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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 B:
Approach, Architecture, and Security Characteristics

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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.

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

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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 prior to such onboarding is crucial for mitigating the risk of potential attacks. There are two sides to such attacks: on the one hand, a device may be convinced to join an unauthorized network, which could take control of the device. On the other hand, a network may be infiltrated by a malicious device. Trust is achieved by attesting and verifying the identity and posture of the device and the network as part of the network-layer onboarding process. Additional safeguards, such as verifying the security posture of the device before other operations occur, can be performed throughout the device lifecycle. 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.

1.1 Challenge

With 40 billion IoT devices expected to be connected worldwide by 2025, 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 technology providers and other members of the NCCoE's IoT Community of Interest 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 planned for demonstration 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 be of benefit to 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. Work implementing the example solutions and developing other parts of the content continues. As a preliminary draft, we will publish at least one additional draft for public comment before it is finalized.

When complete, this guide will contain 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 3 of *NIST SP 1800-36E* will be of particular interest. Section 3, Trusted IoT Device Network-Layer Onboarding and Lifecycle Management Reference Architecture Security 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.

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. As the project progresses, this preliminary draft will be updated, and additional volumes will also be released for comment. 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* [1]. 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 intent [2][3], and application-layer onboarding. The security and other attributes of the onboarding process that are catalogued 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 [4] 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 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 factory use case activities performed by an IoT device manufacturer. Each of the build teams fleshed out the initial architectures of their example implementations, i.e., *builds*. They then used technologies, capabilities, and components from project collaborators to begin creating the builds:

- Build 1 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 [5] and independent (see Section 3.3.2) application-layer onboarding to the Aruba User Experience Insight (UXI) cloud.
- Build 2 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 (still in progress) will use components from Sandelman Software Works to support trusted network-layer onboarding using the Bootstrapping Remote Secure Key Infrastructure (BRSKI) [6] protocol and an independent, third-party Manufacturer Authorized Signing Authority (MASA).
- Build 4 (still in progress) will use components from Silicon Labs to support trusted network-layer onboarding using the Thread Mesh Commissioning Protocol (MeshCoP) [7] and components from Kudelski IoT to support trusted application-layer onboarding to the Amazon Web Services (AWS) IoT core.
- Build 5 (still in progress) will use components from Sandelman Software Works to support trusted network-layer onboarding using the BRSKI protocol over 802.11 [8], and OpenWrt-based open-source components to support trusted network-layer onboarding using Wi-Fi Easy Connect. Additional components from NquiringMinds will support ongoing, policy-based, continuous assurance and authorization.

- The factory use case builds (still being designed) will use software from Foundries.io, devices from NXP, and secure storage element devices and a certificate authority (CA) from WISeKey. They will explore and demonstrate options for provisioning IoT devices with their initial (i.e., *birth*—see Section 3.3) credentials and for making device bootstrapping information available to device owners.

At this time, only builds 1 and 2 have been completed and are documented in this draft practice guide. The remaining builds are planned for inclusion as they are completed in future versions of the guide.

Each build team documented the architecture and design of its build (see Appendices C and D). 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 a mapping of the security capabilities of the reference solution to the *Framework for Improving Critical Infrastructure Cybersecurity* (NIST Cybersecurity Framework) [9] and other relevant standards, guidelines, and recommended practices (see NIST SP 1800-36E).

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

3.1 Audience

The focus of this project is trusted IoT device network-layer onboarding. It demonstrates solutions that are targeted to address the needs of both home and enterprise network owners. Home network owners cannot be assumed to have network administration experience and therefore require plug-and-play functionality whenever possible. Enterprise network owners are assumed to have network administrators with sophisticated understanding and extensive experience deploying, configuring, and operating networks and related devices. However, enterprise network owners may have needs beyond those of home network owners, such as the requirement to be able to onboard IoT devices at scale quickly and easily.

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 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. It 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 onboarding of IP-based devices in the initial phase and will consider using technologies such as Zigbee or Bluetooth in future phases. The scope also includes additional 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 technologies that can potentially be integrated with network-layer onboarding include supply chain management, device attestation, trusted application-layer onboarding, device 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 that device attestation must 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. Lastly, enterprise, consumer, and industrial use cases for trusted IoT device network-layer onboarding are all considered to be in scope at this time.

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 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 installs the birth credential onto an IoT device in the form of an Initial Device Identifier (IDevID) [10] or keypair.

  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
  - 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.

- 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.
- **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.

- **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, device communications intent enforcement, 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; whether they support attestation; whether they are supported by supply-chain tools; whether they support application-layer onboarding; whether they support device communications intent enforcement; and what onboarding and other protocols they support. 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 Specification Immaturity

Ideally, trusted network-layer onboarding solutions selected for widespread implementation and use will be openly available and standards-based. The current level of maturity of some potential solution specifications 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). Table 3-1 lists 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 solutions.

Table 3-1 Technology Partners/Collaborators

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

Table 3-2 summarizes the capabilities and components provided, or planned to be provided, by each partner/collaborator.

Table 3-2 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 to the UXI cloud 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 secure storage of IoT devices.

Collaborator	Security Capability or Component Provided
NquiringMinds	Service that performs ongoing monitoring of connected devices to ensure their continued authorization (i.e., *continuous authorization service*)
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
Silicon Labs	Infrastructure for trusted network-layer onboarding to a Thread network that has access to other networks for application-layer onboarding. IoT device with secure storage for use with Thread network-layer onboarding.
WISeKey	Secure storage and development tools for creating software programs and applications for use with both Wi-Fi Easy Connect and BRSKI network-layer onboarding; certificate authority for signing device certificates

Each of these technology partners and collaborators, as well as the relevant products and capabilities they bring to this trusted onboarding effort, are described 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 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 Figure 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

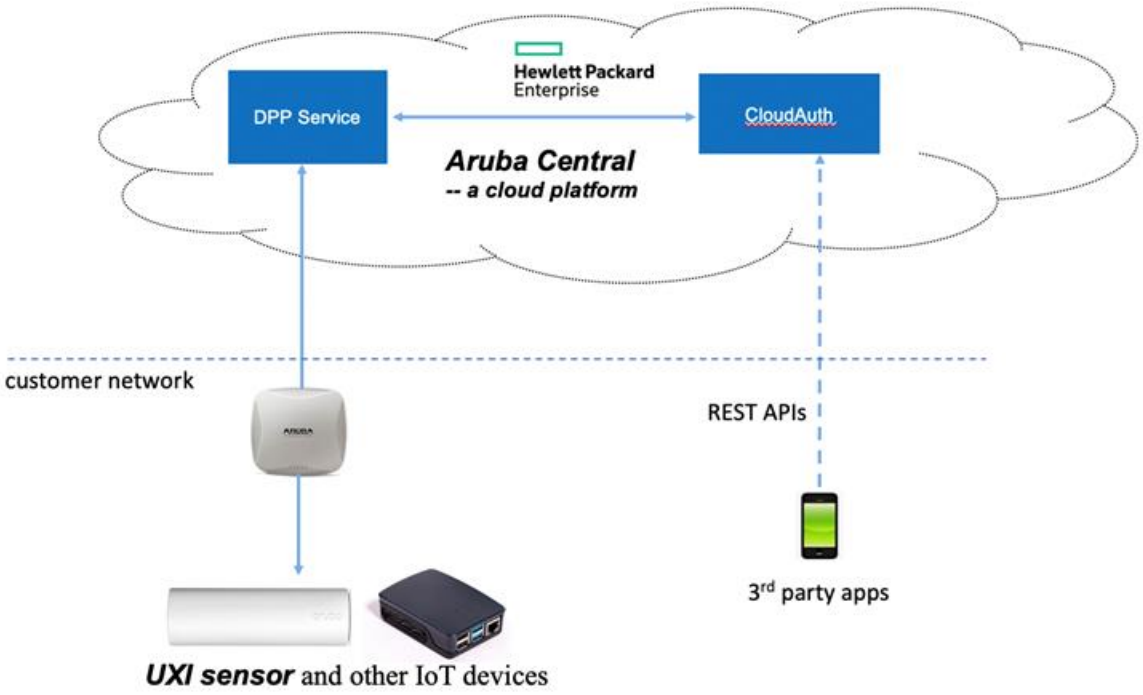
Cloud-native network access control (NAC) solution Cloud Auth delivers time-saving workflows to configure and manage onboarding, authorization, and authentication policies for wired and wireless networks. Cloud Auth integrates with an organization's existing cloud identity store, such as Google Workspace 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 for 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.

