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Secure Zero Touch Provisioning (SZTP)
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Abstract

This draft presents a technique to securely provision a networking device when it is booting in a factory-default state. Variations in the solution enables it to be used on both public and private networks. The provisioning steps are able to update the boot image, commit an initial configuration, and execute arbitrary scripts to address auxiliary needs. The updated device is subsequently able to establish secure connections with other systems. For instance, a device may establish NETCONF (RFC 6241) and/or RESTCONF (RFC 8040) connections with deployment-specific network management systems.

Editorial Note (To be removed by RFC Editor)

This draft contains many placeholder values that need to be replaced with finalized values at the time of publication. This note summarizes all of the substitutions that are needed. No other RFC Editor instructions are specified elsewhere in this document.

Artwork in the IANA Considerations section contains placeholder values for DHCP options pending IANA assignment. Please apply the following replacements:

- "TBD1" --> the assigned value for id-ct-sztpConveyedInfoXML
- "TBD2" --> the assigned value for id-ct-sztpConveyedInfoJSON
- "TBD_IANA_URL" --> the assigned URL for the IANA registry

Artwork in this document contains shorthand references to drafts in progress. Please apply the following replacements:

- "XXXX" --> the assigned numerical RFC value for this draft

Artwork in this document contains placeholder values for the date of publication of this draft. Please apply the following replacement:

- "2019-01-15" --> the publication date of this draft

The following one Appendix section is to be removed prior to publication:

- Appendix D. Change Log

Status of This Memo

Copyright Notice

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1. Introduction

A fundamental business requirement for any network operator is to reduce costs where possible. For network operators, deploying devices to many locations can be a significant cost, as sending trained specialists to each site for installations is both cost prohibitive and does not scale.

This document defines Secure Zero Touch Provisioning (SZTP), a bootstrapping strategy enabling devices to securely obtain bootstrapping data with no installer action beyond physical placement and connecting network and power cables. As such, SZTP enables non-technical personnel to bring up devices in remote locations without the need for any operator input.

The SZTP solution includes updating the boot image, committing an initial configuration, and executing arbitrary scripts to address auxiliary needs. The updated device is subsequently able to establish secure connections with other systems. For instance, a devices may establish NETCONF [RFC8040] and/or RESTCONF [RFC6241] connections with deployment-specific network management systems.

This document primarily regards physical devices, where the setting of the device's initial state, described in Section 5.1, occurs during the device's manufacturing process. The SZTP solution may be extended to support virtual machines or other such logical constructs, but details for how this can be accomplished is left for future work.

1.1. Use Cases

o Device connecting to a remotely administered network

  This use-case involves scenarios, such as a remote branch office or convenience store, whereby a device connects as an access gateway to an ISP's network. Assuming it is not possible to customize the ISP's network to provide any bootstrapping support, and with no other nearby device to leverage, the device has no recourse but to reach out to an Internet-based bootstrap server to bootstrap from.

- Device connecting to a locally administered network

  This use-case covers all other scenarios and differs only in that the device may additionally leverage nearby devices, which may direct it to use a local service to bootstrap from. If no such information is available, or the device is unable to use the information provided, it can then reach out to the network just as it would for the remotely administered network use-case.

Conceptual workflows for how SZTP might be deployed are provided in Appendix C.

1.2. Terminology

This document uses the following terms (sorted by name):

Artifact: The term "artifact" is used throughout to represent any of the three artifacts defined in Section 3 (conveyed information, ownership voucher, and owner certificate). These artifacts collectively provide all the bootstrapping data a device may use.

Bootstrapping Data: The term "bootstrapping data" is used throughout this document to refer to the collection of data that a device may obtain during the bootstrapping process. Specifically, it refers to the three artifacts conveyed information, owner certificate, and ownership voucher, as described in Section 3.

Bootstrap Server: The term "bootstrap server" is used within this document to mean any RESTCONF server implementing the YANG module defined in Section 7.3.

Conveyed Information: The term "conveyed information" is used herein to refer either redirect information or onboarding information. Conveyed information is one of the three bootstrapping artifacts described in Section 3.

Device: The term "device" is used throughout this document to refer to a network element that needs to be bootstrapped. See Section 5 for more information about devices.

Manufacturer: The term "manufacturer" is used herein to refer to the manufacturer of a device or a delegate of the manufacturer.

Network Management System (NMS): The acronym "NMS" is used throughout this document to refer to the deployment-specific management system that the bootstrapping process is responsible for introducing devices to. From a device's perspective, when

the bootstrapping process has completed, the NMS is a NETCONF or RESTCONF client.

Onboarding Information: The term "onboarding information" is used herein to refer to one of the two types of "conveyed information" defined in this document, the other being "redirect information". Onboarding information is formally defined by the "onboarding-information" YANG-data structure in Section 6.3.

Onboarding Server: The term "onboarding server" is used herein to refer to a bootstrap server that only returns onboarding information.

Owner: The term "owner" is used throughout this document to refer to the person or organization that purchased or otherwise owns a device.

Owner Certificate: The term "owner certificate" is used in this document to represent an X.509 certificate that binds an owner identity to a public key, which a device can use to validate a signature over the conveyed information artifact. The owner certificate may be communicated along with its chain of intermediate certificates leading up to a known trust anchor. The owner certificate is one of the three bootstrapping artifacts described in Section 3.

Ownership Voucher: The term "ownership voucher" is used in this document to represent the voucher artifact defined in [RFC8366]. The ownership voucher is used to assign a device to an owner. The ownership voucher is one of the three bootstrapping artifacts described in Section 3.

Redirect Information: The term "redirect information" is used herein to refer to one of the two types of "conveyed information" defined in this document, the other being "onboarding information". Redirect information is formally defined by the "redirect-information" YANG-data structure in Section 6.3.

Redirect Server: The term "redirect server" is used to refer to a bootstrap server that only returns redirect information. A redirect server is particularly useful when hosted by a manufacturer, as a well-known (e.g., Internet-based) resource to redirect devices to deployment-specific bootstrap servers.

Signed Data: The term "signed data" is used throughout to mean conveyed information that has been signed, specifically by a private key possessed by a device's owner.

Unsigned Data: The term "unsigned data" is used throughout to mean conveyed information that has not been signed.

1.3. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

1.4. Tree Diagrams

Tree diagrams used in this document follow the notation defined in [RFC8340].

2. Types of Conveyed Information

This document defines two types of conveyed information that devices can access during the bootstrapping process. These conveyed information types are described in this section. Examples are provided in Section 6.2

2.1. Redirect Information

Redirect information redirects a device to another bootstrap server. Redirect information encodes a list of bootstrap servers, each specifying the bootstrap server's hostname (or IP address), an optional port, and an optional trust anchor certificate that the device can use to authenticate the bootstrap server with.

Redirect information is YANG modeled data formally defined by the "redirect-information" container in the YANG module presented in Section 6.3. This container has the tree diagram shown below.

```
            +--:(redirect-information)
               +-- redirect-information
                  +-- bootstrap-server* [address]
                     +-- address         inet:host
                     +-- port?           inet:port-number
                     +-- trust-anchor?   cms
```

Redirect information may be trusted or untrusted. The redirect information is trusted whenever it is obtained via a secure connection to a trusted bootstrap server, or whenever it is signed by the device's owner. In all other cases, the redirect information is untrusted.

Trusted redirect information is useful for enabling a device to establish a secure connection to a specified bootstrap server, which is possible when the redirect information includes the bootstrap server's trust anchor certificate.

Untrusted redirect information is useful for directing a device to a bootstrap server where signed data has been staged for it to obtain. Note that, when the redirect information is untrusted, devices discard any potentially included trust anchor certificates.

How devices process redirect information is described in Section 5.5.

2.2. Onboarding Information

Onboarding information provides data necessary for a device to bootstrap itself and establish secure connections with other systems. As defined in this document, onboarding information can specify details about the boot image a device must be running, specify an initial configuration the device must commit, and specify scripts that the device must successfully execute.

Onboarding information is YANG modeled data formally defined by the "onboarding-information" container in the YANG module presented in Section 6.3. This container has the tree diagram shown below.

```
         +--:(onboarding-information)
            +-- onboarding-information
               +-- boot-image
               |  +-- os-name?              string
               |  +-- os-version?           string
               |  +-- download-uri*         inet:uri
               |  +-- image-verification* [hash-algorithm]
               |     +-- hash-algorithm    identityref
               |     +-- hash-value        yang:hex-string
               +-- configuration-handling?      enumeration
               +-- pre-configuration-script?    script
               +-- configuration?               binary
               +-- post-configuration-script?   script
```

Onboarding information must be trusted for it to be of any use to a device. There is no option for a device to process untrusted onboarding information.

Onboarding information is trusted whenever it is obtained via a secure connection to a trusted bootstrap server, or whenever it is signed by the device's owner. In all other cases, the onboarding information is untrusted.

How devices process onboarding information is described in Section 5.6.

3. Artifacts

This document defines three artifacts that can be made available to devices while they are bootstrapping. Each source of bootstrapping data specifies how it provides the artifacts defined in this section (see Section 4).

3.1. Conveyed Information

The conveyed information artifact encodes the essential bootstrapping data for the device. This artifact is used to encode the redirect information and onboarding information types discussed in Section 2.

The conveyed information artifact is a CMS structure, as described in [RFC5652], encoded using ASN.1 distinguished encoding rules (DER), as specified in ITU-T X.690 [ITU.X690.2015]. The CMS structure MUST contain content conforming to the YANG module specified in Section 6.3.

The conveyed information CMS structure may encode signed or unsigned bootstrapping data. When the bootstrapping data is signed, it may also be encrypted but, from a terminology perspective, it is still "signed data" Section 1.2.

When the conveyed information artifact is unsigned, as it might be when communicated over trusted channels, the CMS structure's top-most content type MUST be one of the OIDs described in Section 10.3 (i.e., id-ct-sztpConveyedInfoXML or id-ct-sztpConveyedInfoJSON), or the OID id-data (1.2.840.113549.1.7.1). When the OID id-data is used, the encoding (JSON, XML, etc.) SHOULD be communicated externally. In either case, the associated content is an octet string containing "conveyed-information" data in the expected encoding.

When the conveyed information artifact is unsigned and encrypted, as it might be when communicated over trusted channels but, for some reason, the operator wants to ensure that only the device is able to see the contents, the CMS structure's top-most content type MUST be the OID id-envelopedData (1.2.840.113549.1.7.3). Furthermore, the encryptedContentInfo's content type MUST be one of the OIDs described in Section 10.3 (i.e., id-ct-sztpConveyedInfoXML or id-ct-sztpConveyedInfoJSON), or the OID id-data (1.2.840.113549.1.7.1). When the OID id-data is used, the encoding (JSON, XML, etc.) SHOULD be communicated externally. In either case, the associated content is an octet string containing "conveyed-information" data in the expected encoding.

When the conveyed information artifact is signed, as it might be when communicated over untrusted channels, the CMS structure's top-most content type MUST be the OID id-signedData (1.2.840.113549.1.7.2). Furthermore, the inner eContentType MUST be one of the OIDs described in Section 10.3 (i.e., id-ct-sztpConveyedInfoXML or id-ct-sztpConveyedInfoJSON), or the OID id-data (1.2.840.113549.1.7.1). When the OID id-data is used, the encoding (JSON, XML, etc.) SHOULD be communicated externally. In either case, the associated content or eContent is an octet string containing "conveyed-information" data in the expected encoding.

When the conveyed information artifact is signed and encrypted, as it might be when communicated over untrusted channels and privacy is important, the CMS structure's top-most content type MUST be the OID id-envelopedData (1.2.840.113549.1.7.3). Furthermore, the encryptedContentInfo's content type MUST be the OID id-signedData (1.2.840.113549.1.7.2), whose eContentType MUST be one of the OIDs described in Section 10.3 (i.e., id-ct-sztpConveyedInfoXML or id-ct-sztpConveyedInfoJSON), or the OID id-data (1.2.840.113549.1.7.1). When the OID id-data is used, the encoding (JSON, XML, etc.) SHOULD be communicated externally. In either case, the associated content or eContent is an octet string containing "conveyed-information" data in the expected encoding.

3.2. Owner Certificate

The owner certificate artifact is an X.509 certificate [RFC5280] that is used to identify an "owner" (e.g., an organization). The owner certificate can be signed by any certificate authority (CA). The owner certificate either MUST have no Key Usage specified or the Key Usage MUST at least set the "digitalSignature" bit. The values for the owner certificate's "subject" and/or "subjectAltName" are not constrained by this document.

The owner certificate is used by a device to verify the signature over the conveyed information artifact (Section 3.1) that the device should have also received, as described in Section 3.5. In particular, the device verifies the signature using the public key in the owner certificate over the content contained within the conveyed information artifact.

The owner certificate artifact is formally a CMS structure, as specified by [RFC5652], encoded using ASN.1 distinguished encoding rules (DER), as specified in ITU-T X.690 [ITU.X690.2015].

The owner certificate CMS structure MUST contain the owner certificate itself, as well as all intermediate certificates leading to the "pinned-domain-cert" certificate specified in the ownership

voucher. The owner certificate artifact MAY optionally include the "pinned-domain-cert" as well.

In order to support devices deployed on private networks, the owner certificate CMS structure MAY also contain suitably fresh, as determined by local policy, revocation objects (e.g., CRLs). Having these revocation objects stapled to the owner certificate may obviate the need for the device to have to download them dynamically using the CRL distribution point or an OCSP responder specified in the associated certificates.

When unencrypted, the owner certificate artifact's CMS structure's top-most content type MUST be the OID id-signedData (1.2.840.113549.1.7.2). The inner SignedData structure is the degenerate form, whereby there are no signers, that is commonly used to disseminate certificates and revocation objects.

When encrypted, the owner certificate artifact's CMS structure's top-most content type MUST be the OID id-envelopedData (1.2.840.113549.1.7.3), and the encryptedContentInfo's content type MUST be the OID id-signedData (1.2.840.113549.1.7.2), whereby the inner SignedData structure is the degenerate form that has no signers commonly used to disseminate certificates and revocation objects.

3.3. Ownership Voucher

The ownership voucher artifact is used to securely identify a device's owner, as it is known to the manufacturer. The ownership voucher is signed by the device's manufacturer.

The ownership voucher is used to verify the owner certificate (Section 3.2) that the device should have also received, as described in Section 3.5. In particular, the device verifies that the owner certificate has a chain of trust leading to the trusted certificate included in the ownership voucher ("pinned-domain-cert"). Note that this relationship holds even when the owner certificate is a self-signed certificate, and hence also the pinned-domain-cert.

When unencrypted, the ownership voucher artifact is as defined in [RFC8366]. As described, it is a CMS structure whose top-most content type MUST be the OID id-signedData (1.2.840.113549.1.7.2), whose eContentType MUST be OID id-ct-animaJSONVoucher (1.2.840.113549.1.9.16.1), or the OID id-data (1.2.840.113549.1.7.1). When the OID id-data is used, the encoding (JSON, XML, etc.) SHOULD be communicated externally. In either case, the associated content is an octet string containing ietf-voucher data in the expected encoding.

When encrypted, the ownership voucher artifact's CMS structure's top-most content type MUST be the OID id-envelopedData (1.2.840.113549.1.7.3), and the encryptedContentInfo's content type MUST be the OID id-signedData (1.2.840.113549.1.7.2), whose eContentType MUST be OID id-ct-animaJSONVoucher (1.2.840.113549.1.9.16.1), or the OID id-data (1.2.840.113549.1.7.1). When the OID id-data is used, the encoding (JSON, XML, etc.) SHOULD be communicated externally. In either case, the associated content is an octet string containing ietf-voucher data in the expected encoding.

3.4. Artifact Encryption

Each of the three artifacts MAY be individually encrypted. Encryption may be important in some environments where the content is considered sensitive.

Each of the three artifacts are encrypted in the same way, by the unencrypted form being encapsulated inside a CMS EnvelopedData type.

As a consequence, both the conveyed information and ownership voucher artifacts are signed and then encrypted, never encrypted and then signed.

This sequencing has the advantage of shrouding the signer's certificate, and ensuring that the owner knows the content being signed. This sequencing further enables the owner to inspect an unencrypted voucher obtained from a manufacturer and then encrypt the voucher later themselves, perhaps while also stapling in current revocation objects, when ready to place the artifact in an unsafe location.

When encrypted, the CMS MUST be encrypted using a secure device identity certificate for the device. This certificate MAY be the same as the TLS-level client certificate the device uses when connecting to bootstrap servers. The owner must possess the device's identity certificate at the time of encrypting the data. How the owner comes to posses the device's identity certificate for this purpose is outside the scope of this document.

3.5. Artifact Groupings

The previous sections discussed the bootstrapping artifacts, but only certain groupings of these artifacts make sense to return in the various bootstrapping situations described in this document. These groupings are:

Unsigned Data: This artifact grouping is useful for cases when transport level security can be used to convey trust (e.g., HTTPS), or when the conveyed information can be processed in a provisional manner (i.e. unsigned redirect information).

Signed Data, without revocations: This artifact grouping is useful when signed data is needed (i.e., because the data is obtained from an untrusted source and it cannot be processed provisionally) and either revocations are not needed or the revocations can be obtained dynamically.

Signed Data, with revocations: This artifact grouping is useful when signed data is needed (i.e., because the data is obtained from an untrusted source and it cannot be processed provisionally), and revocations are needed, and the revocations cannot be obtained dynamically.

