of the tdx Volt, a local instance of which is run 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

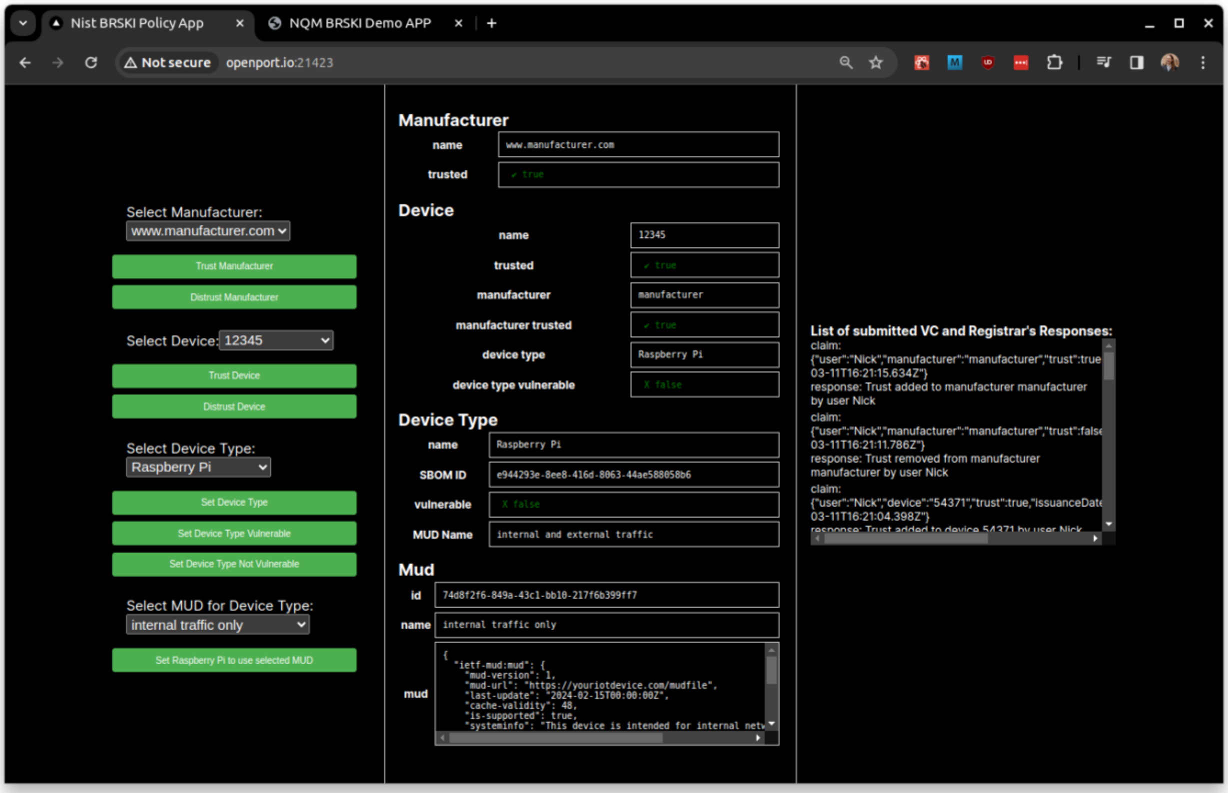
The registrar hosts a REST API which is used to interface with the registrar's SQLite database which stores information about the entities the registrar knows of. This server utilizes the verifiable credential server to verify submitted verifiable credential claims submitted to it.

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 which 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 or not and set the MUD file associated with the device type. All of 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.



6.2.2.5 Application server

The application server sits on a remote server and represents the server for an application which should consume data from the pledge device. The pledge device uses the IDevID certificate to establish a secure TLS connection to onboard onto the application server and begin sending data autonomously, currently OpenSSL s_client is used from the pledge to establish a TLS session with the application server, running on a server off-site, and the date and CPU temperature are sent to be logged on the application server, as a proof of principle.

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

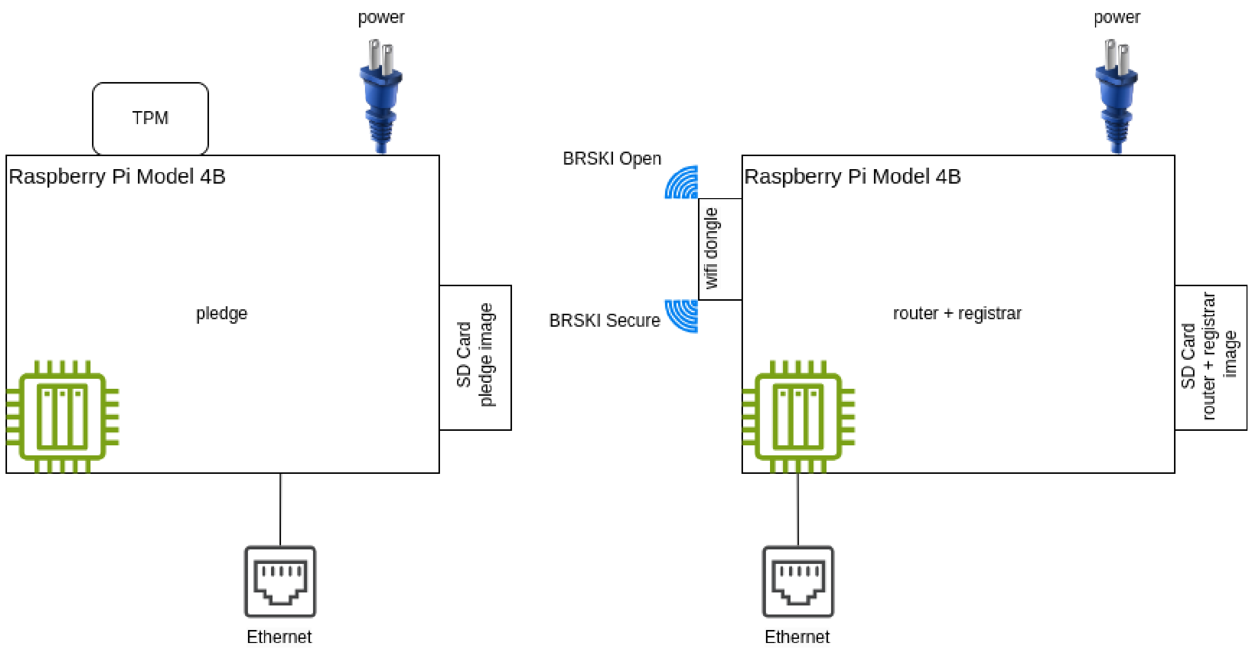
The instructions to use this factory use case code to provision an IDevID onto your pledge are also located at the official NquiringMinds repository in the above section.

6.3 Onboarding Demonstration

6.3.1 Prerequisites

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

957 **Figure 6-2 Diagram of Physical/Logical Components Used to Demonstrate BRSKI Flow**



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

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

964 6.3.2 Onboarding Demonstration

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

967 6.3.3 Continuous Assurance Demonstration

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

970 6.4 BRSKI Factory Provisioning Build

971 This Factory Provisioning Build includes many of the components listed in Section 6.2, including the
972 Pledge, Registrar, and other services. An Infineon Secure Element was also included in the build and
973 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 which is 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. The Infineon Secure Element was connected to a Raspberry Pi via the built-in GPIO pins present on the Pi.

6.4.1.1 Factory Use Case - IDevID provisioning

NquiringMinds provided demonstration code that generates a public/private keypair 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 at the official NquiringMinds documentation.

Initially, it generates a CSR using the TPM secure element to sign it, it then sends the CSR to the MPR server which is the manufacturer's IDevID Certificate Authority and is bootstrapped in 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 at the official NquiringMinds repository referenced above.

6.4.3 Operation and Demonstration

The instructions to use this factory provisioning use case code to provision an IDevID onto the pledge is also located 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
DMZ	Demilitarized Zone
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
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.

NIST SPECIAL PUBLICATION 1800-36D

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

Enhancing Internet Protocol-Based IoT Device and Network Security

Volume D:
Functional Demonstrations

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FEEDBACK

You can improve this guide by contributing feedback. As you review and adopt this solution for your own organization, we ask you and your colleagues to share your experience and advice with us.

Comments on this publication may be submitted to: iot-onboarding@nist.gov.

Public comment period: May 31, 2024 through July 30, 2024

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NATIONAL CYBERSECURITY CENTER OF EXCELLENCE

The National Cybersecurity Center of Excellence (NCCoE), a part of the National Institute of Standards and Technology (NIST), is a collaborative hub where industry organizations, government agencies, and academic institutions work together to address businesses' most pressing cybersecurity issues. This public-private partnership enables the creation of practical cybersecurity solutions for specific industries, as well as for broad, cross-sector technology challenges. Through consortia under Cooperative Research and Development Agreements (CRADAs), including technology partners—from Fortune 50 market leaders to smaller companies specializing in information technology security—the NCCoE applies standards and best practices to develop modular, adaptable example cybersecurity solutions using commercially available technology. The NCCoE documents these example solutions in the NIST Special Publication 1800 series, which maps capabilities to the NIST Cybersecurity Framework and details the steps needed for another entity to re-create the example solution. The NCCoE was established in 2012 by NIST in partnership with the State of Maryland and Montgomery County, Maryland.

To learn more about the NCCoE, visit https://www.nccoe.nist.gov/. To learn more about NIST, visit https://www.nist.gov.

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NIST Cybersecurity Practice Guides (Special Publication 1800 series) target specific cybersecurity challenges in the public and private sectors. They are practical, user-friendly guides that facilitate the adoption of standards-based approaches to cybersecurity. They show members of the information security community how to implement example solutions that help them align with relevant standards and best practices, and provide users with the materials lists, configuration files, and other information they need to implement a similar approach.

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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Gweltas Radenac	SEALSQ, a subsidiary of WISeKey
Kalvin Yang	SEALSQ, a subsidiary of WISeKey

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	Kudelski IoT	Sandelman Software Works
CableLabs	NquiringMinds	Silicon Labs
Cisco	NXP Semiconductors	SEALSQ, a subsidiary of WISeKey
Foundries.io	Open Connectivity Foundation (OCF)	

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Such statements should be addressed to: iot-onboarding@nist.gov.

Contents

List of Tables

1 Introduction

In this project, the National Cybersecurity Center of Excellence (NCCoE) is applying standards, recommended practices, and commercially available technology to demonstrate various mechanisms for trusted network-layer onboarding of IoT devices and lifecycle management of those devices. We show how to provision network credentials to IoT devices in a trusted manner and maintain a secure posture throughout the device lifecycle.

This volume of the NIST Cybersecurity Practice Guide describes functional demonstration scenarios that are designed to showcase the security capabilities and characteristics supported by trusted IoT device network-layer onboarding and lifecycle management solutions. Section 2, Functional Demonstration Playbook, defines the scenarios and lists the capabilities that can be showcased in each one. Section 3, Functional Demonstration Results, reports which capabilities have been demonstrated by each of the project's implemented solutions.

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 and 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 also to help safeguard IoT devices from being taken over by 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.

NIST is adopting an agile process to publish this content. Each volume is being made available as soon as possible rather than delaying release until all volumes are completed.

This guide contains five volumes:

- NIST 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
- 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 **(you are here)**
- 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 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 or security 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 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. Finally, *NIST SP 1800-36E* will be helpful in explaining 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 that 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 welcome your input. Comments, suggestions, and success stories will improve subsequent versions of this guide. Please contribute your thoughts to iot-onboarding@nist.gov.