703 **Figure 3-1 Aruba/HPE DPP Onboarding Components**



704 ## 3.4.2 CableLabs

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

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

713 ### *3.4.2.1 Platform Controller*

714 The controller provides interfaces and messaging for managing service deployment groups, access
715 points with the deployment groups, registration and lifecycle of user services, and the secure
716 onboarding and lifecycle management of users' Wi-Fi devices. The controller also exposes APIs for
717 integration with third-party systems for the purpose of integrating various business flows (e.g.,
718 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 Wi-Fi Alliance (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.

753 The open-source platform interfaces to any cloud and offers Foundries.io customers maximum flexibility
754 for hardware configuration, so organizations can focus on their intellectual property, applications, and
755 value add. For more information, please visit https://foundries.io/.

756 *3.4.4.1 FoundriesFactory*

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

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

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

769 3.4.5 Kudelski IoT

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

776 *3.4.5.1 Kudelski IoT keySTREAM™*

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

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

3.4.6 NquiringMinds

NquiringMinds provides intelligent trusted systems, combining AI-powered analytics with strong 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, fintech, defense, and security sectors.

NquiringMinds collaborates extensively 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 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 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.

3.4.6.2 tdx Volt

tdx Volt is NquiringMinds's 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 integrates with the open source edgeSEC router.

3.4.7 NXP Semiconductors

NXP Semiconductors strives to enable a smarter, safer, and more sustainable world through innovation. With its focus 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 security for 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 devices.

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 Wi-Fi Alliance'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 then all the way up to things like cloud database optimization. But the most optimal cloud database is the one you don't need. 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 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 splitting that up. 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: (1) Sales Integration model, in which the intended owner is known in advance. This model requires customer-specific integrations. Often, they occur at the database level through views or other SQL tools. (2) Trust on first use (TOFU) model, in which the first customer to claim a product becomes its owner.

3.4.10 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.

3.4.10.1 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 3.4.10.2) is made through a USB serial port.

3.4.10.2 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.

3.4.10.3 xG24-DK2601B Thread "End" Device

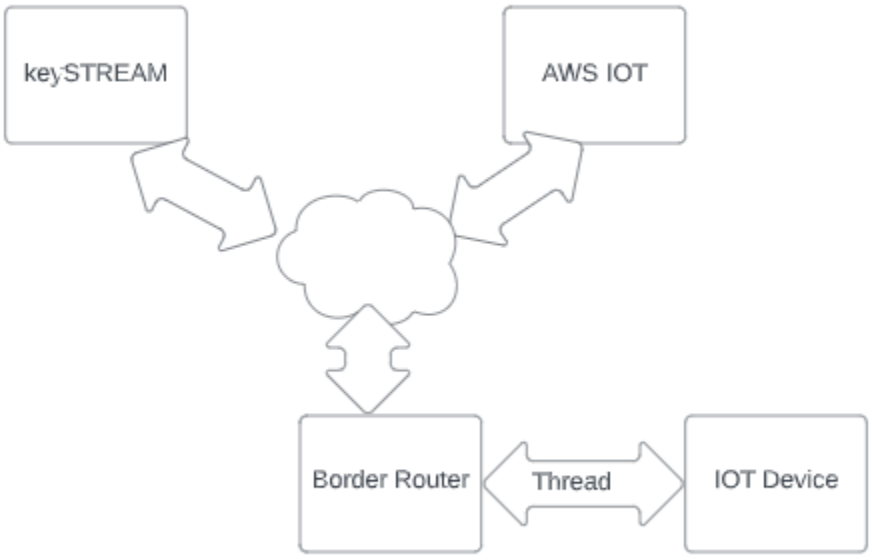
The xG24-DK2601B is the IoT device that is to be onboarded to the cloud service (AWS). It communicates using the Thread wireless protocol. Communication is bridged between the Thread network and the internet by the OTBR.

3.4.10.4 Kudelski IoT keySTREAM™

The Kudelski 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 3.4.10.3 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



3.4.11 WISeKey

WISeKey is a global cybersecurity company with over 20 years of experience deploying large-scale digital identity ecosystems for people and objects, providing trust for the connected world. WISeKey delivers secure semiconductors, digital certificates, and digital IDs, as well as Software as a Service (SaaS) platforms for proof-of-provenance, lifecycle management, and blockchain-driven traceability. WISeKey customers are typically IoT vendors in many areas, including smart buildings, smart cities, drones, agricultural sensors, anti-counterfeiting, health care sensors, servers, computers, and mobile phones.

WISeKey's Swiss-based cryptographic root of trust (RoT) provides a certificate authority for secure authentication and identification, in both physical and virtual environments, for IoT, blockchain, and AI. The WISeKey RoT serves as a common trust anchor to ensure the integrity of online transactions among objects and between objects and people.

3.4.11.1 VaultIC405

The VaultIC405 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. The hardware security protects against hardware attacks such as micro probing and side channel.

The fundamental cryptography of the VaultIC family includes the 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/IoT end node security, platform security, secure boot, secure firmware download, secure communication/TLS, data confidentiality, encryption key storage, and data integrity.

3.4.11.2 INeS Certificate Management System (CMS)

WISeKey's portfolio includes standards-based technologies to manage digital identities for people, applications, and IoT devices. WISeKey offers enterprise-level PKI to scale the number of certificates from hundreds to millions. WISeKey has a long history as a PKI technology provider and a trusted CA.

WISeKey's managed PKI (mPKI) service, called INeS CMS, provides certificate management, CA management, public cloud integration, role-based access control (RBAC), and APIs for custom implementations.

