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Master Thesis in Informatics

**Secure Bootstrapping and
Post-Compromise Security in IoT**

submitted by

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Contents

List of Figures	v
List of Tables	vi
Acronyms	vii
1 Introduction	1
1.1 Introduction and Motivation	1
1.2 Research Questions	1
1.3 Structure of the Thesis	1
2 Background	2
2.1 Certificate	2
2.2 Bootstrapping	2
2.3 Vouchers	2
2.4 Certificate Enrollment	2
2.5 Protocol Formal Modeling	2
2.6 Symmetric Encryption	2
2.7 Asymmetric Encryption	2
2.8 Backward Secrecy	2
2.9 Forward Secrecy	2
2.10 Key Exchange	2
2.11 Ratcheting	2
3 Use Cases	3
3.1 Automated Border Control (ABC)	3
3.2 Internet of Things (IoT)	5
3.3 V2V	5
4 Secure Bootstrapping	6
4.1 Bootstrapping Remote Secure Key Infrastructure (BRSKI)	7
4.1.1 Architecture Overview	7
4.1.2 Protocol Details	9
4.2 Secure Zero Touch Provisioning (SZTP)	13
4.3 Protocols Comparison	13
5 X3DH	14
5.1 Protocol Overview	14
5.1.1 Roles	14
5.1.2 Keys	14

5.1.3	A Protocol Run	15
5.1.3.1	Registration phase	15
5.1.3.2	The initial message	15
5.1.3.3	Bob's <i>SK</i> Derivation	16
5.1.4	Security Considerations	17
5.1.4.1	Authentication	17
5.1.4.2	Protocol Replay	17
5.1.4.3	Server Trust	17
5.2	OFMC Modelling	17
5.2.1	Types section	18
5.2.2	Knowledge section	19
5.2.3	Actions section	19
5.2.4	Goals section	20
5.3	Difference from specification	20
5.3.1	Registration Phase	20
5.3.2	Use of Signatures	20
5.3.3	Use of Certificates	21
5.4	Conclusion	21
6	Double Ratchet Algorithm	22
7	Implementation	23
8	Evaluation	24
9	Conclusion and Future Work	25
	Bibliography	26
A	BRSKI vs. SZTP	28
A.1	Protocol Comparison	28
A.2	Terminology Comparison	32

Abstract

Please write a short abstract summarizing your work.

Acknowledgments

I would first like to thank . . .

List of Figures

3.1	Logical Architecture overview from [13]	4
3.2	Workflow of ABC.	4
4.1	BRSKI Architecture.	7
4.2	A successful BRSKI protocol run.	9
5.1	DH calculations.	16

List of Tables

5.1 X3DH keys. 15

Acronyms

PKI Public Key Infrastructure

ABC Automated Border Control

DAS Document Authentication System

BVS Biometric Verification System

CSI Central Systems Interface

BGMS Border Guard Maintenance System

VMS Visa Management System

RTP Registered Traveler Program

EEMS Entry-Exit Management System

TCP Transmission Control Protocol

UDP User Datagram Protocol

IoT Internet of Things

TLS Transport Layer Security

DTLS Datagram Transport Layer Security

IETF Internet Engineering Task Force

CoAP Constrained Application Protocol

REST Representational state transfer

IDeVID Initial Device Identifier

LDeVID Locally Significant Device Identifier

P2P Peer-to-Peer

BRSKI Bootstrapping Remote Secure Key Infrastructure

SZTP Secure Zero Touch Provisioning

OOB Out-Of-Band

EAP-TLS Extensible Authentication Protocol TLS

GBA Generic Bootstrapping Architecture

EST Enrollment over Secure Transport

CA Certification Authority

MASA Manufacturer Authorized Signing Authority

RA Registration Authority

EE End Entity

DoS Denial of Service

SCRAM Salted Challenge Response Authentication Mechanism

TOFU Trust on first use

NEA Network Endpoint Assessment

1 Introduction

1.1 Introduction and Motivation

Your thesis should be motivated in this chapter. Also outline the research gap to existing work.

1.2 Research Questions

Write down and explain your research questions

1.3 Structure of the Thesis

Explain the structure of your thesis.

2 Background

This chapters gives an overview over concepts important for the protocols and algorithms discussed in further chapters.

2.1 Certificate

2.2 Bootstrapping

2.3 Vouchers

-nonced and nonceless

2.4 Certificate Enrollment

2.5 Protocol Formal Modeling

2.6 Symmetric Encryption

2.7 Asymmetric Encryption

2.8 Backward Secrecy

2.9 Forward Secrecy

2.10 Key Exchange

2.11 Ratcheting

3 Use Cases

3.1 ABC

International passenger traffic has been monitored to continuously increase over the years. Since air transport is one of the most convenient form of long distance transport among passengers, the above claim is indicated by the Airports Council International's Passenger Traffic Summary¹. Despite the current shock due to the Covid-19 pandemic to the air transport industry, the aviation industry has shown resilience over the past decades and is predicted to recover and further grow by 4% over the course of the next 20 years² international border crossing points are forecasted to face more traffic than they already are. Implying the requirement for a solution to the Border control process to mitigate longer queues and waiting times, or the need to hire and train more personnel to conduct the task.

bio-metric passports are widely issued by more than 150 countries and regions, as of 2020³. Such passports contain a contactless smart chip that stores the passport holder's bio-metric information to authenticate his identity at passport control stations. The chips may contain one or more of the following bio-metric data: Iris, Fingerprint, and/or Facial features. In recent years, ABC systems, or E-Gates, started rolling out in airports leveraging the wide deployment of bio-metric passports. They intend to automate the process and improve the management and control of travel flows, serving passengers in a shorter time and reduce queues at airports. Resulting in benefits to the Aircraft operators, Airports, passengers, and Governments [3].