2 Functional Demonstration Playbook

Six scenarios have been defined that demonstrate capabilities related to various aspects of trusted IoT device network-layer onboarding, application-layer onboarding, and device lifecycle management. These scenarios are as follows:

- Scenario 0: Factory Provisioning
- Scenario 1: Trusted Network-Layer Onboarding
- Scenario 2: Trusted Application-Layer Onboarding
- Scenario 3: Re-Onboarding a Device
- Scenario 4: Ongoing Device Validation
- Scenario 5: Establishment and Maintenance of Credential and Device Security Posture Throughout the Lifecycle

We executed the factory provisioning scenario (Scenario 0) using both a Bootstrapping Remote Secure Key Infrastructure (BRSKI) Factory Provisioning Build and a Wi-Fi Easy Connect Factory Provisioning Build that have been implemented as part of this project. We executed the trusted network-layer onboarding and lifecycle management scenarios using each of the onboarding builds that have been implemented as part of this project. The capabilities that were demonstrated depend both on the features of the network-layer onboarding protocol (i.e., Wi-Fi Easy Connect) that the build supports and on any additional mechanisms the build may have integrated (e.g., application-layer onboarding).

Section 2.1 defines the factory provisioning scenario (Scenario 0). Sections 2.2 through Section 2.6 define each of the five onboarding scenarios.

2.1 Scenario 0: Factory Provisioning

This scenario, which simulates the IoT device factory provisioning process, is designed to represent some steps that must be performed in the factory before the device is put into the supply chain. These steps are performed by the device manufacturer or integrator to provision a device with the information it requires to be able to participate in trusted network-layer onboarding and lifecycle management. The device is assumed to have been equipped with secure storage and with the software or firmware needed to support a specific network-layer onboarding protocol (e.g., Wi-Fi Easy Connect or BRSKI). Scenario 0 includes initial provisioning of the IoT device with its birth credential (e.g., its private key and initial device identifier (IDevID) [1]), where it is stored in secure storage to prevent tampering or disclosure. This process includes generation of the credential (e.g., a private key and other information), signing of this credential (if applicable, depending on what onboarding protocol the device is designed to support), and transfer of the device bootstrapping information (e.g., a DPP URI or the device's IDevID) to the appropriate destination to ensure that it will be available for use during the network layer onboarding process. Following provisioning, the birth credential may be used for network-layer or application-layer onboarding. Table 2-1 lists the capabilities that may be demonstrated in this factory provisioning scenario.

Table 2-1 Scenario 0 Factory Provisioning Capabilities That May Be Demonstrated

Demo ID	Capability	Description
S0.C1	Birth Credential Generation and Storage	The device's birth credentials are generated within or generated and provisioned into secure storage on the IoT device. The content and format of the credential are appropriate to the onboarding protocol (e.g., Wi-Fi Easy Connect [2] or BRSKI [3]) that the device is designed to support: • For BRSKI, the credential is a private key, a signed certificate (IDevID), a trust anchor for the manufacturer's certificate authority (CA), and the location of a trusted manufacturer authorized signing authority (MASA). • For Wi-Fi Easy Connect, the credential is a private key and a public bootstrapping key.
S0.C2	Birth Credential Signing	The credential is signed by a trusted CA.
S0.C3	Bootstrapping Information Availability	The bootstrapping information required for onboarding the device is made available as needed. The format and content of the bootstrapping information depends on the onboarding protocol that the device is designed to support: • For BRSKI, the bootstrapping information is the certificate and ownership information that is sent to the MASA. • For Wi-Fi Easy Connect, the bootstrapping information is the Device Provisioning Protocol (DPP) uniform resource identifier (URI) (which contains the public key, and optionally other information such as device serial number).

2.2 Scenario 1: Trusted Network-Layer Onboarding

This scenario involves trusted network-layer onboarding of an authorized IoT device to a local network that is operated by the owner of the IoT device. The device is assumed to have been manufactured to support the type of network-layer onboarding protocol (e.g., Wi-Fi Easy Connect or BRSKI) that is being used by the local network. The device is also assumed to have been provisioned with its birth credential in a manner similar to that described in Scenario 0: Factory Provisioning, including transfer of the device's bootstrapping information (e.g., its public key) to the operator of the local network to ensure that this information will be available to support authentication of the device during the initial phase of the trusted network-layer onboarding process. Onboarding is performed after the device has booted up and is placed in onboarding mode. Because the organization that is operating the local network is the owner of the IoT device, the device is authorized to onboard to the network and the network is authorized to onboard the device. In this scenario, after the identities of the device and the network are authenticated, a *network onboarding component*—a logical component authorized to onboard devices on behalf of the network—authenticates the device and provisions unique network credentials to the device over a secure channel. These network credentials are not just specific to the device; they are also specific to the local network. The device then uses these credentials to connect to the network. Table 2-2 lists the capabilities that may be demonstrated in this scenario.

Table 2-2 Scenario 1 Trusted Network-Layer Onboarding Capabilities That May Be Demonstrated

Demo ID	Capability	Description
S1.C1	Device Authentication	The onboarding mechanism authenticates the device's identity.
S1.C2	Device Authorization	The onboarding mechanism verifies that the device is authorized to onboard to the network.
S1.C3	Network Authentication	The device can verify the network's identity.
S1.C4	Network Authorization	The device can verify that the network is authorized to take control of it.
S1.C5	Secure Local Credentialing	The onboarding mechanism securely provisions local network credentials to the device.
S1.C6	Secure Storage	The local network credentials are provisioned to secure hardware-backed storage on the device.
S1.C7	Network Selection	The onboarding mechanism provides the IoT device with the identifier of the network to which the device should onboard.
S1.C8	Interoperability	The network-layer onboarding mechanism can onboard a minimum of two types of IoT devices (e.g., different device vendors and models).

2.3 Scenario 2: Trusted Application-Layer Onboarding

This scenario involves trusted application-layer onboarding that is performed automatically on an IoT device after the device connects to a network. As a result, this scenario can be thought of as a series of steps that would be performed as an extension of Scenario 1, assuming the device has been designed and provisioned to support application-layer onboarding. As part of these steps, the device automatically mutually authenticates with a trusted application-layer onboarding service and establishes an encrypted connection to that service so the service can provision the device with application-layer credentials. The application-layer credentials could, for example, enable the device to securely connect to a trusted lifecycle management service to check for available updates or patches. For the application-layer onboarding mechanism to be trusted, it must establish an encrypted connection to the device without exposing any information that must be protected to ensure the confidentiality of that connection. Two types of application-layer onboarding are defined in NIST SP 1800-36B: *streamlined* and *independent*. Table 2-3 lists the capabilities that may be demonstrated in this scenario, including both types of application-layer onboarding.

Table 2-3 Scenario 2 Trusted Application-Layer Onboarding Capabilities That May Be Demonstrated

Demo ID	Capability	Description
S2.C1	Automatic Initiation of Streamlined Application-Layer Onboarding	The device can automatically (i.e., with no manual intervention required) initiate trusted application-layer onboarding after performing network-layer onboarding and connecting to the network. In this case, the application-layer onboarding bootstrapping information has been securely conveyed to the device during the network-layer onboarding process.
S2.C2	Automatic Initiation of Independent Application-Layer Onboarding	The device can automatically (i.e., with no manual intervention required) initiate trusted application-layer onboarding after performing network-layer onboarding and connecting to the network. In this case, the application-layer onboarding bootstrapping information has been pre-provisioned to the device by the device manufacturer or integrator (e.g., as part of an application that was installed on the device during the manufacturing process).
S2.C3	Trusted Application-Layer Onboarding	The device and a trusted application service can establish an encrypted connection without exposing any information that must be protected to ensure the confidentiality of the connection. They can then use that secure association to exchange application-layer information.

2.4 Scenario 3: Re-Onboarding a Device

This scenario involves re-onboarding an IoT device to a network after deleting its network credentials so that the device can be re-credentialed and reconnected. If the device also supports application-layer onboarding, application-layer onboarding should also be performed again after the device reconnects to the network. This scenario assumes that the device has been able to successfully demonstrate trusted network-layer onboarding as defined in Scenario 1: Trusted Network-Layer Onboarding. If application-layer re-onboarding is to be demonstrated as well, the scenario assumes that the device has also been able to successfully demonstrate at least one method of application-layer onboarding as defined in Scenario 2: Trusted Application-Layer Onboarding. Table 2-4 lists the capabilities that may be demonstrated in this scenario.

Table 2-4 Scenario 3 Re-Onboarding Capabilities That May Be Demonstrated

Demo ID	Capability	Description
S3.C1	Credential Deletion	The device's network credential can be deleted.
S3.C2	De-Credentialed Device Cannot Connect	After the device's network credential has been deleted, the device is not able to connect to or communicate on the network securely.
S3.C3	Re-Onboarding (network layer)	After the device's network credential has been deleted, the network-layer onboarding mechanism can securely re-provision a network

Demo ID	Capability	Description
		credential to the device, which the device can then use to connect to the network securely.
S3.C4	Re-Onboarding (application layer)	After the device's network and application-layer credentials have been deleted and the device has been re-onboarded at the network layer and reconnected to the network, the device can again perform trusted application-layer onboarding.

2.5 Scenario 4: Ongoing Device Validation

This scenario involves ongoing validation of a device, not only as part of a trusted boot or attestation process prior to permitting the device to undergo network-layer onboarding, but also after the device has connected to the network. It may involve one or more security mechanisms that are designed to evaluate, validate, or respond to device trustworthiness using methods such as examining device behavior, ensuring device authenticity and integrity, and assigning the device to a specific network segment based on its conformance to policy criteria. Table 2-5 lists the capabilities that may be demonstrated in this scenario. None of these capabilities are integral to trusted network-layer onboarding; however, they may be used in conjunction with, or subsequent to, trusted network-layer onboarding to enhance device and network security.

Table 2-5 Scenario 4 Ongoing Device Validation Capabilities That May Be Demonstrated

Demo ID	Capability	Description
S4.C1	Device Attestation (initial)	The network-layer onboarding mechanism requires successful device attestation prior to permitting the device to be onboarded.
S4.C2	Device Attestation (application layer)	The application-layer onboarding mechanism requires successful device attestation prior to permitting the device to be onboarded.
S4.C3	Device Attestation (ongoing)	Successful device attestation is required prior to permitting the device to perform some operation (e.g., accessing a high-value resource).
S4.C4	Local Network Segmentation (initial)	Upon connection, the IoT device is assigned to some local network segment in accordance with policy, which may include an assessment of its security posture.
S4.C5	Behavioral Analysis	Device behavior is observed to determine whether the device meets the policy criteria required to be permitted to perform a given operation (e.g., to access a high-value resource or be placed on a given network segment).
S4.C6	Local Network Segmentation (ongoing)	The IoT device can be reassigned to a different network segment based on ongoing assessments of its conformance to policy criteria.
S4.C7	Periodic Device Reauthentication	After connection, the IoT device's identity is periodically reauthenticated in order to maintain network access.

Demo ID	Capability	Description
S4.C8	Periodic Device Reauthorization	After connection, the IoT device's authorization to access the network is periodically reconfirmed in order to maintain network access.

2.6 Scenario 5: Establishment and Maintenance of Credential and Device Security Posture Throughout the Lifecycle

This scenario involves steps used to help establish and maintain the security posture of both the device's network credentials and the device itself. It includes the capability to download and validate the device's most recent firmware updates, securely integrate with a device communications intent enforcement mechanism (e.g., Manufacturer Usage Description (MUD) [4]), keep the device updated and patched, and establish and maintain the device's network credentials by provisioning X.509 certificates or DPP Connectors to the device and updating expired network credentials. Table 2-6 lists the capabilities that may be demonstrated in this scenario. None of these capabilities are integral to trusted network-layer onboarding; however, they may be used in conjunction with or subsequent to trusted network-layer onboarding to enhance device and network security.