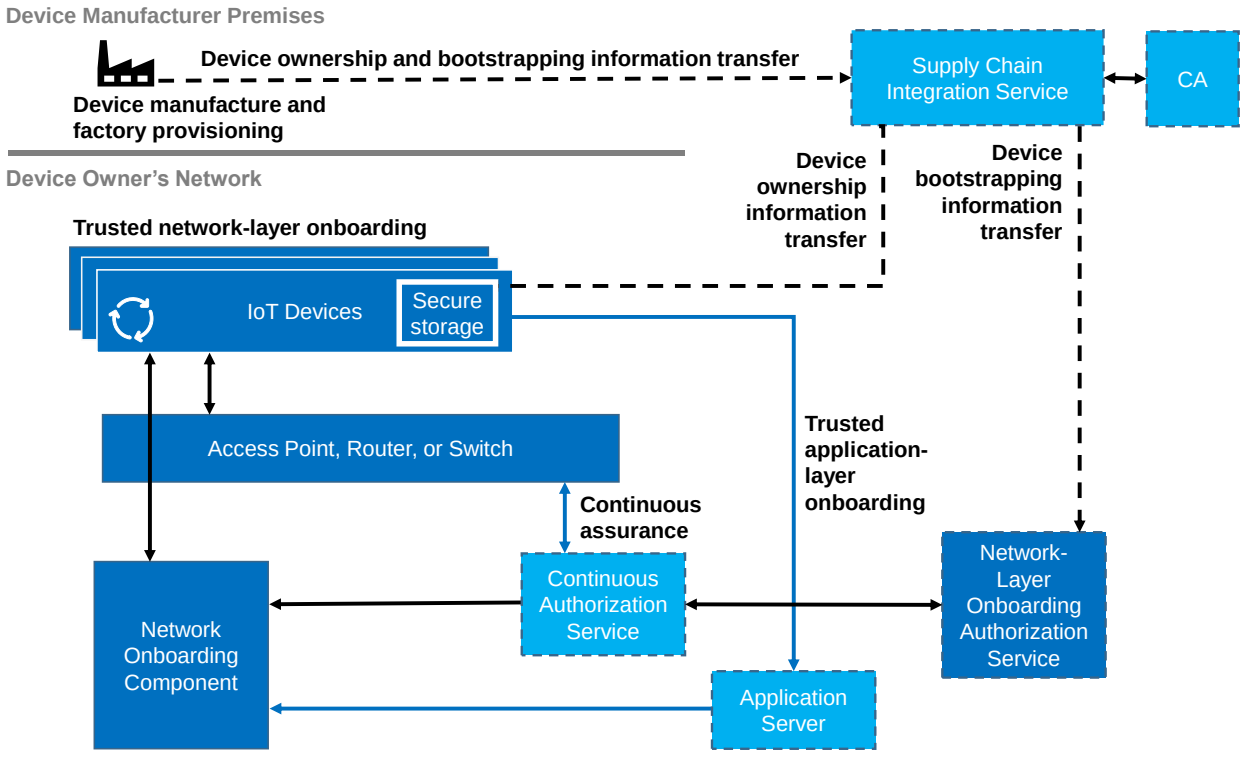
These PKI technologies support large-scale IoT deployment. The endpoints of IoT will require certificates to establish their identities. The INeS CMS platform provides a secure, scalable, and manageable trust model.

4 Reference Architecture

Figure 4-1 depicts the trusted IoT device network-layer onboarding and lifecycle management logical reference architecture. This architecture is high-level, protocol-agnostic, and generic. It is intended to illustrate the essence of trusted network-layer onboarding and lifecycle management simply and generally. It represents the basic components and processes that may be part of any trusted IoT device network-layer onboarding and lifecycle management implementation, regardless of the network-layer onboarding protocol used and the particular device lifecycle management activities supported.

The exact steps that are performed during the execution of a specific implementation of this reference architecture are more nuanced. They 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 and D we present the architectures for builds 1 and 2, 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



For explanatory purposes, we have organized the logical reference architecture according to five high-level processes, as labeled in Figure 4-1. These are the processes that must occur to achieve trusted IoT device network-layer onboarding and lifecycle management. These five processes are as follows:

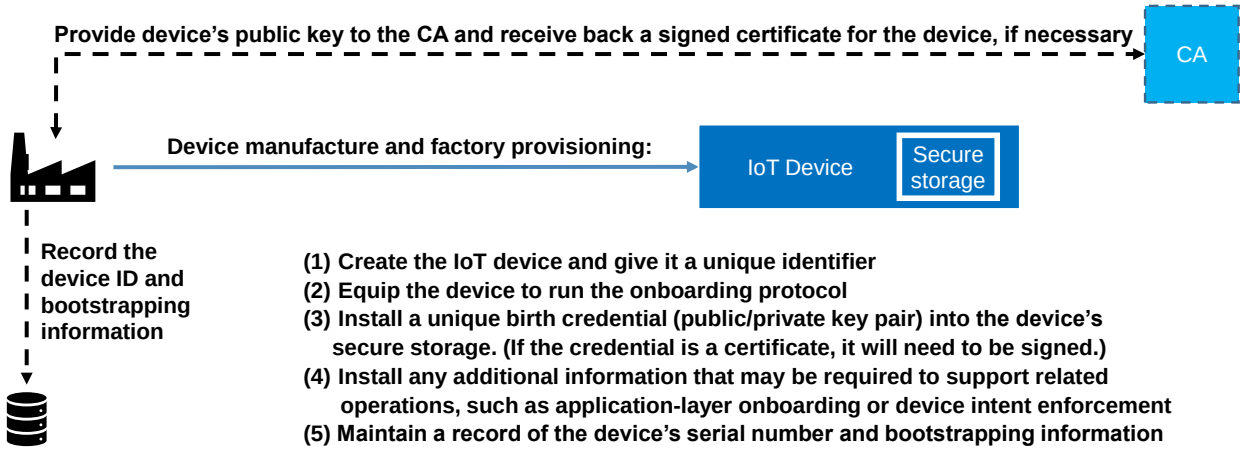
- **Device manufacture and factory provisioning** – the activities that the IoT device manufacturer must perform to prepare the IoT device so that it is capable of network- and application-layer onboarding (Figure 4-2, Section 4.1)
- **Device ownership and bootstrapping information transfer** – the transfer of IoT device ownership and bootstrapping information that must take place from the manufacturer to the device and/or the device's owner to enable 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)
- **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)
- **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)
- **Continuous assurance** – ongoing, policy-based assurance 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

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 CA component is shown in light blue because its use is optional and depends on the type of credential that is being provisioned to the device (i.e., whether or not it is an 802.1AR certificate).

1012 **Figure 4-2 IoT Device Manufacture and Factory Provisioning Process**



1013 At a high level, the steps that the manufacturer or an integrator performs as part of this preparation
1014 process, as shown in Figure 4-2, are as follows:

1015 1. Create the IoT device and assign it a unique identifier (e.g., a serial number). Equip the device
1016 with secure storage.

1017 2. Equip the device to run a specific network-layer onboarding protocol (e.g., Wi-Fi Easy Connect,
1018 BRSKI, Thread MeshCoP). This step includes ensuring that the device has the software/firmware
1019 needed to run the onboarding protocol as well as any additional information that may be
1020 required.

1021 3. Generate or install the device's unique birth credential into the device's secure storage. The
1022 birth credential includes information that must be kept secret (i.e., the device's private key)
1023 because it is what enables the device's identity to be authenticated. The contents of the birth
1024 credential will depend on what network-layer onboarding protocol the device supports. For
1025 example:

1026 a. If the device runs the Wi-Fi Easy Connect protocol, its birth credential will take the form
1027 of a unique private key, which has an associated DPP URI that includes the
1028 corresponding public key and possibly additional information such as Wi-Fi channel and
1029 serial number.