Labati et al. [13] represented two types of communication performed at an E-Gate: communication between systems interconnected within the E-Gate, and communication with External systems. Internally, an E-Gate is composed of 4 subsystems: Document Authentication System (DAS), Biometric Verification System (BVS), Central Systems Interface (CSI), and Border Guard Maintenance System (BGMS). Externally, the E-gate is part of a larger border control infrastructure. It communicates with external systems to query for additional information to verify the traveler's eligibility to be granted access to cross the border. An E-Gate can query the databases of the following external systems: Visa Management System (VMS), Registered Traveler Program (RTP), and Entry-Exit Management System (EEMS). Figure 3.1 from [13] presents an illustrative overview of the E-Gate logical architecture. Essentially, the data transfer between the above systems, internally and externally, must be secure as

¹2017 Passenger Summary - Annual Traffic Data. Jan. 2019. URL: <https://aci.aero/data-centre/annual-traffic-data/passengers/2017-passenger-summary-annual-traffic-data/>.

²Boeing. *Commercial Market Outlook 2020 - 2039*. Tech. rep. 2020. URL: <https://www.boeing.com/commercial/market/commercial-market-outlook/>.

³ReadID. *Which countries have ePassports?* 2020. URL: <https://www.readid.com/blog/countries-epassports> (visited on 08/07/2021).

it includes personal data, bio-metrics, and decision making information that affect a state's national security.

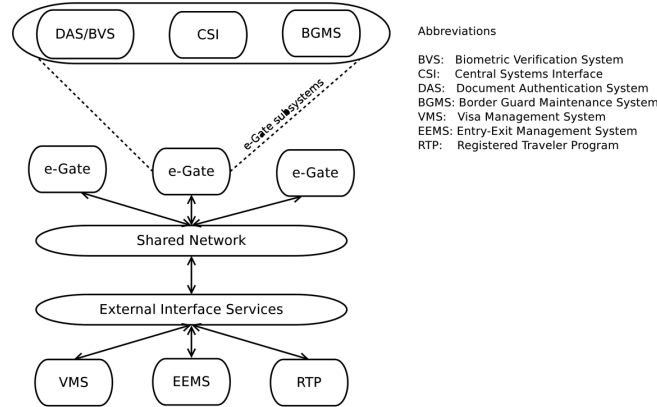


Figure 3.1: Logical Architecture overview from [13]

The workflow of the ABC systems is similar to the one depicted in Figure 3.2. At first, a citizen starts by scanning his passport data page through the gate's scanner. The scanner communicates the image to the Border control system (BCS) which in turn runs its optical data recognition software to extract the data from the scanned data page and verify the document security features. Next, the E-Gate proceeds by reading the embedded electronic chip in the passport. Due to the sensitivity of the bio-metric data, they are not transferred. However, the non-sensitive data stored on the chip, which is equivalent to the data already scanned, is sent to the BCS to cross-check the passport data page. The citizen's facial features and bio-metrics are scanned by the E-Gate to authenticate the citizen against the chip's data. Finally, If the BCS verifies the passport, the E-Gate verifies the bio-metric features, and no match was found in the BCS's watchlists, then the citizen is allowed to pass the border checkpoint.

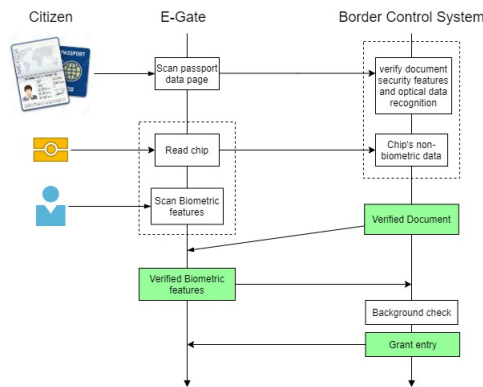


Figure 3.2: Workflow of ABC.

3.2 IoT

IoT is relatively new concept that already has applications in many domains, creating new ways of interactions between humans and small devices, referred to as ‘Smart’ devices. Applications like ‘Smart Airports’, Transportation, Home Automation, and many more, are being revolutionized by this technology [14]. IoT is the deployment of network-connected embedded devices, usually constrained, in the physical environment to link it to the digital world through sensors and actuators. IoT devices are classified into several classes depending on their degree of computing resources and power usage. We may safely assume that they may not be able to process sophisticated or even conventional cryptographic operations. In many use cases, the IoT devices handle critical and private data. This imposes the requirement for data integrity and authenticity guarantees, and -because of privacy- in many cases also confidentiality.

Transport Layer Security (TLS) [24], which relies on Transmission Control Protocol (TCP), has been criticized as inappropriate for IoT [27]. Among the reasons are, the infeasibility of IoT devices to maintain long-lived connections due to energy constraints, high header overhead, and the low-latency requirement that is opposed by the delay due to TCP handshake, especially in a lossy network. Alternatively, Datagram Transport Layer Security (DTLS) [25] provides security for communication channels relying on User Datagram Protocol (UDP). In contrast to TCP, UDP is more suitable for IoT. It is an unreliable protocol as it does not care about message delivery, resulting in a lower header overhead. In addition, it introduces less traffic to the network.

The Internet Engineering Task Force (IETF) introduced Constrained Application Protocol (CoAP) [28] that is intended to be a generic application protocol for constrained environments. Similar to the ubiquitous HTTP [20], CoAP realizes a subset of the Representational state transfer (REST) architecture. Therefore, it easily translates to HTTP. Moreover, CoAP leverages UDP as its transport layer protocol which is secured by DTLS. Hence, CoAP is one of well suited protocols for IoT.

3.3 V2V

- define v2v - architectural overview of v2v - use case messages - secure communication (Tsal, etc...)

4 Secure Bootstrapping

The term “Bootstrapping” is used in a spectrum of contexts including Computing, Law, Finance⁴. It is inspired from the late idiom “to pull oneself up by one’s bootstraps” which means to succeed or elevate yourself without any outside help. In the context of Networking, bootstrapping is an initial procedure between an unconfigured devices which intend to communicate with a network for the first time. Its goal is to provide the device with the required information that enables it to establish subsequent secure communication channels with the desired network. Such information can be certificates, configurations, and metadata.