The presence of each artifact, and any distinguishing characteristics, are identified for each artifact grouping in the table below ("yes/no" regards if the artifact is present in the artifact grouping):

Artifact Grouping	Conveyed Information	Ownership Voucher	Owner Certificate
Unsigned Data	Yes, no sig	No	No
Signed Data, without revocations	Yes, with sig	Yes, without revocations	Yes, without revocations
Signed Data, with revocations	Yes, with sig	Yes, with revocations	Yes, with revocations

4. Sources of Bootstrapping Data

This section defines some sources for bootstrapping data that a device can access. The list of sources defined here is not meant to be exhaustive. It is left to future documents to define additional sources for obtaining bootstrapping data.

For each source of bootstrapping data defined in this section, details are given for how the three artifacts listed in Section 3 are provided.

4.1. Removable Storage

A directly attached removable storage device (e.g., a USB flash drive) MAY be used as a source of SZTP bootstrapping data.

Use of a removable storage device is compelling, as it does not require any external infrastructure to work. It is notable that the raw boot image file can also be located on the removable storage device, enabling a removable storage device to be a fully self-standing bootstrapping solution.

To use a removable storage device as a source of bootstrapping data, a device need only detect if the removable storage device is plugged in and mount its filesystem.

A removable storage device is an untrusted source of bootstrapping data. This means that the information stored on the removable storage device either MUST be signed or MUST be information that can be processed provisionally (e.g., unsigned redirect information).

From an artifact perspective, since a removable storage device presents itself as a filesystem, the bootstrapping artifacts need to be presented as files. The three artifacts defined in Section 3 are mapped to files below.

Artifact to File Mapping:

- Conveyed Information: Mapped to a file containing the binary artifact described in Section 3.1 (e.g., conveyed-information.cms).

- Owner Certificate: Mapped to a file containing the binary artifact described in Section 3.2 (e.g., owner-certificate.cms).

- Ownership Voucher: Mapped to a file containing the binary artifact described in Section 3.3 (e.g., ownership-voucher.cms or ownership-voucher.vcj).

The format of the removable storage device's filesystem and the naming of the files are outside the scope of this document. However, in order to facilitate interoperability, it is RECOMMENDED devices support open and/or standards based filesystems. It is also RECOMMENDED that devices assume a file naming convention that enables more than one instance of bootstrapping data (i.e., for different devices) to exist on a removable storage device. The file naming convention SHOULD additionally be unique to the manufacturer, in

order to enable bootstrapping data from multiple manufacturers to exist on a removable storage device.

4.2. DNS Server

A DNS server MAY be used as a source of SZTP bootstrapping data.

Using a DNS server may be a compelling option for deployments having existing DNS infrastructure, as it enables a touchless bootstrapping option that does not entail utilizing an Internet based resource hosted by a 3rd-party.

DNS is an untrusted source of bootstrapping data. Even if DNSSEC [RFC6698] is used to authenticate the various DNS resource records (e.g., A, AAAA, CERT, TXT, and TLSA), the device cannot be sure that the domain returned to it from e.g., a DHCP server, belongs to its rightful owner. This means that the information stored in the DNS records either MUST be signed (per this document, not DNSSEC), or MUST be information that can be processed provisionally (e.g., unsigned redirect information).

4.2.1. DNS Queries

Devices claiming to support DNS as a source of bootstrapping data MUST first query for device-specific DNS records and, only if doing so does not result in a successful bootstrap, then MUST query for device-independent DNS records.

For each of the device-specific and device-independent queries, devices MUST first query using multicast DNS [RFC6762] and, only if doing so does not result in a successful bootstrap, then MUST query again using unicast DNS [RFC1035] [RFC7766], assuming the address of a DNS server is known, such as it may be using techniques similar to those described in Section 11 of [RFC6763], which is referenced a few times in this document, even though this document does not itself use DNS-SD (RFC 6763 is identified herein as an Informative reference).

When querying for device-specific DNS records, devices MUST query for TXT records [RFC1035] under "<serial-number>._sztp", where <serial-number> is the device's serial number (the same value as in the device's secure device identity certificate), and "_sztp" is the globally scoped DNS attribute registered by this document in Section 10.7.

Example device-specific DNS record queries:

```
TXT in <serial-number>._sztp.local.  (multicast)
TXT in <serial-number>._sztp.<domain>.  (unicast)
```

When querying for device-independent DNS records, devices MUST query for SRV records [RFC2782] under "_sztp._tcp", where "_sztp" is the service name registered by this document in Section 10.6, and "_tcp" is the globally scoped DNS attribute registered by [I-D.ietf-dnsop-attrleaf].

Note that a device-independent response is anyway only able to encode unsigned data, since signed data necessitates the use of a device-specific ownership voucher. Use of SRV records maximumly leverages existing DNS standards. A response containing multiple SRV records is comparable to an unsigned redirect information's list of bootstrap servers.

Example device-independent DNS record queries:

```
SRV in _sztp._tcp.local.  (multicast)
SRV in _sztp._tcp.<domain>.  (unicast)
```

4.2.2. DNS Response for Device-Specific Queries

For device-specific queries, the three bootstrapping artifacts defined in Section 3 are encoded into the TXT records using key/value pairs, similar to the technique described in Section 6.3 of [RFC6763].

Artifact to TXT Record Mapping:

Conveyed Information: Mapped to a TXT record having the key "ci" and the value being the binary artifact described in Section 3.1.

Owner Certificate: Mapped to a TXT record having the key "oc" and the value being the binary artifact described in Section 3.2.

Ownership Voucher: Mapped to a TXT record having the key "ov" and the value being the binary artifact described in Section 3.3.

Devices MUST ignore any other keys that may be returned.

Note that, despite the name, TXT records can and SHOULD (per Section 6.5 of [RFC6763]) encode binary data.

Following is an example of a device-specific response, as it might be presented by a user-agent, containing signed data. This example assumes that the device's serial number is "<serial-number>", the domain is "example.com", and that "<binary data>" represents the binary artifact:

```
<serial-number>._sztp.example.com. 3600 IN TXT "ci=<binary data>"
<serial-number>._sztp.example.com. 3600 IN TXT "oc=<binary data>"
<serial-number>._sztp.example.com. 3600 IN TXT "ov=<binary data>"
```

Note that, in the case that "ci" encodes unsigned data, the "oc" and "ov" keys would not be present in the response.

4.2.3. DNS Response for Device-Independent Queries

For device-independent queries, the three bootstrapping artifacts defined in Section 3 are encoded into the SVR records as follows.

Artifact to SRV Record Mapping:

Conveyed Information: This artifact is not supported directly. Instead, the essence of unsigned redirect information is mapped to SVR records per [RFC2782].

Owner Certificate: Not supported. Device-independent responses are never encode signed data, and hence there is no need for an owner certificate artifact.

Ownership Voucher: Not supported. Device-independent responses are never encode signed data, and hence there is no need for an ownership voucher artifact.

Following is an example of a device-independent response, as it might be presented by a user-agent, containing (effectively) unsigned redirect information to four bootstrap servers. This example assumes that the domain is "example.com" and that there are four bootstrap servers "sztp[1-4]":

```
_sztp._tcp.example.com. 1800 IN SRV 0 0 443 sztp1.example.com.
_sztp._tcp.example.com. 1800 IN SRV 1 0 443 sztp2.example.com.
_sztp._tcp.example.com. 1800 IN SRV 2 0 443 sztp3.example.com.
_sztp._tcp.example.com. 1800 IN SRV 2 0 443 sztp4.example.com.
```

Note that, in this example, "sztp3" and "sztp4" have equal priority, and hence effectively represent a clustered pair of bootstrap servers. While "sztp1" and "sztp2" only have a single SRV record each, it may be that the record points to a load-balancer fronting a cluster of bootstrap servers.

While this document does not use DNS-SD [RFC6763], per Section 12.2 of that RFC, mDNS responses SHOULD also include all address records (type "A" and "AAAA") named in the SRV rdata.

4.2.4. Size of Signed Data

The signed data artifacts are large by DNS conventions. In the smallest-footprint scenario, they are each a few kilobytes in size. However, onboarding information can easily be several kilobytes in size, and has the potential to be many kilobytes in size.

All resource records, including TXT records, have an upper size limit of 65535 bytes, since "RDLENGTH" is a 16-bit field (Section 3.2.1 in [RFC1035]). If it is ever desired to encode onboarding information that exceeds this limit, the DNS records returned should instead encode redirect information, to direct the device to a bootstrap server from which the onboarding information can be obtained.

Given the expected size of the TXT records, it is unlikely that signed data will fit into a UDP-based DNS packet, even with the EDNS(0) Extensions [RFC6891] enabled. Depending on content, signed data may also not fit into a multicast DNS packet, which bounds the size to 9000 bytes, per Section 17 in [RFC6762]. Thus it is expected that DNS Transport over TCP [RFC7766] will be required in order to return signed data.

4.3. DHCP Server

A DHCP server MAY be used as a source of SZTP bootstrapping data.

Using a DHCP server may be a compelling option for deployments having existing DHCP infrastructure, as it enables a touchless bootstrapping option that does not entail utilizing an Internet based resource hosted by a 3rd-party.

A DHCP server is an untrusted source of bootstrapping data. Thus the information stored on the DHCP server either MUST be signed, or it MUST be information that can be processed provisionally (e.g., unsigned redirect information).

However, unlike other sources of bootstrapping data described in this document, the DHCP protocol (especially DHCP for IPv4) is very limited in the amount of data that can be conveyed, to the extent that signed data cannot be communicated. This means that only unsigned redirect information can be conveyed via DHCP.

Since the redirect information is unsigned, it SHOULD NOT include the optional trust anchor certificate, as it takes up space in the DHCP message, and the device would have to discard it anyway. For this reason, the DHCP options defined in Section 8 do not enable the trust anchor certificate to be encoded.

From an artifact perspective, the three artifacts defined in Section 3 are mapped to the DHCP fields specified in Section 8 as follows.

Artifact to DHCP Option Fields Mapping:

Conveyed Information: This artifact is not supported directly. Instead, the essence of unsigned redirect information is mapped to the DHCP options described in Section 8.

Owner Certificate: Not supported. There is not enough space in the DHCP packet to hold an owner certificate artifact.

Ownership Voucher: Not supported. There is not enough space in the DHCP packet to hold an ownership voucher artifact.

4.4. Bootstrap Server

A bootstrap server MAY be used as a source of SZTP bootstrapping data. A bootstrap server is defined as a RESTCONF [RFC8040] server implementing the YANG module provided in Section 7.

Using a bootstrap server as a source of bootstrapping data is a compelling option as it MAY use transport-level security, obviating the need for signed data, which may be easier to deploy in some situations.

Unlike any other source of bootstrapping data described in this document, a bootstrap server is not only a source of data, but it can also receive data from devices using the YANG-defined "report-progress" RPC defined in the YANG module (Section 7.3). The "report-progress" RPC enables visibility into the bootstrapping process (e.g., warnings and errors), and provides potentially useful information upon completion (e.g., the device's SSH host-keys).

A bootstrap server may be a trusted or an untrusted source of bootstrapping data, depending on if the device learned about the bootstrap server's trust anchor from a trusted source. When a bootstrap server is trusted, the conveyed information returned from it MAY be signed. When the bootstrap server is untrusted, the conveyed information either MUST be signed or MUST be information that can be processed provisionally (e.g., unsigned redirect information).

From an artifact perspective, since a bootstrap server presents data conforming to a YANG data model, the bootstrapping artifacts need to be mapped to YANG nodes. The three artifacts defined in Section 3

are mapped to "output" nodes of the "get-bootstrapping-data" RPC defined in Section 7.3 below.

Artifact to Bootstrap Server Mapping:

Conveyed Information: Mapped to the "conveyed-information" leaf in the output of the "get-bootstrapping-data" RPC.

Owner Certificate: Mapped to the "owner-certificate" leaf in the output of the "get-bootstrapping-data" RPC.

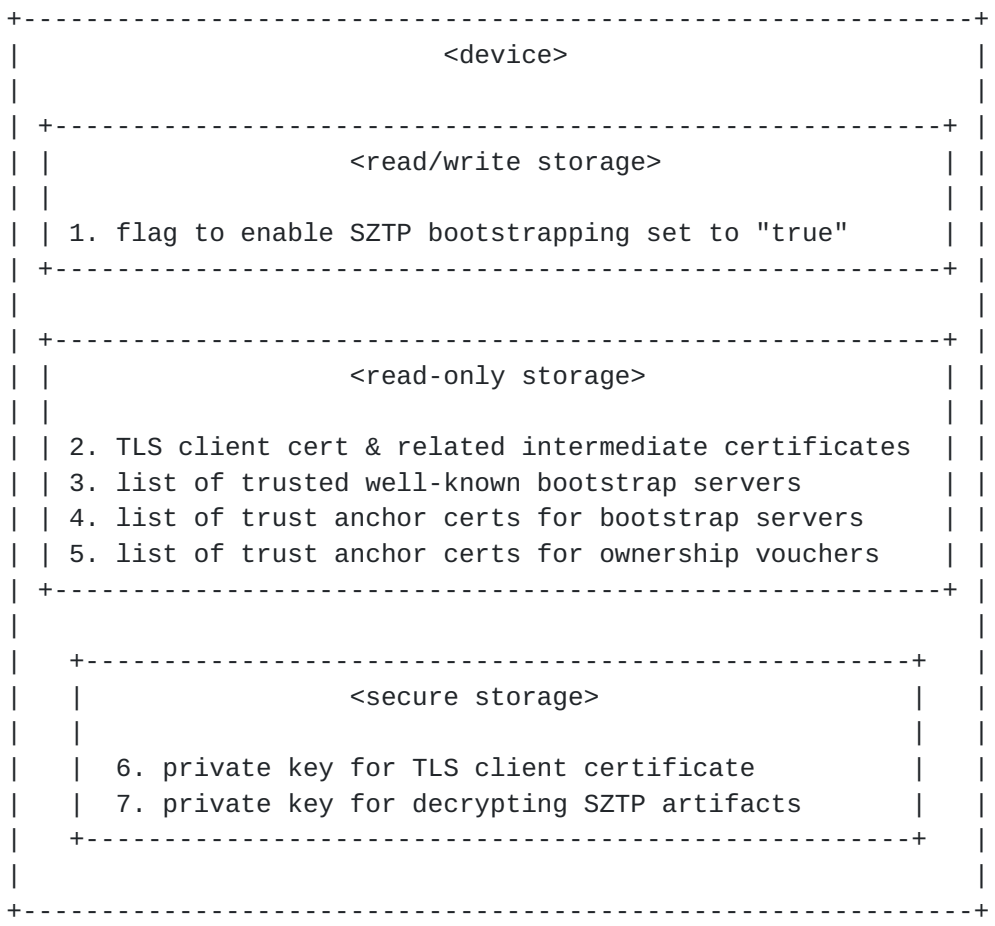
Ownership Voucher: Mapped to the "ownership-voucher" leaf in the output of the "get-bootstrapping-data" RPC.

SZTP bootstrap servers have only two endpoints, one for the "get-bootstrapping-data" RPC and one for the "report-progress" RPC. These RPCs use the authenticated RESTCONF username to isolate the execution of the RPC from other devices.

5. Device Details

Devices supporting the bootstrapping strategy described in this document MUST have the preconfigured state and bootstrapping logic described in the following sections.

5.1. Initial State



Each numbered item below corresponds to a numbered item in the diagram above.

1. Devices MUST have a configurable variable that is used to enable/disable SZTP bootstrapping. This variable MUST be enabled by default in order for SZTP bootstrapping to run when the device first powers on. Because it is a goal that the configuration installed by the bootstrapping process disables SZTP bootstrapping, and because the configuration may be merged into the existing configuration, using a configuration node that relies on presence is NOT RECOMMENDED, as it cannot be removed by the merging process.

2. Devices that support loading bootstrapping data from bootstrap servers (see Section 4.4) SHOULD possess a TLS-level client certificate and any intermediate certificates leading to the certificate's well-known trust-anchor. The well-known trust anchor certificate may be an intermediate certificate or a self-signed root certificate. To support devices not having a client certificate, devices MAY, alternatively or in addition to, identify and authenticate themselves to the bootstrap server

using an HTTP authentication scheme, as allowed by Section 2.5 in [RFC8040]; however, this document does not define a mechanism for operator input enabling, for example, the entering of a password.

3. Devices that support loading bootstrapping data from well-known bootstrap servers MUST possess a list of the well-known bootstrap servers. Consistent with redirect information (Section 2.1, each bootstrap server can be identified by its hostname or IP address, and an optional port.

4. Devices that support loading bootstrapping data from well-known bootstrap servers MUST also possess a list of trust anchor certificates that can be used to authenticate the well-known bootstrap servers. For each trust anchor certificate, if it is not itself a self-signed root certificate, the device SHOULD also possess the chain of intermediate certificates leading up to and including the self-signed root certificate.

5. Devices that support loading signed data (see Section 1.2) MUST possess the trust anchor certificates for validating ownership vouchers. For each trust anchor certificate, if it is not itself a self-signed root certificate, the device SHOULD also possess the chain of intermediate certificates leading up to and including the self-signed root certificate.

