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A TLS/DTLS 1.2 Profile for the Internet of Things
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Abstract

A common design pattern in Internet of Things (IoT) deployments is the use of a constrained device (typically providing sensor data) that makes data available for home automation, industrial control systems, smart cities and other IoT deployments.

This document defines a Transport Layer Security (TLS) and Datagram TLS 1.2 profile that offers communications security for this data exchange thereby preventing eavesdropping, tampering, and message forgery.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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This Internet-Draft will expire on June 18, 2015.

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1. Introduction

An engineer developing an Internet of Things (IoT) device needs to investigate the security threats and decide about the security services that can be used to mitigate these threats.

Enabling IoT devices to make data available often requires authentication of the two endpoints and the ability to provide integrity- and confidentiality-protection of exchanged data. While these security services can be provided at different layers in the protocol stack the use of Transport Layer Security (TLS)/Datagram TLS (DTLS) has been very popular with many application protocols and it is likely to be useful for IoT scenarios as well.

To make Internet protocols fit constrained devices can be difficult but thanks to the standardization efforts new profiles and protocols are available, such as the Constrained Application Protocol (CoAP) [RFC7252]. UDP is mainly used to carry CoAP messages but other transports can be utilized, such as SMS or even TCP.

While this document is inspired by the desire to protect CoAP messages using DTLS 1.2 [RFC6347] the guidance in this document is not limited to CoAP nor to DTLS itself.

Instead, this document defines a profile of DTLS 1.2 [RFC6347] and TLS 1.2 [RFC5246] that offers communication security for IoT applications and is reasonably implementable on many constrained devices. Profile thereby means that available configuration options and protocol extensions are utilized to best support the IoT environment. This document does not alter TLS/DTLS specifications and does not introduce any new TLS/DTLS extensions.

The main target audience for this document is the embedded system developer configuring and using a TLS/DTLS stack. This document may, however, also help those developing or selecting a suitable TLS/DTLS stack for an Internet of Things product development.

2. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "MUST", "MUST NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

Note that "Client" and "Server" in this document refer to TLS/DTLS roles, where the Client initiates the TLS/DTLS handshake. This does

not restrict the interaction pattern of the protocols on top of TLS/DTLS since the record layer allows bi-directional communication. This aspect is further described in Section 4.

RFC 7228 [RFC7228] introduces the notion of constrained-node networks, which are small devices with severe constraints on power, memory, and processing resources. The terms constrained devices, and Internet of Things (IoT) devices are used interchangeably.

3. TLS/DTLS Protocol Overview

The TLS protocol [RFC5246] provides authenticated, confidentiality- and integrity-protected communication between two endpoints. The protocol is composed of two layers: the Record Protocol and the Handshake Protocol. At the lowest level, layered on top of a reliable transport protocol (e.g., TCP), is the Record Protocol. It provides connection security by using symmetric cryptography for confidentiality, data origin authentication, and integrity protection. The Record Protocol is used for encapsulation of various higher-level protocols. One such encapsulated protocol, the Handshake Protocol, allows the server and client to authenticate each other and to negotiate an encryption algorithm and cryptographic keys before the application protocol transmits or receives data.

The design of DTLS [RFC6347] is intentionally very similar to TLS. Since DTLS operates on top of an unreliable datagram transport a few enhancements to the TLS structure are, however necessary. RFC 6347 explains these differences in great detail. As a short summary, for those not familiar with DTLS the differences are:

- An explicit sequence number and an epoch field is included in the Record Protocol. Section 4.1 of RFC 6347 explains the processing rules for these two new fields. The value used to compute the MAC is the 64-bit value formed by concatenating the epoch and the sequence number.

- Stream ciphers must not be used with DTLS. The only stream cipher defined for TLS 1.2 is RC4 and due to cryptographic weaknesses it is not recommended anymore even for use with TLS [I-D.ietf-tls-prohibiting-rc4].

- The TLS Handshake Protocol has been enhanced to include a stateless cookie exchange for Denial of Service (DoS) resistance. For this purpose a new handshake message, the HelloVerifyRequest, was added to DTLS. This handshake message is sent by the server and includes a stateless cookie, which is returned in a ClientHello message back to the server. Although the exchange is optional for the server to execute, a client implementation has to

be prepared to respond to it. Furthermore, the handshake message format has been extended to deal with message loss, reordering, and fragmentation. Retransmission timers have been included to deal with message loss.

4. Communication Models

This document describes a profile of TLS/DTLS 1.2 and, to be useful, it has to make assumptions about the envisioned communication architecture.

Two communication architectures (and consequently two profiles) are described in this document.

4.1. Constrained TLS/DTLS Clients

The communication architecture shown in Figure 1 assumes a unicast communication interaction with an IoT device utilizing a constrained TLS/DTLS client interacting with one or multiple TLS/DTLS servers.

Before a client can initiate the TLS/DTLS handshake it needs to know the IP address of that server and what credentials to use. Application layer protocols, such as CoAP, conveyed on top of DTLS may need additional information, such information about URLs of the endpoints the CoAP needs to register and publish information to. This configuration information (including credentials) may be conveyed to clients as part of a firmware/software package or via a configuration protocol. The following credential types are supported by this profile:

- For PSK-based authentication (see Section 6.1), this includes the paired "PSK identity" and shared secret to be used with each server.

- For raw public key-based authentication (see Section 6.2), this includes either the server's public key or the hash of the server's public key.

- For certificate-based authentication (see Section 6.3), this includes a pre-populated trust anchor store that allows the DTLS stack to perform path validation for the certificate obtained during the handshake with the server.

This document focuses on the description of the DTLS client-side functionality but, quite naturally, the equivalent server-side support has to be available.