1030 b. If the device runs the BRSKI protocol, its birth credential takes the form of an 802.1AR
1031 certificate that gets installed as the device's IDevID and corresponding private key. The
1032 IDevID includes the device's public key, the location of the MASA, and trust anchors that
1033 can be used to verify vouchers signed by the MASA. The 802.1AR certificate needs to be
1034 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 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 demonstrates independent application-layer onboarding.)

    b. **device intent**, then the URI required to enable the network to locate the device's intent information will 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 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, so the manufacturer must have a record of the bootstrapping information that goes with each device. 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.

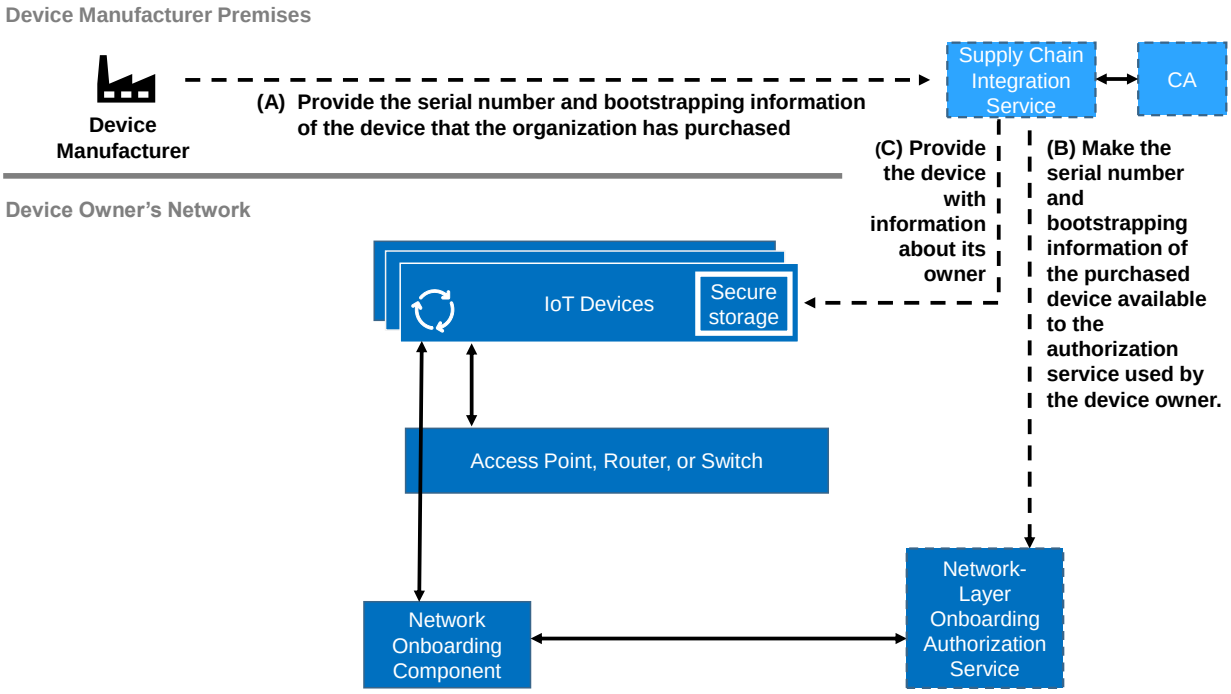
    b. If the device runs the BRSKI protocol, its bootstrapping information is its 802.1AR certificate.

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. 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 component and its 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:

A) 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 will 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. In reality, the 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 vary according to the 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).

B) The supply chain integration service forwards the device serial number and bootstrapping information to an authorization service that has connectivity to the device owner's network-layer onboarding component so that the device owner can use this information to authenticate the device and verify that it is expected and authorized to be onboarded to the device owner's network. Again, this forwarding may take many forms—e.g., enterprise case or consumer 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 device owner'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.

C) 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 manufacturer has installed

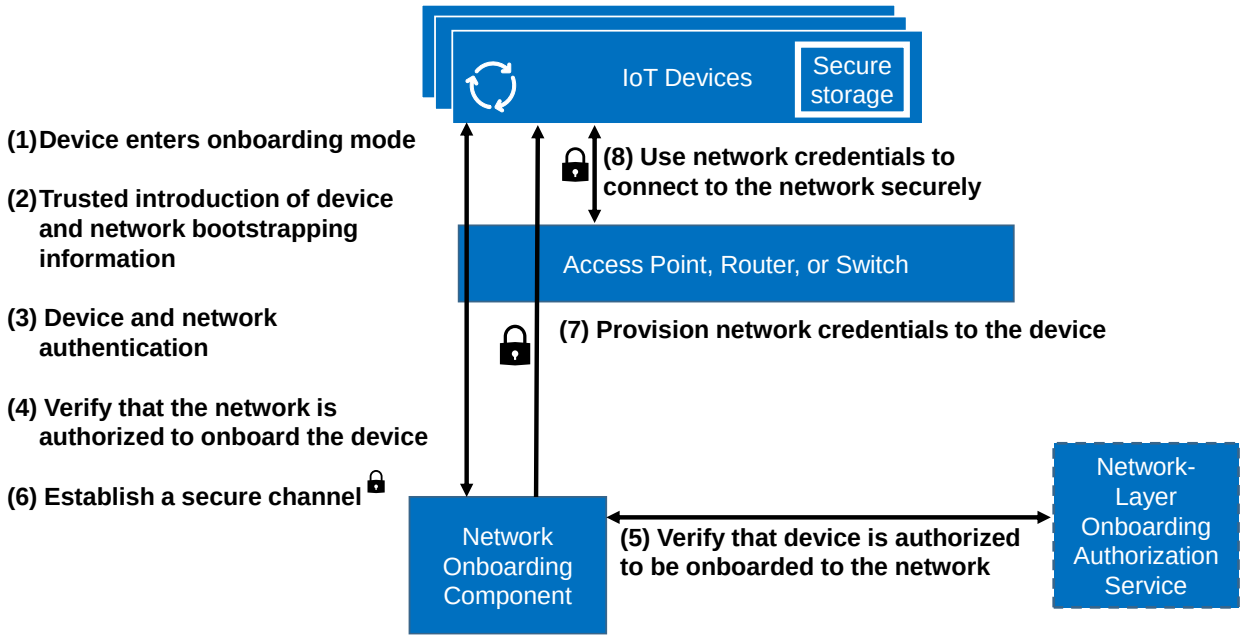
trust anchors for the MASA onto the device, the device trusts the MASA. It is also able to verify the MASA's signature.

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.