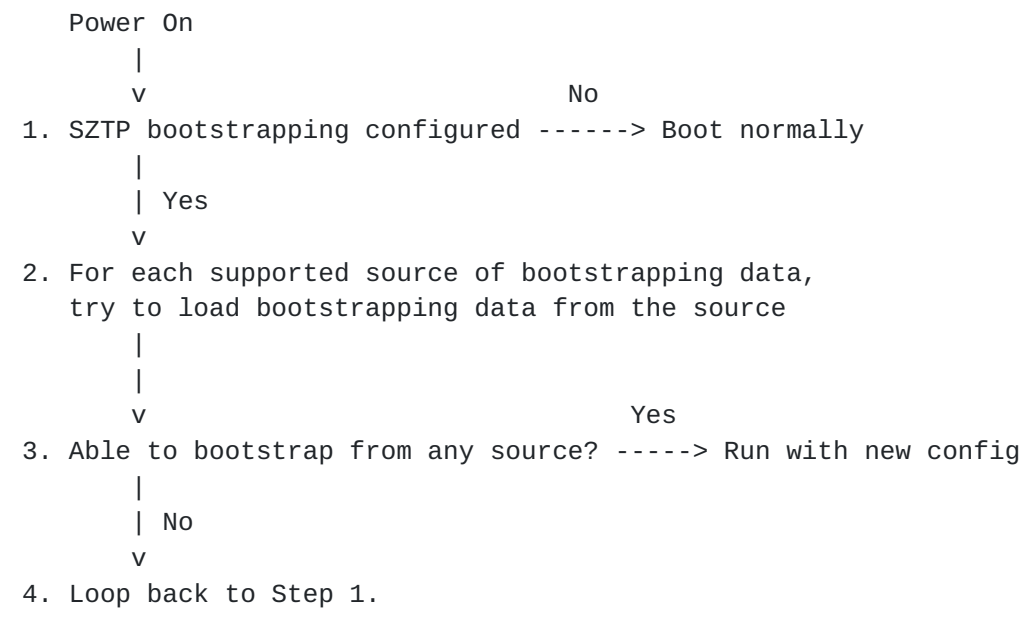
6. Devices that support using a TLS-level client certificate to identify and authenticate themselves to a bootstrap server MUST possess the private key that corresponds to the public key encoded in the TLS-level client certificate. This private key SHOULD be securely stored, ideally in a cryptographic processor, such as a trusted platform module (TPM) chip.

7. Devices that support decrypting SZTP artifacts MUST posses the private key that corresponds to the public key encoded in the secure device identity certificate used when encrypting the artifacts. This private key SHOULD be securely stored, ideally in a cryptographic processor, such as a trusted platform module (TPM) chip. This private key MAY be the same as the one associated to the TLS-level client certificate used when connecting to bootstrap servers.

A YANG module representing this data is provided in Appendix A.

5.2. Boot Sequence

A device claiming to support the bootstrapping strategy defined in this document MUST support the boot sequence described in this section.



Note: At any time, the device MAY be configured via an alternate provisioning mechanism (e.g., CLI).

Each numbered item below corresponds to a numbered item in the diagram above.

1. When the device powers on, it first checks to see if SZTP bootstrapping is configured, as is expected to be the case for the device's preconfigured initial state. If SZTP bootstrapping is not configured, then the device boots normally.

2. The device iterates over its list of sources for bootstrapping data (Section 4). Details for how to processes a source of bootstrapping data are provided in Section 5.3.

3. If the device is able to bootstrap itself from any of the sources of bootstrapping data, it runs with the new bootstrapped configuration.

4. Otherwise the device MUST loop back through the list of bootstrapping sources again.

This document does not limit the simultaneous use of alternate provisioning mechanisms. Such mechanisms may include, for instance, a command line interface (CLI), a web-based user interface, or even another bootstrapping protocol. Regardless how it is configured, the configuration SHOULD unset the flag enabling SZTP bootstrapping discussed in Section 5.1.

5.3. Processing a Source of Bootstrapping Data

This section describes a recursive algorithm that devices can use to, ultimately, obtain onboarding information. The algorithm is recursive because sources of bootstrapping data may return redirect information, which causes the algorithm to run again, for the newly discovered sources of bootstrapping data. An expression that captures all possible successful sequences of bootstrapping data is: zero or more redirect information responses, followed by one onboarding information response.

An important aspect of the algorithm is knowing when data needs to be signed or not. The following figure provides a summary of options:

Kind of Bootstrapping Data	Untrusted Source Can Provide?	Trusted Source Can Provide?
Unsigned Redirect Info	Yes+	Yes
Signed Redirect Info	Yes	Yes*
Unsigned Onboarding Info	No	Yes
Signed Onboarding Info	Yes	Yes*

The '+' above denotes that the source redirected to MUST return signed data, or more unsigned redirect information.

The '*' above denotes that, while possible, it is generally unnecessary for a trusted source to return signed data.

The recursive algorithm uses a conceptual global-scoped variable called "trust-state". The trust-state variable is initialized to FALSE. The ultimate goal of this algorithm is for the device to process onboarding information (Section 2.2) while the trust-state variable is TRUE.

If the source of bootstrapping data (Section 4) is a bootstrap server (Section 4.4), and the device is able to authenticate the bootstrap server using X.509 certificate path validation ([RFC6125], Section 6) to one of the device's preconfigured trust anchors, or to a trust anchor that it learned from a previous step, then the device MUST set trust-state to TRUE.

When establishing a connection to a bootstrap server, whether trusted or untrusted, the device MUST identify and authenticate itself to the bootstrap server using a TLS-level client certificate and/or an HTTP authentication scheme, per Section 2.5 in [RFC8040]. If both authentication mechanisms are used, they MUST both identify the same serial number.

When sending a client certificate, the device MUST also send all of the intermediate certificates leading up to, and optionally including, the client certificate's well-known trust anchor certificate.

For any source of bootstrapping data (e.g., Section 4), if any artifact obtained is encrypted, the device MUST first decrypt it using the private key associated with the device certificate used to encrypt the artifact.

If the conveyed information artifact is signed, and the device is able to validate the signed data using the algorithm described in Section 5.4, then the device MUST set trust-state to TRUE; otherwise, if the device is unable to validate the signed data, the device MUST set trust-state to FALSE. Note, this is worded to cover the special case when signed data is returned even from a trusted source of bootstrapping data.

If the conveyed information artifact contains redirect information, the device MUST, within limits of how many recursive loops the device allows, process the redirect information as described in Section 5.5. Implementations MUST limit the maximum number of recursive redirects allowed; the maximum number of recursive redirects allowed SHOULD be no more than ten. This is the recursion step, it will cause the device to reenter this algorithm, but this time the data source will definitely be a bootstrap server, as redirect information is only able to redirect devices to bootstrap servers.

If the conveyed information artifact contains onboarding information, and trust-state is FALSE, the device MUST exit the recursive algorithm (as this is not allowed, see the figure above), returning to the bootstrapping sequence described in Section 5.2. Otherwise, the device MUST attempt to process the onboarding information as described in Section 5.6. Whether the processing of the onboarding information succeeds or fails, the device MUST exit the recursive algorithm, returning to the bootstrapping sequence described in Section 5.2, the only difference being in how it responds to the "Able to bootstrap from any source?" conditional described in the figure in the section.

5.4. Validating Signed Data

Whenever a device is presented signed data, it MUST validate the signed data as described in this section. This includes the case where the signed data is provided by a trusted source.

Whenever there is signed data, the device MUST also be provided an ownership voucher and an owner certificate. How all the needed

artifacts are provided for each source of bootstrapping data is described in Section 4.

In order to validate signed data, the device MUST first authenticate the ownership voucher by validating its signature to one of its preconfigured trust anchors (see Section 5.1), which may entail using additional intermediate certificates attached to the ownership voucher. If the device has an accurate clock, it MUST verify that the ownership voucher was created in the past (i.e., "created-on" < now) and, if the "expires-on" leaf is present, the device MUST verify that the ownership voucher has not yet expired (i.e., now < "expires-on"). The device MUST verify that the ownership voucher's "assertion" value is acceptable (e.g., some devices may only accept the assertion value "verified"). The device MUST verify that the ownership voucher specifies the device's serial number in the "serial-number" leaf. If the "idevid-issuer" leaf is present, the device MUST verify that the value is set correctly. If the authentication of the ownership voucher is successful, the device extracts the "pinned-domain-cert" node, an X.509 certificate, that is needed to verify the owner certificate in the next step.

The device MUST next authenticate the owner certificate by performing X.509 certificate path verification to the trusted certificate extracted from the ownership voucher's "pinned-domain-cert" node. This verification may entail using additional intermediate certificates attached to the owner certificate artifact. If the ownership voucher's "domain-cert-revocation-checks" node's value is set to "true", the device MUST verify the revocation status of the certificate chain used to sign the owner certificate and, if suitably-fresh revocation status is unattainable or if it is determined that a certificate has been revoked, the device MUST NOT validate the owner certificate.

Finally, the device MUST verify that the conveyed information artifact was signed by the validated owner certificate.

If any of these steps fail, the device MUST invalidate the signed data and not perform any subsequent steps.

5.5. Processing Redirect Information

In order to process redirect information (Section 2.1), the device MUST follow the steps presented in this section.

Processing redirect information is straightforward; the device sequentially steps through the list of provided bootstrap servers until it can find one it can bootstrap from.

If a hostname is provided, and the hostname's DNS resolution is to more than one IP address, the device MUST attempt to connect to all of the DNS resolved addresses at least once, before moving on to the next bootstrap server. If the device is able to obtain bootstrapping data from any of the DNS resolved addresses, it MUST immediately process that data, without attempting to connect to any of the other DNS resolved addresses.

If the redirect information is trusted (e.g., trust-state is TRUE), and the bootstrap server entry contains a trust anchor certificate, then the device MUST authenticate the specified bootstrap server's TLS server certificate using X.509 certificate path validation ([RFC6125], Section 6) to the specified trust anchor. If the bootstrap server entry does not contain a trust anchor certificate device, the device MUST establish a provisional connection to the bootstrap server (i.e., by blindly accepting its server certificate), and set trust-state to FALSE.

If the redirect information is untrusted (e.g., trust-state is FALSE), the device MUST discard any trust anchors provided by the redirect information and establish a provisional connection to the bootstrap server (i.e., by blindly accepting its TLS server certificate).

5.6. Processing Onboarding Information

In order to process onboarding information (Section 2.2), the device MUST follow the steps presented in this section.

When processing onboarding information, the device MUST first process the boot image information (if any), then execute the pre-configuration script (if any), then commit the initial configuration (if any), and then execute the post-configuration script (if any), in that order.

When the onboarding information is obtained from a trusted bootstrap server, the device MUST send the "bootstrap-initiated" progress report, and send either a terminating "boot-image-installed-rebooting", "bootstrap-complete", or error specific progress report. If the bootstrap server's "get-bootstrapping-data" RPC-reply's "reporting-level" node is set to "verbose", the device MUST additionally send all appropriate non-terminating progress reports (e.g., initiated, warning, complete, etc.). Regardless of the reporting-level indicated by the bootstrap server, the device MAY send progress reports beyond the mandatory ones specified for the given reporting level.

When the onboarding information is obtained from an untrusted bootstrap server, the device MUST NOT send any progress reports to the bootstrap server, even though the onboarding information was, necessarily, signed and authenticated. Please be aware that bootstrap servers are recommended to promote untrusted connections to trusted connections, in the last paragraph of Section 9.6, so as to, in part, be able to collect progress reports from devices.

If the device encounters an error at any step, it MUST stop processing the onboarding information and return to the bootstrapping sequence described in Section 5.2. In the context of a recursive algorithm, the device MUST return to the enclosing loop, not back to the very beginning. Some state MAY be retained from the bootstrapping process (e.g., updated boot image, logs, remnants from a script, etc.). However, the retained state MUST NOT be active in any way (e.g., no new configuration or running of software), and MUST NOT hinder the ability for the device to continue the bootstrapping sequence (i.e., process onboarding information from another bootstrap server).

At this point, the specific ordered sequence of actions the device MUST perform is described.

If the onboarding information is obtained from a trusted bootstrap server, the device MUST send a "bootstrap-initiated" progress report. It is an error if the device does not receive back the "204 No Content" HTTP status line. If an error occurs, the device MUST try to send a "bootstrap-error" progress report before exiting.

The device MUST parse the provided onboarding information document, to extract values used in subsequent steps. Whether using a stream-based parser or not, if there is an error when parsing the onboarding information, and the device is connected to a trusted bootstrap server, the device MUST try to send a "parsing-error" progress report before exiting.

If boot image criteria are specified, the device MUST first determine if the boot image it is running satisfies the specified boot image criteria. If the device is already running the specified boot image, then it skips the remainder of this step. If the device is not running the specified boot image, then it MUST download, verify, and install, in that order, the specified boot image, and then reboot. If connected to a trusted bootstrap server, the device MAY try to send a "boot-image-mismatch" progress report. To download the boot image, the device MUST only use the URIs supplied by the onboarding information. To verify the boot image, the device MUST either use one of the verification fingerprints supplied by the onboarding information, or use a cryptographic signature embedded into the boot

image itself using a mechanism not described by this document. Before rebooting, if connected to a trusted bootstrap server, the device MUST try to send a "boot-image-installed-rebooting" progress report. Upon rebooting, the bootstrapping process runs again, which will eventually come to this step again, but then the device will be running the specified boot image, and thus will move to processing the next step. If an error occurs at any step while the device is connected to a trusted bootstrap server (i.e., before the reboot), the device MUST try to send a "boot-image-error" progress report before exiting.

If a pre-configuration script has been specified, the device MUST execute the script, capture any output emitted from the script, and check if the script had any warnings or errors. If an error occurs while the device is connected to a trusted bootstrap server, the device MUST try to send a "pre-script-error" progress report before exiting.

If an initial configuration has been specified, the device MUST atomically commit the provided initial configuration, using the approach specified by the "configuration-handling" leaf. If an error occurs while the device is connected to a trusted bootstrap server, the device MUST try to send a "config-error" progress report before exiting.

If a post-configuration script has been specified, the device MUST execute the script, capture any output emitted from the script, and check if the script had any warnings or errors. If an error occurs while the device is connected to a trusted bootstrap server, the device MUST try to send a "post-script-error" progress report before exiting.

If the onboarding information was obtained from a trusted bootstrap server, and the result of the bootstrapping process did not disable the "flag to enable SZTP bootstrapping" described in Section 5.1, the device SHOULD send an "bootstrap-warning" progress report.

If the onboarding information was obtained from a trusted bootstrap server, the device MUST send a "bootstrap-complete" progress report. It is an error if the device does not receive back the "204 No Content" HTTP status line. If an error occurs, the device MUST try to send a "bootstrap-error" progress report before exiting.

At this point, the device has completely processed the bootstrapping data.

The device is now running its initial configuration. Notably, if NETCONF Call Home or RESTCONF Call Home [RFC8071] is configured, the

device initiates trying to establish the call home connections at this time.

Implementation Notes:

Implementations may vary in how to ensure no unwanted state is retained when an error occurs.

Following are some guidelines for if the implementation chooses to undo previous steps:

* When an error occurs, the device must rollback the current step and any previous steps.

* Most steps are atomic. For example, the processing of a configuration is specified above as atomic, and the processing of scripts is similarly specified as atomic in the "ietf-sztp-conveyed-info" YANG module.

* In case the error occurs after the initial configuration was committed, the device must restore the configuration to the configuration that existed prior to the configuration being committed.

* In case the error occurs after a script had executed successfully, it may be helpful for the implementation to define scripts as being able to take a conceptual input parameter indicating that the script should remove its previously set state.

6. The Conveyed Information Data Model

This section defines a YANG 1.1 [RFC7950] module that is used to define the data model for the conveyed information artifact described in Section 3.1. This data model uses the "yang-data" extension statement defined in [RFC8040]. Examples illustrating this data model are provided in Section 6.2.

6.1. Data Model Overview

The following tree diagram provides an overview of the data model for the conveyed information artifact.

```
module: ietf-sztp-conveyed-info

  yang-data conveyed-information:
    +-- (information-type)
       +--:(redirect-information)
       |  +-- redirect-information
       |     +-- bootstrap-server* [address]
       |        +-- address         inet:host
       |        +-- port?           inet:port-number
       |        +-- trust-anchor?   cms
       +--:(onboarding-information)
          +-- onboarding-information
             +-- boot-image
             |  +-- os-name?              string
             |  +-- os-version?           string
             |  +-- download-uri*         inet:uri
             |  +-- image-verification* [hash-algorithm]
             |     +-- hash-algorithm    identityref
             |     +-- hash-value        yang:hex-string
             +-- configuration-handling?      enumeration
             +-- pre-configuration-script?    script
             +-- configuration?               binary
             +-- post-configuration-script?   script
```

6.2. Example Usage

The following example illustrates how redirect information (Section 2.1) can be encoded using JSON.

```
{
  "ietf-sztp-conveyed-info:redirect-information" : {
    "bootstrap-server" : [
      {
        "address" : "sztp1.example.com",
        "port" : 8443,
        "trust-anchor" : "base64encodedvalue=="
      },
      {
        "address" : "sztp2.example.com",
        "port" : 8443,
        "trust-anchor" : "base64encodedvalue=="
      },
      {
        "address" : "sztp3.example.com",
        "port" : 8443,
        "trust-anchor" : "base64encodedvalue=="
      }
    ]
  }
}
```

The following example illustrates how onboarding information (Section 2.2) can be encoded using JSON.

[Note: '\' line wrapping for formatting only]

```
{
  "ietf-sztp-conveyed-info:onboarding-information" : {
    "boot-image" : {
      "os-name" : "VendorOS",
      "os-version" : "17.2R1.6",
      "download-uri" : [ "http://some/path/to/raw/file" ],
      "image-verification" : [
        {
          "hash-algorithm" : "ietf-sztp-conveyed-info:sha-256",
          "hash-value" : "ba:ec:cf:a5:67:82:b4:10:77:c6:67:a6:22:ab:\
7d:50:04:a7:8b:8f:0e:db:02:8b:f4:75:55:fb:c1:13:b2:33"
        }
      ]
    },
    "configuration-handling" : "merge",
    "pre-configuration-script" : "base64encodedvalue==",
    "configuration" : "base64encodedvalue==",
    "post-configuration-script" : "base64encodedvalue=="
  }
}
```

6.3. YANG Module

The conveyed information data model is defined by the YANG module presented in this section.