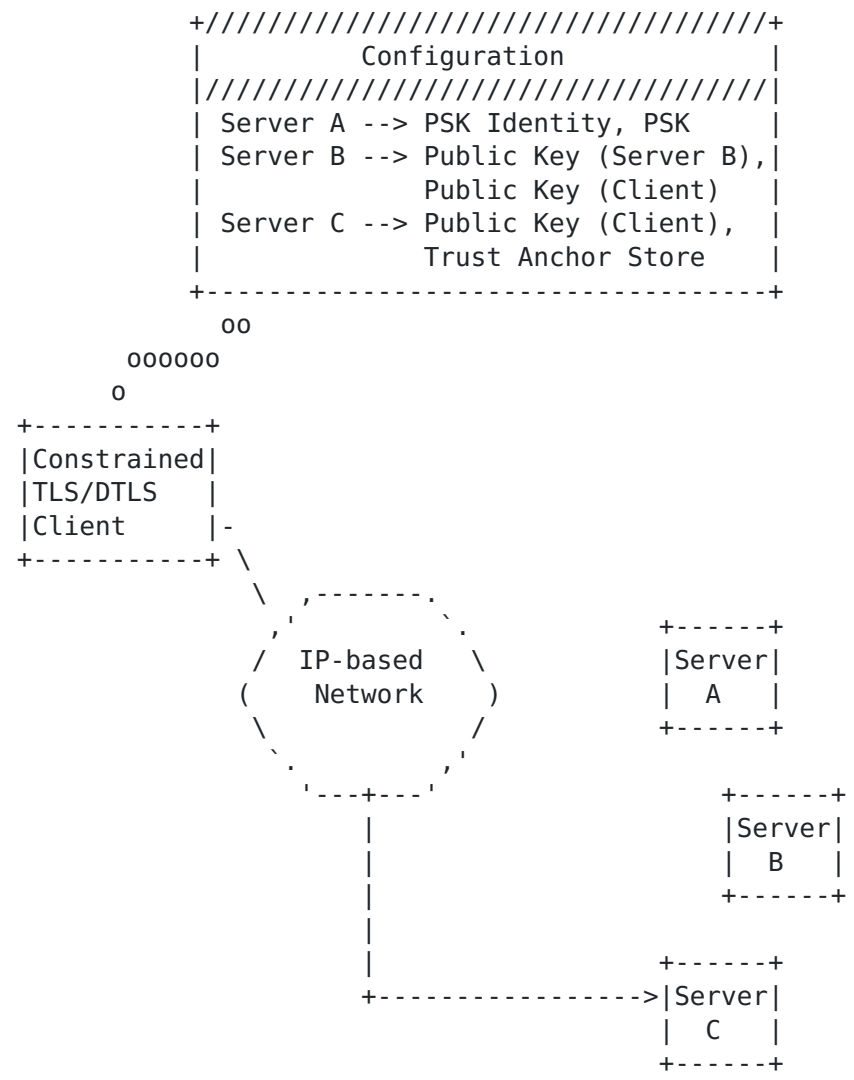


Figure 1: Constrained Client Profile.

4.1.1. Examples of Constrained Client Exchanges

4.1.1.1. Network Access Authentication Example

Re-use is a recurring theme when considering constrained environments and is behind a lot of the directions taken in developments for constrained environments. The corollary of re-use is to not add functionality if it can be avoided. An example relevant to the use of TLS is network access authentication, which takes place when a device connects to a network and needs to go through an authentication and access control procedure before it is allowed to communicate with other devices or connect to the Internet.

Figure 2 shows the network access architecture with the IoT device initiating the communication to an access point in the network using the procedures defined for a specific physical layer. Since credentials may be managed and stored centrally, in the Authentication, Authorization, and Accounting (AAA) server, the security protocol exchange may need to be relayed via the Authenticator, i.e., functionality running on the access point, to the AAA server. The authentication and key exchange protocol itself is encapsulated within a container, the Extensible Authentication Protocol (EAP), and messages are conveyed back and forth between the EAP endpoints, namely the EAP peer located on the IoT device and the EAP server located on the AAA server or the access point. To route EAP messages from the access point, acting as a AAA client, to the AAA server requires an adequate protocol mechanism, name RADIUS or Diameter.

More details about the concepts and a description about the terminology can be found in RFC 5247 [RFC5247].