Integrity and confidentiality of information flow between the two ends of the communication are vital for secure channels. Authentication, whether unilateral or mutual, is another fundamental aspect to achieve channel security. Existing protocols, such as TLS, can achieve End-to-end security between parties. However, analogous protocols rely digital certificates and credentials which are managed by local or third party Public Key Infrastructure (PKI). Therefore to ensure correct and secure execution of protocols certificates must be securely provisioned to their corresponding identities. Typically at the manufacturing phase, the manufacturer usually installs globally unique manufacturer provided identifiers known as the Initial Device Identifier (IDevID) [11]. Its main use is for identity verification purposes and it should not be used to enforce data integrity nor confidentiality. Upon successful completion of the bootstrapping process, the device should posses identifiers that allows for subsequent establishment of secure channels with the network domain. An identifier in this set of identifiers is known as Locally Significant Device Identifier (LDevID) [11].

Bootstrapping approaches differ in the degree of manual user involvement and the amount of information on the device which must be pre-configured by the manufacturer. The survey by Sethi et al. [26] provides a classification for Bootstrapping mechanisms into general categories: Managed methods, Peer-to-Peer (P2P) and Ad-hoc methods, Opportunistic methods, and Hybrid methods.

- *Managed methods*: These bootstrapping approaches count on pre-established credentials and trust anchors for authentication and security. The required initial information and cryptographic material can be acquired either at manufacture time in the factory, or through Out-Of-Band (OOB) means, e.g. using a smart card or a USB. Examples of this method are Extensible Authentication Protocol TLS (EAP-TLS) [30] and Generic Bootstrapping Architecture (GBA) [2].
- *P2P methods*: Contrary to managed methods, these bootstrapping methods do not rely on any pre-established cryptographic material or information. Instead, the bootstrapping protocol results in credentials being established for subsequent secure communication. Typically, resulting credentials are authenticated using an OOB channel. This

⁴*Bootstrapping*. URL: <https://en.wikipedia.org/wiki/Bootstrapping> (visited on 08/08/2021).

category of methods may be utilized if the manufacturer is incapable or untrustworthy to generate the desired credential.

- *Opportunistic methods*: Unlike previous methods where the authenticity of the initially presented identity is verified, approaches which fall under this category rely on verification of the continuity of the initial identity provided. Bergmann et al. [4] have developed a secure bootstrapping mechanism that is an example of this category.
- *Hybrid methods*: A wide range of deployed approaches use components from both managed and P2P methods. Such approaches are categorized as hybrid methods.

This chapter discusses two voucher-based bootstrapping protocols that aim at being zero touch protocols by eliminating the user interference. These protocols are Bootstrapping Remote Secure Key Infrastructure (BRSKI) [22] and Secure Zero Touch Provisioning (SZTP) [29]. Both protocols fall under the managed methods category.

4.1 Bootstrapping Remote Secure Key Infrastructure (BRSKI)

BRSKI is a product of the ANIMA working group of the IETF. It is an automated bootstrapping protocol that enables an unconfigured device to discover and securely join an unfamiliar network domain it is installed in. BRSKI results in the device acquiring an X.509 root certificate to authenticate the network domains' elements and establish consecutive secure channels. Moreover, the device can use the obtained certificate to perform further certificate enrollment protocols, like Enrollment over Secure Transport (EST) [21]. BRSKI is capable of realizing a large scale of thousands of devices in a risk prone environment. For example, customer devices provided by ISPs which are directly shipped to the customers.

4.1.1 Architecture Overview

The environment of BRSKI is composed of three general entities: the network domain, the pledge, and the manufacturer services. Figure 4.1 shows an overview of the protocols architecture.

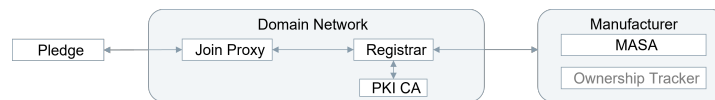


Figure 4.1: BRSKI Architecture.

The network domain is the domain of the alleged new owner of the device, i.e the network that is expecting the device to be connected to it. The domain is a network of entities who share a common local trust anchor. It incorporates a PKI to govern the issuance of digital certificates to provide unique digital identifiers for clients and establish end-to-end security.

A join proxy is another component of the domain. It helps with the discovery of pledges that intend to join the network. In addition, it is responsible for discovering the domain

registrar(s) and determining the proxy mechanisms supported by the registrar and utilizing the lowest impact mechanism. Pledge discovery methods can be classified into passive and active methods. GRASP flooding [7] is a pledge passive discovery method for autonomic networks [12]. It is short for GeneRic Autonomic Signaling Protocol. It is used for signaling between autonomic service agents. GRASP provides discovery, flooding, synchronization, and negotiation functionalities for the technical objectives through respective GRASP messages. Pledge discovery via GRASP multicast flooding is the normative and mandatory method for BRSKI. On the other hand, DNS-based Service Discovery [8] over Multicast DNS [9] as well as DHCP [10] are pledge active discovery methods. They can be used as secondary discovery methods in parallel to GRASP. Moreover, A proxy provides HTTPS connectivity and forwards messages without examination between a pledge and a registrar in the network, and without interfering with the protocol messages.

A pledge is an unconfigured device attempting to join the network domain. Its goal is to be securely bootstrapped in a zero-touch fashion. To achieve this goal, the pledge establishes a TLS connection with one or more of the domain's registrars through the domain's proxy. It is necessary for the pledge and the registrar to establish mutual authentication. A manufacturer installed IDevID is used for pledge authentication to the domain's registrar. It is installed during the manufacturing process and includes certificates signed by the manufacturer and unique identifiers that represent the pledge, in addition to, the pledge unique serial number given by the manufacturer. It is recommended that The provided certificates are used for authentication with the registrar and the signing of voucher requests. The unique serial number is used in vouchers and voucher requests to ensure linkability.

A registrar is an element of the domain that is responsible to carry out the bootstrap process for the pledge. Also, it can be considered as the Registration Authority (RA) for the domain's PKI. A domain can have one or more registrars which all have to be recognized by the domain proxy. If the pledge is capable to concurrently connect to multiple registrars, it is advisable to do so as this protects against a malicious proxy attempting a Denial of Service (DoS) attack like Slowloris.