Table 2-6 Scenario 5 Credential and Device Posture Establishment and Maintenance Capabilities That May Be Demonstrated

Demo ID	Capability	Description
S5.C1	Trusted Firmware Updates	The device can download the most recent firmware update and verify its signature before it is installed.
S5.C2	Credential Certificate Provisioning	The onboarding mechanism can interact with a certificate authority to sign a device's X.509 certificate and provision it onto the device.
S5.C3	Credential Update	The device's network credential can be updated after it expires.
S5.C4	Server Attestation	Successful server attestation is required prior to permitting the server to perform some operation on the device (e.g., prior to downloading and installing updates onto the device).
S5.C5	Secure Integration with MUD	The network-layer onboarding mechanism can convey necessary device communications intent information (e.g., the IoT device's MUD URL) to the network in encrypted form, thereby securely binding this information to the device and ensuring its confidentiality and integrity.
S5.C6	Lifecycle Management Establishment	The device has a lifecycle management service and can automatically establish a secure association with it after performing network-layer onboarding and connecting to the network.

3 Functional Demonstration Results

This section records the capabilities that were demonstrated for each of the builds.

3.1 Build 1 Demonstration Results

Table 3-1 lists the capabilities that were demonstrated by Build 1.

Table 3-1 Build 1 Capabilities Demonstrated

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
Scenario 0: Factory Provisioning				
S0.C1	Birth Credential Generation and Storage	The device's birth credentials are generated within or generated and provisioned into secure storage on the IoT device. For Wi-Fi Easy Connect, the credential is a private key and a public bootstrapping key.	Yes	Public/private key-pair is generated within the SEALSQ VaultIC secure element.
S0.C2	Birth Credential Signing	The credential is signed by a trusted CA.	No	There is no requirement to support this capability in this build. Birth credentials for devices supporting Wi-Fi Easy Connect onboarding do not need to be signed.
S0.C3	Bootstrapping Information Availability	The bootstrapping information required for onboarding the device is made available as needed. For Wi-Fi Easy Connect, the bootstrapping information is the Device Provisioning Protocol (DPP) uniform resource identifier (URI) (which contains the public key, and optionally other information such as device serial number).	Yes	The device's DPP URI is generated using the public/private keypair that was generated in the device's secure element. This DPP URI is encoded in a QR code that is written to a Portable Network Graphics (PNG) file and may be transferred from a vendor cloud upon acquisition of the device.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
Scenario 1: Trusted Network-Layer Onboarding				
S1.C1	Device Authentication	The onboarding mechanism authenticates the device's identity.	Yes	DPP performs device authentication.
S1.C2	Device Authorization	The onboarding mechanism verifies that the device is authorized to onboard to the network.	Yes	When the device's URI is found on the HPE cloud service, this verifies that the device is authorized to onboard to the network.
S1.C3	Network Authentication	The device can verify the network's identity.	No	This could be supported by providing the IoT device with the DPP URI of the network, but the Aruba User Experience Insight (UXI) sensor used in this build lacks the user interface needed to do so.
S1.C4	Network Authorization	The device can verify that the network is authorized to take control of it.	Yes	The network that possesses the device's public key is implicitly authorized to onboard the device by virtue of its knowledge of the device's public key. While this is not cryptographic, it does provide a certain level of assurance that the "wrong" network doesn't take control of the device.
S1.C5	Secure Local Credentialing	The onboarding mechanism securely provisions local network credentials to the device.	Yes	DPP provisions the device's network credentials over an encrypted channel.
S1.C6	Secure Storage	The local network credentials are provisioned to secure hardware-backed storage on the device.	No	The bootstrapping credentials are stored in a Trusted Platform Module (TPM) 2.0 hardware enclave, but the local network credentials are not
S1.C7	Network Selection	The onboarding mechanism provides	Yes	The network responds to device chirps.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
		the IoT device with the identifier of the network to which the device should onboard.		
S1.C8	Interoperability	The network-layer onboarding mechanism can onboard a minimum of two types of IoT devices (e.g., different device vendors and models).	Yes	IoT devices from Build 2 were successfully onboarded in Build 1.
Scenario 2: Trusted Application-Layer Onboarding				
S2.C1	Automatic Initiation of Streamlined Application-Layer Onboarding	The device can automatically (i.e., with no manual intervention required) initiate trusted application-layer onboarding after performing network-layer onboarding and connecting to the network. In this case, the application-layer onboarding bootstrapping information has been securely conveyed to the device during the network-layer onboarding process.	No	Not supported in this build.
S2.C2	Automatic Initiation of Independent Application-Layer Onboarding	The device can automatically (i.e., with no manual intervention required) initiate trusted application-layer onboarding after performing network-layer onboarding and connecting to the network. In this case, the application-layer onboarding bootstrapping information has been	Yes	Once onboarded, the UXI sensor automatically initiates application-layer onboarding to the UXI application.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
		pre-provisioned to the device by the device manufacturer or integrator (e.g., as part of an application that was installed on the device during the manufacturing process).		
S2.C3	Trusted Application- Layer Onboarding	The device and a trusted application service can establish an encrypted connection without exposing any information that must be protected to ensure the confidentiality of the connection. They can then use that secure association to exchange application-layer information.	Yes	Once onboarded, the UXI sensor establishes a secure connection with the UXI cloud, which provisions the sensor with its credentials for the UXI application. Later, the sensor uploads data to the UXI application securely.
Scenario 3: Re-Onboarding a Device				
S3.C1	Credential Deletion	The device's network credential can be deleted.	Yes	Factory reset and manual credential removal were leveraged.
S3.C2	De-Credentialed Device Cannot Connect	After the device's network credential has been deleted, the device is not able to connect to or communicate on the network securely.	Yes	Observed.
S3.C3	Re-Onboarding (network layer)	After the device's network credential has been deleted, the network-layer onboarding mechanism can security re-provision a network credential to the device, which the device can then use to	Yes	Observed.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
		connect to the network securely.		
S3.C4	Re-Onboarding (application layer)	After the device's network and application-layer credentials have been deleted and the device has been re-onboarded at the network layer and re-connected to the network, the device can again perform trusted application-layer onboarding.	Yes	Observed.
Scenario 4: Ongoing Device Validation				
S4.C1	Device Attestation (initial)	The network-layer onboarding mechanism requires successful device attestation prior to permitting the device to be onboarded.	No	Not supported in this build.
S4.C2	Device Attestation (application layer)	The application-layer onboarding mechanism requires successful device attestation prior to permitting the device to be onboarded.	No	Not supported in this build.
S4.C3	Device Attestation (ongoing)	Successful device attestation is required prior to permitting the device to perform some operation (e.g., accessing a high-value resource).	No	Not supported in this build.
S4.C4	Local Network Segmentation (initial)	Upon connection, the IoT device is assigned to some local network segment in accordance with policy, which may	No	Not demonstrated in this phase.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
		include an assessment of its security posture.		
S4.C5	Behavioral Analysis	Device behavior is observed to determine whether the device meets the policy criteria required to be permitted to perform a given operation (e.g., to access a high-value resource or be placed on a given network segment).	No	Not supported in this build.
S4.C6	Local Network Segmentation (ongoing)	The IoT device can be reassigned to a different network segment based on ongoing assessments of its conformance to policy criteria.	No	Not supported in this build.
S4.C7	Periodic Device Reauthentication	After connection, the IoT device's identity is periodically reauthenticated in order to maintain network access.	No	Not supported in this build.
S4.C8	Periodic Device Reauthorization	After connection, the IoT device's authorization to access the network is periodically reconfirmed in order to maintain network access.	No	Not supported in this build.
Scenario 5: Establishment and Maintenance of Credential and Device Security Posture Throughout the Lifecycle				
S5.C1	Trusted Firmware Updates	The device can download the most recent firmware update and verify its signature before it is installed.	No	Not supported in this build.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
S5.C2	Credential Certificate Provisioning	The onboarding mechanism can interact with a certificate authority to sign a device's X.509 certificate and provision it onto the device.	Yes	This capability has been successfully demonstrated with the SEALSQ INeS CA.
S5.C3	Credential Update	The device's network credential can be updated after it expires.	No	Not demonstrated in this phase.
S5.C4	Server Attestation	Successful server attestation is required prior to permitting the server to perform some operation on the device (e.g., prior to downloading and installing updates onto the device).	No	Not supported in this build.
S5.C5	Secure Integration with MUD	The network-layer onboarding mechanism can convey necessary device communications intent information (e.g., the IoT device's MUD URL) to the network in encrypted form, thereby securely binding this information to the device and ensuring its confidentiality and integrity.	No	Supported by DPP, but not demonstrated because Build 1 is not integrated with MUD or any other device communications intent enforcement mechanism.
S5.C6	Lifecycle Management Establishment	The device has a lifecycle management service and can automatically establish a secure association with it after performing network-layer onboarding and	No	Not supported in this build.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
		connecting to the network.		

309 ## 3.2 Build 2 Demonstration Results

310 Table 3-2 lists the capabilities that were demonstrated by Build 2.

311 **Table 3-2 Build 2 Capabilities Demonstrated**

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
Scenario 1: Trusted Network-Layer Onboarding				
S1.C1	Device Authentication	The onboarding mechanism authenticates the device's identity.	Yes	DPP performs device authentication.
S1.C2	Device Authorization	The onboarding mechanism verifies that the device is authorized to onboard to the network.	Yes	Only devices that have been added/approved by the administrator are onboarded. When the device's URI is found, the controller authorizes the device to join the network.
S1.C3	Network Authentication	The device can verify the network's identity.	No	This could be supported by providing the IoT device with the DPP URI of the network, but this is not currently implemented.
S1.C4	Network Authorization	The device can verify that the network is authorized to take control of it.	Yes	The network that possesses the device's public key is implicitly authorized to onboard the device by virtue of its knowledge of the device's public key. While this is not cryptographic, it does provide a certain level of assurance that the "wrong" network doesn't take control of the device.
S1.C5	Secure Local Credentialing	The onboarding mechanism securely provisions local	Yes	DPP provisions the device's network credentials over an encrypted channel.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
		network credentials to the device.		
S1.C6	Secure Storage	The local network credentials are provisioned to secure hardware-backed storage on the device.	No	The IoT device does not have secure hardware-backed storage.
S1.C7	Network Selection	The onboarding mechanism provides the IoT device with the identifier of the network to which the device should onboard.	Yes	Network responds to device chirps.
S1.C8	Interoperability	The network-layer onboarding mechanism can onboard a minimum of two types of IoT devices (e.g., different device vendors and models).	Yes	Build 2 was able to onboard the IoT devices from Build 1.
Scenario 2: Trusted Application-Layer Onboarding				
S2.C1	Automatic Initiation of Streamlined Application-Layer Onboarding	The device can automatically (i.e., with no manual intervention required) initiate trusted application-layer onboarding after performing network-layer onboarding and connecting to the network. In this case, the application-layer onboarding bootstrapping information has been securely conveyed to the device during the network-layer onboarding process.	Yes	This has been demonstrated with the OCF Iotivity [5] custom extension. Iotivity is an open-source software framework that implements OCF standards and enables seamless device-to-device connectivity.
S2.C2	Automatic Initiation of Independent	The device can automatically (i.e., with no manual intervention required) initiate	No	Not supported in this build.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
	Application-Layer Onboarding	trusted application-layer onboarding after performing network-layer onboarding and connecting to the network. In this case, the application-layer onboarding bootstrapping information has been pre-provisioned to the device by the device manufacturer or integrator (e.g., as part of an application that was installed on the device during the manufacturing process).		
S2.C3	Trusted Application-Layer Onboarding	The device and a trusted application service can establish an encrypted connection without exposing any information that must be protected to ensure the confidentiality of the connection. They can then use that secure association to exchange application-layer information.	Yes	Once the device is onboarded to the network using DPP, the credentials for the application layer onboarding are sent over the secure channel and provisioned by the onboarding tool (OBT).
Scenario 3: Re-Onboarding a Device				
S3.C1	Credential Deletion	The device's network credential can be deleted.	Yes	Supports factory reset.
S3.C2	De-Credentialed Device Cannot Connect	After the device's network credential has been deleted, the device is not able to connect to or communicate on the network securely.	Yes	Observed.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
S3.C3	Re-Onboarding (network layer)	After the device's network credential has been deleted, the network-layer onboarding mechanism can security re-provision a network credential to the device, which the device can then use to connect to the network securely.	Yes	Observed.
S3.C4	Re-Onboarding (application layer)	After the device's network and application-layer credentials have been deleted and the device has been re-onboarded at the network layer and re-connected to the network, the device can again perform trusted application-layer onboarding.	Yes	Observed.
Scenario 4: Ongoing Device Validation				
S4.C1	Device Attestation (initial)	The network-layer onboarding mechanism requires successful device attestation prior to permitting the device to be onboarded.	No	Not supported in this build.
S4.C2	Device Attestation (application layer)	The application-layer onboarding mechanism requires successful device attestation prior to permitting the device to be onboarded.	No	Not supported in this build.
S4.C3	Device Attestation (ongoing)	Successful device attestation is required prior to permitting the device to perform some operation (e.g.,	No	Not supported in this build.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
		accessing a high-value resource).		
S4.C4	Local Network Segmentation (initial)	Upon connection, the IoT device is assigned to some local network segment in accordance with policy, which may include an assessment of its security posture.	Yes	When the device is connected to the network, the gateway places it in a restricted network segment based on policy.
S4.C5	Behavioral Analysis	Device behavior is observed to determine whether the device meets the policy criteria required to be permitted to perform a given operation (e.g., to access a high-value resource or be placed on a given network segment).	No	Not supported in this build.
S4.C6	Local Network Segmentation (ongoing)	The IoT device can be reassigned to a different network segment based on ongoing assessments of its conformance to policy criteria.	Yes	Device can be moved to new network segments programmatically. The policy to do this is not defined in this build.
S4.C7	Periodic Device Reauthentication	After connection, the IoT device's identity is periodically reauthenticated in order to maintain network access.	No	Not supported in this build.
S4.C8	Periodic Device Reauthorization	After connection, the IoT device's authorization to access the network is periodically reconfirmed in order to maintain network access.	No	Not supported in this build.
Scenario 5: Establishment and Maintenance of Credential and Device Security Posture Throughout the Lifecycle				