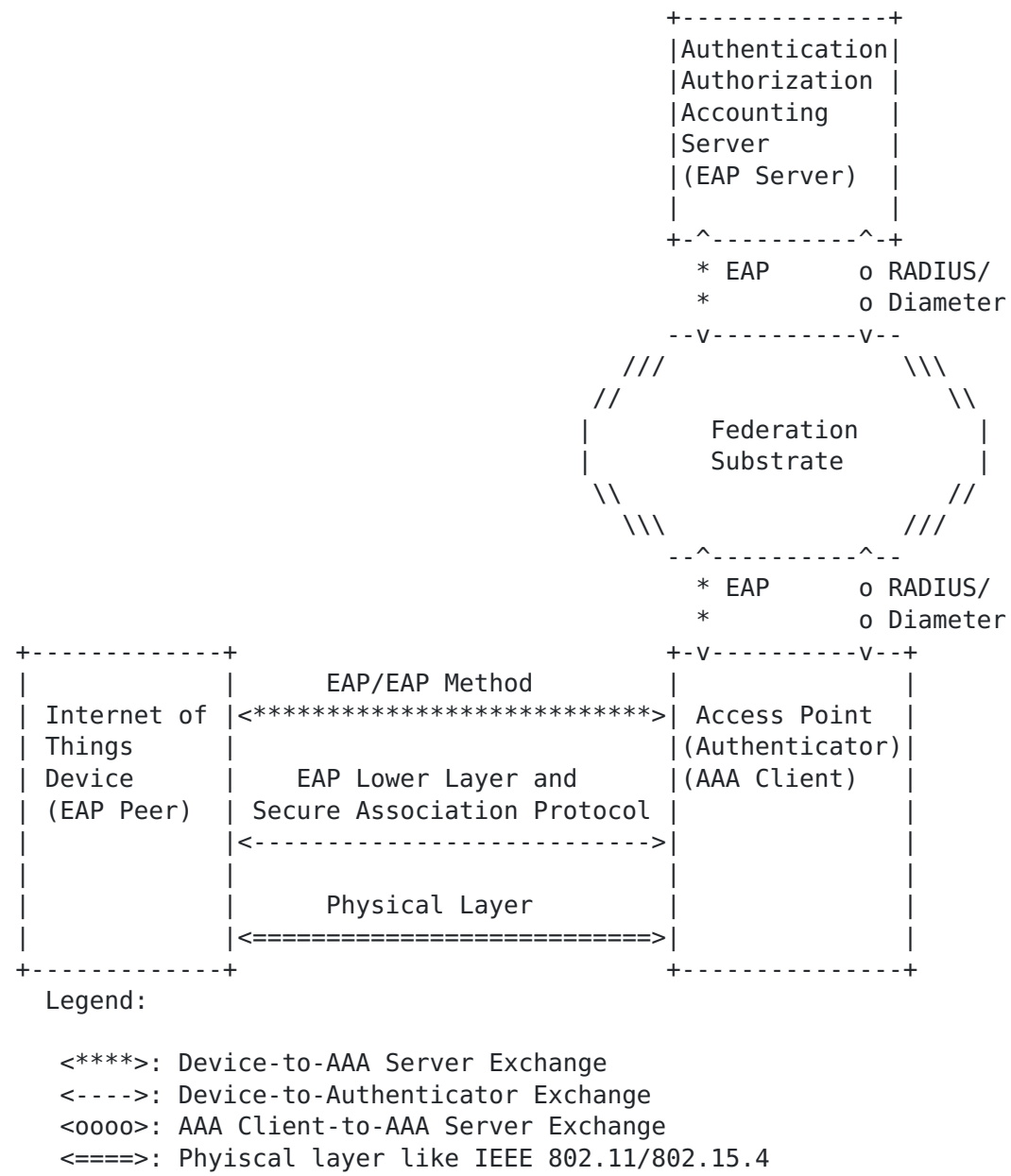


Figure 2: Network Access Architecture..

One standardized EAP method is EAP-TLS, defined in RFC 5216 [RFC5216], which re-uses the TLS-based protocol exchange and encapsulates it inside the EAP payload. In terms of re-use this allows many components of the TLS protocol to be shared between the network access security functionality and the TLS functionality needed for securing application layer traffic. The EAP-TLS exchange is shown in Figure 3 where it is worthwhile to point out that in EAP

the client / server roles are reversed but with the use of EAP-TLS the IoT device acts as a TLS client.

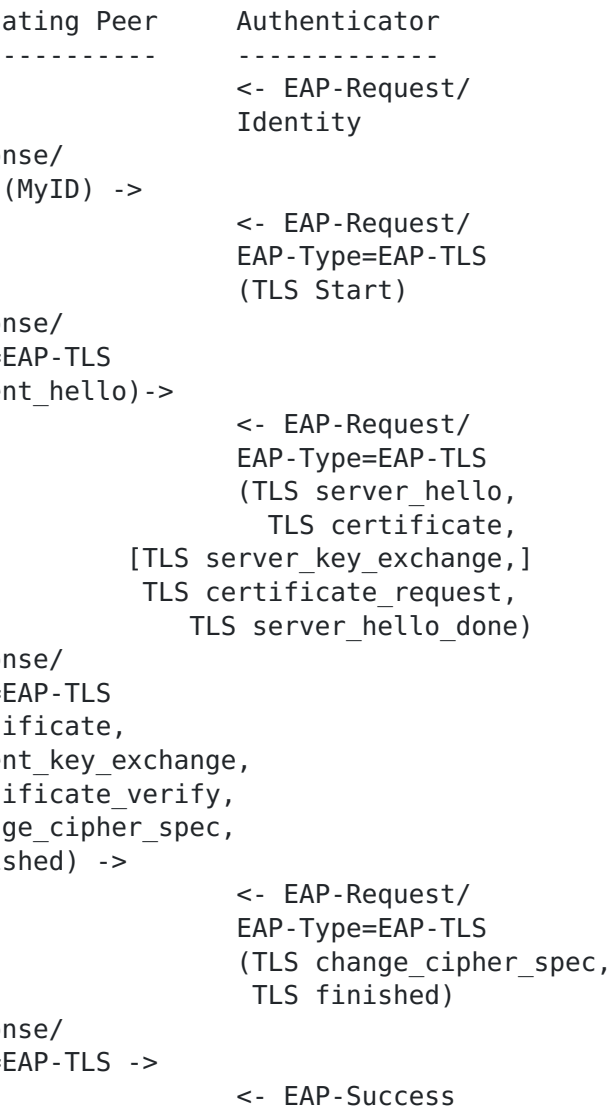


Figure 3: EAP-TLS Exchange.

The guidance in this document also applies to the use of EAP-TLS for network access authentication. An IoT device using a network access authentication solution based on TLS can re-use most parts of the code for the use of DTLS/TLS at the application layer thereby saving a significant amount of flash memory. Note, however, that the credentials used for network access authentication and those used for application layer security are very likely different.

4.1.1.2. CoAP-based Data Exchange Example

When a constrained client uploads sensor data to a server infrastructure it may use CoAP by pushing the data via a POST to a pre-configured endpoint on the server. In certain circumstances this might be too limiting and additional functionality is needed, as shown in Figure 4, where the IoT device itself runs a CoAP server hosting the resource that is made accessible to other entities. Despite running a CoaP server on the IoT device it is still the DTLS client on the IoT device that initiates the interaction with the non-constrained resource server in our scenario.

Figure 4 shows a sensor starting with a DTLS exchange with a resource server to register available resources. The initial DTLS interaction between the sensor, acting as a DTLS client, and the resource server, acting as a DTLS server, will be a full DTLS handshake. Once this handshake is complete both parties have established the DTLS record layer, which can subsequently be used to secure the CoAP message exchange, which starts with a the resource registration. Details about the resource registry capabilities can be found in [I-D.ietf-core-resource-directory].

After some time (assuming that the client regularly refreshes its registration) the resource server receives a request (not shown) from an application to retrieve the temperature information from the sensor. This request is relayed by the resource directory to the sensor using a GET message exchange. The already established DTLS record layer can be used to secure the message exchange.