A manufacturer is the entity that produced the device and set up its initial configuration (IDevID). It provides two distinct services: the Manufacturer Authorized Signing Authority (MASA) service and ownership tracking and validation. MASA can be a third party service that signs the vouchers issued for the bootstrapping process. It is also responsible for providing a repository for audit-log information of bootstrapping events. The service is contacted each time a pledge performs a zero-touch bootstrap in an attempt to enroll into a domain. It takes the decision whether or not issue the voucher according to the MASA policy. Voucher issuance could be done blindly at the lowest security level or it could be tightly bound to the sales channel that verifies the actual ownership of the domain. Hence, the manufacturer can provide protection against stolen devices or illegitimate resale of devices by declining voucher issuance to the suspected pledge.

Ownership tracking and validation is an optional manufacturer service. It is supposed to log all claim attempts and to know which device is owned by which domain and provide such information to registrars. A verified log entry indicates that the pledge was issued a voucher as a result of positive verification of ownership.

4.1.2 Protocol Details

This section describes the message sequence of BRSKI illustrated in figure 4.2 and elaborates on content of the exchanged messages. The numbering sequence referenced through this section refers to the message numbers in figure 4.2.

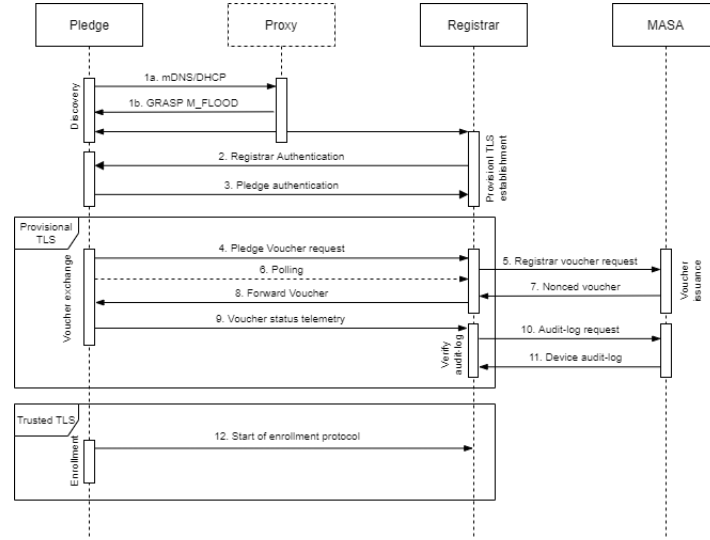


Figure 4.2: A successful BRSKI protocol run.

- *Message 1a, 1b (Discovery phase):* It is the first phase of the protocol where the pledge identifies the domain proxy. This can be performed by a pledge initiated mechanism as in message (1a) or via a proxy initiated mechanism as in message (1b). After successful discovery, the pledge can address a domain registrar through the proxy.
- *Message 2, 3 (Provisional TLS establishment):* The pledge attempts to establish a TLS channel with each discovered registrar to ensure End-to-End security. The pledge must not use any TLS version lower than TLS 1.2, while TLS 1.3 is the encouraged version to be used. To establish the channel, mutual authentication has to be performed. At first, in message (2), the pledge receives the registrar's server certificate. However, the pledge does not possess any trust anchors to verify it yet. Therefore, the pledge accepts the registrar's certificate provisionally. Next in message (3), the pledge is authenticated via the installed IDevID. The registrar must be able to verify the provided certificate, however the distribution of the trust anchors for this task is out-of-scope of BRSKI. Meaning, the information received by the pledge must be untrusted, although it is in a TLS channel, till a trusted trust anchor to verify the certificate is received.
- *Message 4:* Having established a secure provisional TLS channel, the pledge initiates the voucher exchange by sending a pledge voucher request to the registrar in message (4). The request must contain a unique nonce per bootstrapping attempt to protect against replay attacks. Also, the request contains the 'proximity-registrar-cert' and the pledge serial number. The 'proximity-registrar-cert' is the End Entity (EE) certificate of the registrar which is also used to establish the provisional TLS channel. Pledge serial number is a manufacturer defined unique identifier for each device. It is different

from the IDevID certificate serial number. Since not all devices have a real-time clock, depending on the device capabilities, the request is recommended to have the 'created-on' value. Finally, the request must be signed using the pledge's IDevID certificate.

The registrar authorizes the pledge based on the authenticated information presented in the pledge's IDevID and the registrar's policy. The policy can be either to allow any device from a specific vendor, to allow any device of a specific type, or to allow a specific type of devices from a specific vendor.

- ***Message 5 (Polling): TODO***

- *BRSKI-EST TLS channel:* The registrar initiates a TLS 1.2 or newer channel with the MASA where all subsequent communication between the two parties occur within this secure channel. The MASA URL is obtained from the pledge IDevID, as mentioned earlier. To authenticate the MASA, the registrar should be configurable with trust anchors on a per vendor MASA basis as part of the sales process. Moreover, the registrar should also support client authentication mechanisms such as TLS client certificate, HTTP Basic, Digest, or Salted Challenge Response Authentication Mechanism (SCRAM); however TLS Client Certificate based authentication is the recommended method.
- *Message 6:* After obtaining the pledge's voucher request, the registrar constructs a registrar voucher request that is sent to the MASA to obtain a voucher for the pledge. The registrar voucher request is a JSON document that is signed using a CMS structure. The JSON document encapsulates the pledge voucher request CMS object that was sent to the registrar and is referred to as 'prior-signed-voucher-request'. Moreover, the request contains the 'created-on' field which holds the timestamp the request was formed on. In addition, it consists of other fields which relate to the pledge request like the pledge serial number, the nonce used produced by the pledge and used in the pledge request, and 'idevid-issuer' field which holds the issuer value of the pledge IDevID certificate. The registrar includes some certificates in the registrar voucher request CMS object as well. Those certificates are used by the MASA to be pinned into the voucher to be later used by the pledge as a trust anchor for authenticating the domain registrar. Therefore, the certificates enclosed by the registrar in the request have to be part of the chain it wishes the MASA to pin in the voucher. Hence the specificity of the attached certificates is considerably significant. A 'pinned-domain-cert' can be as specific as the registrar's TLS EE certificate. On the other hand, if it is as general as a public webPKI Certification Authority (CA) it could permit any entity that possess a certificate issued by that authority to claim ownership of the device.

In case of nonceless vouchers ...