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
S5.C1	Trusted Firmware Updates	The device can download the most recent firmware update and verify its signature before it is installed.	No	Not supported in this build.
S5.C2	Credential Certificate Provisioning	The onboarding mechanism can interact with a certificate authority to sign a device's X.509 certificate and provision it onto the device.	No	Not supported in this build.
S5.C3	Credential Update	The device's network credential can be updated after it expires.	No	Not demonstrated in this phase.
S5.C4	Server Attestation	Successful server attestation is required prior to permitting the server to perform some operation on the device (e.g., prior to downloading and installing updates onto the device).	No	Not supported in this build.
S5.C5	Secure Integration with MUD	The network-layer onboarding mechanism can convey necessary device communications intent information (e.g., the IoT device's MUD URL) to the network in encrypted form, thereby securely binding this information to the device and ensuring its confidentiality and integrity.	No	Supported by DPP, but not demonstrated because Build 2 is not integrated with MUD or any other device communications intent enforcement mechanism.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
S5.C6	Lifecycle Management Establishment	The device has a lifecycle management service and can automatically establish a secure association with it after performing network-layer onboarding and connecting to the network.	No	Not supported in this build.

3.3 Build 3 Demonstration Results

Table 3-3 lists the capabilities that were demonstrated by Build 3.

Table 3-3 Build 3 Capabilities Demonstrated

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
Scenario 1: Trusted Network-Layer Onboarding				
S1.C1	Device Authentication	The onboarding mechanism authenticates the device's identity.	Yes	The local domain registrar receives the voucher request.
S1.C2	Device Authorization	The onboarding mechanism verifies that the device is authorized to onboard to the network.	Yes	The registrar verifies that the device is from an authorized manufacturer.
S1.C3	Network Authentication	The device can verify the network's identity.	Yes	Demonstrated by the voucher.
S1.C4	Network Authorization	The device can verify that the network is authorized to take control of it.	Yes	The registrar examines the new voucher and passes it to the device for onboarding.
S1.C5	Secure Local Credentialing	The onboarding mechanism securely provisions local network credentials to the device.	Yes	A local device identifier (LDevID) (i.e., the device's network credential) [1] is provisioned to the device after the device authentication and authorization process.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
S1.C6	Secure Storage	The local network credentials are provisioned to secure hardware-backed storage on the device.	No	Not demonstrated in this phase.
S1.C7	Network Selection	The onboarding mechanism provides the IoT device with the identifier of the network to which the device should onboard.	No	Not demonstrated in this build.
S1.C8	Interoperability	The network-layer onboarding mechanism can onboard a minimum of two types of IoT devices (e.g., different device vendors and models).	No	Supported by BRSKI, but not demonstrated in this build.
Scenario 2: Trusted Application-Layer Onboarding				
S2.C1	Automatic Initiation of Streamlined Application-Layer Onboarding	The device can automatically (i.e., with no manual intervention required) initiate trusted application-layer onboarding after performing network-layer onboarding and connecting to the network. In this case, the application-layer onboarding bootstrapping information has been securely conveyed to the device during the network-layer onboarding process.	No	Not supported in this build.
S2.C2	Automatic Initiation of Independent Application-Layer Onboarding	The device can automatically (i.e., with no manual intervention required) initiate trusted application-layer onboarding after	No	Not supported in this build.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
		performing network-layer onboarding and connecting to the network. In this case, the application-layer onboarding bootstrapping information has been pre-provisioned to the device by the device manufacturer or integrator (e.g., as part of an application that was installed on the device during the manufacturing process).		
S2.C3	Trusted Application-Layer Onboarding	The device and a trusted application service can establish an encrypted connection without exposing any information that must be protected to ensure the confidentiality of the connection. They can then use that secure association to exchange application-layer information.	No	Not supported in this build.
Scenario 3: Re-Onboarding a Device				
S3.C1	Credential Deletion	The device's network credential can be deleted.	Yes	Observed.
S3.C2	De-Credentialed Device Cannot Connect	After the device's network credential has been deleted, the device is not able to connect to or communicate on the network securely.	Yes	Observed.
S3.C3	Re-Onboarding (network-layer)	After the device's network credential has been deleted, the	Yes	Observed.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
		network-layer onboarding mechanism can security re-provision a network credential to the device, which the device can then use to connect to the network securely.		
S3.C4	Re-Onboarding (application layer)	After the device's network credentials have been deleted and the device has been re-onboarded at the network layer and re-connected to the network, the device can perform application-layer onboarding automatically.	No	Not supported in this build.
Scenario 4: Ongoing Device Validation				
S4.C1	Device Attestation (initial)	The network-layer onboarding mechanism requires successful device attestation prior to permitting the device to be onboarded.	No	Not supported in this build.
S4.C2	Device Attestation (application layer)	The application-layer onboarding mechanism requires successful device attestation prior to permitting the device to be onboarded.	No	Not supported in this build.
S4.C3	Device Attestation (ongoing)	Successful device attestation is required prior to permitting the device to perform some operation (e.g., accessing a high-value resource).	No	Not supported in this build.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
S4.C4	Local Network Segmentation (initial)	Upon connection, the IoT device is assigned to some local network segment in accordance with policy, which may include an assessment of its security posture.	No	Not supported in this build.
S4.C5	Behavioral Analysis	Device behavior is observed to determine whether the device meets the policy criteria required to be permitted to perform a given operation (e.g., to access a high-value resource or be placed on a given network segment).	No	Not supported in this build.
S4.C6	Local Network Segmentation (ongoing)	The IoT device can be reassigned to a different network segment based on ongoing assessments of its conformance to policy criteria.	No	Not supported in this build.
S4.C7	Periodic Device Reauthentication	After connection, the IoT device's identity is periodically reauthenticated in order to maintain network access.	No	Not supported in this build.
S4.C8	Periodic Device Reauthorization	After connection, the IoT device's authorization to access the network is periodically reconfirmed in order to maintain network access.	No	Not supported in this build.
Scenario 5: Establish and Maintain Credential and Device Security Posture Throughout the Lifecycle				
S5.C1	Trusted Firmware Updates	The device can download the most recent firmware update	No	Not supported in this build.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
		and verify its signature before it is installed.		
S5.C2	Credential Certificate Provisioning	The onboarding mechanism can interact with a certificate authority to sign a device's X.509 certificate and provision it onto the device.	Yes	A vendor-installed X.509 certificate and a vendor's authorizing service use link-local connectivity to provision device credentials.
S5.C3	Credential Update	The device's network credential (e.g., its LDevID or X.509 certificate) can be updated after it expires.	No	Will be demonstrated in a future implementation of this build.
S5.C4	Server Attestation	Successful server attestation is required prior to permitting the server to perform some operation on the device (e.g., prior to downloading and installing updates onto the device).	No	Not supported in this build.
S5.C5	Secure Integration with MUD	The network-layer onboarding mechanism can convey necessary device communications intent information (e.g., the IoT device's MUD URL) to the network in encrypted form, thereby securely binding this information to the device and ensuring its confidentiality and integrity.	No	Supported by BRSKI, but not demonstrated because Build 3 is not integrated with MUD or any other device communications intent enforcement mechanism.
S5.C6	Lifecycle Management Establishment	The device has a lifecycle management service and can automatically establish a secure association	No	Not supported in this build.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
		with it after performing network-layer onboarding and connecting to the network.		

315 ## 3.4 Build 4 Demonstration Results

316 Table 3-4 lists the capabilities that were demonstrated by Build 4.

317 **Table 3-4 Build 4 Capabilities Demonstrated**

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
Scenario 1: Trusted Network-Layer Onboarding				
S1.C1	Device Authentication	The onboarding mechanism authenticates the device's identity.	No	The build performs trusted application-layer onboarding only.
S1.C2	Device Authorization	The onboarding mechanism verifies that the device is authorized to onboard to the network.	No	The build performs trusted application-layer onboarding only.
S1.C3	Network Authentication	The device can verify the network's identity.	No	The build performs trusted application-layer onboarding only.
S1.C4	Network Authorization	The device can verify that the network is authorized to take control of it.	No	The build performs trusted application-layer onboarding only.
S1.C5	Secure Local Credentialing	The onboarding mechanism securely provisions local network credentials to the device.	No	The build performs trusted application-layer onboarding only.
S1.C6	Secure Storage	The local network credentials are provisioned to secure hardware-backed storage on the device.	Yes	The local network credentials are stored in the Silicon Labs Secure Vault on the Thunderboard.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
S1.C7	Network Selection	The onboarding mechanism provides the IoT device with the identifier of the network to which the device should onboard.	No	The device generates a pre-shared key that is manually entered in the OpenThread Border Router [6].
S1.C8	Interoperability	The network-layer onboarding mechanism can onboard a minimum of two types of IoT devices (e.g., different device vendors and models).	No	Not supported in this build.
Scenario 2: Trusted Application-Layer Onboarding				
S2.C1	Automatic Initiation of Streamlined Application-Layer Onboarding	The device can automatically (i.e., with no manual intervention required) initiate trusted application-layer onboarding after performing network-layer onboarding and connecting to the network. In this case, the application-layer onboarding bootstrapping information has been securely conveyed to the device during the network-layer onboarding process.	No	Not supported in this build.
S2.C2	Automatic Initiation of Independent Application-	The device can automatically (i.e., with no manual intervention required) initiate	Yes	Trusted application-layer onboarding using Kudelski keySTREAM is configured to proceed automatically pending

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
	Layer Onboarding	trusted application-layer onboarding after performing network-layer onboarding and connecting to the network. In this case, the application-layer onboarding bootstrapping information has been pre-provisioned to the device by the device manufacturer or integrator (e.g., as part of an application that was installed on the device during the manufacturing process).		confirmation from a user (through the press of a button).
S2.C3	Trusted Application-Layer Onboarding	The device and a trusted application service can establish an encrypted connection without exposing any information that must be protected to ensure the confidentiality of the connection. They can then use that secure association to exchange application-layer information.	Yes	Application Layer Onboarding via Kudelski keySTREAM GUI / AWS IoT Core and through the Silicon Labs Simplicity Studio Device Console
Scenario 3: Re-Onboarding a Device				
S3.C1	Credential Deletion	The device's network credential can be deleted.	Yes	The device can be removed from the network via the Open Thread Border Router