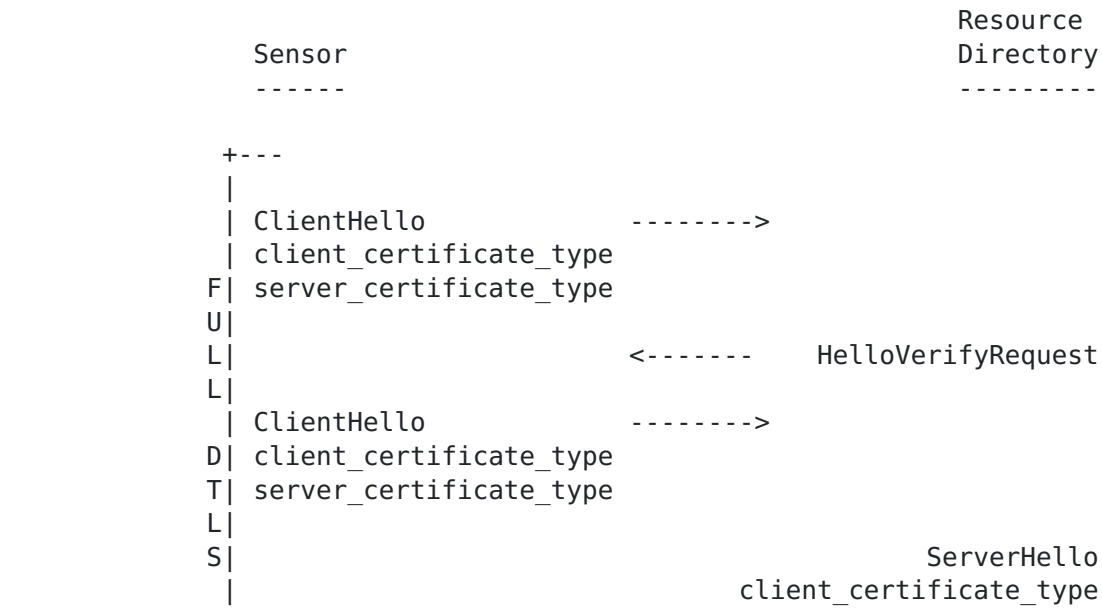


Figure 4: DTLS/CoAP exchange using Resource Directory.

4.2. Constrained TLS/DTLS Servers

TEXT TO BE DONE

5. The TLS/DTLS Ciphersuite Concept

TLS (and consequently DTLS) has the concept of ciphersuites and an IANA registry [IANA-TLS] was created to register the suites. A ciphersuite (and the specification that defines it) contains the following information:

- Authentication and key exchange algorithm (e.g., PSK)
- Cipher and key length (e.g., Advanced Encryption Standard (AES) with 128 bit keys [AES])
- Mode of operation (e.g., Counter with Cipher Block Chaining - Message Authentication Code (CBC-MAC) Mode (CCM) for AES) [RFC3610]
- Hash algorithm for integrity protection, such as the Secure Hash Algorithm (SHA) in combination with Keyed-Hashing for Message Authentication (HMAC) (see [RFC2104] and [RFC4634])
- Hash algorithm for use with the pseudorandom function (e.g., HMAC with the SHA-256)
- Misc information (e.g., length of authentication tags)
- Information whether the ciphersuite is suitable for DTLS or only for TLS

The TLS ciphersuite TLS_PSK_WITH_AES_128_CCM_8, for example, uses a pre-shared authentication and key exchange algorithm. RFC 6655 [RFC6655] defines this ciphersuite. It uses the Advanced Encryption Standard (AES) encryption algorithm, which is a block cipher. Since the AES algorithm supports different key lengths (such as 128, 192 and 256 bits) this information has to be specified as well and the selected ciphersuite supports 128 bit keys. A block cipher encrypts plaintext in fixed-size blocks and AES operates on fixed block size of 128 bits. For messages exceeding 128 bits, the message is partitioned into 128-bit blocks and the AES cipher is applied to these input blocks with appropriate chaining, which is called mode of operation.

TLS 1.2 introduced Authenticated Encryption with Associated Data (AEAD) ciphersuites (see [RFC5116] and [RFC6655]). AEAD is a class of block cipher modes which encrypt (parts of) the message and

authenticate the message simultaneously. Examples of such modes include the Counter with Cipher Block Chaining - Message Authentication Code (CBC-MAC) Mode (CCM) mode, and the Galois/Counter Mode (GCM) (see [RFC5288] and [RFC7251]).

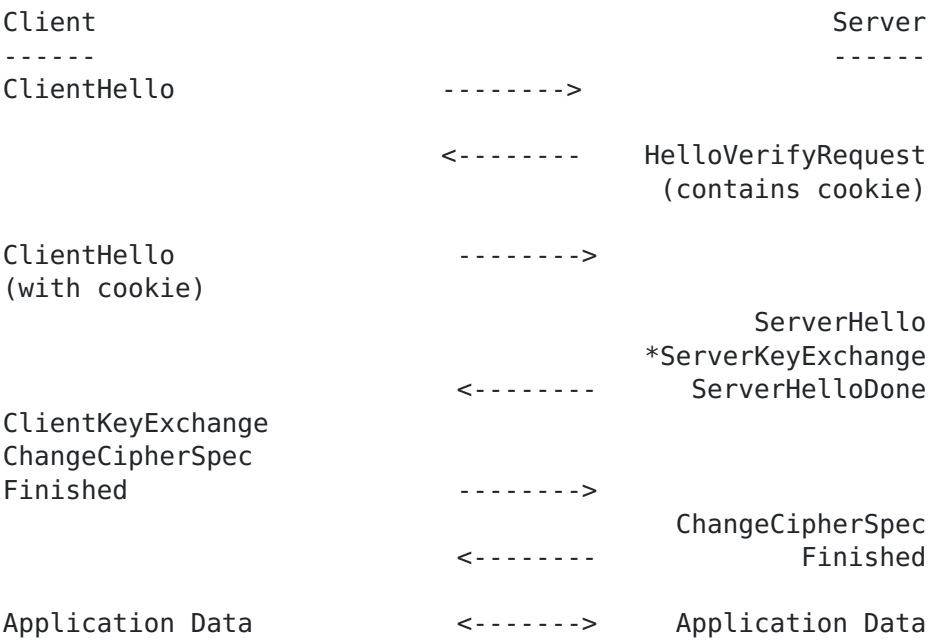
Some AEAD ciphersuites have shorter authentication tags and are therefore more suitable for networks with low bandwidth where small message size matters. The TLS_PSK_WITH_AES_128_CCM_8 ciphersuite that ends in "_8" has an 8-octet authentication tag, while the regular CCM ciphersuites have, at the time of writing, 16-octet authentication tags.