This module uses data types defined in [RFC5280], [RFC5652], [RFC6234], and [RFC6991], an extension statement from [RFC8040], and an encoding defined in [ITU.X690.2015].

```
<CODE BEGINS> file "ietf-sztp-conveyed-info@2019-01-15.yang"
module ietf-sztp-conveyed-info {
  yang-version 1.1;
  namespace "urn:ietf:params:xml:ns:yang:ietf-sztp-conveyed-info";
  prefix sztp-info;

  import ietf-yang-types {
    prefix yang;
    reference "RFC 6991: Common YANG Data Types";
  }
  import ietf-inet-types {
    prefix inet;
    reference "RFC 6991: Common YANG Data Types";
  }
  import ietf-restconf {
    prefix rc;
    reference "RFC 8040: RESTCONF Protocol";
  }

  organization
    "IETF NETCONF (Network Configuration) Working Group";

  contact
    "WG Web:   http://tools.ietf.org/wg/netconf
     WG List:  <mailto:netconf@ietf.org>
     Author:   Kent Watsen <mailto:kwatsen@juniper.net>";

  description
   "This module defines the data model for the Conveyed
    Information artifact defined in RFC XXXX: Secure Zero Touch
    Provisioning (SZTP).

    The key words 'MUST', 'MUST NOT', 'REQUIRED', 'SHALL',
    'SHALL NOT', 'SHOULD', 'SHOULD NOT', 'RECOMMENDED',
    'NOT RECOMMENDED', 'MAY', and 'OPTIONAL' in this document
    are to be interpreted as described in BCP 14 (RFC 2119,
    RFC 8174) when, and only when, they appear in all
    capitals, as shown here.
```

```
  revision 2019-01-15 {
    description
      "Initial version";
    reference
      "RFC XXXX: Secure Zero Touch Provisioning (SZTP)";
  }

  // identities

  identity hash-algorithm {
    description
      "A base identity for hash algorithm verification";
  }

  identity sha-256 {
    base "hash-algorithm";
    description "The SHA-256 algorithm.";
    reference "RFC 6234: US Secure Hash Algorithms.";
  }

  // typedefs

  typedef cms {
    type binary;
    description
      "A ContentInfo structure, as specified in RFC 5652,
       encoded using ASN.1 distinguished encoding rules (DER),
       as specified in ITU-T X.690.";
    reference
      "RFC 5652:
         Cryptographic Message Syntax (CMS)
       ITU-T X.690:
         Information technology - ASN.1 encoding rules:
         Specification of Basic Encoding Rules (BER),
         Canonical Encoding Rules (CER) and Distinguished
         Encoding Rules (DER).";
```

```
    }

    // yang-data

    rc:yang-data "conveyed-information" {
      choice information-type {
        mandatory true;
        description
          "This choice statement ensures the response contains
           redirect-information or onboarding-information.";
        container redirect-information {
          description
            "Redirect information is described in Section 2.1 in
             RFC XXXX.  Its purpose is to redirect a device to
             another bootstrap server.";
          reference
            "RFC XXXX: Secure Zero Touch Provisioning (SZTP)";
          list bootstrap-server {
            key "address";
            min-elements 1;
            description
              "A bootstrap server entry.";
            leaf address {
              type inet:host;
              mandatory true;
              description
               "The IP address or hostname of the bootstrap server the
                device should redirect to.";
            }
            leaf port {
              type inet:port-number;
              default "443";
              description
               "The port number the bootstrap server listens on.  If no
                port is specified, the IANA-assigned port for 'https'
                (443) is used.";
            }
            leaf trust-anchor {
              type cms;
              description
                "A CMS structure that MUST contain the chain of
                 X.509 certificates needed to authenticate the TLS
                 certificate presented by this bootstrap server.

                 The CMS MUST only contain a single chain of
                 certificates.  The bootstrap server MUST only
                 authenticate to last intermediate CA certificate
                 listed in the chain.
```

```
                In all cases, the chain MUST include a self-signed
                root certificate.  In the case where the root
                certificate is itself the issuer of the bootstrap
                server's TLS certificate, only one certificate
                is present.

                If needed by the device, this CMS structure MAY
                also contain suitably fresh revocation objects
                with which the device can verify the revocation
                status of the certificates.

                This CMS encodes the degenerate form of the SignedData
                structure that is commonly used to disseminate X.509
                certificates and revocation objects (RFC 5280).";
              reference
                "RFC 5280:
                  Internet X.509 Public Key Infrastructure Certificate
                  and Certificate Revocation List (CRL) Profile.";
            }
          }
        }
        container onboarding-information {
          description
            "Onboarding information is described in Section 2.2 in
             RFC XXXX.  Its purpose is to provide the device everything
             it needs to bootstrap itself.";
          reference
            "RFC XXXX: Secure Zero Touch Provisioning (SZTP)";
          container boot-image {
            description
              "Specifies criteria for the boot image the device MUST
               be running, as well as information enabling the device
               to install the required boot image.";
            leaf os-name {
              type string;
              description
                "The name of the operating system software the device
                 MUST be running in order to not require a software
                 image upgrade (ex. VendorOS).";
            }
            leaf os-version {
              type string;
              description
                "The version of the operating system software the
                 device MUST be running in order to not require a
                 software image upgrade (ex. 17.3R2.1).";
            }
            leaf-list download-uri {
```

```
            type inet:uri;
            ordered-by user;
            description
              "An ordered list of URIs to where the same boot image
               file may be obtained.  How the URI schemes (http, ftp,
               etc.) a device supports are known is vendor specific.
               If a secure scheme (e.g., https) is provided, a device
               MAY establish an untrusted connection to the remote
               server, by blindly accepting the server's end-entity
               certificate, to obtain the boot image.";
          }
          list image-verification {
            must '../download-uri' {
              description
                "Download URIs must be provided if an image is to
                 be verified.";
            }
            key hash-algorithm;
            description
              "A list of hash values that a device can use to verify
               boot image files with.";
            leaf hash-algorithm {
              type identityref {
                base "hash-algorithm";
              }
              description
                "Identifies the hash algorithm used.";
            }
            leaf hash-value {
              type yang:hex-string;
              mandatory true;
              description
                "The hex-encoded value of the specified hash
                 algorithm over the contents of the boot image
                 file.";
            }
          }
        }
        leaf configuration-handling {
          type enumeration {
            enum "merge" {
              description
                "Merge configuration into the running datastore.";
            }
            enum "replace" {
              description
                "Replace the existing running datastore with the
                 passed configuration.";
```

```
            }
          }
          must '../configuration';
          description
            "This enumeration indicates how the server should process
             the provided configuration.";
        }
        leaf pre-configuration-script {
          type script;
          description
            "A script that, when present, is executed before the
             configuration has been processed.";
        }
        leaf configuration {
          type binary;
          must '../configuration-handling';
          description
            "Any configuration known to the device.  The use of
             the 'binary' type enables e.g., XML-content to be
             embedded into a JSON document.  The exact encoding
             of the content, as with the scripts, is vendor
             specific.";
        }
        leaf post-configuration-script {
          type script;
          description
            "A script that, when present, is executed after the
             configuration has been processed.";
        }
      }
    }
  }

  typedef script {
    type binary;
    description
      "A device specific script that enables the execution of
       commands to perform actions not possible thru configuration
       alone.

       No attempt is made to standardize the contents, running
       context, or programming language of the script, other than
       that it can indicate if any warnings or errors occurred and
       can emit output.  The contents of the script are considered
       specific to the vendor, product line, and/or model of the
       device.

       If the script execution indicates that an warning occurred,
```

```
          then the device MUST assume that the script had a soft error
          that the script believes will not affect manageability.

          If the script execution indicates that an error occurred,
          the device MUST assume the script had a hard error that the
          script believes will affect manageability.  In this case,
          the script is required to gracefully exit, removing any
          state that might hinder the device's ability to continue
          the bootstrapping sequence (e.g., process onboarding
          information obtained from another bootstrap server).";
      }
    }
    <CODE ENDS>
```

7. The SZTP Bootstrap Server API

This section defines the API for bootstrap servers. The API is defined as that produced by a RESTCONF [RFC8040] server that supports the YANG 1.1 [RFC7950] module defined in this section.

7.1. API Overview

The following tree diagram provides an overview for the bootstrap server RESTCONF API.

```
module: ietf-sztp-bootstrap-server

  rpcs:
    +---x get-bootstrapping-data
    |  +---w input
    |  |  +---w signed-data-preferred?   empty
    |  |  +---w hw-model?                string
    |  |  +---w os-name?                 string
    |  |  +---w os-version?              string
    |  |  +---w nonce?                   binary
    |  +--ro output
    |     +--ro reporting-level?    enumeration {onboarding-server}?
    |     +--ro conveyed-information    cms
    |     +--ro owner-certificate?      cms
    |     +--ro ownership-voucher?      cms
    +---x report-progress {onboarding-server}?
       +---w input
          +---w progress-type         enumeration
          +---w message?              string
          +---w ssh-host-keys
          |  +---w ssh-host-key* []
          |     +---w algorithm    string
          |     +---w key-data     binary
          +---w trust-anchor-certs
             +---w trust-anchor-cert*   cms
```

7.2. Example Usage

This section presents three examples illustrating the bootstrap server's API. Two examples are provided for the "get-bootstrapping-data" RPC (once to an untrusted bootstrap server, and again to a trusted bootstrap server), and one example for the "report-progress" RPC.

The following example illustrates a device using the API to fetch its bootstrapping data from a untrusted bootstrap server. In this example, the device sends the "signed-data-preferred" input parameter and receives signed data in the response.

```
REQUEST

[Note: '\' line wrapping for formatting only]

POST /restconf/operations/ietf-sztp-bootstrap-server:get-bootstrappi\
ng-data HTTP/1.1
HOST: example.com
Content-Type: application/yang.data+xml

<input
  xmlns="urn:ietf:params:xml:ns:yang:ietf-sztp-bootstrap-server">
  <signed-data-preferred/>
</input>

RESPONSE

HTTP/1.1 200 OK
Date: Sat, 31 Oct 2015 17:02:40 GMT
Server: example-server
Content-Type: application/yang.data+xml

<output
  xmlns="urn:ietf:params:xml:ns:yang:ietf-sztp-bootstrap-server">
  <conveyed-information>base64encodedvalue==</conveyed-information>
  <owner-certificate>base64encodedvalue==</owner-certificate>
  <ownership-voucher>base64encodedvalue==</ownership-voucher>
</output>
```

The following example illustrates a device using the API to fetch its bootstrapping data from a trusted bootstrap server. In this example, the device sends addition input parameters to the bootstrap server, which it may use when formulating its response to the device.

REQUEST

[Note: '\' line wrapping for formatting only]

```
POST /restconf/operations/ietf-sztp-bootstrap-server:get-bootstrappi\
ng-data HTTP/1.1
HOST: example.com
Content-Type: application/yang.data+xml

<input
  xmlns="urn:ietf:params:xml:ns:yang:ietf-sztp-bootstrap-server">
  <hw-model>model-x</hw-model>
  <os-name>vendor-os</os-name>
  <os-version>17.3R2.1</os-version>
  <nonce>extralongbase64encodedvalue=</nonce>
</input>
```

RESPONSE

```
HTTP/1.1 200 OK
Date: Sat, 31 Oct 2015 17:02:40 GMT
Server: example-server
Content-Type: application/yang.data+xml

<output
  xmlns="urn:ietf:params:xml:ns:yang:ietf-sztp-bootstrap-server">
  <reporting-level>verbose</reporting-level>
  <conveyed-information>base64encodedvalue==</conveyed-information>
</output>
```

The following example illustrates a device using the API to post a progress report to a bootstrap server. Illustrated below is the "bootstrap-complete" message, but the device may send other progress reports to the server while bootstrapping. In this example, the device is sending both its SSH host keys and a TLS server certificate, which the bootstrap server may, for example, pass to an NMS, as discussed in Appendix C.3.

```
   REQUEST

   [Note: '\' line wrapping for formatting only]

   POST /restconf/operations/ietf-sztp-bootstrap-server:report-progress\
    HTTP/1.1
   HOST: example.com
   Content-Type: application/yang.data+xml

   <input
     xmlns="urn:ietf:params:xml:ns:yang:ietf-sztp-bootstrap-server">
     <progress-type>bootstrap-complete</progress-type>
     <message>example message</message>
     <ssh-host-keys>
       <ssh-host-key>
         <algorithm>ssh-rsa</algorithm>
         <key-data>base64encodedvalue==</key-data>
       </ssh-host-key>
       <ssh-host-key>
         <algorithm>rsa-sha2-256</algorithm>
         <key-data>base64encodedvalue==</key-data>
       </ssh-host-key>
     </ssh-host-keys>
     <trust-anchor-certs>
       <trust-anchor-cert>base64encodedvalue==</trust-anchor-cert>
     </trust-anchor-certs>
   </input>

   RESPONSE

   HTTP/1.1 204 No Content
   Date: Sat, 31 Oct 2015 17:02:40 GMT
   Server: example-server
```

7.3. YANG Module

The bootstrap server's device-facing API is normatively defined by the YANG module defined in this section.