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
				GUI and cannot rejoin without entering a new pre-shared key.
S3.C2	De-Credentialed Device Cannot Connect	After the device's network credential has been deleted, the device is not able to connect to or communicate on the network securely.	Yes	Observed.
S3.C3	Re-Onboarding (network layer)	After the device's network credential has been deleted, the network-layer onboarding mechanism can security re-provision a network credential to the device, which the device can then use to connect to the network securely.	Yes	Observed.
S3.C4	Re-Onboarding (application layer)	After the device's network and application-layer credentials have been deleted and the device has been re-onboarded at the network layer and re-connected to the network, the device can again perform trusted application-layer onboarding.	Yes	Observed.
Scenario 4: Ongoing Device Validation				
S4.C1	Device Attestation (initial)	The network-layer onboarding mechanism requires successful device attestation prior to permitting the	No	Not supported in this build.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
		device to be onboarded.		
S4.C2	Device Attestation (application layer)	The application-layer onboarding mechanism requires successful device attestation prior to permitting the device to be onboarded.	No	Not supported in this build.
S4.C3	Device Attestation (ongoing)	Successful device attestation is required prior to permitting the device to perform some operation (e.g., accessing a high-value resource).	No	Not supported in this build.
S4.C4	Local Network Segmentation (initial)	Upon connection, the IoT device is assigned to some local network segment in accordance with policy, which may include an assessment of its security posture.	No	Not supported in this build.
S4.C5	Behavioral Analysis	Device behavior is observed to determine whether the device meets the policy criteria required to be permitted to perform a given operation (e.g., to access a high-value resource or be placed on a given network segment).	No	Not supported in this build.
S4.C6	Local Network Segmentation (ongoing)	The IoT device can be reassigned to a different network	No	Not supported in this build.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
		segment based on ongoing assessments of its conformance to policy criteria.		
S4.C7	Periodic Device Reauthentication	After connection, the IoT device's identity is periodically reauthenticated in order to maintain network access.	No	Not supported in this build.
S4.C8	Periodic Device Reauthorization	After connection, the IoT device's authorization to access the network is periodically reconfirmed in order to maintain network access.	No	Not supported in this build.
Scenario 5: Establishment and Maintenance of Credential and Device Security Posture Throughout the Lifecycle				
S5.C1	Trusted Firmware Updates	The device can download the most recent firmware update and verify its signature before it is installed.	No	Not supported in this build.
S5.C2	Credential Certificate Provisioning	The onboarding mechanism can interact with a certificate authority to sign a device's X.509 certificate and provision it onto the device.	No	Not supported in this build.
S5.C3	Credential Update	The device's network credential can be updated after it expires.	No	Not supported in this build.
S5.C4	Server Attestation	Successful server attestation is required prior to permitting the	No	Not supported in this build.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
		server to perform some operation on the device (e.g., prior to downloading and installing updates onto the device).		
S5.C5	Secure Integration with MUD	The network-layer onboarding mechanism can convey necessary device communications intent information (e.g., the IoT device's MUD URL) to the network in encrypted form, thereby securely binding this information to the device and ensuring its confidentiality and integrity.	No	Not supported in this build.
S5.C6	Lifecycle Management Establishment	The device has a lifecycle management service and can automatically establish a secure association with it after performing network-layer onboarding and connecting to the network.	No	Not supported in this build.

3.5 Build 5 Demonstration Results

Table 3-5 lists the capabilities that were demonstrated by Build 5.

320 **Table 3-5 Build 5 Capabilities Demonstrated**

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
Scenario 0: Factory Provisioning				
S0.C1	Birth Credential Generation and Storage	The device's birth credentials are generated within or generated and provisioned into secure storage on the IoT device. For BRSKI, the credential is an IDevID certificate.	Yes	Supporting public/private keypair is generated within the secure element, and signed IDevID certificate is placed into the secure element.
S0.C2	Birth Credential Signing	The credential is signed by a trusted CA.	Yes	The IDevID certificate is signed by the Build 5 Manufacturer Provisioning Root (MPR).
S0.C3	Bootstrapping Information Availability	The bootstrapping information required for onboarding the device is made available as needed. For BRSKI, the bootstrapping information is the IDevID certificate provisioned into the device's secure element.	Yes	The device's IDevID certificate is generated using the public/private keypair that was generated in the device's secure element. This IDevID certificate is presented to verify the device's identity during network-layer onboarding.
Scenario 1: Trusted Network-Layer Onboarding				
S1.C1	Device Authentication	The onboarding mechanism authenticates the device's identity.	Yes	The device is authenticated using its provisioned IDevID.
S1.C2	Device Authorization	The onboarding mechanism verifies that the device is authorized to onboard to the network.	Yes	The device is implicitly granted authorization during the onboarding process within the registrar implementation. However, this authorization is contingent upon the device satisfying the policy

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
				requirements for onboarding.
S1.C3	Network Authentication	The device can verify the network's identity.	Yes	Demonstrated by the voucher.
S1.C4	Network Authorization	The device can verify that the network is authorized to take control of it.	Yes	The device authenticates to the network using EAP-TLS. The registrar gets a voucher from the MASA verifying that the network is authorized to onboard the device and it passes this voucher to the device so the device can verify that the network is authorized to onboard it.
S1.C5	Secure Local Credentialing	The onboarding mechanism securely provisions local network credentials to the device.	Yes	A local device identifier (LDevID) (i.e., the device's network credential) [1] is provisioned to the device as the culmination of the network-layer onboarding process.
S1.C6	Secure Storage	The local network credentials are provisioned to secure hardware-backed storage on the device.	No	The IDevID (birth credential) keys are generated with a TPM secure element. The EAP-TLS negotiation is configured to use keys from the secure element. The local network credentials (LDevID) are not scored in secure storage.
S1.C7	Network Selection	The onboarding mechanism provides the IoT device with the identifier of the network to which the device should onboard.	Yes	The identifier of the network is passed back in the common name field of the LDevID X.509 certificate.
S1.C8	Interoperability	The network-layer onboarding mechanism can onboard a minimum of two types of IoT devices (e.g., different device vendors and models).	Yes	Supported by BRSKI over IEEE 802.11 [7], but not demonstrated in this build.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
Scenario 2: Trusted Application-Layer Onboarding				
S2.C1	Automatic Initiation of Streamlined Application-Layer Onboarding	The device can automatically (i.e., with no manual intervention required) initiate trusted application-layer onboarding after performing network-layer onboarding and connecting to the network. In this case, the application-layer onboarding bootstrapping information has been securely conveyed to the device during the network-layer onboarding process.	No	Not supported in this build
S2.C2	Automatic Initiation of Independent Application-Layer Onboarding	The device can automatically (i.e., with no manual intervention required) initiate trusted application-layer onboarding after performing network-layer onboarding and connecting to the network. In this case, the application-layer onboarding bootstrapping information has been pre-provisioned to the device by the device manufacturer or integrator (e.g., as part of an application that was installed on the device during the manufacturing process).	Yes	The pledge can use its IDevID and the private key in the secure element to automatically establish a TLS connection to an application server using OpenSSL s_client. The address of the application server has been pre-provisioned to the device by the manufacturer.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
S2.C3	Trusted Application-Layer Onboarding	The device and a trusted application service can establish an encrypted connection without exposing any information that must be protected to ensure the confidentiality of the connection. They can then use that secure association to exchange application-layer information.	Yes	The pledge can use its IDevID and the private key in the secure element to automatically establish a TLS connection to an application server using OpenSSL s_client. The address of the application server has been pre-provisioned to the device by the manufacturer.
Scenario 3: Re-Onboarding a Device				
S3.C1	Credential Deletion	The device's network credential can be deleted.	Yes	The device is removed from Radius server by revoking its voucher.
S3.C2	De-Credentialed Device Cannot Connect	After the device's network credential has been deleted, the device is not able to connect to or communicate on the network securely.	Yes	If credential is removed from the registrar/radius server, the device will not connect. Certificate revocation through CRL is also implemented.
S3.C3	Re-Onboarding (network-layer)	After the device's network credential has been deleted, the network-layer onboarding mechanism can securely re-provision a network credential to the device, which the device can then use to connect to the network securely.	Yes	Upon a voucher being revoked, the LDevID is invalidated. The pledge can then perform the onboarding process again with a newly generated LDevID.
S3.C4	Re-Onboarding (application layer)	After the device's network credentials have been deleted and the device has been re-onboarded at the	Yes	After re-establishing a network connection, application onboarding happens automatically.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
		network layer and re-connected to the network, the device can perform application-layer onboarding automatically.		
Scenario 4: Ongoing Device Validation				
S4.C1	Device Attestation (initial)	The network-layer onboarding mechanism requires successful device attestation prior to permitting the device to be onboarded.	No	Not supported in this build.
S4.C2	Device Attestation (application layer)	The application-layer onboarding mechanism requires successful device attestation prior to permitting the device to be onboarded.	No	Not supported in this build.
S4.C3	Device Attestation (ongoing)	Successful device attestation is required prior to permitting the device to perform some operation (e.g., accessing a high-value resource).	No	Not supported in this build.
S4.C4	Local Network Segmentation (initial)	Upon connection, the IoT device is assigned to some local network segment in accordance with policy, which may include an assessment of its security posture.	No	Not supported in this build.
S4.C5	Behavioral Analysis	Device behavior is observed to determine whether the device meets the policy criteria required to be permitted to perform a given operation (e.g., to access a high-value	Yes	Real time network events are propagated from the gateway(s) to the policy engine. When suspicious behavior is identified (e.g., contact denylisted IP address) device network access is revoked.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
		resource or be placed on a given network segment).		
S4.C6	Local Network Segmentation (ongoing)	The IoT device can be reassigned to a different network segment based on ongoing assessments of its conformance to policy criteria.	No	Not supported in this build.
S4.C7	Periodic Device Reauthentication	After connection, the IoT device's identity is periodically reauthenticated in order to maintain network access.	No	Not supported in this build.
S4.C8	Periodic Device Reauthorization	After connection, the IoT device's authorization to access the network is periodically reconfirmed in order to maintain network access.	Yes	The continuous assurance policy is checked periodically, every 30 seconds in the demo. The policy sets the requirements for a device to be authorized to have access to the network. If a device fails this check, its voucher is revoked, invalidating the device's LDevID.
Scenario 5: Establish and Maintain Credential and Device Security Posture Throughout the Lifecycle				
S5.C1	Trusted Firmware Updates	The device can download the most recent firmware update and verify its signature before it is installed.	No	Not supported in this build.
S5.C2	Credential Certificate Provisioning	The onboarding mechanism can interact with a certificate authority to sign a device's X.509 certificate and provision it onto the device.	Yes	In the BRSKI flows, the onboarding process results in an LDevID (X.509) certificate being provisioned on the device, after the trustworthiness checks have been completed. This LDevID certificate is signed by the Domain CA.

Demo ID	Capability	Description	Demonstrated?	Explanation/Notes
S5.C3	Credential Update	The device's network credential (e.g., its LDevID or X.509 certificate) can be updated after it expires.	Yes	Device will automatically generate a new LDevID and re-onboard if LDevID expires.
S5.C4	Server Attestation	Successful server attestation is required prior to permitting the server to perform some operation on the device (e.g., prior to downloading and installing updates onto the device).	No	Not supported in this build.
S5.C5	Secure Integration with MUD	The network-layer onboarding mechanism can convey necessary device communications intent information (e.g., the IoT device's MUD URL) to the network in encrypted form, thereby securely binding this information to the device and ensuring its confidentiality and integrity.	Yes	The continuous assurance policy engine sporadically resolves the MUD document of each unique connected device using all information available. In this build we use the D3DB method of resolution, which resolves using chained verifiable credentials; specifically, the MUD document is bound to the device ID using a simulated managed firmware service. This provides a verifiable credential binding a device identifier (IDevID) to a full MUD document.
S5.C6	Lifecycle Management Establishment	The device has a lifecycle management service and can automatically establish a secure association with it after performing network-layer onboarding and connecting to the network.	No	Not supported in this build.