- *Message 7:* upon receiving the voucher request, the MASA performs a set of checks to decide weather to issue the requested voucher. Given the fact that vouchers have a short lifetime, the request may be from a registrar that has been issued a voucher previously, i.e a voucher renewal request. In this case, the request should be automatically authorized by the MASA.

The MASA extracts the certificate chain attached in the signed CMS object. If the domain CA is unknown to the MASA it is considered as a temporary trust anchor as the intention is not to authenticate the message rather to establish consistency of the

domain PKI. According to the MASA's policy, it decides which certificate of the chain supplied by the registrar it chooses to pin. It may be the farthest certificate of the chain, or it may be as close as the EE TLS certificate of the registrar. If revocation information is available for that certificate, it must be checked by the MASA to prevent issuance of new or renewed vouchers to unauthorized registrars. Next, the CMS signature is validated using the domain's CA extracted from the voucher request. Also, the signing certificate is verified to contain the 'id-kp-cmcRA' Extended Key Usage. This ensures that the signer is an entity that is authorized to be a registrar of the domain. Hence, assures domains that a MASA only accepts requests from domain registrars.

In case of nonceless requests, It is mandatory for the MASA to authenticate the registrar.

In case of nonced voucher requests, the MASA verifies that the 'prior-signed-voucher-request', enclosed in the registrar request, contains a 'proximity-registrar-cert' that is coherent to the certificate used to sign the registrar voucher request. Moreover, the nonce is verified to be consistent between the registrar voucher request and the 'prior-signed-voucher-request'.

Subsequent to a successful validation of the request, the MASA responds with an issued voucher in message (6). Any issued voucher by the MASA is recorded in the audit-log. Otherwise if a problem occurs, a response with the appropriate http signaling as described in [22]. For example, a 403 status code response if the voucher request is not signed correctly, or a 406 status code response if the requested voucher type or algorithms cannot be issued due to the MASA's awareness that such pledge is not capable of processing them.

- *Message 8:* The registrar evaluates the received voucher solely for transparency and future audit-log verification. The received voucher is forwarded to the pledge without any interference or modification from the registrar.
- *Message 9:* After the pledge successfully receives a voucher, the pledge must indicate its status regarding the voucher to the domain. This occurs by sending a status message to the registrar. The pledge decides weather to accept the voucher or not through the voucher validation process. If acceptable, the message should contain the version of BRSKI and a boolean status field to indicate the acceptance status. In case of an unacceptable voucher or a failure, the pledge is expected to fail gracefully. The message should contain a Reason field with a string commenting on the cause. Nevertheless, the Reason should not be excessively descriptive as it may be sent to an unauthenticated and potentially malicious registrar.

Bearing the voucher, the pledge verifies its validity. It verifies the signature using the manufacturer installed MASA trust anchor. It verifies also that the serial number enclosed in the voucher matches its own. For nonced vouchers, the pledge verifies the voucher nonce corresponds to the nonce it sent earlier in the voucher request. However nonceless vouchers can be accepted according to pledge local policy. The pledge can be configured to always accept nonceless vouchers to realize the use case where the MASA is unreachable at the time of pledge deployment.

A pledge could be operating in other similar security reduced mode that skip voucher validation in favor of offline or emergency touch-based deployment bootstrapping procedures. For example, Trust on first use (TOFU) or physical presence methods such as

the use of serial console or depressing a physical button during bootstrapping. However, TOFU must not be available unless a hardware-assisted Network Endpoint Assessment (NEA) is supported. Meanwhile, it is only recommended for other methods of skipping voucher validation. This recommendation serves as a prevention against unintended use of offline methods when autonomic methods fail or are unavailable.

- *Message 10:* After receiving the pledge status telemetry message, the registrar requests the MASA audit-log from the MASA. The log data helps the registrar make a knowledgeable decision regarding further proceeding of the bootstrapping process. The decision making criteria is based upon the security requirements of the registrar domain. Hence, the criteria is out of the protocol's scope. The request content is the exact same registrar voucher-request sent earlier to the MASA, but is directed through a different URI specific for requesting the audit log, which is `"/.well-known/brski/requestauditlog"`. Reusing the same message minimizes the required cryptographic and message operations on both ends. The registrar may reuse the cached voucher request and the MASA may take advantage of its internal state to correlate the message with the already verified request averting additional operations.
- *Message 11:* A MASA can infer the proper pledge log to be prepared from the `"idevid-issuer"` and the `"serial-number"` information included in the received request of the previous message. Instead of immediately responding with the audit-log, the MASA can a HTTP 201 `"Created"` response with a URL in the `"Location"` header field redirecting to actual audit-log. The response log is a JSON format document consisting of all the log entries associated with the pledge. Nevertheless, a MASA that sends out URLs has to ensure they are unpredictable to avoid enumeration attacks against device audit-logs.

The log format structure consists of several entries: `"version"`, `"events"`, and `"truncation"`. `"version"` is an integer value representing the log format version. `"events"` is an array of event objects that are associated to the device. Each of the event objects is comprised of a set of entries. The `"date"` entry represents the event's timestamp in the format according to [19]. The `"domainID"` is a unique identifier for the domain's registrar that encodes the pinned-domain-cert's SubjectKeyIdentifier or SPKI fingerprint in base64. A `"nonce"`, if exists, is a base64 encoding of the same nonce used in the voucher request and issued voucher. If it is a nonceless voucher, then the field should preferably be set to null rather than omitting it. The `"assertion"` field indicates the level of verification with which the MASA issued the voucher. It can have one of three values: `"verified"`, `"logged"`, and `"proximity"`; the latter being the one supported by this protocol. `"truncated"` field shows the number of event truncations for the specified domainID. Lastly, since audit-logs can be arbitrarily large, duplicated or old entries may be truncated as an optimization for the log structure. The `"truncation"` entry contains meta-information about truncated entries such as `"nonced duplicates"`, `"nonced duplicates"`, and `"arbitrary"`.

On the pledge side,

- *Message 12:*

4.2 Secure Zero Touch Provisioning (SZTP)

4.3 Protocols Comparison

5 X3DH

FIXME

Key establishment protocols are utilized by communicating parties to establish shared secrets, in some cases, with the aid of a trusted third party [16]. As per [16], key agreement is a key establishment technique in which a shared secret is derived by parties as a function of information related to them, such that the secret is not predeterminable nor deducible by outsiders.