TLS 1.2 also replaced the combination of MD5/SHA-1 hash functions in the TLS pseudo random function (PRF) used in earlier versions of TLS with cipher-suite-specified PRFs. For this reason authors of more recent TLS 1.2 ciphersuite specifications explicitly indicate the MAC algorithm and the hash functions used with the TLS PRF.

6. Credential Types

6.1. Pre-Shared Secret

The use of pre-shared secret credentials is one of the most basic techniques for TLS/DTLS since it is both computational efficient and bandwidth conserving. Pre-shared secret based authentication was introduced to TLS with RFC 4279 [RFC4279]. The exchange shown in Figure 5 illustrates the DTLS exchange including the cookie exchange. While the server is not required to initiate a cookie exchange with every handshake, the client is required to implement and to react on it when challenged. The cookie exchange allows the server to react to flooding attacks.



Legend:

* indicates an optional message payload

Figure 5: DTLS PSK Authentication including the Cookie Exchange.

[RFC4279] does not mandate the use of any particular type of client identity and the client and server have to agree on the identities and keys to be used. The mandated encoding of identities in Section 5.1 of RFC 4279 aims to improve interoperability for those cases where the identity is configured by a person using some management interface. Many IoT devices do, however, not have a user interface and most of their credentials are bound to the device rather than the user. Furthermore, credentials are often provisioned into trusted hardware modules or in the firmware by developers. As such, the encoding considerations are not applicable to this usage environment. For use with this profile the PSK identities SHOULD NOT assume a structured format (as domain names, Distinguished Names, or IP addresses have) and a bit-by-bit comparison operation can then be used by the server-side infrastructure.

The client indicates which key it uses by including a "PSK identity" in the ClientKeyExchange message. As described in Section 4 clients may have multiple pre-shared keys with a single server and to help the client in selecting which PSK identity / PSK pair to use, the server can provide a "PSK identity hint" in the ServerKeyExchange message. If the hint for PSK key selection is based on the domain

name of the server then servers SHOULD NOT send the "PSK identity hint" in the ServerKeyExchange message. In general, servers SHOULD NOT send the "PSK identity hint" in the ServerKeyExchange message and client MUST ignore the message. This approach is inline with RFC 4279 [RFC4279]. Note: The TLS Server Name Indication (SNI) extension allows the client to tell a server the name of the server it is contacting, which is relevant for hosting environments. A server using the identity hint needs to guide the selection based on a received SNI value from the client.

RFC 4279 requires TLS implementations supporting PSK ciphersuites to support arbitrary PSK identities up to 128 octets in length, and arbitrary PSKs up to 64 octets in length. This is a useful assumption for TLS stacks used in the desktop and mobile environments where management interfaces are used to provision identities and keys. For the IoT environment, keys are distributed as part of hardware modules or are embedded into the firmware and, as such, these restrictions are not applicable to this profile.

Constrained Application Protocol (CoAP) [RFC7252] currently specifies TLS_PSK_WITH_AES_128_CCM_8 as the mandatory to implement ciphersuite for use with shared secrets. This ciphersuite uses the AES algorithm with 128 bit keys and CCM as the mode of operation. The label "_8" indicates that an 8-octet authentication tag is used. This ciphersuite makes use of the default TLS 1.2 Pseudorandom Function (PRF), which uses an HMAC with the SHA-256 hash function. (Note that all IoT implementations will need a SHA-256 implementation due to the construction of the pseudo-random number function in DTLS/TLS 1.2.)

A device compliant with the profile in this section MUST implement TLS_PSK_WITH_AES_128_CCM_8 and follow the guidance from this section.

6.2. Raw Public Key

The use of raw public keys with TLS/DTLS, as defined in [RFC7250], is the first entry point into public key cryptography without having to pay the price of certificates and a public key infrastructure (PKI). The specification re-uses the existing Certificate message to convey the raw public key encoded in the SubjectPublicKeyInfo structure. To indicate support two new extensions had been defined, as shown in Figure 6, namely the server_certificate_type and the client_certificate_type. To operate this mechanism securely it is necessary to authenticate and authorize the public keys out-of-band. This document therefore assumes that a client implementation comes with one or multiple raw public keys of servers, it has to communicate with, pre-provisioned. Additionally, a device will have its own raw public key. To replace, delete, or add raw public key to

this list requires a software update, for example using a firmware update mechanism.