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:

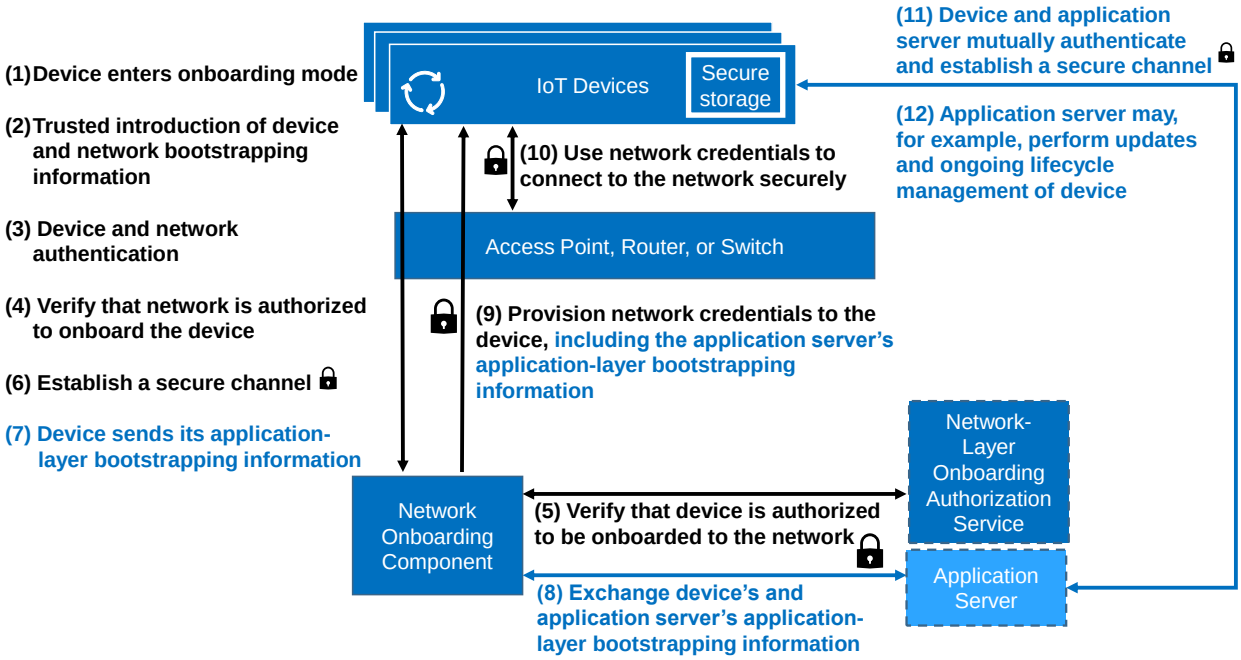
1. The IoT device to be onboarded is placed in onboarding mode, i.e., it is put into a state such that it is actively listening for and/or sending initial onboarding protocol messages.
2. Any required device bootstrapping information that has not already been provided to the network and any required 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.

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.

1172 **Figure 4-5 Trusted Streamlined Application-Layer Onboarding Process**



1173 As is the case with Figure 4-4, the steps in this diagram are assumed to occur after any device ownership
1174 and bootstrapping information transfer activities that may need to be performed. Steps 1-6 in this figure
1175 are identical to Steps 1-6 in the trusted network-layer onboarding diagram of Figure 4-4, but steps 7 and
1176 8 are different. With the completion of steps 1-6 in Figure 4-5, a secure channel has been established
1177 between the IoT device and the network-layer onboarding component. However, the device does not
1178 get provisioned with its network-layer credentials until step 9. To support streamlined application-layer
1179 onboarding, additional steps are required. Steps 1-12 are as follows:

1180 1. The IoT device to be onboarded is placed in onboarding mode, i.e., it is put into a state such that
1181 it is actively listening for and/or sending initial onboarding protocol messages.

1182 2. Any required device bootstrapping information that has not already been provided to the
1183 network and any required network bootstrapping information that has not already been
1184 provided to the device are introduced in a trusted manner.

1185 3. Using the device and network bootstrapping information that has been provided, the network
1186 authenticates the identity of the IoT device (e.g., by ensuring that the IoT device is in possession
1187 of the private key that corresponds with the public key for the device that was provided as part
1188 of the device's bootstrapping information), and the IoT device authenticates the identity of the
1189 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.

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

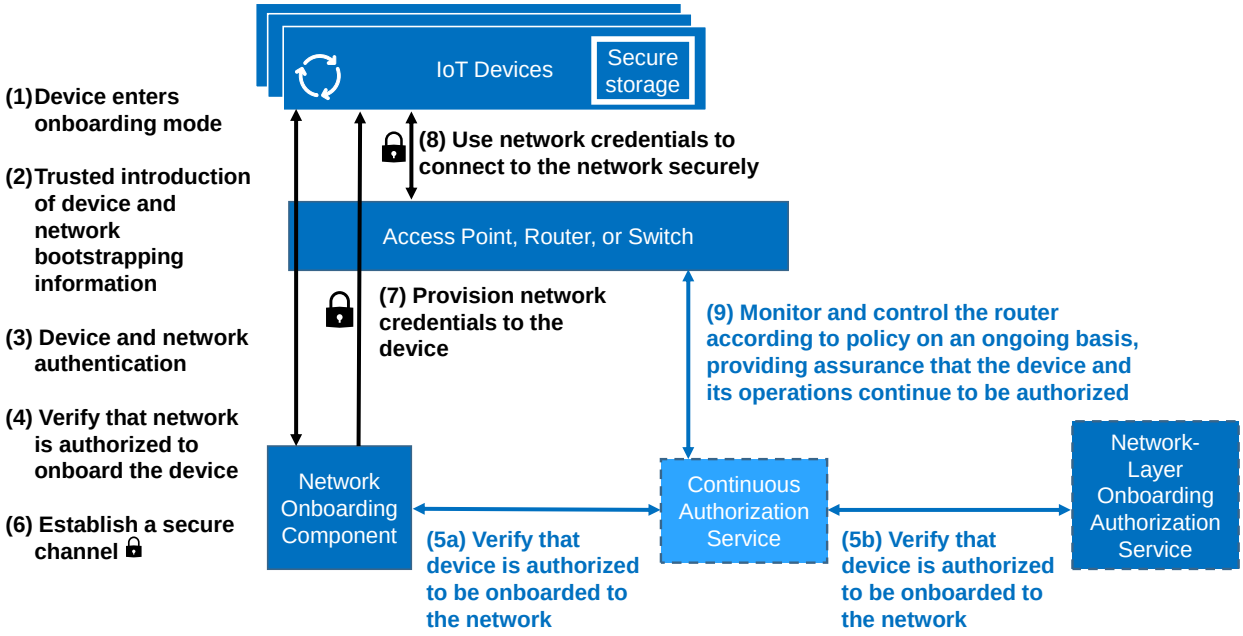
of the IoT device and the IoT device authenticates the identity of the application server. Then they establish a secure (i.e., encrypted) channel.

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 start executing. 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 Assurance

Figure 4-6 depicts the steps that are performed to support continuous assurance. 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 Assurance



When continuous assurance 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 back 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 assurance and authorization checks on the device throughout its lifecycle.