The Security of protocols is required to be proven to avoid the devastating effects of malicious attacks. Therefore, verification of security protocols is a vital process. Verification is proving that a protocol model is secure by achieving a set of security goals. There are various model checking tools that provide verification.

X3DH is a key agreement protocol intended for asynchronous settings [15]. The protocol can establish a shared secret between two parties in an environment where it is recurring that one of the parties is offline and the other wishes to send it an encrypted message. Also, X3DH provides the desired feature of forward secrecy.

This chapter discusses the Extended Triple Diffie-Hellmann (X3DH) key agreement protocol [15] and verifies the security of the protocol using the OFMC model checker [18].

5.1 Protocol Overview

5.1.1 Roles

A protocol run involves three roles: Alice, Bob, and a server. In this description, Alice wants to send an encrypted message to Bob. Bob is the party that may be offline at that time and wishes to enable other parties to derive a shared secret with it, through a set of public information Bob publishes. The server is responsible for 1. storing the public information published by Bob, and 2. storing messages for offline parties till they are fetched. The server is not trusted, however, it is assumed to be resilient against DoS.

5.1.2 Keys

X3DH utilizes Elliptic Curve asymmetric key pairs. All keys used in a protocol run must all be derived from the same curve, either X25519 or X448. Each role has to have a set of keys to run the protocol. Table 5.1 lists the public keys required for each role. Note that for each public key, there exists a corresponding private key at its owner.

Owning Role	Notation	Description
Alice	IK_A	Long-term identity Key
	EK_A	Ephemeral Key
Bob	IK_B	Identity Key
	SPK_B	Signed Prekey
	OPK_B	one-time Prekey

Table 5.1: X3DH keys.

- *Identity keys*: They are long-term public keys known by their corresponding parties before the protocol run.
- *Ephemeral Keys*: This type of key pair is freshly generated within the protocol run.
- *Signed Prekey*: This key pair is generated and signed by its owner. The prekey is signed using the private identity key. The life time of this key pair is shorter than that of the identity key pairs as it is updated periodically by its owner. The corresponding role owns only one signed prekey at a time.
- *One-time Prekey*: The corresponding role generates multiple one-time prekey. Each is can be used for only one protocol run. The responsible party is supposed to supply the these keys as they should not run out. In case there are not any keys left, the protocol can run, however without one of the DH operations as explained in section 2.3.

5.1.3 A Protocol Run

5.1.3.1 Registration phase

Initially, The party acting in the role of Bob publishes to server the public information required to run the protocol with it by any party acting as Alice. Bob publishes his IK_B , SPK_B , Bob's prekey signature, and a set of OPK_B .

5.1.3.2 The initial message

First of all, Alice fetches a 'prekey bundle' from the server to contact Bob. This bundle contains:

- Bob's Identity key IK_B .
- Bob's signed prekey SPK_B
- Bob's prekey signature
- If exists, a one-time prekey OPK_B . The server deletes the OPK_B sent to Alice.

Alice verifies the prekey signature and quits the protocol if the verification fails.

At this point, Alice has enough information from Bob to deduce a shared secret. Alice generates her Ephemeral key pair EK_A . With the set of available keys, Alice performs three

Diffie-Hellmann operations which can be extended to four if a OPK_B is available.

$$\begin{aligned} DH1 &= DH(IK_{A_p}^5, SPK_B) \\ DH2 &= DH(EK_{A_p}, IK_B) \\ DH3 &= DH(EK_{A_p}, SPK_B) \\ DH4 &= DH(EK_{A_p}, OPK_B) \end{aligned}$$

Figure 5.1 presented by the authors of [15] further illustrates the relation between the keys. The DH outputs are fed into a key derivation function (KDF) to generate the shared secret

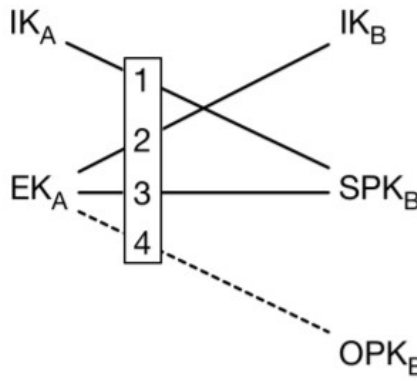


Figure 5.1: DH calculations.

SK . Next, Alice deletes her EK_{A_p} and all DH outputs for forward secrecy. At this moment, Alice is ready to send the initial message with the content encrypted using SK . The initial message from Alice to Bob has to have enough information for Bob to generate the same SK . The initial message contains:

- IK_A
- EK_A
- Identifiers of Bob's prekeys used by Alice
- An initial ciphertext. The ciphertext can be used as an initial message for a post-X3DH communication protocol, e.g. Double ratchet algorithm.

5.1.3.3 Bob's SK Derivation

Using the key identifiers sent by Alice, Bob loads the private keys corresponding to the public keys Alice used. In combination with the keys IK_A and EK_A Alice sent, Bob can compute the same SK by doing the three (or four) DH operations.

Next, Bob attempts to decrypt the ciphertext. If the message is successfully decrypted to the expected format, e.g. the format of the first message of the post-X3DH protocol, then the protocol run was successful. Otherwise, Bob aborts the protocol and discards the SK .

⁵'p' indicates the private key of the key pair.

5.1.4 Security Considerations

5.1.4.1 Authentication

Authentication is essential for both parties to guarantee the identity of who they are communicating with. Thus, Alice and Bob must authenticate the keys IK_A and IK_B . The specification does not discuss authentication methods.

5.1.4.2 Protocol Replay

The one-time prekey used in the fourth and optional DH calculation is for protection against replay attacks as they ensure freshness of the protocol run. Absence of a one-time prekey could lead a replayed message to be accepted by Bob believing that Alice had sent it in the current protocol run.

5.1.4.3 Server Trust

A server can be a cause of attacks if malicious. It can carry out a Denial of Service attack if it refuses to forward the messages. It can deliberately not distribute one-time prekeys, exposing the protocol to replay attacks. Also, one party can drain all the one-time prekeys, if the server is not attentive to such action, leading to replay attacks.