This module uses data types defined in [RFC4253], [RFC5652], [RFC5280], [RFC6960], and [RFC8366], uses an encoding defined in [ITU.X690.2015], and makes a reference to [RFC4250] and [RFC6187].

```
   <CODE BEGINS> file "ietf-sztp-bootstrap-server@2019-01-15.yang"
   module ietf-sztp-bootstrap-server {
     yang-version 1.1;
     namespace "urn:ietf:params:xml:ns:yang:ietf-sztp-bootstrap-server";
     prefix sztp-svr;
```

```
     organization
       "IETF NETCONF (Network Configuration) Working Group";

     contact
       "WG Web:   <http://tools.ietf.org/wg/netconf/>
        WG List:  <mailto:netconf@ietf.org>
        Author:   Kent Watsen <mailto:kwatsen@juniper.net>";

     description
      "This module defines an interface for bootstrap servers, as
       defined by RFC XXXX: Secure Zero Touch Provisioning (SZTP).

       The key words 'MUST', 'MUST NOT', 'REQUIRED', 'SHALL',
       'SHALL NOT', 'SHOULD', 'SHOULD NOT', 'RECOMMENDED',
       'NOT RECOMMENDED', 'MAY', and 'OPTIONAL' in this document
       are to be interpreted as described in BCP 14 (RFC 2119,
       RFC 8174) when, and only when, they appear in all
       capitals, as shown here.

       Copyright (c) 2019 IETF Trust and the persons identified as
       authors of the code. All rights reserved.

       Redistribution and use in source and binary forms, with or
       without modification, is permitted pursuant to, and subject
       to the license terms contained in, the Simplified BSD License
       set forth in Section 4.c of the IETF Trust's Legal Provisions
       Relating to IETF Documents (http://trustee.ietf.org/license-info)

       This version of this YANG module is part of RFC XXXX; see the
       RFC itself for full legal notices.";

     revision 2019-01-15 {
       description
         "Initial version";
       reference
         "RFC XXXX: Secure Zero Touch Provisioning (SZTP)";
     }

     // features
     feature redirect-server {
       description
        "The server supports being a 'redirect server'.";
     }

     feature onboarding-server {
       description
        "The server supports being an 'onboarding server'.";
     }
```

```
     // typedefs

     typedef cms {
       type binary;
       description
         "A CMS structure, as specified in RFC 5652, encoded using
          ASN.1 distinguished encoding rules (DER), as specified in
          ITU-T X.690.";
       reference
         "RFC 5652:
            Cryptographic Message Syntax (CMS)
          ITU-T X.690:
            Information technology - ASN.1 encoding rules:
            Specification of Basic Encoding Rules (BER),
            Canonical Encoding Rules (CER) and Distinguished
            Encoding Rules (DER).";
     }

     // RPCs

     rpc get-bootstrapping-data {
       description
         "This RPC enables a device, as identified by the RESTCONF
          username, to obtain bootstrapping data that has been made
          available for it.";
       input {
         leaf signed-data-preferred {
           type empty;
           description
             "This optional input parameter enables a device to
              communicate to the bootstrap server that it prefers
              to receive signed data.  Devices SHOULD always send
              this parameter when the bootstrap server is untrusted.
              Upon receiving this input parameter, the bootstrap
              server MUST return either signed data, or unsigned
              redirect information; the bootstrap server MUST NOT
              return unsigned onboarding information.";
         }
         leaf hw-model {
           type string;
           description
             "This optional input parameter enables a device to
              communicate to the bootstrap server its vendor specific
              hardware model number.  This parameter may be needed,
              for instance, when a device's IDevID certificate does
              not include the 'hardwareModelName' value in its
              subjectAltName field, as is allowed by 802.1AR-2009.";
           reference
```

```
            "IEEE 802.1AR-2009: IEEE Standard for Local and
               metropolitan area networks - Secure Device Identity";
          }
          leaf os-name {
            type string;
            description
              "This optional input parameter enables a device to
               communicate to the bootstrap server the name of its
               operating system.  This parameter may be useful if
               the device, as identified by its serial number, can
               run more than one type of operating system (e.g.,
               on a white-box system.";
          }
          leaf os-version {
            type string;
            description
              "This optional input parameter enables a device to
               communicate to the bootstrap server the version of its
               operating system.  This parameter may be used by a
               bootstrap server to return an operating system specific
               response to the device, thus negating the need for a
               potentially expensive boot-image update.";
          }
          leaf nonce {
            type binary {
              length "16..32";
            }
            description
              "This optional input parameter enables a device to
               communicate to the bootstrap server a nonce value.
               This may be especially useful for devices lacking
               an accurate clock, as then the bootstrap server
               can dynamically obtain from the manufacturer a
               voucher with the nonce value in it, as described
               in RFC 8366.";
            reference
              "RFC 8366:
                A Voucher Artifact for Bootstrapping Protocols";
          }
        }
        output {
          leaf reporting-level {
            if-feature onboarding-server;
            type enumeration {
              enum standard {
                description
                  "Send just the progress reports required by RFC XXXX.";
                reference
```

```
            "RFC XXXX: Secure Zero Touch Provisioning (SZTP)";
        }
        enum verbose {
          description
            "Send additional progress reports that might help
             troubleshooting an SZTP bootstrapping issue.";
        }
      }
      default standard;
      description
        "Specifies the reporting level for progress reports the
         bootstrap server would like to receive when processing
         onboarding information.  Progress reports are not sent
         when processing redirect information, or when the
         bootstrap server is untrusted (e.g., device sent the
         '<signed-data-preferred>' input parameter).";
    }
    leaf conveyed-information {
      type cms;
      mandatory true;
      description
        "An SZTP conveyed information artifact, as described in
         Section 3.1 of RFC XXXX.";
      reference
        "RFC XXXX: Secure Zero Touch Provisioning (SZTP)";
    }
    leaf owner-certificate {
      type cms;
      must '../ownership-voucher' {
        description
          "An ownership voucher must be present whenever an owner
           certificate is presented.";
      }
      description
        "An owner certificate artifact, as described in Section
         3.2 of RFC XXXX.  This leaf is optional because it is
         only needed when the conveyed information artifact is
         signed.";
      reference
        "RFC XXXX: Secure Zero Touch Provisioning (SZTP)";
    }
    leaf ownership-voucher {
      type cms;
      must '../owner-certificate' {
        description
          "An owner certificate must be present whenever an
           ownership voucher is presented.";
      }
```

```
          description
            "An ownership voucher artifact, as described by Section
             3.3 of RFC XXXX.  This leaf is optional because it is
             only needed when the conveyed information artifact is
             signed.";
          reference
            "RFC XXXX: Secure Zero Touch Provisioning (SZTP)";
        }
      }
    }

    rpc report-progress {
      if-feature onboarding-server;
      description
        "This RPC enables a device, as identified by the RESTCONF
         username, to report its bootstrapping progress to the
         bootstrap server.  This RPC is expected to be used when
         the device obtains onboarding-information from a trusted
         bootstap server.";
      input {
        leaf progress-type {
          type enumeration {
            enum "bootstrap-initiated" {
              description
                "Indicates that the device just used the
                 'get-bootstrapping-data' RPC.  The 'message' node
                 below MAY contain any additional information that
                 the manufacturer thinks might be useful.";
            }
            enum "parsing-initiated" {
              description
                "Indicates that the device is about to start parsing
                 the onboarding information.  This progress type is
                 only for when parsing is implemented as a distinct
                 step.";
            }
            enum "parsing-warning" {
              description
                "Indicates that the device had a non-fatal error when
                 parsing the response from the bootstrap server.  The
                 'message' node below SHOULD indicate the specific
                 warning that occurred.";
            }
            enum "parsing-error" {
              description
                "Indicates that the device encountered a fatal error
                 when parsing the response from the bootstrap server.
                 For instance, this could be due to malformed encoding,
```

```
            the device expecting signed data when only unsigned
            data is provided, the ownership voucher not listing
            the device's serial number, or because the signature
            didn't match.  The 'message' node below SHOULD
            indicate the specific error.  This progress type
            also indicates that the device has abandoned trying
            to bootstrap off this bootstrap server.";
          }
          enum "parsing-complete" {
            description
              "Indicates that the device successfully completed
               parsing the onboarding information.  This progress
               type is only for when parsing is implemented as a
               distinct step.";
          }
          enum "boot-image-initiated" {
            description
              "Indicates that the device is about to start
               processing the boot-image information.";
          }
          enum "boot-image-warning" {
            description
              "Indicates that the device encountered a non-fatal
               error condition when trying to install a boot-image.
               A possible reason might include a need to reformat a
               partition causing loss of data.  The 'message' node
               below SHOULD indicate any warning messages that were
               generated.";
          }
          enum "boot-image-error" {
            description
              "Indicates that the device encountered an error when
               trying to install a boot-image, which could be for
               reasons such as a file server being unreachable,
               file not found, signature mismatch, etc.  The
               'message' node SHOULD indicate the specific error
               that occurred.  This progress type also indicates
               that the device has abandoned trying to bootstrap
               off this bootstrap server.";
          }
          enum "boot-image-mismatch" {
            description
              "Indicates that the device that has determined that
               it is not running the correct boot image.  This
               message SHOULD precipitate trying to download
               a boot image.";
          }
          enum "boot-image-installed-rebooting" {
```

```
        description
          "Indicates that the device successfully installed
           a new boot image and is about to reboot.  After
           sending this progress type, the device is not
           expected to access the bootstrap server again
           for this bootstrapping attempt.";
      }
      enum "boot-image-complete" {
        description
          "Indicates that the device believes that it is
           running the correct boot-image.";
      }
      enum "pre-script-initiated" {
        description
          "Indicates that the device is about to execute the
           'pre-configuration-script'.";
      }
      enum "pre-script-warning" {
        description
          "Indicates that the device obtained a warning from the
           'pre-configuration-script' when it was executed.  The
           'message' node below SHOULD capture any output the
           script produces.";
      }
      enum "pre-script-error" {
        description
          "Indicates that the device obtained an error from the
           'pre-configuration-script' when it was executed. The
           'message' node below SHOULD capture any output the
           script produces.  This progress type also indicates
           that the device has abandoned trying to bootstrap
           off this bootstrap server.";
      }
      enum "pre-script-complete" {
        description
          "Indicates that the device successfully executed the
           'pre-configuration-script'.";
      }
      enum "config-initiated" {
        description
          "Indicates that the device is about to commit the
           initial configuration.";
      }
      enum "config-warning" {
        description
          "Indicates that the device obtained warning messages
           when it committed the initial configuration.  The
           'message' node below SHOULD indicate any warning
```

```
          messages that were generated.";
      }
      enum "config-error" {
        description
          "Indicates that the device obtained error messages
           when it committed the initial configuration.  The
           'message' node below SHOULD indicate the error
           messages that were generated.  This progress type
           also indicates that the device has abandoned trying
           to bootstrap off this bootstrap server.";
      }
      enum "config-complete" {
        description
          "Indicates that the device successfully committed
           the initial configuration.";
      }
      enum "post-script-initiated" {
        description
          "Indicates that the device is about to execute the
           'post-configuration-script'.";
      }
      enum "post-script-warning" {
        description
          "Indicates that the device obtained a warning from the
           'post-configuration-script' when it was executed. The
           'message' node below SHOULD capture any output the
           script produces.";
      }
      enum "post-script-error" {
        description
          "Indicates that the device obtained an error from the
           'post-configuration-script' when it was executed. The
           'message' node below SHOULD capture any output the
           script produces.  This progress type also indicates
           that the device has abandoned trying to bootstrap
           off this bootstrap server.";
      }
      enum "post-script-complete" {
        description
          "Indicates that the device successfully executed the
           'post-configuration-script'.";
      }
      enum "bootstrap-warning" {
       description
         "Indicates that a warning condition occurred for which
          there no other 'progress-type' enumeration is deemed
          suitable.  The 'message' node below SHOULD describe
          the warning.";
```

```
            }
            enum "bootstrap-error" {
             description
               "Indicates that an error condition occurred for which
                there no other 'progress-type' enumeration is deemed
                suitable.  The 'message' node below SHOULD describe
                the error.  This progress type also indicates that
                the device has abandoned trying to bootstrap off
                this bootstrap server.";
            }
            enum "bootstrap-complete" {
              description
                "Indicates that the device successfully processed
                 all 'onboarding-information' provided, and that it
                 is ready to be managed.  The 'message' node below
                 MAY contain any additional information that the
                 manufacturer thinks might be useful.  After sending
                 this progress type, the device is not expected to
                 access the bootstrap server again.";
            }
            enum "informational" {
              description
                "Indicates any additional information not captured
                 by any of the other progress types. For instance,
                 a message indicating that the device is about to
                 reboot after having installed a boot-image could
                 be provided.  The 'message' node below SHOULD
                 contain information that the manufacturer thinks
                 might be useful.";
            }
          }
          mandatory true;
          description
            "The type of progress report provided.";
        }
        leaf message {
          type string;
          description
            "An optional arbitrary value.";
        }
        container ssh-host-keys {
          when "../progress-type = 'bootstrap-complete'" {
            description
              "SSH host keys are only sent when the progress type
               is 'bootstrap-complete'.";
          }
          description
            "A list of SSH host keys an NMS may use to authenticate
```

```
            subsequent SSH-based connections to this device (e.g.,
            netconf-ssh, netconf-ch-ssh).";
          list ssh-host-key {
            description
              "An SSH host key an NMS may use to authenticate
               subsequent SSH-based connections to this device
               (e.g., netconf-ssh, netconf-ch-ssh).";
            reference
              "RFC 4253: The Secure Shell (SSH) Transport Layer
                         Protocol";
            leaf algorithm {
              type string;
              mandatory true;
              description
                "The public key algorithm name for this SSH key.

                 Valid values are listed in the 'Public Key Algorithm
                 Names' subregistry of the 'Secure Shell (SSH) Protocol
                 Parameters' registry maintained by IANA.";
              reference
                "RFC 4250: The Secure Shell (SSH) Protocol Assigned
                           Numbers
                 IANA URL: https://www.iana.org/assignments/ssh-param\\
                           eters/ssh-parameters.xhtml#ssh-parameters-19
                           ('\\' added for formatting reasons)";
            }
            leaf key-data {
              type binary;
              mandatory true;
              description
                "The binary public key data for this SSH key, as
                 specified by RFC 4253, Section 6.6, i.e.:

                   string    certificate or public key format
                             identifier
                   byte[n]   key/certificate data.";
              reference
                "RFC 4253: The Secure Shell (SSH) Transport Layer
                           Protocol";
            }
          }
        }
        container trust-anchor-certs {
          when "../progress-type = 'bootstrap-complete'" {
            description
              "Trust anchors are only sent when the progress type
               is 'bootstrap-complete'.";
          }
```

```
          description
            "A list of trust anchor certificates an NMS may use to
             authenticate subsequent certificate-based connections
             to this device (e.g., restconf-tls, netconf-tls, or
             even netconf-ssh with X.509 support from RFC 6187).
             In practice, trust anchors for IDevID certificates do
             not need to be conveyed using this mechanism.";
          reference
            "RFC 6187:
               X.509v3 Certificates for Secure Shell Authentication.";
          leaf-list trust-anchor-cert {
            type cms;
            description
             "A CMS structure whose top-most content type MUST be the
              signed-data content type, as described by Section 5 in
              RFC 5652.

              The CMS MUST contain the chain of X.509 certificates
              needed to authenticate the certificate presented by
              the device.

              The CMS MUST contain only a single chain of
              certificates.  The last certificate in the chain
              MUST be the issuer for the device's end-entity
              certificate.

              In all cases, the chain MUST include a self-signed
              root certificate.  In the case where the root
              certificate is itself the issuer of the device's
              end-entity certificate, only one certificate is
              present.

              This CMS encodes the degenerate form of the SignedData
              structure that is commonly used to disseminate X.509
              certificates and revocation objects (RFC 5280).";
            reference
              "RFC 5280:
                 Internet X.509 Public Key Infrastructure
                 Certificate and Certificate Revocation List (CRL)
                 Profile.
               RFC 5652:
                 Cryptographic Message Syntax (CMS)";
          }
        }
      }
    }
  }
  <CODE ENDS>
```

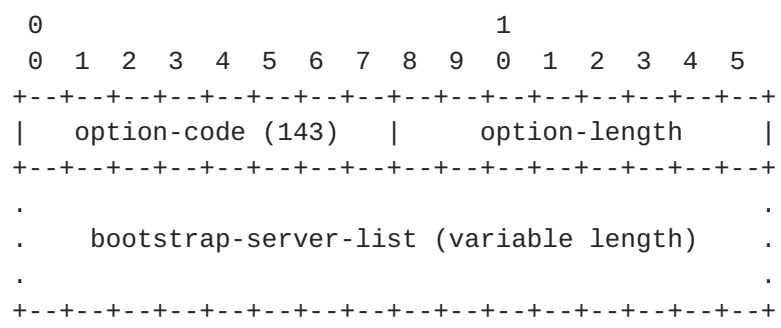
8. DHCP Options

This section defines two DHCP options, one for DHCPv4 and one for DHCPv6. These two options are semantically the same, though syntactically different.

8.1. DHCPv4 SZTP Redirect Option

The DHCPv4 SZTP Redirect Option is used to provision the client with one or more URIs for bootstrap servers that can be contacted to attempt further configuration.

DHCPv4 SZTP Redirect Option



* option-code: OPTION_V4_SZTP_REDIRECT (143)
* option-length: The option length in octets.
* bootstrap-server-list: A list of servers for the client to attempt contacting, in order to obtain further bootstrapping data, in the format shown in Section 8.3.

DHCPv4 Client Behavior

Clients MAY request the OPTION_V4_SZTP_REDIRECT by including its option code in the Parameter Request List (55) in DHCP request messages.

On receipt of a DHCPv4 Reply message which contains the OPTION_V4_SZTP_REDIRECT, the client processes the response according to Section 5.5, with the understanding that the "address" and "port" values are encoded in the URIs.

Any invalid URI entries received in the uri-data field are ignored by the client. If OPTION_V4_SZTP_REDIRECT does not contain at least one valid URI entry in the uri-data field, then the client MUST discard the option.

As the list of URIs may exceed the maximum allowed length of a single DHCPv4 option (255 octets), the client MUST implement [RFC3396], allowing the URI list to be split across a number of OPTION_V4_SZTP_REDIRECT option instances.

DHCPv4 Server Behavior

The DHCPv4 server MAY include a single instance of Option OPTION_V4_SZTP_REDIRECT in DHCP messages it sends. Servers MUST NOT send more than one instance of the OPTION_V4_SZTP_REDIRECT option.

The server's DHCP message MUST contain only a single instance of the OPTION_V4_SZTP_REDIRECT's 'bootstrap-server-list' field. However, the list of URIs in this field may exceed the maximum allowed length of a single DHCPv4 option (per [RFC3396]).

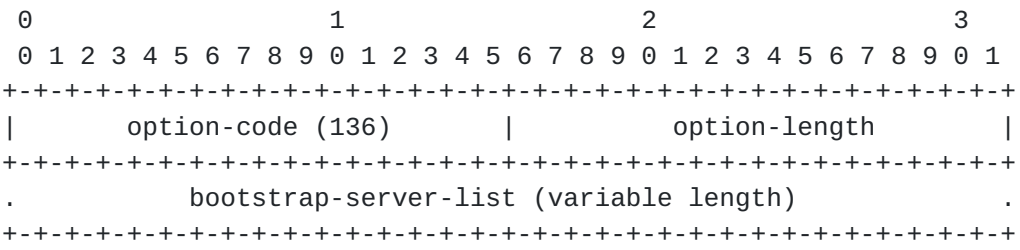
If the length of 'bootstrap-server-list' is small enough to fit into a single instance of OPTION_V4_SZTP_REDIRECT, the server MUST NOT send more than one instance of this option.

If the length of the 'bootstrap-server-list' field is too large to fit into a single option, then OPTION_V4_SZTP_REDIRECT MUST be split into multiple instances of the option according to the process described in [RFC3396].

8.2. DHCPv6 SZTP Redirect Option

The DHCPv6 SZTP Redirect Option is used to provision the client with one or more URIs for bootstrap servers that can be contacted to attempt further configuration.

DHCPv6 SZTP Redirect Option



* option-code: OPTION_V6_SZTP_REDIRECT (136)
* option-length: The option length in octets.
* bootstrap-server-list: A list of servers for the client to attempt contacting, in order to obtain further bootstrapping data, in the format shown in Section 8.3.

DHCPv6 Client Behavior

Clients MAY request the OPTION_V6_SZTP_REDIRECT option, as defined in [RFC8415], Sections 18.2.1, 18.2.2, 18.2.4, 18.2.5, 18.2.6, and 21.7. As a convenience to the reader, we mention here that the client includes requested option codes in the Option Request Option.

On receipt of a DHCPv6 Reply message which contains the OPTION_V6_SZTP_REDIRECT, the client processes the response according to Section 5.5, with the understanding that the "address" and "port" values are encoded in the URIs.

Any invalid URI entries received in the uri-data field are ignored by the client. If OPTION_V6_SZTP_REDIRECT does not contain at least one valid URI entry in the uri-data field, then the client MUST discard the option.

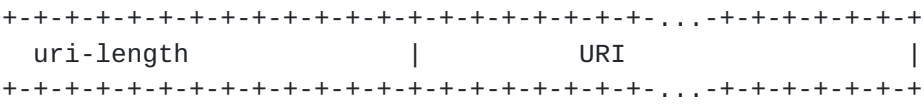
DHCPv6 Server Behavior

Section 18.3 of [RFC8415] governs server operation in regard to option assignment. As a convenience to the reader, we mention here that the server will send a particular option code only if configured with specific values for that option code and if the client requested it.

Option OPTION_V6_SZTP_REDIRECT is a singleton. Servers MUST NOT send more than one instance of the OPTION_V6_SZTP_REDIRECT option.

8.3. Common Field Encoding

Both of the DHCPv4 and DHCPv6 options defined in this section encode a list of bootstrap server URIs. The "URI" structure is a DHCP option that can contain multiple URIs (see [RFC7227], Section 5.7). Each URI entry in the bootstrap-server-list is structured as follows:



* uri-length: 2 octets long, specifies the length of the URI data.
* URI: URI of SZTP bootstrap server.