Appendix A References

[1] *IEEE Standard for Local and Metropolitan Area Networks - Secure Device Identity*, IEEE Std 802.1AR-2018 (Revision of IEEE Std 802.1AR-2009), 2 Aug. 2018, 73 pp. Available: https://ieeexplore.ieee.org/document/8423794

[2] Wi-Fi Alliance, *Wi-Fi Easy Connect™ Specification Version 3.0*, 2022. Available: https://www.wi-fi.org/system/files/Wi-Fi_Easy_Connect_Specification_v3.0.pdf

[3] M. Pritikin, M. Richardson, T.T.E. Eckert, M.H. Behringer, and K.W. Watsen, *Bootstrapping Remote Secure Key Infrastructure (BRSKI)*, IETF Request for Comments (RFC) 8995, October 2021. Available: https://datatracker.ietf.org/doc/rfc8995/

[4] E. Lear, R. Droms, and D. Romascanu, *Manufacturer Usage Description Specification,* IETF Request for Comments (RFC) 8520, March 2019. Available: https://tools.ietf.org/html/rfc8520

[5] Open Connectivity Foundation (OCF) Iotivity: https://iotivity.org/

[6] Thread 1.1.1 Specification, February 13, 2017.

[7] O. Friel, E. Lear, M. Pritikin, and M. Richardson, *BRSKI over IEEE 802.11*, IETF Internet-Draft (Individual), July 2018. Available: https://datatracker.ietf.org/doc/draft-friel-brski-over-802dot11/01/

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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 E:
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FEEDBACK

You can improve this guide by contributing feedback on the mappings included in this volume. Do you find the mappings that we have provided in this document helpful to you as you try to achieve your cybersecurity goals? Could the mappings that we have provided be improved, either in terms of their content or format? Are there additional standards, best practices, or other guidance documents that you would like us to map to and from trusted IoT device network-layer onboarding and lifecycle management capabilities? Are there additional use cases for these mappings that we should consider in the future? As you review and adopt this solution for your own organization, we ask you and your colleagues to share your experience and advice with us.

Comments on this publication may be submitted to: iot-onboarding@nist.gov.

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

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The National Cybersecurity Center of Excellence (NCCoE), a part of the National Institute of Standards and Technology (NIST), is a collaborative hub where industry organizations, government agencies, and academic institutions work together to address businesses' most pressing cybersecurity issues. This public-private partnership enables the creation of practical cybersecurity solutions for specific industries, as well as for broad, cross-sector technology challenges. Through consortia under Cooperative Research and Development Agreements (CRADAs), including technology partners—from Fortune 50 market leaders to smaller companies specializing in information technology security—the NCCoE applies standards and best practices to develop modular, adaptable example cybersecurity solutions using commercially available technology. The NCCoE documents these example solutions in the NIST Special Publication 1800 series, which maps capabilities to the NIST Cybersecurity Framework and details the steps needed for another entity to re-create the example solution. The NCCoE was established in 2012 by NIST in partnership with the State of Maryland and Montgomery County, Maryland.

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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
CableLabs
Cisco
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Kudelski IoT
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The assurance shall also indicate that it is intended to be binding on successors-in-interest regardless of whether such provisions are included in the relevant transfer documents.

Such statements should be addressed to: iot-onboarding@nist.gov.

Contents

1 Introduction

In this project, the National Cybersecurity Center of Excellence (NCCoE) applies standards, recommended practices, and commercially available technology to demonstrate various mechanisms for trusted network-layer onboarding of IoT devices and lifecycle management of those devices. We show how to provision network credentials to IoT devices in a trusted manner and maintain a secure posture throughout the device lifecycle.

This volume of the NIST Cybersecurity Practice Guide discusses risks addressed by the trusted IoT device network-layer onboarding and lifecycle management reference design. It also maps between cybersecurity functionality provided by logical components of the reference design and Subcategories in the NIST Cybersecurity Framework (CSF) and controls in NIST Special Publication (SP) 800-53, *Security and Privacy Controls for Information Systems and Organizations*. (Note: The reference design is described in detail in NIST SP 1800-36B, Section 4.)

Mappings are also provided between cybersecurity functionality provided by specific network-layer onboarding protocols (e.g., Wi-Fi Easy Connect and Bootstrapping Remote Secure Key Infrastructure [BRSKI]) and those same Subcategories and controls, as well as between cybersecurity functionality provided by builds of the reference design that have been implemented as part of this project and those same Subcategories and controls. (Note: the composition of the builds is described in detail in the appendices of NIST SP 1800-36B.)

None of the mappings we provide is intended to be exhaustive; the mappings focus on the strongest relationships involving each reference design cybersecurity function in order to help organizations prioritize their work. The mappings help users understand how trusted IoT device network-layer onboarding and lifecycle management can help them achieve their cybersecurity goals in terms of CSF Subcategories and SP 800-53 controls. The mappings also help users understand how they can implement trusted onboarding and lifecycle management by identifying how trusted onboarding functionality is supported by the user's existing implementations of CSF Subcategories and SP 800-53 controls.

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 and 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 help safeguard IoT devices from being taken over by 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.

NIST is adopting an agile process to publish this content. Each volume is being made available as soon as possible rather than delaying release until all volumes are completed.

This guide contains five volumes:

- NIST 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
- 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 best practices **(you are here)**

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

Business decision makers, including chief 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 or security 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 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. Finally, *NIST SP 1800-36E* will be helpful in explaining 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 that 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 welcome your input. Comments, suggestions, and success stories will improve subsequent versions of this guide. Please contribute your thoughts to iot-onboarding@nist.gov.

2 Risks Addressed by Trusted Network-Layer Onboarding and Lifecycle Management

Historically, IoT devices have not tended to be onboarded to networks in a trusted manner. This has left networks open to the threat of having unauthorized devices connect to them. It has also left devices open to the threat of being onboarded to networks that are not authorized to control them.

2.1 Risks to the Network

Unauthorized devices that are able to connect to a network pose many risks to that network. They may be able to send and receive data on that network, scan the network for vulnerabilities, eavesdrop on the communications of other devices, and attack other connected devices to exfiltrate or modify their data or to compromise those devices and co-opt them into service to launch distributed denial of service (DDoS) attacks.

2.1.1 Risks to the Network Due to Device Limitations

Many IoT devices are manufactured to be as inexpensive as possible, which sometimes means that the devices are not equipped with secure storage, cryptographic modules, unique authoritative birth credentials, or other features needed to enable the devices to be identified and authenticated. This can make it impossible for a network to determine if a device attempting to connect to it is the intended device. Lack of these features can also make it impossible to protect the confidentiality of a device's network credentials, both during the provisioning process and after the credentials have been installed on the device.

2.1.2 Risks to the Network Due to Use of Shared Network Credentials

If a network uses a single network password that is shared among all devices rather than providing each device with a unique network credential, the network will be vulnerable to having unauthorized devices connect to it if the shared network password falls into the wrong hands, which can happen relatively easily. It also means that the network will permit devices to connect to it simply because a device presents the correct shared password, regardless of the device's type or identity, or whether it has any legitimate reason to connect to the network.

2.1.3 Risks to the Network Due to Insecure Network Credential Provisioning

If devices are manually provisioned with their network credentials, the provisioning process is error-prone, cumbersome, and vulnerable to having the device's network credentials disclosed. If the devices are provisioned automatically over Wi-Fi or some other interface that does not use an encrypted channel, the credentials are also vulnerable to unauthorized disclosure. If the network credentials are not provisioned in a trusted manner, the credentials are vulnerable to disclosure not only the first time the device is onboarded to the network, but every time it is onboarded, which may occur many times during the device lifecycle. For example, the device may need to be re-onboarded periodically to change its credentials in accordance with security policy, or it may need to be re-onboarded due to a security breach, hardware repair, security update, or other reasons. Any insecure features of the onboarding process, therefore, will render the device and network vulnerable every time the device is onboarded.

2.1.4 Risks to the Network Due to Supply Chain Attacks

If a device is compromised while in the supply chain or at some other point prior to being onboarded, then even though the device may be onboarded in a trusted manner, it may still pose a threat to the network, its data, and all devices connected to it. If, on the other hand, the trusted network-layer onboarding mechanism is integrated with a device attestation or supply chain management service that is capable of evaluating the integrity and provenance of the device and detecting that it has been compromised or may have been tampered with, the trusted network-layer onboarding mechanism could prevent such a compromised device from being onboarded and connected to the network.

2.2 Risks to the Device

Although it is relatively easy for one network to masquerade as another, IoT devices often do not authenticate the identity of the networks to which they allow themselves to be onboarded and connected. Devices may be unwittingly tricked into onboarding and connecting to imposter networks that are not authorized to onboard them. This makes those devices vulnerable to being taken control of by those unauthorized networks and thereby prevented from connecting to and providing their intended function on their authorized network.

2.3 Risks to Secure Lifecycle Management

Even if a device is authorized to connect to a network and the network is authorized to control the device, if the device has not been onboarded in a trusted manner, then other security-related operations that are performed after the device has connected to the network may not have as secure a foundation as they would if the device had been onboarded in a trusted manner. For example, if device communications intent enforcement is performed but the integrity and confidentiality of the communicated device intent information was not protected (as it would be by a trusted network-layer onboarding mechanism), then trust in the device communications intent enforcement mechanism may not be as robust as it could have been. Similarly, if application-layer onboarding is performed after the device connects, but the information needed to bootstrap the application-layer onboarding process did not have its integrity and confidentiality protected (as it would be by a trusted network-layer onboarding mechanism), then trust in the application-layer onboarding mechanism may not be as robust as it could have been. Lack of trust in the application-layer onboarding mechanism may, in turn, undermine trust in the device lifecycle management or other application-layer service that is invoked as part of the application-layer onboarding process.

2.4 Limitations and Dependencies of Trusted Onboarding

While implementing trusted IoT device network-layer onboarding and lifecycle management addresses many risks, it also has limitations. Use of trusted network-layer onboarding is designed to enable IoT devices to be provisioned with unique local network credentials in a manner that preserves credential confidentiality. As part of the trusted network-layer onboarding process, the device and the network may mutually authenticate one another, thereby protecting the network from having unauthorized devices connect to it and the device from being taken over by an unauthorized network. However, if the network also enables devices that do not support the trusted network-layer onboarding solution to be provisioned with network credentials and connect to it using a different (untrusted) onboarding solution, the network and all devices on it will still be at risk from IoT devices that have been onboarded using untrusted mechanisms, and the devices that are onboarded using untrusted mechanisms will still be at risk of being taken over by networks that are not authorized to control them.

The trusted network-layer onboarding solution leverages the device's unique, authoritative *birth credentials*, which are provisioned to the device by the device manufacturer and must consist, at a minimum, of a unique device identity and a secret. The trustworthiness of the network-layer onboarding process and the network credentials that it provisions to the device depends on the uniqueness, integrity, and confidentiality of the device's birth credentials which, in many cases, depend on the device's hardware root of trust. If the manufacturer does not ensure that the device's credentials are unique, the identity of the device cannot be definitively authenticated. If the manufacturer is not able to maintain the confidentiality of the secret that is part of the device credentials, the trustworthiness of the device authentication process will be undermined, and the channel over which the device's credentials are provisioned will be vulnerable to eavesdropping.