5.2 OFMC Modelling

Presented in listing 5.1 the code for modelling the protocol in OFMC using the language AnB. This section explains the code of the model section by section.

```

1 Protocol : X3DH #Protocol name

3 Types :
4     Agent A, B, s;
5     Function kdf, pk, ik;
6     Number g, NA, EKA, OTP, PREKEY, MSG1, MSG2;

8 Knowledge :
9     A : A, B, s, g, pk(s), pk(B), pk(A), inv(pk(A)), ik(A), {A, pk(A)}
      ↪ inv(pk(s)), kdf;

11     B : A, B, s, g, pk(s), pk(A), pk(B), inv(pk(B)), ik(B), kdf;

13     s : A, B, s, g, pk, inv(pk(s)), kdf, ik;

15 where A!=B

17 Actions:
```

```

19      B -> s: {B, exp(g, ik(B)), exp(g, OTP), {exp(g, PREKEY)}inv(pk(B)) }
      ↪ pk(s) # B registers at server

21      s -> A: {B, pk(B)}inv(pk(s)) # s announces B is ready

23      A -> s : A, B, NA # later in time, A asks to communicate with B

25      s -> A : { A, B, exp(g, ik(B)), exp(g, OTP), {exp(g, PREKEY)}inv(pk(B
      ↪ )), NA }inv(pk(s))

27      A -> B : {A, pk(A)}inv(pk(s)),

29          {exp(g, OTP), exp(g,EKA),exp(g, ik(A)), exp(g,PREKEY)}inv(pk(
      ↪ A)),

31          {| A, B, MSG1 |}kdf(
32              exp(exp(g,ik(A)), PREKEY), #DH1
33              exp(exp(g,EKA), ik(B)), #DH2
34              exp(exp(g,EKA), PREKEY), #DH3
35              exp(exp(g,OTP), EKA) #DH4
36          )

38      B -> A : {| B, A, MSG2 |}kdf(
39          exp(exp(g,ik(A)), PREKEY), #DH1
40          exp(exp(g,EKA), ik(B)), #DH2
41          exp(exp(g,EKA), PREKEY), #DH3
42          exp(exp(g,OTP), EKA) #DH4
43      )

46  Goals:
47      B authenticates A on exp(g, EKA), exp(g, ik(A))
48      A authenticates s on exp(g, OTP), exp(g, PREKEY), exp(g, ik(B))
49      B authenticates s on exp(g, OTP), exp(g, PREKEY), exp(g, ik(B))
50      MSG1 secret between A,B
51      MSG2 secret between A,B

```

Listing 5.1: X3DH OFMC Model

5.2.1 Types section

Here, the parameters of the protocol are defined, e.g. variables, constants, roles, etc. Line 4 defines the participants of the protocol of type **Agent**.

- A and B: Variables indicating Alice and Bob. A variable may be dishonest in an OFMC protocol run.

- s: Constant indicating the server. Constants act as trusted third parties.

Line 5 defines the functions of the protocol.

- kdf: Key derivation function.
- pk: A function to model asymmetric key pairs. A public key for Alice is modeled as $\text{pk}(A)$ and the corresponding private key is computed using the internal function $\text{inv}()$ as follows $\text{inv}(\text{pk}(A))$.
- ik: models the private component of the identity key of a party for the DH calculations.

Alice and Bob have long-term signing keys modeled by the function ' $\text{pk}()$ ' and long-term identity keys modeled by the function ' $\text{ik}()$ '.

Line 6 defines the numbers used in the protocol. Lower-case numbers are constants, while upper-case numbers are random and freshly generated during a protocol run. Some private components of keys are modeled as numbers as they are required to be freshly generated during a protocol run which can not be done using functions.

- g: Public exponent base for DH calculations.
- NA: Alice's Nonce.
- EKA: The private component of Alice's Ephemeral key.
- OTP: The One-time prekey's private component.
- PREKEY: the prekey's private component.
- MSG1 and MSG2: Random numbers used as placeholders for random and fresh messages.

5.2.2 Knowledge section

This section of the model defines what knowledge is initially known to each party before the protocol starts. Line 9 defines Alice's knowledge which contains, in addition to the previously defined parameters, Alice's certificate modeled as ' $\{A, \text{pk}(A)\}\text{inv}(\text{pk}(s))$ '. This translates to Alice's identity ' A ' and Alice's public key ' $\text{pk}(A)$ ' are signed using the servers private key ' $\text{inv}(\text{pk}(s))$ '.

Line 15 holds a 'where' clause that strictly defines A and B as different parties to avoid the scenario where A or B talk to itself.

5.2.3 Actions section

The Actions section states the protocol's message sequence between the participating parties for a successful protocol run. Throughout this section messages are referred to according to their line number, e.g message 19 is the message in line number 19 of the model code.

Message 19 represents the registration phase where Bob publishes his public information to the server. The message contains the following:

- $\text{exp}(g, (XX))$: The public DH key of the corresponding private key XX
- $\{\text{exp}(g, \text{PREKEY})\}\text{inv}(\text{pk}(B))$: The prekey of Bob signed by Bob's signing key.

The whole message is encrypted for the server for authenticity.

Message 21 is not an actual part of the protocol, however, it is included for the sake of modeling the protocol with the chosen tool. This is because of the asynchronous communication model of OFMC and the strands concept [17].

In message 23, Alice requests to fetch from the server a key bundle to communicate with Bob. A nonce 'NA' is attached for freshness.

Message 25 is the server's response to Alice's key bundle request. The message contains the requested key bundle required to communicate with Bob, as well as Alice's nonce. The whole message is integrity protected by the server's signature.

Message 27 represents the initial message from Alice to Bob. It is composed of the following:

- Alice's certificate for authenticity.
- (Line 29) The Bob's keys which Alice will use to compute SK . All these keys are signed by Alice for integrity protection.
- (Line 31) The initial ciphertext encrypted by the symmetric key SK . The output of the 4 DH operations is input into the KDF resulting in SK .

Message 38 is the last message of the protocol run. It is where Bob shows he is able to compute the same SK .