The URI of the SZTP bootstrap server MUST use the "https" URI scheme defined in Section 2.7.2 of [RFC7230], and MUST be in form "https://<ip-address-or-hostname>[:<port>]".

9. Security Considerations

9.1. Clock Sensitivity

The solution in this document relies on TLS certificates, owner certificates, and ownership vouchers, all of which require an accurate clock in order to be processed correctly (e.g., to test validity dates and revocation status). Implementations SHOULD ensure devices have an accurate clock when shipped from manufacturing facilities, and take steps to prevent clock tampering.

If it is not possible to ensure clock accuracy, it is RECOMMENDED that implementations disable the aspects of the solution having clock sensitivity. In particular, such implementations should assume that TLS certificates, ownership vouchers, and owner certificates never expire and are not revokable. From an ownership voucher perspective, manufacturers SHOULD issue a single ownership voucher for the lifetime of such devices.

Implementations SHOULD NOT rely on NTP for time, as NTP is not a secure protocol at this time. Note, there is an IETF work-in-progress to secure NTP [I-D.ietf-ntp-using-nts-for-ntp].

9.2. Use of IDevID Certificates

IDevID certificates, as defined in [Std-802.1AR-2018], are RECOMMENDED, both for the TLS-level client certificate used by devices when connecting to a bootstrap server, as well as for the device identity certificate used by owners when encrypting the SZTP bootstrapping data artifacts.

9.3. Immutable Storage for Trust Anchors

Devices MUST ensure that all their trust anchor certificates, including those for connecting to bootstrap servers and verifying ownership vouchers, are protected from external modification.

It may be necessary to update these certificates over time (e.g., the manufacturer wants to delegate trust to a new CA). It is therefore expected that devices MAY update these trust anchors when needed through a verifiable process, such as a software upgrade using signed software images.

9.4. Secure Storage for Long-lived Private Keys

Manufacturer-generated device identifiers may have very long lifetimes. For instance, [Std-802.1AR-2018] recommends using the "notAfter" value 99991231235959Z in IDevID certificates. Given the

long-lived nature of these private keys, it is paramount that they are stored so as to resist discovery, such as in a secure cryptographic processor, such as a trusted platform module (TPM) chip.

9.5. Blindly Authenticating a Bootstrap Server

This document allows a device to blindly authenticate a bootstrap server's TLS certificate. It does so to allow for cases where the redirect information may be obtained in an unsecured manner, which is desirable to support in some cases.

To compensate for this, this document requires that devices, when connected to an untrusted bootstrap server, assert that data downloaded from the server is signed.

9.6. Disclosing Information to Untrusted Servers

This document allows devices to establish connections to untrusted bootstrap servers. However, since the bootstrap server is untrusted, it may be under the control of an adversary, and therefore devices SHOULD be cautious about the data they send to the bootstrap server in such cases.

Devices send different data to bootstrap servers at each of the protocol layers TCP, TLS, HTTP, and RESTCONF.

At the TCP protocol layer, devices may relay their IP address, subject to network translations. Disclosure of this information is not considered a security risk.

At the TLS protocol layer, devices may use a client certificate to identify and authenticate themselves to untrusted bootstrap servers. At a minimum, the client certificate must disclose the device's serial number, and may disclose additional information such as the device's manufacturer, hardware model, public key, etc. Knowledge of this information may provide an adversary with details needed to launch an attack. It is RECOMMENDED that secrecy of the network constituency is not relied on for security.

At the HTTP protocol layer, devices may use an HTTP authentication scheme to identify and authenticate themselves to untrusted bootstrap servers. At a minimum, the authentication scheme must disclose the device's serial number and, concerningly, may, depending on the authentication mechanism used, reveal a secret that is only supposed to be known to the device (e.g., a password). Devices SHOULD NOT use an HTTP authentication scheme (e.g., HTTP Basic) with an untrusted

bootstrap server that reveals a secret that is only supposed to be known to the device.

At the RESTCONF protocol layer, devices use the "get-bootstrapping-data" RPC, but not the "report-progress" RPC, when connected to an untrusted bootstrap server. The "get-bootstrapping-data" RPC allows additional input parameters to be passed to the bootstrap server (e.g., "os-name", "os-version", "hw-model"). It is RECOMMENDED that devices only pass the "signed-data-preferred" input parameter to an untrusted bootstrap server. While it is okay for a bootstrap server to immediately return signed onboarding information, it is RECOMMENDED that bootstrap servers instead promote the untrusted connection to a trusted connection, as described in Appendix B, thus enabling the device to use the "report-progress" RPC while processing the onboarding information.

9.7. Sequencing Sources of Bootstrapping Data

For devices supporting more than one source for bootstrapping data, no particular sequencing order has to be observed for security reasons, as the solution for each source is considered equally secure. However, from a privacy perspective, it is RECOMMENDED that devices access local sources before accessing remote sources.

9.8. Safety of Private Keys used for Trust

The solution presented in this document enables bootstrapping data to be trusted in two ways, either through transport level security or through the signing of artifacts.

When transport level security (i.e., a trusted bootstrap server) is used, the private key for the end-entity certificate must be online in order to establish the TLS connection.

When artifacts are signed, the signing key is required to be online only when the bootstrap server is returning a dynamically generated signed-data response. For instance, a bootstrap server, upon receiving the "signed-data-preferred" input parameter to the "get-bootstrapping-data" RPC, may dynamically generate a response that is signed.

Bootstrap server administrators are RECOMMENDED to follow best practice to protect the private key used for any online operation. For instance, use of a hardware security module (HSM) is RECOMMENDED. If an HSM is not used, frequent private key refreshes are RECOMMENDED, assuming all bootstrapping devices have an accurate clock (see Section 9.1).

For best security, it is RECOMMENDED that owners only provide bootstrapping data that has been signed, using a protected private key, and encrypted, using the device's public key from its secure device identity certificate.

9.9. Increased Reliance on Manufacturers

The SZTP bootstrapping protocol presented in this document shifts some control of initial configuration away from the rightful owner of the device and towards the manufacturer and its delegates.

The manufacturer maintains the list of well-known bootstrap servers its devices will trust. By design, if no bootstrapping data is found via other methods first, the device will try to reach out to the well-known bootstrap servers. There is no mechanism to prevent this from occurring other than by using an external firewall to block such connections. Concerns related to trusted bootstrap servers are discussed in Section 9.10.

Similarly, the manufacturer maintains the list of voucher signing authorities its devices will trust. The voucher signing authorities issue the vouchers that enable a device to trust an owner's domain certificate. It is vital that manufacturers ensure the integrity of these voucher signing authorities, so as to avoid incorrect assignments.

Operators should be aware that this system assumes that they trust all the pre-configured bootstrap servers and voucher signing authorities designated by the manufacturers. While operators may use points in the network to block access to the well-known bootstrap servers, operators cannot prevent voucher signing authorities from generating vouchers for their devices.

9.10. Concerns with Trusted Bootstrap Servers

Trusted bootstrap servers, whether well-known or discovered, have the potential to cause problems, such as the following.

- A trusted bootstrap server that has been compromised may be modified to return unsigned data of any sort. For instance, a bootstrap server that is only suppose to return redirect information might be modified to return onboarding information. Similarly, a bootstrap server that is only supposed to return signed data, may be modified to return unsigned data. In both cases, the device will accept the response, unaware that it wasn't supposed to be any different. It is RECOMMENDED that maintainers of trusted bootstrap servers ensure that their systems are not easily compromised and, in case of compromise, have mechanisms in

place to detect and remediate the compromise as expediently as possible.

- o A trusted bootstrap server hosting either unsigned, or signed but not encrypted, data may disclose information to unwanted parties (e.g., an administrator of the bootstrap server). This is a privacy issue only, but could reveal information that might be used in a subsequent attack. Disclosure of redirect information has limited exposure (it is just a list of bootstrap servers), whereas disclosure of onboarding information could be highly revealing (e.g., network topology, firewall policies, etc.). It is RECOMMENDED that operators encrypt the bootstrapping data when its contents are considered sensitive, even to the point of hiding it from the administrators of the bootstrap server, which may be maintained by a 3rd-party.

9.11. Validity Period for Conveyed Information

The conveyed information artifact does not specify a validity period. For instance, neither redirect information nor onboarding information enable "not-before" or "not-after" values to be specified, and neither artifact alone can be revoked.

For unsigned data provided by an untrusted source of bootstrapping data, it is not meaningful to discuss its validity period when the information itself has no authenticity and may have come from anywhere.

For unsigned data provided by a trusted source of bootstrapping data (i.e., a bootstrap server), the availability of the data is the only measure of it being current. Since the untrusted data comes from a trusted source, its current availability is meaningful and, since bootstrap servers use TLS, the contents of the exchange cannot be modified or replayed.

For signed data, whether provided by an untrusted or trusted source of bootstrapping data, the validity is constrained by the validity of the both the ownership voucher and owner certificate used to authenticate it.

The ownership voucher's validity is primarily constrained by the ownership voucher's "created-on" and "expires-on" nodes. While [RFC8366] recommends short-lived vouchers (see Section 6.1), the "expires-on" node may be set to any point in the future, or omitted altogether to indicate that the voucher never expires. The ownership voucher's validity is secondarily constrained by the manufacturer's PKI used to sign the voucher; whilst an ownership voucher cannot be revoked directly, the PKI used to sign it may be.

The owner certificate's validity is primarily constrained by the X.509's validity field, the "notBefore" and "notAfter" values, as specified by the certificate authority that signed it. The owner certificate's validity is secondarily constrained by the validity of the PKI used to sign the voucher. Owner certificates may be revoked directly.

For owners that wish to have maximum flexibility in their ability to specify and constrain the validity of signed data, it is RECOMMENDED that a unique owner certificate is created for each signed artifact. Not only does this enable a validity period to be specified, for each artifact, but it also enables to the validity of each artifact to be revoked.

9.12. Cascading Trust via Redirects

Redirect Information (Section 2.1), by design, instructs a bootstrapping device to initiate a HTTPS connection to the specified bootstrap servers.

When the redirect information is trusted, the redirect information can encode a trust anchor certificate used by the device to authenticate the TLS end-entity certificate presented by each bootstrap server.

As a result, any compromise in an interaction providing redirect information may result in compromise of all subsequent interactions.

9.13. Possible Reuse of Private Keys

This document describes two uses for secure device identity certificates.

The primary use is for when the device authenticates itself to a bootstrap server, using its private key for TLS-level client-certificate based authentication.

A secondary use is for when the device needs to decrypt provided bootstrapping artifacts, using its private key to decrypt the data or, more precisely, per Section 6 in [RFC5652], decrypt a symmetric key used to decrypt the data.

This document, in Section 3.4 allows for the possibility that the same secure device identity certificate is used for both uses, as [Std-802.1AR-2018] states that a DevID certificate MAY have the "keyEncipherment" KeyUsage bit, in addition to the "digitalSignature" KeyUsage bit, set.

While it is understood that it is generally frowned upon to reuse private keys, this document views such reuse acceptable as there are not any known ways to cause a signature made in one context to be (mis)interpreted as valid in the other context.

9.14. Non-Issue with Encrypting Signed Artifacts

This document specifies the encryption of signed objects, as opposed to the signing of encrypted objects, as might be expected given well-publicized oracle attacks (e.g., the padding oracle attack).

This document does not view such attacks as feasible in the context of the solution because the decrypted text never leaves the device.

9.15. The "ietf-sztp-conveyed-info" YANG Module

The ietf-sztp-conveyed-info module defined in this document defines a data structure that is always wrapped by a CMS structure. When accessed by a secure mechanism (e.g., protected by TLS), then the CMS structure may be unsigned. However, when accessed by an insecure mechanism (e.g., removable storage device), then the CMS structure must be signed, in order for the device to trust it.

Implementations should be aware that signed bootstrapping data only protects the data from modification, and that the contents are still visible to others. This doesn't affect security so much as privacy. That the contents may be read by unintended parties when accessed by insecure mechanisms is considered next.

The ietf-sztp-conveyed-info module defines a top-level "choice" statement that declares the contents are either "redirect-information" or "onboarding-information". Each of these two cases are now considered.

When the content of the CMS structure is redirect-information, an observer can learn about the bootstrap servers the device is being directed to, their IP addresses or hostnames, ports, and trust anchor certificates. Knowledge of this information could provide an observer some insight into a network's inner structure.

When the content of the CMS structure is onboarding information, an observer could learn considerable information about how the device is to be provisioned. This information includes the operating system version, initial configuration, and script contents. This information should be considered sensitive and precautions should be taken to protect it (e.g., encrypt the artifact using the device's public key).

9.16. The "ietf-sztp-bootstrap-server" YANG Module

The ietf-sztp-bootstrap-server module defined in this document specifies an API for a RESTCONF [RFC8040]. The lowest RESTCONF layer is HTTPS, and the mandatory-to-implement secure transport is TLS [RFC8446].

The NETCONF Access Control Model (NACM) [RFC8341] provides the means to restrict access for particular users to a preconfigured subset of all available protocol operations and content.

This module presents no data nodes (only RPCs). There is no need to discuss the sensitivity of data nodes.

This module defines two RPC operations that may be considered sensitive in some network environments. These are the operations and their sensitivity/vulnerability:

get-bootstrapping-data: This RPC is used by devices to obtain their bootstrapping data. By design, each device, as identified by its authentication credentials (e.g. client certificate), can only obtain its own data. NACM is not needed to further constrain access to this RPC.

report-progress: This RPC is used by devices to report their bootstrapping progress. By design, each device, as identified by its authentication credentials (e.g. client certificate), can only report data for itself. NACM is not needed to further constrain access to this RPC.

10. IANA Considerations

10.1. The IETF XML Registry

This document registers two URIs in the "ns" subregistry of the IETF XML Registry [RFC3688] maintained at https://www.iana.org/assignments/xml-registry/xml-registry.xhtml#ns. Following the format in [RFC3688], the following registrations are requested:

```
URI: urn:ietf:params:xml:ns:yang:ietf-sztp-conveyed-info
Registrant Contact: The NETCONF WG of the IETF.
XML: N/A, the requested URI is an XML namespace.

URI: urn:ietf:params:xml:ns:yang:ietf-sztp-bootstrap-server
Registrant Contact: The NETCONF WG of the IETF.
XML: N/A, the requested URI is an XML namespace.
```

10.2. The YANG Module Names Registry

This document registers two YANG modules in the YANG Module Names registry [RFC6020] maintained at https://www.iana.org/assignments/yang-parameters/yang-parameters.xhtml. Following the format defined in [RFC6020], the below registrations are requested:

```
name:      ietf-sztp-conveyed-info
namespace: urn:ietf:params:xml:ns:yang:ietf-sztp-conveyed-info
prefix:    sztp-info
reference: RFC XXXX

name:      ietf-sztp-bootstrap-server
namespace: urn:ietf:params:xml:ns:yang:ietf-sztp-bootstrap-server
prefix:    sztp-svr
reference: RFC XXXX
```

10.3. The SMI Security for S/MIME CMS Content Type Registry

This document registers two SMI security codes in the "SMI Security for S/MIME CMS Content Type" registry (1.2.840.113549.1.9.16.1) maintained at https://www.iana.org/assignments/smi-numbers/smi-numbers.xhtml#security-smime-1. Following the format used in Section 3.4 of [RFC7107], the below registrations are requested:

Decimal	Description	References
TBD1	id-ct-sztpConveyedInfoXML	[RFCXXXX]
TBD2	id-ct-sztpConveyedInfoJSON	[RFCXXXX]

id-ct-sztpConveyedInfoXML indicates that the "conveyed-information" is encoded using XML. id-ct-sztpConveyedInfoJSON indicates that the "conveyed-information" is encoded using JSON.

10.4. The BOOTP Manufacturer Extensions and DHCP Options Registry

This document registers one DHCP code point in the "BOOTP Manufacturer Extensions and DHCP Options" registry maintained at http://www.iana.org/assignments/bootp-dhcp-parameters. Following the format used by other registrations, the below registration is requested:

```
Tag:         143
Name:        OPTION_V4_SZTP_REDIRECT
Data Length: N
Meaning:     This option provides a list of URIs
             for SZTP bootstrap servers
Reference:   [RFCXXXX]
```

Note: this request is to make permanent a previously registered early code point allocation.

10.5. The Dynamic Host Configuration Protocol for IPv6 (DHCPv6) Registry

This document registers one DHCP code point in "Option Codes" subregistry of the "Dynamic Host Configuration Protocol for IPv6 (DHCPv6)" registry maintained at http://www.iana.org/assignments/dhcpv6-parameters. Following the format used by other registrations, the below registration is requested:

```
Value:            136
Description:      OPTION_V6_SZTP_REDIRECT
Client ORO:       Yes
Singleton Option: Yes
Reference:        [RFCXXXX]
```

Note: this request is to make permanent a previously registered early code point allocation.

10.6. The Service Name and Transport Protocol Port Number Registry

This document registers one service name in the Service Name and Transport Protocol Port Number Registry [RFC6335] maintained at https://www.iana.org/assignments/service-names-port-numbers/service-names-port-numbers.xhtml. Following the format defined in Section 8.1.1 of [RFC6335], the below registration is requested:

```
Service Name:            sztp
Transport Protocol(s):   TCP
Assignee:                IESG <iesg@ietf.org>
Contact:                 IETF Chair <chair@ietf.org>
Description:             This service name is used to construct the
                         SRV service label "_sztp" for discovering
                         SZTP bootstrap servers.
Reference:               [RFCXXXX]
Port Number:             N/A
Service Code:            N/A
Known Unauthorized Uses: N/A
Assignment Notes:        This protocol uses HTTPS as a substrate.
```

10.7. The DNS Underscore Global Scoped Entry Registry

This document registers one service name in the DNS Underscore Global Scoped Entry Registry [I-D.ietf-dnsop-attrleaf] maintained at TBD_IANA_URL. Following the format defined in Section 4.3 of [I-D.ietf-dnsop-attrleaf], the below registration is requested:

RR Type:	TXT
_NODE NAME:	_sztp
Reference:	[RFCXXXX]

11. References

11.1. Normative References

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Appendix A. Example Device Data Model

This section defines a non-normative data model that enables the configuration of SZTP bootstrapping and discovery of what parameters are used by a device's bootstrapping logic.