The trusted network-layer onboarding solution depends upon the trustworthiness of the device's secure storage to ensure the confidentiality of the device and network credentials. If the device's secure storage is vulnerable, the trustworthiness of the network-layer onboarding process and the confidentiality of the device's network credentials will be compromised. If the secure storage in which the device's network credentials are stored is vulnerable, the network will be at risk of having unauthorized devices attach to it.

If the trusted network-layer onboarding mechanism is integrated with additional security capabilities such as device attestation, device communications intent enforcement, application-layer onboarding, and device lifecycle management, it can further increase trust in both the IoT device and, by extension, the network to which the device connects, assuming that these additional security capabilities themselves are secure and robust. If these security capabilities are not implemented correctly, then integrating with them is of no additional value and in fact may provide a false sense of security.

3 Mapping Use Cases, Approach, and Terminology

A *mapping* indicates that one concept is related to another concept. The remainder of this volume describes the mappings between trusted IoT device network-layer onboarding and lifecycle management cybersecurity functions and the security characteristics enumerated in relevant cybersecurity documents.

For this mapping, we have used the supportive relationship mapping style as defined in Section 4.2 of draft NIST Internal Report (IR) 8477, *Mapping Relationships Between Documentary Standards, Regulations, Frameworks, and Guidelines: Developing Cybersecurity and Privacy Concept Mappings* [1].

Each set of mappings involves one of the following types of trusted IoT device network-layer onboarding and lifecycle management cybersecurity functions:

- Cybersecurity functions performed by the reference design's logical components (see NIST SP 1800-36B Section 4)
- Cybersecurity functions provided by specific network-layer onboarding protocols (e.g., Wi-Fi Easy Connect and BRSKI)
- Cybersecurity functions provided by builds of the reference design that have been implemented as part of this project

Each of the cybersecurity functions is mapped to the security characteristics concepts found in the following widely used cybersecurity guidance documents:

- Subcategories from the NIST Cybersecurity Framework (CSF) 1.1 [2] which are also mapped to *The NIST Cybersecurity Framework 2.0 (CSF 2.0)* [3]. The CSF identifies enterprise-level security outcomes. Stakeholders have identified these outcomes as helpful for managing cybersecurity risk, but organizations adopting the CSF need to determine how to achieve the outcomes. Executive Order (EO) 13800, *Strengthening the Cybersecurity of Federal Networks and Critical Infrastructure* [4], made the CSF mandatory for federal government agencies, and other government agencies and sectors have also made the CSF mandatory.
- Security controls from NIST SP 800-53r5 (*Security and Privacy Controls for Information Systems and Organizations*) [5]. NIST SP 800-53 identifies security controls that apply to systems on which those enterprises are reliant. Which SP 800-53 controls need to be employed depends on system functions and a risk assessment of the perceived impact of loss of system functionality or exposure of information from the system to unauthorized entities. In the case of systems owned by or operated on behalf of federal government enterprises, the risk assessment and applicable SP 800-53 controls are mandated under the Federal Information Security Modernization Act (FISMA) [6]. Many other governments and private sector organizations voluntarily employ the Risk Management Framework [7] and associated SP 800-53 controls.

3.1 Use Cases

All of the elements in these mappings—the trusted IoT device network-layer onboarding and lifecycle management cybersecurity functions, cybersecurity functions provided by specific network-layer onboarding protocols, cybersecurity functions provided by specific builds, CSF Subcategories, and SP 800-53 controls—are concepts involving ways to reduce cybersecurity risk.

There are two primary use cases for this mapping. They are not intended to be comprehensive, but rather to capture the strongest relationships involving the trusted IoT device network-layer onboarding and lifecycle management cybersecurity functions.

1. **Why should organizations implement trusted IoT device network-layer onboarding and lifecycle management?** This use case identifies how implementing trusted IoT device network-layer onboarding and lifecycle management can support organizations with achieving CSF Subcategories and SP 800-53 controls. This helps communicate to an organization's chief information security officer, security team, and senior management that expending resources to implement trusted IoT device network-layer onboarding and lifecycle management can also aid in fulfilling other security requirements.
2. **How can organizations implement trusted IoT device network-layer onboarding and lifecycle management?** This use case identifies how an organization's existing implementations of CSF Subcategories and SP 800-53 controls can help support a trusted IoT device network-layer onboarding and lifecycle management implementation. An organization wanting to implement trusted IoT device network-layer onboarding and lifecycle management might first assess its current security capabilities so that it can plan how to add missing capabilities and enhance existing capabilities. Organizations can leverage their existing security investments and prioritize future security technology deployment to address the gaps.

These mappings are intended to be used by any organization that is interested in implementing trusted IoT device network-layer onboarding and lifecycle management or that has begun or completed an implementation.

3.2 Mapping Producers

The NCCoE trusted IoT device network-layer onboarding and lifecycle management project team performed the mappings between the cybersecurity functions performed by the reference design's logical components (see NIST SP 1800 36B Section 4) and the security characteristics in the cybersecurity documents. They also performed the mappings between the cybersecurity functions performed by the specific network-layer onboarding protocols (i.e., Wi-Fi Easy Connect and BRSKI) and the security characteristics in the cybersecurity documents. These mappings were performed with input and feedback from the collaborators who have contributed technology to the builds of the reference design. Collaborators for each build, in conjunction with the NCCoE trusted IoT device network-layer onboarding and lifecycle management project team, performed the mappings between the cybersecurity functions provided by their contributed technologies in each build and the security characteristics in the cybersecurity documents.

3.3 Mapping Approach

In addition to performing general mappings between the reference design's cybersecurity functions and various sets of security characteristics, as well as between specific network-layer onboarding protocol cybersecurity functions and various sets of security characteristics, the NCCoE asked the collaborators for each build to indicate the mapping between the cybersecurity functions their technology components provide in that build and the sets of security characteristics.

Using the logical components in the reference design as the organizing principle for the initial mapping of cybersecurity functions to security characteristics and then providing onboarding protocol-specific mappings was intended to make it easier for collaborators to map their build-specific technology contributions. Using this approach, the build-specific technology mappings are instantiations of the project's general reference design and protocol-specific mappings for each document.

3.3.1 Mapping Terminology

In this publication, we use the following relationship types from NIST IR 8477 [1] to describe how the functions in our reference design are related to the NIST reference documents. Note that the *Supports* relationship applies only to use case 1 in Section 3.1 and the *Is Supported By* relationship applies only to use case 2.

- **Supports:** Trusted IoT device network-layer onboarding and lifecycle management function X *supports* security control/Subcategory/capability/requirement Y when X can be applied alone or in combination with one or more other functions to achieve Y in whole or in part.
- **Is Supported By:** Trusted IoT device network-layer onboarding and lifecycle management function X is *supported by* security control/Subcategory/capability/requirement Y when Y can be applied alone or in combination with one or more other security controls/Subcategories/capabilities/requirements to achieve X in whole or in part.

Each *Supports* and *Is Supported By* relationship has one of the following properties assigned to it:

- **Example of:** The supporting concept X is one way (*an example*) of achieving the supported concept Y in whole or in part. However, Y could also be achieved without applying X.
- **Integral to:** The supporting concept X is *integral to* and a component of the supported concept Y. X must be applied as part of achieving Y.
- **Precedes:** The supporting concept X *precedes* the supported concept Y when X must be achieved before applying Y. In other words, X is a prerequisite for Y.

When determining whether a reference design function's support for a given CSF Subcategory or SP 800-53 control is integral to that support versus an example of that support, we do not consider how that function may in general be used to support the Subcategory, control, capability, or requirement. Rather, we consider only how that function is intended to support that Subcategory, control, capability, or requirement within the context of our reference design.

Also, when determining whether a function is supported by a CSF Subcategory, SP 800-53 control, capability, etc. with the relationship property of *precedes*, we do not consider whether it is possible to apply the function without first achieving the Subcategory, control, capability, or requirement. Rather, we consider whether, according to our reference design, the Subcategory, control, capability, or requirement is to be achieved prior to applying that function.

3.3.2 Mapping Process

The process that the NCCoE used to create the mapping from the logical components of the reference design to the security characteristics of a given document was as follows:

1. Create a table that lists each of the logical components of the reference design in column 1.

2. Describe each logical component's cybersecurity function in column 2.
3. Map each cybersecurity function to each of the security characteristics in the document to which the function is most strongly related, and list each of these security characteristics on different sub-rows within column 3. Begin each security characteristic entry with an underlined keyword that describes the mapping's relationship type (i.e., *Supports*, *Is Supported By*). After the keyword indicating the relationship type, put in parentheses the underlined keyword describing the relationship's property (i.e., *Example of*, *Integral to*, or *Precedes*).
4. In the fourth column, provide a brief explanation of why that relationship type and property apply to the mapping.
5. After completing the mapping table entries as described above for all the logical components in the reference design, examine the mapping in the other direction, i.e., starting with the security characteristics listed in the document and considering whether they have a relationship to the logical components' cybersecurity functions in the reference design. In other words, step through each of the security characteristics in the document and determine if there is some logical component in the reference design that has a strong relationship to that security characteristic. If so, add an entry for that security characteristic mapping to that logical component's row in the table. By examining the mapping in both directions in this manner, security characteristic mappings are less likely to be overlooked or omitted.
6. Once these steps are complete, any rows in the table that don't have any mappings should be deleted.

The NCCoE applied this mapping process separately for each reference document. None of the mappings is intended to be exhaustive; they all focus on the strongest relationships involving each cybersecurity function in order to help organizations prioritize their work. Mapping every possible relationship, no matter how tenuous, would create so many mappings that they would not have any value in prioritization.

4 Mappings

The mappings are provided in the form of Excel files. Links to the mapping Excel files are organized in the remainder of this document as follows:

- Section 4.1 – NIST CSF 1.1 [2] and NIST CSF 2.0 [3] mappings. These include:
  - Section 4.1.1 – Mappings between reference design functions and NIST CSF Subcategories
  - Section 4.1.2 – Mappings between specific onboarding protocol (i.e., Wi-Fi Easy Connect and BRSKI) functions and NIST CSF Subcategories
  - Section 4.1.3 – Mappings between specific build functions and NIST CSF Subcategories
- Section 4.2 – NIST SP 800-53r5 [5] mappings. These include:
  - Section 4.2.1 – Mappings between reference design functions and NIST SP 800-53r5 controls

- ○ Section 4.2.2 – Mappings between specific onboarding protocol (i.e., Wi-Fi Easy Connect and BRSKI) functions and NIST SP 800-53r5 controls
- ○ Section 4.2.3 – Mappings between specific build functions and NIST SP 800-53r5 controls

4.1 NIST CSF Subcategory Mappings

This section provides links to mappings between various elements that provide trusted network-layer onboarding functionality and NIST CSF Subcategories.

4.1.1 Mappings Between Reference Design Functions and NIST CSF Subcategories

This Excel file provides mappings between the logical components of the reference design and the NIST CSF Subcategories. These mappings indicate how trusted IoT device network-layer onboarding and lifecycle management functions help support CSF Subcategories and vice versa.

Link to the Excel file called "IoT Volume E CSF 1-1 and 2-0", and to the tab called "CSF-to-Reference Arch" (first tab)

4.1.2 Mappings Between Specific Onboarding Protocols and NIST CSF Subcategories

This section provides mappings between the functionality provided by two network-layer onboarding protocols, Wi-Fi Easy Connect and BRSKI, and the NIST CSF Subcategories.

4.1.2.1 Mapping Between Wi-Fi Easy Connect and NIST CSF Subcategories

This Excel file provides a mapping between the functionality provided by the Wi-Fi Easy Connect protocol and the NIST CSF Subcategories. These mappings indicate how Wi-Fi Easy Connect functionality helps support CSF Subcategories and vice versa.

Link to the Excel file called "CSF 1.1 and 2.0 Tables", and to the tab called "CSF-to-Wi-Fi EasyCnct" (third tab)

4.1.2.2 Mapping Between BRSKI and NIST CSF Subcategories

This Excel file provides a mapping between the functionality provided by BRSKI and the NIST CSF Subcategories. These mappings indicate how BRSKI functionality helps support CSF Subcategories and vice versa.