5.2.4 Goals section

This section of the model lists the security goals which the protocol must achieve at the end of a run. There are two types of goals

- Authenticity: When a party wants to make sure a certain message has been generated and sent by the other party. In this model, Alice and Bob authenticate each others' public keys. Bob authenticates the server on the keys he received in message 27 from Alice, to be sure that the keys are forwarded by Alice from the server without tampering.
- Secrecy: The requirement for a message to be secret only between some parties.

5.3 Difference from specification

5.3.1 Registration Phase

The specification was not specific about how to securely publish Bob's keys to the server and the security of the connection between the server and the communicating parties. Therefore, the registration message from Bob to the server is encrypted by the server's public key.

5.3.2 Use of Signatures

The specification discouraged the use of signatures as they reduce deniability which is a desired feature in the messaging application setting which the protocol is intended for. However, this model used signatures.

- a) Signature are used in responses from the server to assure integrity of messages to receivers.
- b) Alice and Bob have an additional key pair for signing other than the identity key pairs. They are used to sign parts of messages which were vulnerable to attacks by intruders and would break the protocol's security. For example, Bob's keys which Alice used to compute SK in message 27.

5.3.3 Use of Certificates

Alice used a certificate signed by the server to authenticate itself in-band as opposed to the specification which ruled the authentication between the parties as a necessary but out of scope operation.

5.4 Conclusion

TODO: concluding paragraph

6 Double Ratchet Algorithm

7 Implementation

8 Evaluation

9 Conclusion and Future Work

Summarize the thesis and provide a outlook on future work.

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A BRSKI vs. SZTP

A.1 Protocol Comparison

	BRSKI		SZTP
standardization	RFC 8995		RFC 8572
Related RFCs	Voucher artifact [RFC 8366]		
Aim	Results in the pledge storing a root certificate sufficient for verifying the registrar identity. The installed trust anchor can be used for later certificate enrollment protocols (typically, EST)		
communication channels covered by the protocol	Pledge \leftrightarrow Registrar \leftrightarrow MASA		
remote(Internet accessible)/local bootstrapping sources support	remote (\rightarrow wellknown/...) and local		
Device bootstrap sources	Domain Registrar	Removable storage, DNS server, DHCP server, or Bootstrap server	
protocol initiator	Pledge (Device)	Device	
Functionality support (M): Mandatory (O): Optional	<ul style="list-style-type: none"> - (M) Pledge-Registrar Discovery - (M) MASA: voucher issuance - (M) MASA: voucher renewal - (M) Pledge: polling - (M) MASA voucher audit log - (M) if EST following BRSKI: CSR attributes retrieval request - (O) Manufacturer: Ownership tracking 	<ul style="list-style-type: none"> (M) Device: polling (M) MASA: voucher issuance (M) if Bootstrap server is used: provide redirect information and/or onboarding information (M) DHCP/DNS server: can provide redirect information only due to technical limitations 	

	BRSKI	SZTP
device initial state	IDeVID manufacturer installed trust anchor(s) associated with the manufacturer's MASA	<ul style="list-style-type: none"> - IDeVID Optional: <ul style="list-style-type: none"> - TLS client cert & related intermediate certs - Trust anchors to validate ownership voucher (signed by manufacturer) - List of well-known bootstrap servers - Trust anchors to authenticate configured well-known bootstrap servers
discovery of bootstrap sources	yes, mDNS/ GRASP	only through redirections from device supported bootstrap sources
Device authentication	IDeVID	IDeVID
device authorization	<ul style="list-style-type: none"> - a specific device (serial number) from a specific vendor - a specific device type or a specific vendor 	based on device's serial number
bootstrap source authentication	Initially, Provisional TLS	Initially, Provisional TLS if no TA available
enrollment protocol integration	(R) EST	draft-ietf-netconf-sztp-csr-05
bootstrap data	voucher LDeVID	redirect information (auxiliary) onboarding information: boot image, configuration, post-config scripts, voucher, owner certificate
bootstrapping data protection	<ul style="list-style-type: none"> - voucher signed by manufacturer - LDeVID signed by domain CA - no additional encryption (only TLS encryption in Transit) 	trusted channel: may be signed and/or encrypted untrusted channel: signed and may be encrypted

	BRSKI	SZTP
owner voucher-request time	nonced: in-band nonceless: Out-of-band	nonceless: owner-manufacturer enrollment phase nonced: in-band
Acceptance of device by Domain	checking voucher and its presence in the MASA audit-log	checking the voucher
determining MASA to contact	URI in IDevID or manual configuration of registrar	out of scope
progress reports	yes, voucher status telemetry	yes, only to trusted servers
Timeliness	nonceless vouchers: expiry time nonced vouchers: nonces (and expiry time)	
revocation checks	- No revocation for vouchers - certificate revocation checks only, depending on pledge capabilities	
ownership transfer	yes, By voucher issuance	out-of-scope (Owner- \mathcal{I} MASA communication is not inherent to the protocol, but ownership transfer is possible through new vouchers by the MASA)
updatable Manufacturer Trust Anchors (before bootstrap process)	out-of-scope	out of scope (through a verifiable process, such as a software upgrade using signed software images)
transport protocol	HTTP (or CoAP) / TLS1.2+	HTTP/TLS
Required crypto algorithms	None	None
Domain specific configuration provisioning to device	out of scope	yes

A.2 Terminology Comparison

BRSKI		SZTP	
Pledge	the unconfigured device to be bootstrapped	Device	the unconfigured device to be bootstrapped
Manufacturer	the entity that created the device	Manufacturer	- the entity that created the device - through out the RFC, the term generally covers the services provided by the manufacturer without explicitly referring to them, like, MASA.
Domain	The set of entities, belonging to the owner of the device, that share a common local trust anchor. This includes the proxy, registrar, Domain Certificate Authority, etc..	Owner	The person or organization that purchased or otherwise owns a device - The term is used through out the RFC to represent the the sub-entities the owner might be using within their domain, like registrar, proxy, or CA, without explicitly referring to them.
Registrar	A representative of the domain that is configured, to decide whether a new device is allowed to join the domain.		
Proxy	A domain entity that helps the pledge join the domain. A join proxy facilitates communication for devices that find themselves in an environment where they are not provided connectivity until after they are validated as members of the domain. - The pledge is unaware that they are communicating with a proxy rather than directly with a registrar.		
voucher	RFC 8366	ownership voucher	RFC8366