A.1. Data Model Overview

The following tree diagram provides an overview for the SZTP device data model.

```
 module: example-device-data-model
   +--rw sztp
      +--rw enabled?                          boolean
      +--ro idevid-certificate?               ct:end-entity-cert-cms
      |       {bootstrap-servers}?
      +--ro bootstrap-servers {bootstrap-servers}?
      |  +--ro bootstrap-server* [address]
      |     +--ro address    inet:host
      |     +--ro port?      inet:port-number
      +--ro bootstrap-server-trust-anchors {bootstrap-servers}?
      |  +--ro reference*   ta:pinned-certificates-ref
      +--ro voucher-trust-anchors {signed-data}?
         +--ro reference*   ta:pinned-certificates-ref
```

In the above diagram, notice that there is only one configurable node "enabled". The expectation is that this node would be set to "true" in device's factory default configuration and that it would either be set to "false" or deleted when the SZTP bootstrapping is longer needed.

A.2. Example Usage

Following is an instance example for this data model.

```
<sztp xmlns="https://example.com/sztp-device-data-model">
  <enabled>true</enabled>
  <idevid-certificate>base64encodedvalue==</idevid-certificate>
  <bootstrap-servers>
    <bootstrap-server>
      <address>sztp1.example.com</address>
      <port>8443</port>
    </bootstrap-server>
    <bootstrap-server>
      <address>sztp2.example.com</address>
      <port>8443</port>
    </bootstrap-server>
    <bootstrap-server>
      <address>sztp3.example.com</address>
      <port>8443</port>
    </bootstrap-server>
  </bootstrap-servers>
  <bootstrap-server-trust-anchors>
    <reference>manufacturers-root-ca-certs</reference>
  </bootstrap-server-trust-anchors>
  <voucher-trust-anchors>
    <reference>manufacturers-root-ca-certs</reference>
  </voucher-trust-anchors>
</sztp>
```

A.3. YANG Module

The device model is defined by the YANG module defined in this section.

This module uses data types defined in [RFC6991], [I-D.ietf-netconf-crypto-types], and [I-D.ietf-netconf-trust-anchors].

```
module example-device-data-model {
  yang-version 1.1;
  namespace "https://example.com/sztp-device-data-model";
  prefix sztp-ddm;

  import ietf-inet-types {
    prefix inet;
    reference "RFC 6991: Common YANG Data Types";
  }

  import ietf-crypto-types {
    prefix ct;
    revision-date 2018-06-04;
    description
```

```
        "This revision is defined in the -00 version of
         draft-ietf-netconf-crypto-types";
      reference
       "draft-ietf-netconf-crypto-types:
          Common YANG Data Types for Cryptography";
    }

    import ietf-trust-anchors {
      prefix ta;
      revision-date 2018-06-04;
      description
       "This revision is defined in -00 version of
        draft-ietf-netconf-trust-anchors.";
      reference
       "draft-ietf-netconf-trust-anchors:
          YANG Data Model for Global Trust Anchors";
    }

    organization
      "Example Corporation";

    contact
      "Author: Bootstrap Admin <mailto:admin@example.com>";

    description
      "This module defines a data model to enable SZTP
       bootstrapping and discover what parameters are used.
       This module assumes the use of an IDevID certificate,
       as opposed to any other client certificate, or the
       use of an HTTP-based client authentication scheme.";

    revision 2019-01-15 {
      description
        "Initial version";
      reference
        "RFC XXXX: Secure Zero Touch Provisioning (SZTP)";
    }

    // features

    feature bootstrap-servers {
      description
        "The device supports bootstrapping off bootstrap servers.";
    }

    feature signed-data {
      description
        "The device supports bootstrapping off signed data.";
```

```
    }

    // protocol accessible nodes

    container sztp {
      description
        "Top-level container for SZTP data model.";
      leaf enabled {
        type boolean;
        default false;
        description
          "The 'enabled' leaf controls if SZTP bootstrapping is
           enabled or disabled.  The default is 'false' so that, when
           not enabled, which is most of the time, no configuration
           is needed.";
      }
      leaf idevid-certificate {
        if-feature bootstrap-servers;
        type ct:end-entity-cert-cms;
        config false;
        description
          "This CMS structure contains the IEEE 802.1AR-2009
           IDevID certificate itself, and all intermediate
           certificates leading up to, and optionally including,
           the manufacturer's well-known trust anchor certificate
           for IDevID certificates.  The well-known trust anchor
           does not have to be a self-signed certificate.";
        reference
          "IEEE 802.1AR-2009:
             IEEE Standard for Local and metropolitan area
             networks - Secure Device Identity.";
      }
      container bootstrap-servers {
        if-feature bootstrap-servers;
        config false;
        description
          "List of bootstrap servers this device will attempt
           to reach out to when bootstrapping.";
        list bootstrap-server {
          key "address";
          description
            "A bootstrap server entry.";
          leaf address {
            type inet:host;
            mandatory true;
            description
              "The IP address or hostname of the bootstrap server the
               device should redirect to.";
```

```
          }
          leaf port {
            type inet:port-number;
            default "443";
            description
              "The port number the bootstrap server listens on.  If no
               port is specified, the IANA-assigned port for 'https'
               (443) is used.";
          }
        }
      }
      container bootstrap-server-trust-anchors {
        if-feature bootstrap-servers;
        config false;
        description "Container for a list of trust anchor references.";
        leaf-list reference {
          type ta:pinned-certificates-ref;
          description
            "A reference to a list of pinned certificate authority (CA)
             certificates that the device uses to validate bootstrap
             servers with.";
        }
      }
      container voucher-trust-anchors {
        if-feature signed-data;
        config false;
        description "Container for a list of trust anchor references.";
        leaf-list reference {
          type ta:pinned-certificates-ref;
          description
            "A reference to a list of pinned certificate authority (CA)
             certificates that the device uses to validate ownership
             vouchers with.";
        }
      }
    }
  }
```

Appendix B. Promoting a Connection from Untrusted to Trusted

The following diagram illustrates a sequence of bootstrapping activities that promote an untrusted connection to a bootstrap server to a trusted connection to the same bootstrap server. This enables a device to limit the amount of information it might disclose to an adversary hosting an untrusted bootstrap server.

The interactions in the above diagram are described below.

1. The device initiates an untrusted connection to a bootstrap server, as is indicated by putting "HTTPS" in double quotes above. It is still an HTTPS connection, but the device is unable to authenticate the bootstrap server's TLS certificate. Because the device is unable to trust the bootstrap server, it sends the "signed-data-preferred" input parameter, and optionally also the "nonce" input parameter, in the "get-bootstrapping-data" RPC. The "signed-data-preferred" parameter informs the bootstrap server that the device does not trust it and may be holding back some additional input parameters from the server (e.g., other input parameters, progress reports, etc.). The "nonce" input parameter enables the bootstrap server to dynamically obtain an ownership voucher from a MASA, which may be important for devices that do not have a reliable clock.

2. The bootstrap server, seeing the "signed-data-preferred" input parameter, knows that it can either send unsigned redirect information or signed data of any type. But, in this case, the bootstrap server has the ability to sign data and chooses to respond with signed redirect information, not signed onboarding information as might be expected, securely redirecting the device back to it again. Not displayed but, if the "nonce" input parameter was passed, the bootstrap server could dynamically connect to a download a voucher from the MASA having the nonce value in it. Details regarding a protocol enabling this integration is outside the scope of this document.

3. Upon validating the signed redirect information, the device establishes a secure connection to the bootstrap server. Unbeknownst to the device, it is the same bootstrap server it was connected to previously but, because the device is able to authenticate the bootstrap server this time, it sends its normal "get-bootstrapping-data" request (i.e., with additional input parameters) as well as its progress reports (not depicted).

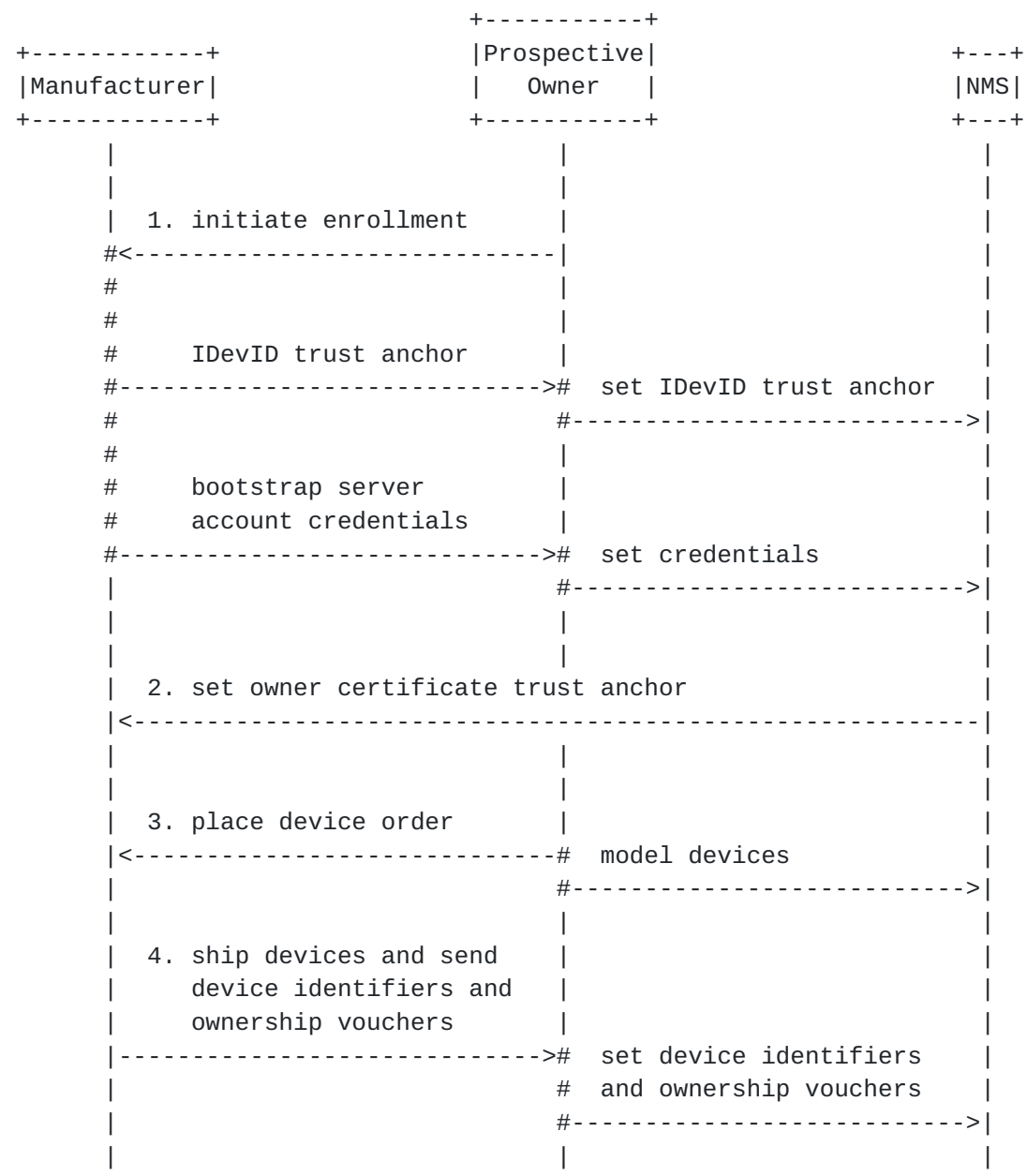
4. This time, because the "signed-data-preferred" parameter was not passed, having access to all of the device's input parameters, the bootstrap server returns, in this example, unsigned onboarding information to the device. Note also that, because the bootstrap server is now trusted, the device will send progress reports to the server.

Appendix C. Workflow Overview

The solution presented in this document is conceptualized to be composed of the non-normative workflows described in this section. Implementation details are expected to vary. Each diagram is followed by a detailed description of the steps presented in the diagram, with further explanation on how implementations may vary.

C.1. Enrollment and Ordering Devices

The following diagram illustrates key interactions that may occur from when a prospective owner enrolls in a manufacturer's SZTP program to when the manufacturer ships devices for an order placed by the prospective owner.



Each numbered item below corresponds to a numbered item in the diagram above.

1. A prospective owner of a manufacturer's devices initiates an enrollment process with the manufacturer. This process includes the following:

   * Regardless how the prospective owner intends to bootstrap their devices, they will always obtain from the manufacturer the trust anchor certificate for the IDevID certificates. This certificate will is installed on the prospective owner's

NMS so that the NMS can authenticate the IDevID certificates when they are presented to subsequent steps.

* If the manufacturer hosts an Internet based bootstrap server (e.g., a redirect server) such as described in Section 4.4, then credentials necessary to configure the bootstrap server would be provided to the prospective owner. If the bootstrap server is configurable through an API (outside the scope of this document), then the credentials might be installed on the prospective owner's NMS so that the NMS can subsequently configure the manufacturer-hosted bootstrap server directly.

2. If the manufacturer's devices are able to validate signed data (Section 5.4), and assuming that the prospective owner's NMS is able to prepare and sign the bootstrapping data itself, the prospective owner's NMS might set a trust anchor certificate onto the manufacturer's bootstrap server, using the credentials provided in the previous step. This certificate is the trust anchor certificate that the prospective owner would like the manufacturer to place into the ownership vouchers it generates, thereby enabling devices to trust the owner's owner certificate. How this trust anchor certificate is used to enable devices to validate signed bootstrapping data is described in Section 5.4.

3. Some time later, the prospective owner places an order with the manufacturer, perhaps with a special flag checked for SZTP handling. At this time, or perhaps before placing the order, the owner may model the devices in their NMS, creating virtual objects for the devices with no real-world device associations. For instance the model can be used to simulate the device's location in the network and the configuration it should have when fully operational.

4. When the manufacturer fulfills the order, shipping the devices to their intended locations, they may notify the owner of the devices' serial numbers and shipping destinations, which the owner may use to stage the network for when the devices power on. Additionally, the manufacturer may send one or more ownership vouchers, cryptographically assigning ownership of those devices to the owner. The owner may set this information on their NMS, perhaps binding specific modeled devices to the serial numbers and ownership vouchers.

C.2. Owner Stages the Network for Bootstrap

The following diagram illustrates how an owner might stage the network for bootstrapping devices.

Each numbered item below corresponds to a numbered item in the diagram above.

1. Having previously modeled the devices, including setting their fully operational configurations and associating device serial numbers and (optionally) ownership vouchers, the owner might "activate" one or more modeled devices. That is, the owner tells the NMS to perform the steps necessary to prepare for when the real-world devices power up and initiate the bootstrapping process. Note that, in some deployments, this step might be combined with the last step from the previous workflow. Here it

is depicted that an NMS performs the steps, but they may be performed manually or through some other mechanism.

2. If it is desired to use a deployment-specific bootstrap server, it must be configured to provide the bootstrapping data for the specific devices. Configuring the bootstrap server may occur via a programmatic API not defined by this document. Illustrated here as an external component, the bootstrap server may be implemented as an internal component of the NMS itself.

3. If it is desired to use a manufacturer hosted bootstrap server, it must be configured to provide the bootstrapping data for the specific devices. The configuration must be either redirect or onboarding information. That is, either the manufacturer hosted bootstrap server will redirect the device to another bootstrap server, or provide the device with the onboarding information itself. The types of bootstrapping data the manufacturer hosted bootstrap server supports may vary by implementation; some implementations may only support redirect information, or only support onboarding information, or support both redirect and onboarding information. Configuring the bootstrap server may occur via a programmatic API not defined by this document.