Link to the Excel file called "CSF 1.1 and 2.0 Tables", and to the tab called "CSF-to-BRSKI" (second tab)

4.1.3 Mappings Between Specific Builds and NIST CSF Subcategories

This section provides mappings between the functionality provided by builds of the trusted IoT device network-layer onboarding and lifecycle management reference design that were implemented as part of this project and the NIST CSF Subcategories.

4.1.3.1 Mapping Between Build 1 and NIST CSF Subcategories

Build 1 is an implementation of network-layer onboarding that uses the Wi-Fi Easy Connect protocol. The onboarding infrastructure and related technology components for Build 1 have been provided by Aruba/HPE. IoT devices that were onboarded using Build 1 were provided by Aruba/HPE and CableLabs. The technologies used in Build 1 are detailed in Appendix C of SP 1800-36B.

This Excel file details the mapping between the functionality provided by Build 1 components and CSF Subcategories. These mappings indicate how these components help support CSF Subcategories and vice versa.

Link to the Excel file called "CSF 1.1 and 2.0 Tables", and to the tab called "CSF-to-B1" (fourth tab)

4.1.3.2 Mapping Between Build 2 and NIST CSF Subcategories

Build 2 is an implementation of network-layer onboarding that uses the Wi-Fi Easy Connect protocol. The onboarding infrastructure and related technology components for Build 2 have been provided by CableLabs and OCF. IoT devices that were onboarded using Build 2 were provided by CableLabs, OCF, and Aruba/HPE. The technologies used in Build 2 are detailed in Appendix D of SP 1800-36B.

This Excel file details the mapping between the functionality provided by Build 2 components and CSF Subcategories. These mappings indicate how these components help support CSF Subcategories and vice versa.

Link to the Excel file called "CSF 1.1 and 2.0 Tables", and to the tab called "CSF-to-B2" (fifth tab)

4.1.3.3 Mapping Between Build 3 and NIST CSF Subcategories

Build 3 is an implementation of network-layer onboarding that uses BRSKI. The onboarding infrastructure and related technology components for Build 3 have been provided by Sandelman Software Works. The IoT device that was used to demonstrate onboarding in Build 3 was a pledge simulator provided by Sandelman. The technologies used in Build 3 are detailed in Appendix E of SP 1800-36B.

This Excel file details the mapping between the functionality provided by Build 3 components and CSF Subcategories. These mappings indicate how these components help support CSF Subcategories and vice versa.

Link to the Excel file called "CSF 1.1 and 2.0 Tables", and to the tab called "CSF-to-B3" (sixth tab)

4.1.3.4 Mapping Between Build 4 and NIST CSF Subcategories

Build 4 is an implementation of network-layer connection to an OpenThread network using pre-provisioned network credentials as well as independent application-layer onboarding using the Kudelski KeySTREAM service. The network infrastructure and related technology components for Build 4 have been provided by Silicon Labs and Kudelski. The IoT device that was used to demonstrate onboarding in Build 4 was provided by Silicon Labs. The technologies used in Build 4 are detailed in Appendix F of SP 1800-36B.

This Excel file details the mapping between the functionality provided by Build 4 components and CSF Subcategories These mappings indicate how these components help support CSF Subcategories and vice versa.

Link to the Excel file called "CSF 1.1 and 2.0 Tables", and to the tab called "CSF-to-B4" (seventh tab)

4.1.3.5 Mapping Between Build 5 and NIST CSF Subcategories

Build 5 is an implementation of network-layer onboarding using BRSKI over Wi-Fi, as well as demonstration of a continuous authorization service. The network layer onboarding infrastructure and related technology components for Build 5 have been provided by NquiringMinds. The IoT devices that were used to demonstrate onboarding in Build 5 were provided by NquiringMinds. The technologies used in Build 5 are detailed in Appendix G of SP 1800-36B.

This Excel file details the mapping between the functionality provided by Build 5 components and CSF Subcategories. These mappings indicate how these components help support CSF Subcategories and vice versa.

Link to the Excel file called "CSF 1.1 and 2.0 Tables", and to the tab called "CSF-to-B5" (eighth tab)

4.2 NIST SP 800-53 Control Mappings

This section provides mappings between various elements that provide trusted network-layer onboarding functionality and NIST SP 800-53 controls.

4.2.1 Mappings Between Reference Design Functions and NIST SP 800-53 Controls

This Excel file provides a mapping between the logical components of the reference design and NIST SP 800-53 security controls. These mappings indicate how trusted IoT device network-layer onboarding and lifecycle management functions help support NIST SP 800-53 controls. Because hundreds of NIST SP 800-53 controls can help support these functions, we have limited use case 2 (see Section 3.1) mappings to those controls on which specified supporting controls directly depend (e.g., dependence of cryptographic protection on key management). Readers needing to determine how their trusted IoT device network-layer onboarding and lifecycle management implementations support RMF processes can refer to these mappings.

Link to the Excel file called "800-53 Tables", and to the tab called "800-53-to-Reference Arch" (first tab)

4.2.2 Mappings Between Specific Onboarding Protocols and NIST SP 800-53 Controls

This section provides mappings between the functionality provided by specific network-layer onboarding protocols and the NIST SP 800-53 controls. Mappings are provided for both the Wi-Fi Easy Connect protocol and BRSKI.

4.2.2.1 Mapping Between Wi-Fi Easy Connect and NIST SP 800-53 Controls

This Excel file provides a mapping between the functionality provided by the Wi-Fi Easy Connect protocol and the NIST SP 800-53 controls. These mappings indicate how Wi-Fi Easy Connect functions help support NIST SP 800-53 controls and vice versa.

Link to the Excel file called "800-53 Tables", and to the tab called "800-53-to-Wi-Fi EasyCnct" (second tab)

4.2.2.2 Mapping Between BRSKI and NIST SP 800-53 Controls

This Excel file provides a mapping between the functionality provided by BRSKI and the NIST SP 800-53 controls. These mappings indicate how BRSKI functions help support NIST SP 800-53 controls and vice versa.

Link to the Excel file called "800-53 Tables", and to the tab called "800-53-to-BRSKI" (third tab)

4.2.3 Mappings Between Specific Builds and NIST SP 800-53 Controls

This section provides mappings between the functionality provided by builds of the trusted IoT device network-layer onboarding and lifecycle management reference design that were implemented as part of this project and the NIST SP 800-53 controls.

4.2.3.1 Mapping Between Build 1 and NIST SP 800-53 Controls

Build 1 is an implementation of network-layer onboarding that uses the Wi-Fi Easy Connect protocol. The onboarding infrastructure and related technology components for Build 1 have been provided by Aruba/HPE. IoT devices that were onboarded using Build 1 were provided by Aruba/HPE and CableLabs. The technologies used in Build 1 are detailed in Appendix C of SP 1800-36B.

This Excel file details the mapping between the functionality provided by Build 1 components and SP 800-53 controls. These mappings indicate how these components help support SP 800-53 controls and vice versa.

Link to the Excel file called "800-53 Tables", and to the tab called "800-53-to-B1" (fourth tab)

4.2.3.2 Mapping Between Build 2 and NIST SP 800-53 Controls

Build 2 is an implementation of network-layer onboarding that uses the Wi-Fi Easy Connect protocol. The onboarding infrastructure and related technology components for Build 2 have been provided by CableLabs and OCF. IoT devices that were onboarded using Build 2 were provided by CableLabs, OCF, and Aruba/HPE. The technologies used in Build 1 are detailed in Appendix D of SP 1800-36B.

This Excel file details the mapping between the functionality provided by Build 2 components and SP 800-53 controls These mappings indicate how these components help support SP 800-53 controls and vice versa.

Link to the Excel file called "800-53 Tables", and to the tab called "800-53-to-B2" (fifth tab)

4.2.3.3 Mapping Between Build 3 and NIST SP 800-53 Controls

Build 3 is an implementation of network-layer onboarding that uses BRSKI. The onboarding infrastructure and related technology components for Build 3 have been provided by Sandelman Software Works. The IoT device that was used to demonstrate onboarding in Build 3 was a pledge simulator provided by Sandelman. The technologies used in Build 3 are detailed in Appendix E of SP 1800-36B.

This Excel file details the mapping between the functionality provided by Build 3 components and SP 800-53 controls. These mappings indicate how these components help support SP 800-53 controls and vice versa.

Link to the Excel file called "800-53 Tables", and to the tab called "800-53-to-B3" (sixth tab)

4.2.3.4 Mapping Between Build 4 and NIST SP 800-53 Controls

Build 4 is an implementation of network-layer connection to an OpenThread network using pre-provisioned network credentials as well as independent application-layer onboarding using the Kudelski KeySTREAM service. The network infrastructure and related technology components for Build 4 have been provided by Silicon Labs and Kudelski. The IoT device that was used to demonstrate onboarding in Build 4 was provided by Silicon Labs. The technologies used in Build 4 are detailed in Appendix F of SP 1800-36B.

This Excel file details the mapping between the functionality provided by Build 4 components and SP 800-53 controls. These mappings indicate how these components help support SP 800-53 controls and vice versa.

Link to the Excel file called "800-53 Tables", and to the tab called "800-53-to-B4" (seventh tab)

4.2.3.5 Mapping Between Build 5 and NIST SP 800-53 Controls

Build 5 is an implementation of network-layer onboarding using BRSKI over Wi-Fi, as well as demonstration of a continuous authorization service. The network layer onboarding infrastructure and related technology components for Build 5 have been provided by NquiringMinds. The IoT devices that were used to demonstrate onboarding in Build 5 were provided by NquiringMinds. The technologies used in Build 5 are detailed in Appendix G of SP 1800-36B.

This Excel file details the mapping between the functionality provided by Build 5 components and SP 800-53 controls. These mappings indicate how these components help support SP 800-53 controls and vice versa.

Link to the Excel file called "800-53 Tables", and to the tab called "800-53-to-B5" (eighth tab)

Appendix A References

[1] K. Scarfone, M. Souppaya, and M. Fagan, Mapping Relationships Between Documentary Standards, Regulations, Frameworks, and Guidelines: Developing Cybersecurity and Privacy Content Mappings, National Institute of Standards and Technology (NIST) Internal Report (IR) 8477, Gaithersburg, Md., August 2023, 26 pp. Available: https://doi.org/10.6028/NIST.IR.8477.ipd

[2] National Institute of Standards and Technology (2018) Framework for Improving Critical Infrastructure Cybersecurity, Version 1.1. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Cybersecurity White Paper (CSWP) NIST CSWP 6. https://doi.org/10.6028/NIST.CSWP.6

[3] National Institute of Standards and Technology, Version 2.0. The NIST Cybersecurity Framework 2.0 (CSF 2.0) (National Institute of Standards and Technology, Gaithersburg, MD), https://csrc.nist.gov/pubs/cswp/29/the-nist-cybersecurity-framework-20/ipd

[4] Executive Order 13800 (2017) Strengthening the Cybersecurity of Federal Networks and Critical Infrastructure. (The White House, Washington, DC), DCPD-201700327, May 11, 2017. https://www.govinfo.gov/app/details/DCPD-201700327

[5] Joint Task Force (2020) Security and Privacy Controls for Information Systems and Organizations. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-53, Rev. 5. Includes updates as of December 10, 2020. https://doi.org/10.6028/NIST.SP.800-53r5

[6] S.2521 - Federal Information Security Modernization Act of 2014, 113th Congress (2013-2014), Became Public Law No: 113-283, December 18, 2014. Available: https://www.congress.gov/bill/113th-congress/senate-bill/2521

[7] Joint Task Force (2018) Risk Management Framework for Information Systems and Organizations: A System Life Cycle Approach for Security and Privacy. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) 800-37, Rev. 2. https://doi.org/10.6028/NIST.SP.800-37r2