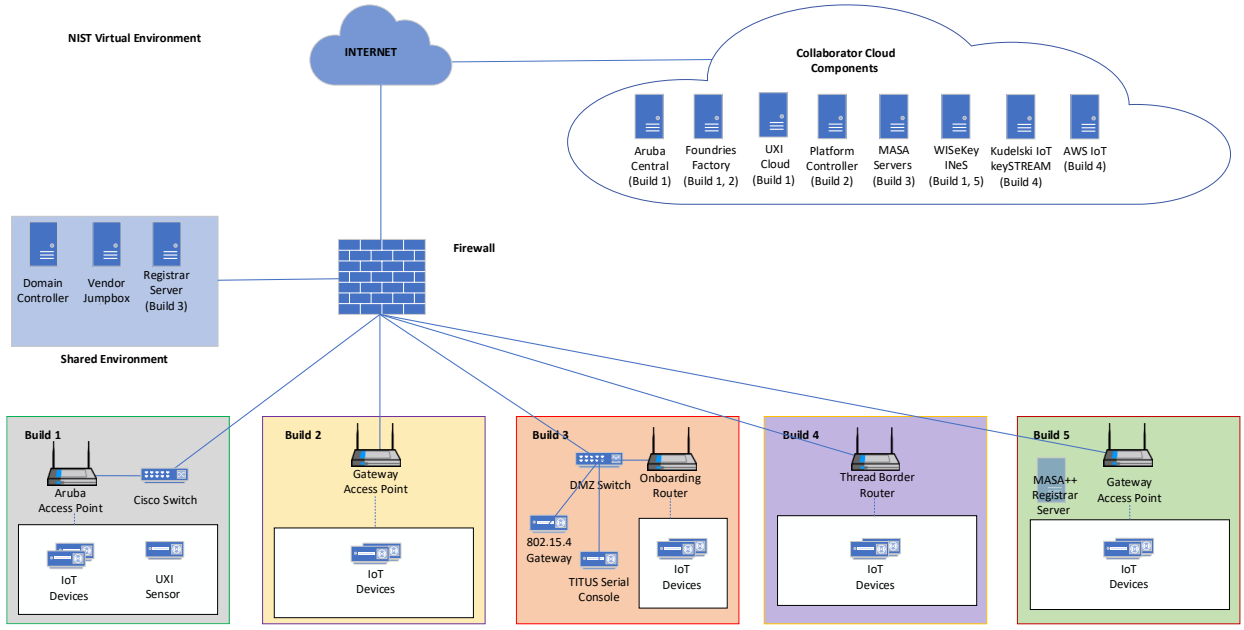
5 Laboratory Physical Architecture

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 use case build 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), Platform Controller (Build 2), a MASA server (Build 3), Kudelski keySTREAM application-layer onboarding service and AWS IoT (Build 4), and FoundriesFactory and WISeKey INeS, which we anticipate will be used across numerous builds.

1278 **Figure 5-1 NCCoE IoT Onboarding Laboratory Physical Architecture**



1279 All five network-layer onboarding laboratory environments, as depicted in the diagram, have been
1280 installed:

1281 ▪ The Build 1 network infrastructure within the NCCoE lab consists of two components: the Aruba
1282 Access Point and the Cisco Switch. Build 1 also requires support from Aruba Central for network-
1283 layer onboarding and the UXI Cloud for application-layer onboarding. These components are in
1284 the cloud and accessed via the internet. The IoT devices that are onboarded using Build 1
1285 include the UXI Sensor and the Raspberry Pi.

1286 ▪ The Build 2 network infrastructure within the NCCoE lab consists of a single component: the
1287 Gateway Access Point. Build 2 requires support from the Platform Controller, which also hosts
1288 the IoTivity Cloud Service. The IoT devices that are onboarded using Build 2 include three
1289 Raspberry Pis.

1290 ▪ The Build 3 network infrastructure components within the NCCoE lab include a Wi-Fi capable
1291 home router (including Join Proxy), a DMZ switch (for management), and an ESP32A Xtensa
1292 board acting as a Wi-Fi IoT device, as well as an nRF52840 board acting as an IEEE 802.15.4
1293 device. A management system acts as a serial console (the “titus” machine). A registrar server
1294 (“minerva-fountain”) has been deployed as a virtual appliance on the NCCoE private cloud
1295 system. Build 3 also requires support from a MASA server which is accessed via the internet. In
1296 addition, an RPI3 (“satine”) provides an ethernet/802.15.4 gateway, as well as a test platform.

- The Build 4 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 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 Thunderboard (BRD2601A) with an EFR32MG24 System-on-Chip. The application service to which it onboards is AWS IoT.
- The Build 5 network infrastructure components within the NCCoE lab include an OpenWRT router, a Turis Omnia Wi-Fi access point, the MASA++ Registration Server, and a USB hub. This build leverages the NquiringMinds' component called tdx Volt in conjunction with the RADIUS service that resides on the router to provide authentication capabilities for network-layer onboarding to take place. The IoT device that is onboarded using Build 5 is a Feather HUZAH ESP8266.

A factory use case build is also currently being planned. It will make use of the FoundriesFactory and the WISeKey INeS, both of which are in the cloud and accessible via the internet.

The details of the physical architecture of Builds 1 and 2, 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. The physical architectures of Builds 3, 4, and 5 will be described in future versions of this document when those builds are complete. The details of Builds 1 and 2 are provided in Appendix C (Build 1) and Appendix D (Build 2).

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 enabled focus to rest on each of the builds and allowed collaborators to work together throughout the build process.

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.

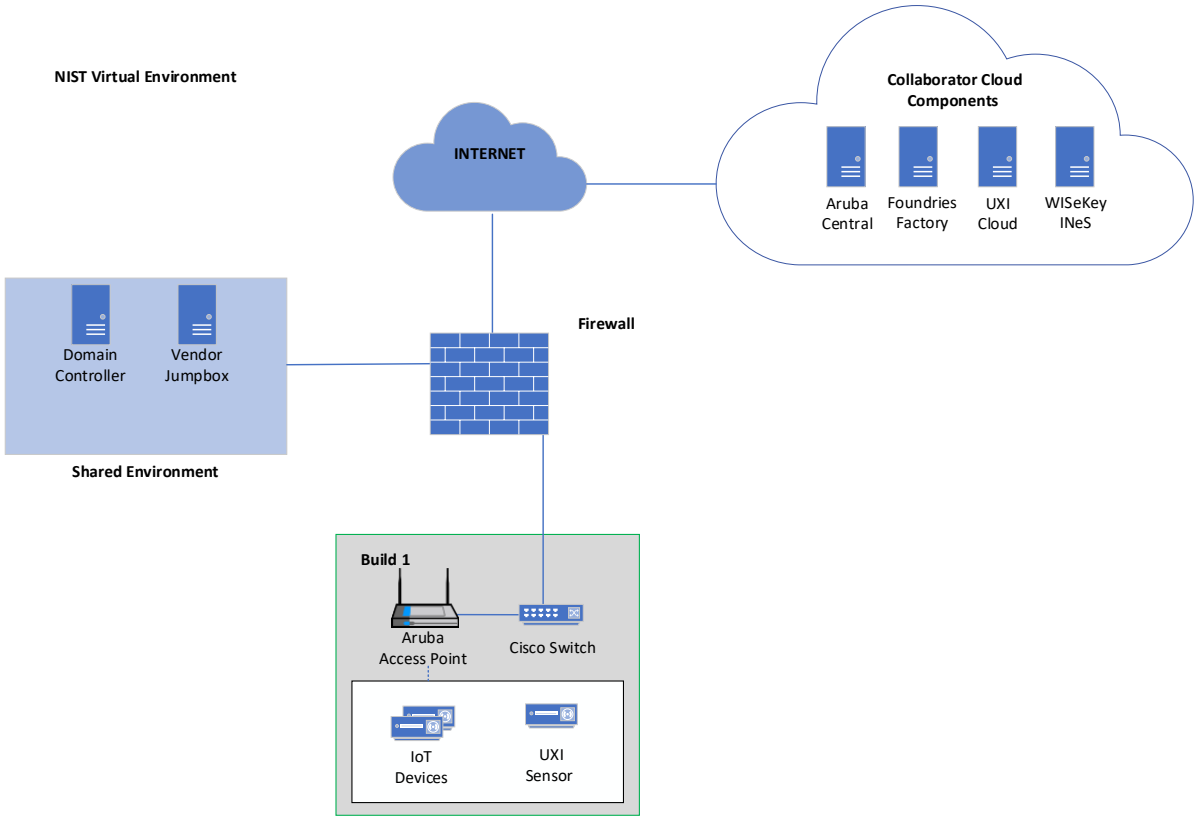
5.2 Build 1 Physical Architecture

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, 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. It also supports network segmentation.
- 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.
- FoundriesFactory and WISeKey INeS are not currently implemented in Build 1. The plan is to integrate Build 1 with the WISeKey CA (which is part of WISeKey INeS) to sign X.509 certificate credentials that Build 1 provisions to IoT devices.