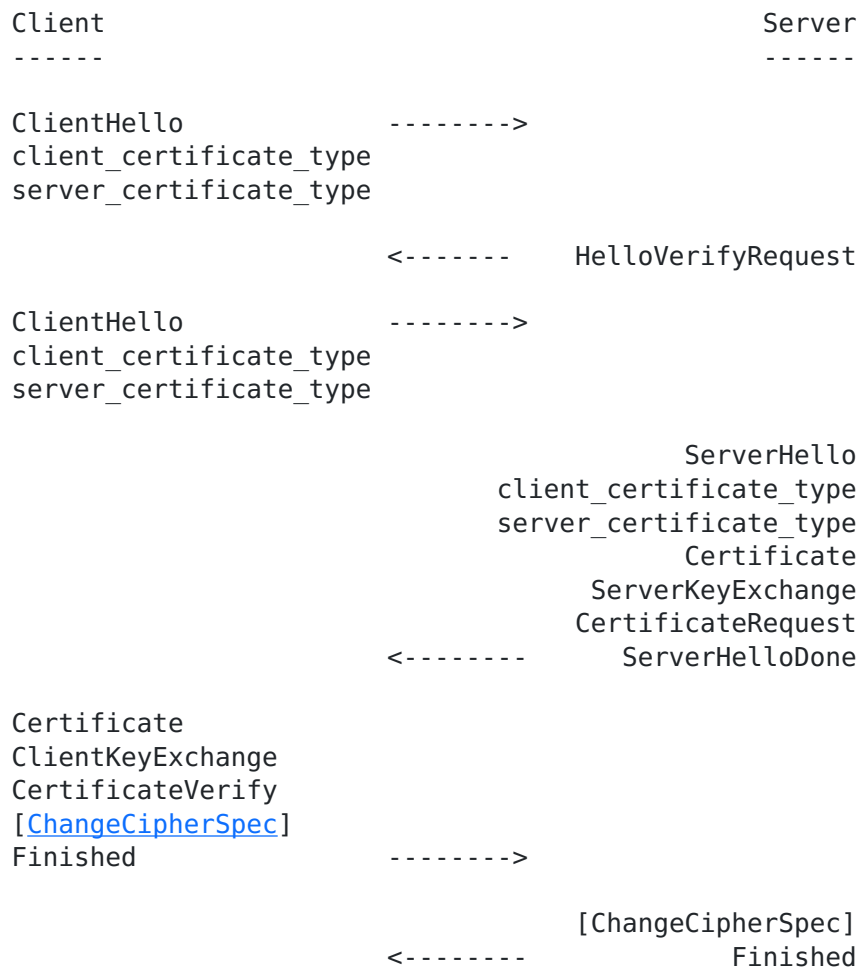


Figure 6: DTLS Raw Public Key Exchange including the Cookie Exchange.

The CoAP recommended ciphersuite for use with this credential type is TLS_ECDHE_ECDSA_WITH_AES_128_CCM_8 [RFC7251]. This elliptic curve cryptography (ECC) based AES-CCM TLS ciphersuite uses the Ephemeral Elliptic Curve Diffie-Hellman (ECDHE) as the key establishment mechanism and an Elliptic Curve Digital Signature Algorithm (ECDSA) for authentication. Due to the use of Ephemeral Elliptic Curve Diffie-Hellman (ECDHE) the recently introduced named Diffie-Hellman groups [I-D.ietf-tls-negotiated-dl-dhe] are not applicable to this profile. This ciphersuite make use of the AEAD capability in DTLS 1.2 and utilizes an eight-octet authentication tag. The use of a

Diffie-Hellman key exchange adds perfect forward secrecy (PFS). More details about PFS can be found in Section 11.

RFC 6090 [RFC6090] provides valuable information for implementing Elliptic Curve Cryptography algorithms, particularly for choosing methods that have been available in the literature for a long time (i.e., 20 years and more).

A device compliant with the profile in this section MUST implement TLS_ECDHE_ECDSA_WITH_AES_128_CCM_8 and follow the guidance from this section.

6.3. Certificates

The use of mutual certificate-based authentication is shown in Figure 7, which makes use of the cached info extension [I-D.ietf-tls-cached-info]. Support of the cached info extension is REQUIRED. Caching certificate chains allows the client to reduce the communication overhead significantly since otherwise the server would provide the end entity certificate, and the certificate chain. Because certificate validation requires that root keys be distributed independently, the self-signed certificate that specifies the root certificate authority is omitted from the chain. Client implementations MUST be provisioned with a trust anchor store that contains the root certificates. The use of the Trust Anchor Management Protocol (TAMP) [RFC5934] is, however, not envisioned. Instead IoT devices using this profile MUST rely on a software update mechanism to provision these trust anchors.

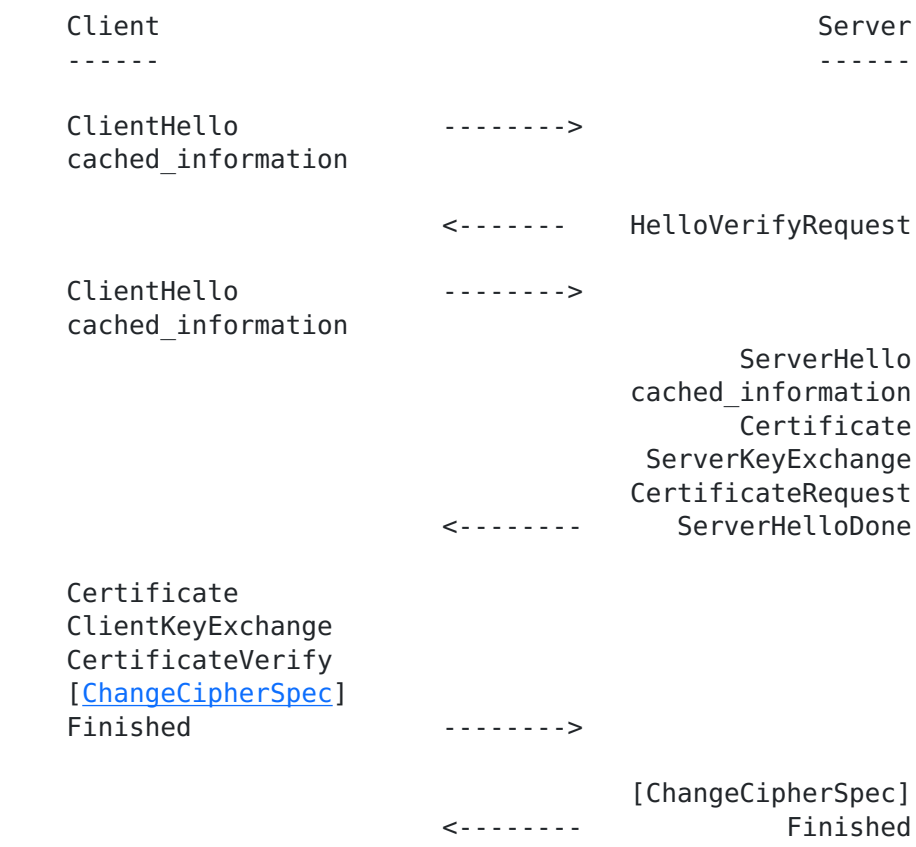


Figure 7: DTLS Mutual Certificate-based Authentication.