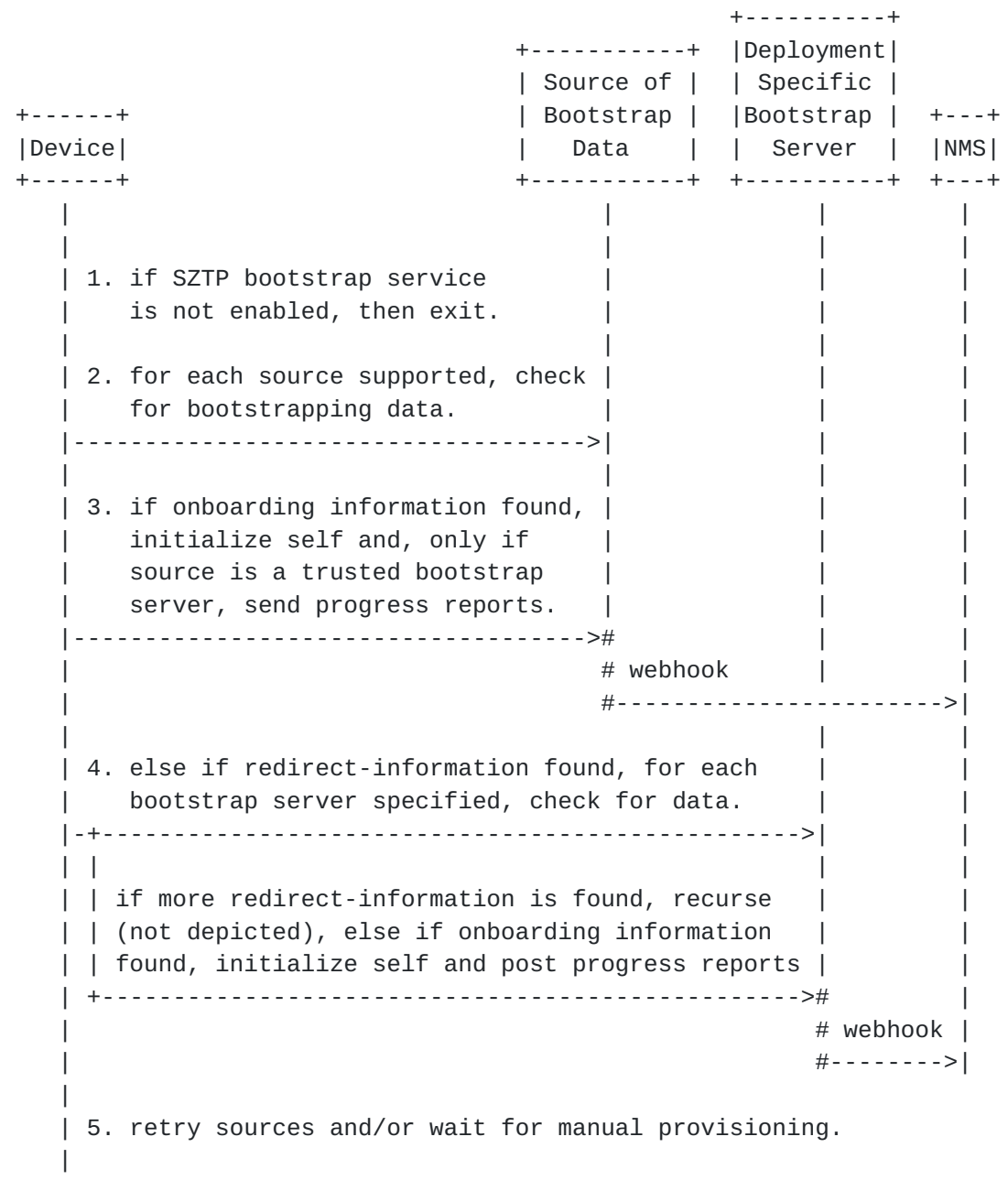
4. If it is desired to use a DNS server to supply bootstrapping data, a DNS server needs to be configured. If multicast DNS-SD is desired, then the DNS server must reside on the local network, otherwise the DNS server may reside on a remote network. Please see Section 4.2 for more information about how to configure DNS servers. Configuring the DNS server may occur via a programmatic API not defined by this document.

5. If it is desired to use a DHCP server to supply bootstrapping data, a DHCP server needs to be configured. The DHCP server may be accessed directly or via a DHCP relay. Please see Section 4.3 for more information about how to configure DHCP servers. Configuring the DHCP server may occur via a programmatic API not defined by this document.

6. If it is desired to use a removable storage device (e.g., USB flash drive) to supply bootstrapping data, the data would need to be placed onto it. Please see Section 4.1 for more information about how to configure a removable storage device.

C.3. Device Powers On

The following diagram illustrates the sequence of activities that occur when a device powers on.



The interactions in the above diagram are described below.

1. Upon power being applied, the device checks to see if SZTP bootstrapping is configured, such as must be the case when running its "factory default" configuration. If SZTP bootstrapping is not configured, then the bootstrapping logic exits and none of the following interactions occur.

2. For each source of bootstrapping data the device supports, preferably in order of closeness to the device (e.g., removable

storage before Internet based servers), the device checks to see if there is any bootstrapping data for it there.

3. If onboarding information is found, the device initializes itself accordingly (e.g., installing a boot-image and committing an initial configuration). If the source is a bootstrap server, and the bootstrap server can be trusted (i.e., TLS-level authentication), the device also sends progress reports to the bootstrap server.

   * The contents of the initial configuration should configure an administrator account on the device (e.g., username, SSH public key, etc.), and should configure the device either to listen for NETCONF or RESTCONF connections or to initiate call home connections [RFC8071], and should disable the SZTP bootstrapping service (e.g., the "enabled" leaf in data model presented in Appendix A).

   * If the bootstrap server supports forwarding device progress reports to external systems (e.g., via a webhook), a "bootstrap-complete" progress report (Section 7.3) informs the external system to know when it can, for instance, initiate a connection to the device. To support this scenario further, the "bootstrap-complete" progress report may also relay the device's SSH host keys and/or TLS certificates, with which the external system can use to authenticate subsequent connections to the device.

   If the device successfully completes the bootstrapping process, it exits the bootstrapping logic without considering any additional sources of bootstrapping data.

4. Otherwise, if redirect information is found, the device iterates through the list of specified bootstrap servers, checking to see if the bootstrap server has bootstrapping data for the device. If the bootstrap server returns more redirect information, then the device processes it recursively. Otherwise, if the bootstrap server returns onboarding information, the device processes it following the description provided in (3) above.

5. After having tried all supported sources of bootstrapping data, the device may retry again all the sources and/or provide manageability interfaces for manual configuration (e.g., CLI, HTTP, NETCONF, etc.). If manual configuration is allowed, and such configuration is provided, the configuration should also disable the SZTP bootstrapping service, as the need for bootstrapping would no longer be present.

Appendix D. Change Log

D.1. ID to 00

- Major structural update; the essence is the same. Most every section was rewritten to some degree.
- Added a Use Cases section
- Added diagrams for "Actors and Roles" and "NMS Precondition" sections, and greatly improved the "Device Boot Sequence" diagram
- Removed support for physical presence or any ability for configlets to not be signed.
- Defined the Conveyed Information DHCP option
- Added an ability for devices to also download images from configuration servers
- Added an ability for configlets to be encrypted
- Now configuration servers only have to support HTTP/S - no other schemes possible

D.2. 00 to 01

- Added boot-image and validate-owner annotations to the "Actors and Roles" diagram.
- Fixed 2nd paragraph in section 7.1 to reflect current use of anyxml.
- Added encrypted and signed-encrypted examples
- Replaced YANG module with XSD schema
- Added IANA request for the Conveyed Information DHCP Option
- Added IANA request for media types for boot-image and configuration

D.3. 01 to 02

- Replaced the need for a configuration signer with the ability for each NMS to be able to sign its own configurations, using manufacturer signed ownership vouchers and owner certificates.

- Renamed configuration server to bootstrap server, a more representative name given the information devices download from it.

- Replaced the concept of a configlet by defining a southbound interface for the bootstrap server using YANG.

- Removed the IANA request for the boot-image and configuration media types

D.4. 02 to 03

- Minor update, mostly just to add an Editor's Note to show how this draft might integrate with the draft-pritikin-anima-bootstrapping-keyinfra.

D.5. 03 to 04

- Major update formally introducing unsigned data and support for Internet-based redirect servers.

- Added many terms to Terminology section.

- Added all new "Guiding Principles" section.

- Added all new "Sources for Bootstrapping Data" section.

- Rewrote the "Interactions" section and renamed it "Workflow Overview".

D.6. 04 to 05

- Semi-major update, refactoring the document into more logical parts

- Created new section for information types

- Added support for DNS servers

- Now allows provisional TLS connections

- Bootstrapping data now supports scripts

- Device Details section overhauled

- Security Considerations expanded

- Filled in enumerations for notification types

D.7. 05 to 06

- Minor update
- Added many Normative and Informative references.
- Added new section Other Considerations.

D.8. 06 to 07

- Minor update
- Added an Editorial Note section for RFC Editor.
- Updated the IANA Considerations section.

D.9. 07 to 08

- Minor update
- Updated to reflect review from Michael Richardson.

D.10. 08 to 09

- Added in missing "Signature" artifact example.
- Added recommendation for manufacturers to use interoperable formats and file naming conventions for removable storage devices.
- Added configuration-handling leaf to guide if config should be merged, replaced, or processed like an edit-config/yang-patch document.
- Added a pre-configuration script, in addition to the post-configuration script from -05 (issue #15).

D.11. 09 to 10

- Factored ownership voucher and voucher revocation to a separate document: draft-kwatsen-netconf-voucher. (issue #11)
- Removed <configuration-handling> options "edit-config" and "yang-patch". (issue #12)
- Defined how a signature over signed-data returned from a bootstrap server is processed. (issue #13)

- Added recommendation for removable storage devices to use open/standard file systems when possible. (issue #14)
- Replaced notifications "script-[warning/error]" with "[pre/post]-script-[warning/error]". (goes with issue #15)
- switched owner-certificate to be encoded using the PKCS #7 format. (issue #16)
- Replaced md5/sha1 with sha256 inside a choice statement, for future extensibility. (issue #17)
- A ton of editorial changes, as I went thru the entire draft with a fine-toothed comb.

D.12. 10 to 11

- fixed yang validation issues found by IETFYANGPageCompilation. note: these issues were NOT found by pyang --ietf or by the submission-time validator...
- fixed a typo in the yang module, someone the config false statement was removed.

D.13. 11 to 12

- fixed typo that prevented Appendix B from loading the examples correctly.
- fixed more yang validation issues found by IETFYANGPageCompilation. note: again, these issues were NOT found by pyang --ietf or by the submission-time validator...
- updated a few of the notification enumerations to be more consistent with the other enumerations (following the warning/error pattern).
- updated the information-type artifact to state how it is encoded, matching the language that was in Appendix B.

D.14. 12 to 13

- defined a standalone artifact to encode the old information-type into a PKCS #7 structure.
- standalone information artifact hardcodes JSON encoding (to match the voucher draft).

- combined the information and signature PKCS #7 structures into a single PKCS #7 structure.

- moved the certificate-revocations into the owner-certificate's PKCS #7 structure.

- eliminated support for voucher-revocations, to reflect the voucher-draft's switch from revocations to renewals.

D.15. 13 to 14

- Renamed "bootstrap information" to "onboarding information".

- Rewrote DHCP sections to address the packet-size limitation issue, as discussed in Chicago.

- Added Ian as an author for his text-contributions to the DHCP sections.

- Removed the Guiding Principles section.

D.16. 14 to 15

- Renamed action "notification" to "update-progress" and, likewise "notification-type" to "update-type".

- Updated examples to use "base64encodedvalue==" for binary values.

- Greatly simplified the "Artifact Groupings" section, and moved it as a subsection to the "Artifacts" section.

- Moved the "Workflow Overview" section to the Appendix.

- Renamed "bootstrap information" to "update information".

- Removed "Other Considerations" section.

- Tons of editorial updates.

D.17. 15 to 16

- tweaked language to refer to "initial state" rather than "factory default configuration", so as accommodate white-box scenarios.

- added a paragraph to Intro regarding how the solution primarily regards physical machines, but could be extended to VMs by a future document.

- added a pointer to the Workflow Overview section (recently moved to the Appendix) to the Intro.
- added a note that, in order to simplify the verification process, the "Conveyed Information" PKCS #7 structure MUST also contain the signing X.509 certificate.
- noted that the owner certificate's must either have no Key Usage or the Key Usage must set the "digitalSignature" bit.
- noted that the owner certificate's subject and subjectAltName values are not constrained.
- moved/consolidated some text from the Artifacts section down to the Device Details section.
- tightened up some ambiguous language, for instance, by referring to specific leaf names in the Voucher artifact.
- reverted a previously overzealous s/unique-id/serial-number/ change.
- modified language for when ZTP runs from when factory-default config is running to when ZTP is configured, which the factory-defaults should set .

D.18. 16 to 17

- Added an example for how to promote an untrusted connection to a trusted connection.
- Added a "query parameters" section defining some parameters enabling scenarios raised in last call.
- Added a "Disclosing Information to Untrusted Servers" section to the Security Considerations.

D.19. 17 to 18

- Added Security Considerations for each YANG module.
- Reverted back to the device always sending its DevID cert.
- Moved data tree to "get-bootstrapping-data" RPC.
- Moved the "update-progress" action to a "report-progress" RPC.

- Added an "signed-data-preferred" parameter to "get-bootstrapping-data" RPC.

- Added the "ietf-zerotouch-device" module.

- Lots of small updates.

D.20. 18 to 19

- Fixed "must" expressions, by converting "choice" to a "list" of "image-verification", each of which now points to a base identity called "hash-algorithm". There's just one algorithm currently defined (sha-256). Wish there was a standard crypto module that could identify such identities.

D.21. 19 to 20

- Now references I-D.ietf-netmod-yang-tree-diagrams.

- Fixed tree-diagrams in Section 2 to always reflect current YANG (now they are now dynamically generated).

- The "redirect-information" container's "trust-anchor" is now a CMS structure that can contain a chain of certificates, rather than a single certificate.

- The "onboarding-information" container's support for image verification reworked to be extensible.

- Added a reference to the "Device Details" section to the new example-device-data-model module.

- Clarified that the device must always pass its IDevID certificate, even for untrusted bootstrap servers.

- Fixed the description statement for the "script" typedef to refer to the [pre/post]-script-[warning/error] enums, rather than the legacy script-[warning/error] enums.

- For the get-bootstrapping-data RPC's input, removed the "remote-id" and "circuit-id" fields, and added a "hw-model" field.

- Improved DHCP error handling text.

- Added MUST requirement for DHCPv6 client and server implementing [RFC3396] to handle URI lists longer than 255 octets.

- Changed the "configuration" value in onboarding-information to be type "binary" instead of "anydata".
- Moved everything from PKCS#7 to CMS (this shows up as a big change).
- Added the early code point allocation assignments for the DHCP Options in the IANA Considerations section, and updated the RFC Editor note accordingly.
- Added RFC Editor request to replace the assigned values for the CMS content types.
- Relaxed auth requirements from device needing to always send IDevID cert to device needing to always send authentication credentials, as this better matches what RFC 8040 Section 2.5 says.
- Moved normative module "ietf-zerotouch-device" to non-normative module "example-device-data-model".
- Updated Title, Abstract, and Introduction per discussion on list.

D.22. 20 to 21

- Now any of the three artifact can be encrypted.
- Fixed some line-too-long issues.

D.23. 21 to 22

- Removed specifics around how scripts indicate warnings or errors and how scripts emit output.
- Moved the SZTP Device Data Model section to the Appendix.
- Modified the YANG module in the SZTP Device Data Model section to reflect the latest trust-anchors and keystore drafts.
- Modified types in other YANG modules to more closely emulate what is in draft-ietf-netconf-crypto-types.

D.24. 22 to 23

- Rewrote section 5.6 (processing onboboarding information) to be clearer about error handling and retained state. Specifically:

  * Clarified that a script, upon having an error, must gracefully exit, cleaning up any state that might hinder subsequent executions.

  * Added ability for scripts to be executed again with a flag enabling them to clean up state from a previous execution.

  * Clarified that the conifguration commit is atomic.

  * Clarified that any error encountered after committing the configuration (e.g., in the "post-configuration-script") must rollback the configuration to the previous configuration.

  * Clarified that failure to successfully deliver the "bootstrap-initiated" and "bootstrap-complete" progress types must be treated as an error.

  * Clarified that "return to bootstrapping sequence" is to be interpreted in the recursive context. Meaning that the device rolls-back one loop, rather than start over from scratch.

- Changed how a device verifies a boot-image from just "MUST match one of the supplied fingerprints" to also allow for the verification to use an cryptographic signature embedded into the image itself.

- Added more "progress-type" enums for visibility reasons, enabling more strongly-typed debug information to be sent to the bootstrap server.

- Added Security Considerations based on early SecDir review.

- Added recommendation for device to send warning if the initial config does not disable the bootstrapping process.

D.25. 23 to 24

- Follow-ups from SecDir and Shepherd.

- Added "boot-image-complete" enumeration.

D.26. 24 to 25

- Removed remaining old "bootstrapping information" term usage.

- Fixed DHCP Option length definition.

- Added reference to RFC 6187.

D.27. 25 to 26

- Updated URI structure text (sec 8.3) and added norm. ref to RFC7230 reflecting Alexey Melnikov's comment.
- Added IANA registration for the 'zerotouch' service, per IESG review from Adam Roach.
- Clarified device's looping behavior and support for alternative provisioning mechanisms, per IESG review from Mirja Kuehlewind.
- Updated "ietf-sztp-bootstrap-server:ssh-host-key" from leaf-list to list, per IESG review from Benjamin Kaduk.
- Added option size text to DHCPv4 option size to address Suresh Krishnan's IESG review discuss point.
- Updated RFC3315 to RFC8415 and associated section references.
- Revamped the DNS Server section, after digging into Alexey Melnikov comment.
- Fixed IETF terminology template section in both YANG modules.

D.28. 26 to 27

- Added Security Consideration for cascading trust via redirects.
- Modified the get-bootstrapping-data RPC's "nonce" input parameter to being a minimum of 16-bytes (used to be 8-bytes).
- Added Security Consideration regarding possible reuse of device's private key.
- Added Security Consideration regarding use of sign-then-encrypt.
- Renamed "Zero Touch"/"zerotouch" throughout. Now uses "SZTP" when referring to the draft/solution, and "conveyed" when referring to the bootstrapping artifact.
- Added missing text for "encrypted unsigned conveyed information" case.
- Renamed "untrusted-connection" input paramter to "signed-data-preferred"
- Switch yd:yang-data back to rc:yang-data

- Added a couple features to the bootstrap-server module.

D.29. 27 to 28

- Modified DNS section to no longer reference DNS-SD (now just plain TXT and SRV lookups, via multicast or unicast.

- Registers "_sztp" in the DNS Underscore Global Scoped Entry Registry.

- Updated 802.1AR reference to current spec version.

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