1351 **Figure 5-2 Physical Architecture of Build 1**

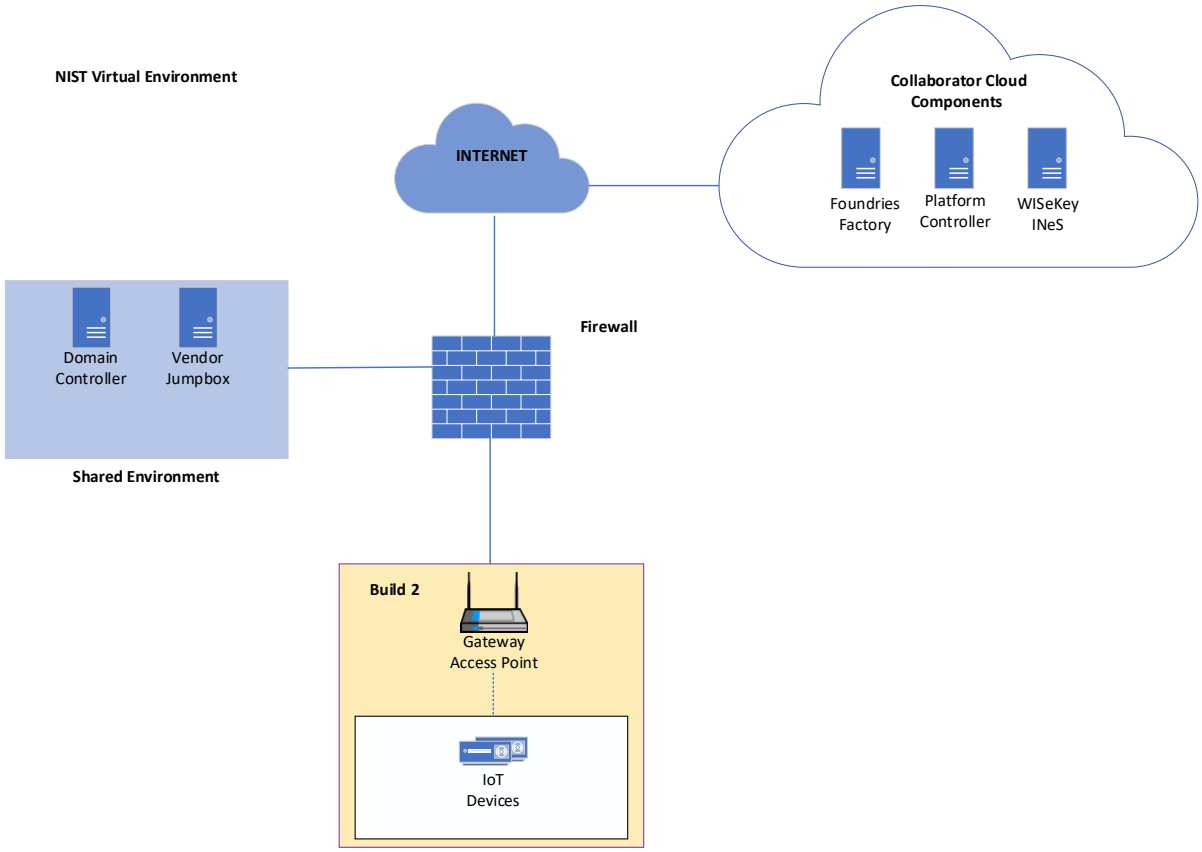


1352 5.3 Build 2 Physical Architecture

1353 Figure 5-3 is a view of the high-level physical architecture of Build 2 in the NCCoE IoT Onboarding
1354 laboratory. The Build 2 components include the Gateway Access Point, three IoT devices, and the
1355 Platform Controller, which hosts the application-layer IoTivity service.

1356 • The Gateway Access Point acts as the Custom Connectivity Gateway Agent described in Section
1357 3.4.2.2 and controls all network-layer onboarding activity within the network. It also hosts OCF
1358 IoTivity functions, such as the OCF OBT and the OCF Diplomat.
1359 • The Platform Controller described in Section 3.4.2.1 provides management capabilities for the
1360 Custom Connectivity Gateway Agent. It also hosts the application-layer IoTivity service for the
1361 IoT devices as described in Section 3.4.8.1.
1362 • The IoT devices serve as reference clients, as described in Section 3.4.2.3. They run OCF
1363 reference implementations. The IoT devices are onboarded to the network and complete both
1364 application-layer and network-layer onboarding.
1365 • FoundriesFactory and WISeKey INeS are not currently implemented in Build 2.

1366 **Figure 5-3 Physical Architecture of Build 2**



1367 5.4 Build 3 Physical Architecture

1368 The Build 3 physical architecture will be described in a future version of this document.

1369 5.5 Build 4 Physical Architecture

1370 The Build 4 physical architecture will be described in a future version of this document.

1371 5.6 Build 5 Physical Architecture

1372 The Build 5 physical architecture will be described in a future version of this document.

1373 5.7 Factory Use Case Build Physical Architecture

1374 The architecture for the factory use case is currently still being developed. It will be provided in a future
1375 version of this document.

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. Both of the builds that have been completed so far and are documented here 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.

6.2 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. In the future, if devices with user interfaces are available for use with builds 1 and 2, perhaps this capability could be demonstrated.

6.3 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 [11]. 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.

6.4 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 builds 1 and 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.

7 Future Build Considerations

In addition to the builds that have been completed and those that are in progress, future work could potentially 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. In addition, the scope of the project could potentially be expanded beyond its current focus on IP-based networks. While our goal so far has been to tackle what is currently implementable, the subsections that follow briefly discuss areas that could potentially be addressed as part of the project's future roadmap.

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 Intent

Future builds could be designed to demonstrate the use of network-layer onboarding protocols to securely transmit device intent information from the device to the network (i.e., to transmit this information in encrypted form with integrity protections). Secure conveyance of device 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 it to fulfill its purpose.

7.3 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 will 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.

7.4 Network Credential Renewal

Some devices may be provisioned 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.

7.5 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.

7.6 Attestation

Future projects 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.

7.7 Mutual Attestation

Future projects 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.

7.8 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, effectively evicting it from the network, be quarantined, or have its interaction with other devices restricted in some way.

7.9 Device Trustworthiness Scale

Perhaps in the future the project's scope could be broadened to include the additional 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.

7.10 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, the project could potentially 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.