When DTLS is used to secure CoAP messages then the server provided certificates MUST contain the fully qualified DNS domain name or "FQDN" as dNSName. The coaps URI scheme is described in Section 6.2 of [RFC7252]. This FQDN is stored in the SubjectAltName or in the leftmost CN component of subject name, as explained in Section 9.1.3.3 of [RFC7252], and used by the client to match it against the FQDN used during the look-up process, as described in RFC 6125 [RFC6125]. For the profile in this specification does not assume dynamic discovery of local servers.

For client certificates the identifier used in the SubjectAltName or in the CN MUST be an EUI-64 [EUI64], as mandated in Section 9.1.3.3 of [RFC7252].

For certificate revocation neither the Online Certificate Status Protocol (OCSP) nor Certificate Revocation Lists (CRLs) are used. Instead, this profile relies on a software update mechanism. While multiple OCSP stapling [RFC6961] has recently been introduced as a mechanism to piggyback OCSP request/responses inside the DTLS/TLS

handshake to avoid the cost of a separate protocol handshake further investigations are needed to determine its suitability for the IoT environment.

Regarding the ciphersuite choice the discussion in Section 6.2 applies. Further details about X.509 certificates can be found in Section 9.1.3.3 of [RFC7252]. The TLS_ECDHE_ECDSA_WITH_AES_128_CCM_8 ciphersuite description in Section 6.2 is also applicable to this section.

When using certificates, IoT devices MUST provide support for a server certificate chain of at least 3 not including the trust anchor and MAY reject connections from servers offering chains longer than 3. IoT devices MAY have client certificate chains of any length. Obviously, longer chains require more resources to process, transmit or receive.

A device compliant with the profile in this section MUST implement TLS_ECDHE_ECDSA_WITH_AES_128_CCM_8 and follow the guidance from this section.

6.3.1. Client Certificate URLs

RFC 6066 [RFC6066] allows to avoid sending client-side certificates and uses URLs instead. This reduces the over-the-air transmission. Note that the TLS cached info extension does not provide any help with caching client certificates.

Recommendation: Add support for client certificate URLs for those environments where client-side certificates are used.

6.3.2. Trusted CA Indication

RFC 6066 [RFC6066] allows clients to indicate what trust anchor they support. With certificate-based authentication a DTLS server conveys its end entity certificate to the client during the DTLS exchange provides. Since the server does not necessarily know what trust anchors the client has stored it includes intermediate CA certs in the certificate payload as well to facilitate with certification path construction and path validation.

Today, in most IoT deployments there is a fairly static relationship between the IoT device (and the software running on them) and the server- side infrastructure and no such dynamic indication of trust anchors is needed.

Recommendation: For IoT deployments where clients talk to a fixed, pre-configured set of servers and where a software update mechanism

is available this extension is not recommended. Environments where the client needs to interact with dynamically discovered TLS/DTLS servers this extension may be useful to reduce the communication overhead. Note, however, in that case the TLS cached info extension may help to reduce the communication overhead for everything but the first protocol interaction.

7. Signature Algorithm Extension

The "signature_algorithms" extension, defined in Section 7.4.1.4.1 of RFC 5246 [RFC5246], allows the client to indicate to the server which signature/hash algorithm pairs may be used in digital signatures. The client MUST send this extension to select the use of SHA-256 since otherwise absent this extension RFC 5246 defaults to SHA-1 / ECDSA for the ECDH_ECDSA and the ECDHE_ECDSA key exchange algorithms.

The "signature_algorithms" extension is not applicable to the PSK-based ciphersuite described in Section 6.1.

8. Error Handling

TLS/DTLS uses the Alert protocol to convey error messages and specifies a longer list of errors. However, not all error messages defined in the TLS/DTLS specification are applicable to this profile. In general, there are two categories of errors (as defined in Section 7.2 of RFC 5246), namely fatal errors and warnings. Alert messages with a level of fatal result in the immediate termination of the connection. If possible, developers should try to develop strategies to react to those fatal errors, such as re-starting the handshake or informing the user using the (often limited) user interface. Warnings may be ignored by the application since many IoT devices will either have limited ways to log errors or no ability at all. In any case, implementers have to carefully evaluate the impact of errors and ways to remedy the situation since a commonly used approach for delegating decision making to users is difficult (or impossible) to accomplish in a timely fashion.

All error messages marked as RESERVED are only supported for backwards compatibility with SSL and are therefore not applicable to this profile. Those include decryption_failed_RESERVED, no_certificate_RESERVE, and export_restriction_RESERVED.

A number of the error messages are applicable only for certificate-based authentication ciphersuites. Hence, for PSK and raw public key use the following error messages are not applicable:

- bad_certificate,

- unsupported_certificate,
- certificate_revoked,
- certificate_expired,
- certificate_unknown,
- unknown_ca, and
- access_denied.

Since this profile does not make use of compression at the TLS layer the decompression_failure error message is not applicable either.

RFC 4279 introduced a new alert message unknown_psk_identity for PSK ciphersuites. As stated in Section 2 of RFC 4279 the decryption_error error message may also be used instead. For this profile the TLS server MUST return the decryption_error error message instead of the unknown_psk_identity since the two mechanisms exist and provide the same functionality.

Furthermore, the following errors should not occur with devices and servers supporting this specification but implementations MUST be prepared to process these errors to deal with servers that are not compliant to the profiles in this document:

protocol_version: While this document focuses only on one version of the TLS/DTLS protocol, namely version 1.2, ongoing work on TLS/DTLS 1.3 is in progress at the time of writing.

insufficient_security: This error message indicates that the server requires ciphers to be more secure. This document specifies only only one ciphersuite per profile but it is likely that additional ciphtersuites get added over time.

user_canceled: Many IoT devices are unattended and hence this error message is unlikely to occur.

9. Session Resumption

Session resumption is a feature of TLS/DTLS that allows a client to continue with an earlier established session state. The resulting exchange is shown in Figure 8. In addition, the server may choose not to do a cookie exchange when a session is resumed. Still, clients have to be prepared to do a cookie exchange with every handshake.

Figure 8: DTLS Session Resumption.

Clients MUST implement session resumption to improve the performance of the handshake (in terms of reduced number of message exchanges, lower computational overhead, and less bandwidth conserved).