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
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
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
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 Networking
WFA	Wi-Fi Alliance
WPA2	Wi-Fi Protected Access 2
WPA3	Wi-Fi Protected Access 3

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

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. 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

Currently, an internal, private CA is used to obtain and sign certificates when the Build 1 configurator is onboarding devices and issuing credentials for 802.1X network access. However, future plans are to integrate Build 1 with the WISeKey CA on the WISeKey INeS so that this CA can be used to obtain and sign such certificates. 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 both a network onboarding component, router, and wireless access point.

1518 **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.
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 role 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.

Component	Product	Function
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)	Private CA	Issues and signs certificates as needed.
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 these to authenticate to the UXI application, with which it interacts.
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.
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.

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).

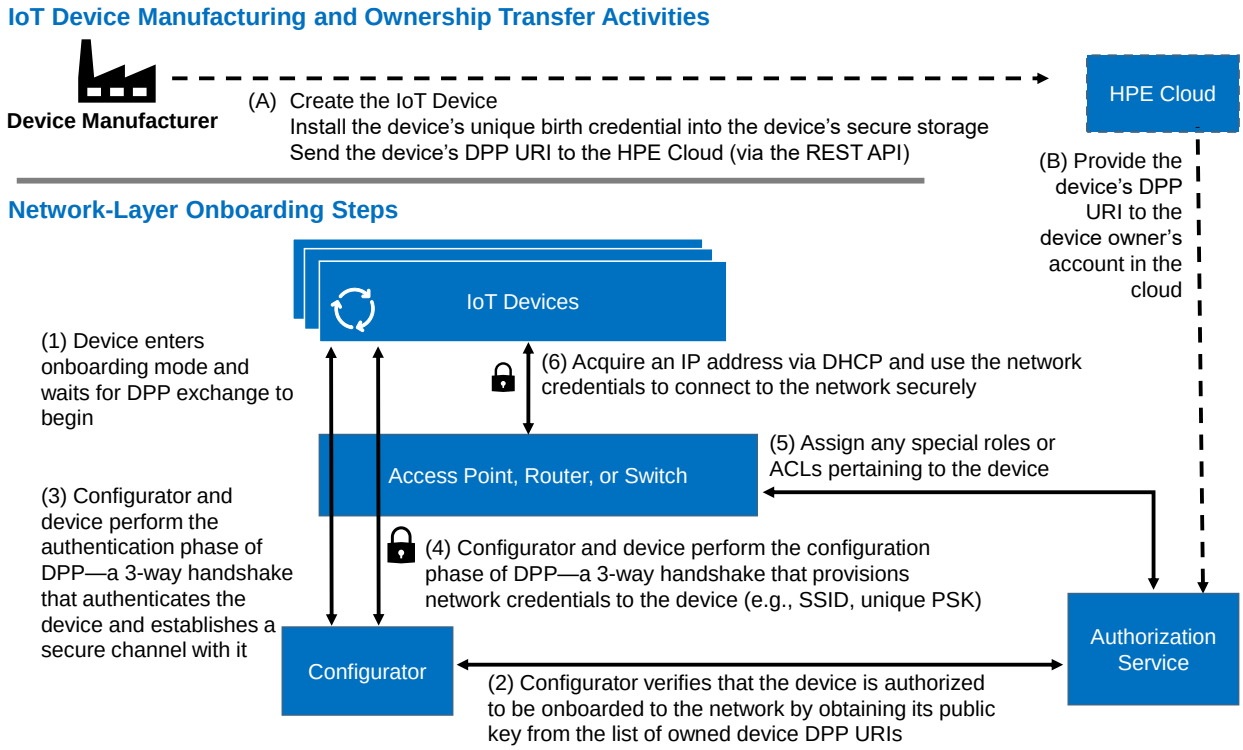
The device manufacturer:

A) 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.

B) 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 that 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

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, router, and 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: routes all traffic exchanged between IoT devices and the rest of the network 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 yet implemented)	Issues and signs certificates as needed.

Component	Product	Function
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.
Manufacturing Component	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:

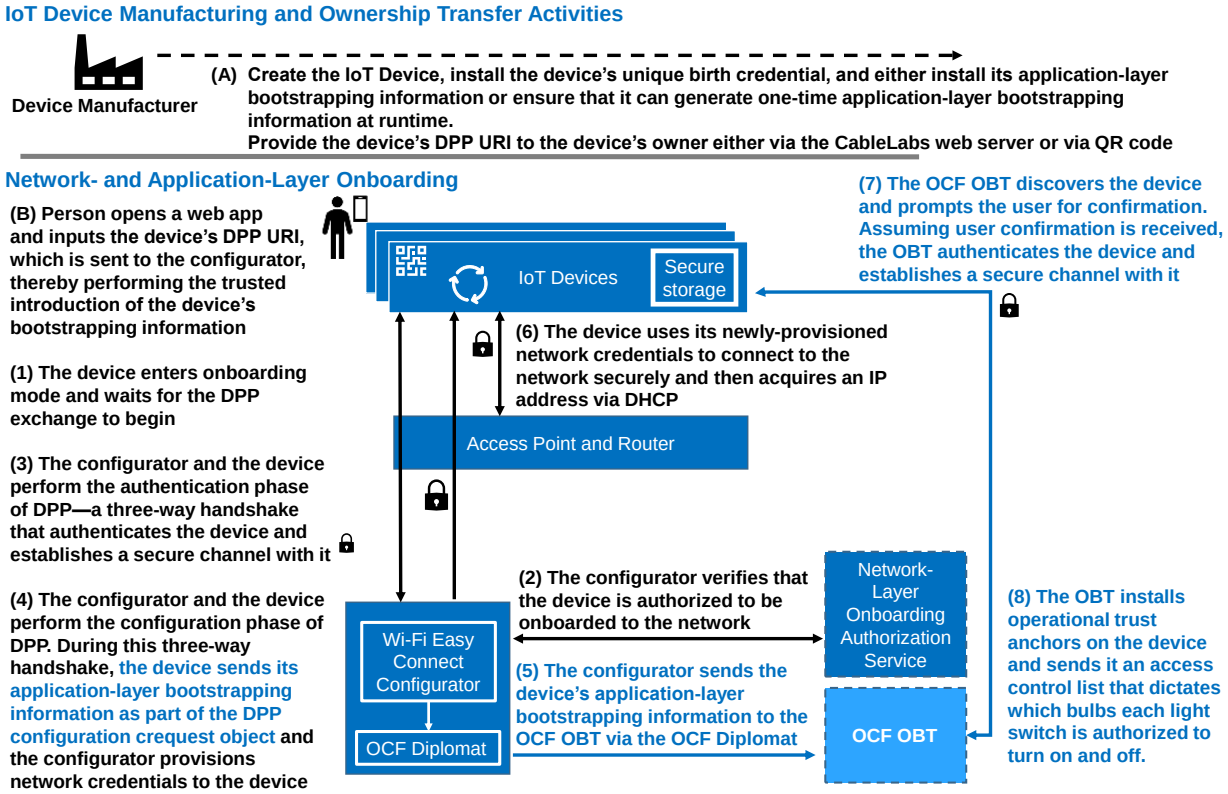
A) Creates the device and installs a unique birth credential into secure storage on the device. Because the device created for use in build 2 will also perform application-layer onboarding into the OCF security domain, as part of the manufacturing process the manufacturer also either installs application-layer 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. Figure 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.

B) 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 that 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 bi-directionally, 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 those and 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 References

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