Since the communication model described in Section 4 does not assume that the server is constrained, RFC 5077 [RFC5077] specifying TLS/DTLS session resumption without server-side state is not utilized by this profile.

10. Compression

Section 3.3 of [I-D.ietf-uta-tls-bcp] recommends to disable TLS/DTLS-level compression due to attacks, such as CRIME. For IoT applications compression at the TLS/DTLS layer is not needed since application layer protocols are highly optimized and the compression algorithms at the DTLS layer increases code size and complexity.

Recommendation: This TLS/DTLS profile MUST NOT implement and use TLS/DTLS layer compression.

11. Perfect Forward Secrecy

Perfect forward secrecy (PFS) is a property that preserves the confidentiality of past conversations even in situations where the long-term secret is compromised.

The PSK ciphersuite recommended in Section 6.1 does not offer this property since it does not utilize a Diffie-Hellman exchange. New ciphersuites that support PFS for PSK-based authentication, such as proposed in [I-D.schmertmann-dice-ccm-psk-pfs], might become available as standardized ciphersuite in the (near) future. The recommended PSK-based ciphersuite offers excellent performance, a very small memory footprint, and has the lowest on the wire overhead at the expense of not using any public cryptography. For deployments

where public key cryptography is acceptable the raw public might offer an acceptable middleground between the PSK ciphersuite in terms of out-of-band validation and the functionality offered by asymmetric cryptography.

The use of PFS is a trade-off decision since on one hand the compromise of long-term secrets of embedded devices is more likely than with many other Internet hosts but on the other hand a Diffie-Hellman exchange requires ephemeral key pairs to be generated, which is demanding from a performance point of view. For performance reasons some implementations re-use key pairs over multiple exchanges (rather than generating new keys for each exchange) for the obvious performance improvement. Note, however, that such key re-use over long periods voids the benefits of forward secrecy when an attack gains access to this DH key pair.

The impact of the disclosure of past conversations and the desire to increase the cost for pervasive monitoring (as demanded by [RFC7258]) has to be taken into account when making a deployment decision.

Recommendation: Client implementations claiming support of this profile MUST implement the ciphersuites listed in Section 6 according to the selected credential type.

12. Keep-Alive

RFC 6520 [RFC6520] defines a heartbeat mechanism to test whether the other peer is still alive. The same mechanism can also be used to perform Path Maximum Transmission Unit (MTU) Discovery.

A recommendation about the use of RFC 6520 depends on the type of message exchange an IoT device performs. There are three types of exchanges that need to be analysed:

Client-Initiated, One-Shot Messages

This is a common communication pattern where IoT devices upload data to a server on the Internet on an irregular basis. The communication may be triggered by specific events, such as opening a door.

Since the upload happens on an irregular and unpredictable basis and due to renumbering and Network Address Translation (NAT) the DTLS handshake may need to be re-started (ideally using session resumption, if possible).

In this case there is no use for a keep-alive extension for this scenario.

Client-Initiated, Regular Data Uploads

This is a variation of the previous case whereby data gets uploaded on a regular basis, for example, based on frequent temperature readings. If neither NAT bindings nor IP address changes occurred then the record layer will not notice any changes. For the case where the IP address and port number changes, it is necessary to re-create the record layer using session resumption.

In this scenario there is no use for a keep-alive extension. It is also very likely that the device will enter a sleep cycle in between data transmissions to keep power consumption low.

Server-Initiated Messages

In the two previous scenarios the client initiated the protocol interaction but in this case we consider server-initiated messages. Since messages to the client may get blocked by intermediaries, such as NATs (including IPv4/IPv6 protocol translators) and stateful packet filtering firewalls, the initial connection setup is triggered by the client and then kept alive. Since state at middleboxes expires fairly quickly (according to measurements described in [HomeGateway]), regular heartbeats are necessary whereby these keep-alive messages may be exchanged at the application layer or within DTLS itself.

For this message exchange pattern the use of DTLS heartbeat messages is quite useful but may interfere with registrations kept at the application layer (for example when the CoAP resource directory is used). The MTU discovery mechanism, which is also part of [RFC6520], is less likely to be relevant since for many IoT deployments the most constrained link is the wireless interface between the IoT device and the network itself (rather than some links along the end-to-end path). Only in more complex network topologies, such as multi-hop mesh networks, path MTU discovery might be appropriate. It also has to be noted that DTLS itself already provides a basic path discovery mechanism (see Section 4.1.1.1 of RFC 6347 by using the fragmentation capability of the handshake protocol).

For server-initiated messages the heartbeat extension can be RECOMMENDED.

13. Timeouts

To connect to the Internet a variety of wired and wireless technologies are available. Many of the low power radio technologies, such as IEEE 802.15.4 or Bluetooth Smart, only support small frame sizes (e.g., 127 bytes in case of IEEE 802.15.4 as explained in RFC 4919 [RFC4919]). Other radio technologies, such as the Global System for Mobile Communications (GSM) using the short messaging service (SMS) have similar constraints in terms of payload sizes, such as 140 bytes without the optional segmentation and reassembly scheme known as Concatenated SMS, but show higher latency.

The DTLS handshake protocol adds a fragmentation and reassembly mechanism to the TLS handshake protocol since each DTLS record must fit within a single transport layer datagram, as described in Section 4.2.3 of [RFC6347]. Since handshake messages are potentially bigger than the maximum record size, the mechanism fragments a handshake message over a number of DTLS records, each of which can be transmitted separately.

To deal with the unreliable message delivery provided by UDP, DTLS adds timeouts and re-transmissions, as described in Section 4.2.4 of [RFC6347]. Although the timeout values are implementation specific, recommendations are provided in Section 4.2.4.1 of [RFC6347], with an initial timer value of 1 second and twice the value at each retransmission up to no less than 60 seconds. Due to the nature of some radio technologies, these values are too aggressive and lead to spurious failures when messages in flight need longer.

Note: If a round-trip time estimator (such as proposed in [I-D.bormann-core-cocoa]) is available in the protocol stack of the device, it could be used to dynamically update the setting of the retransmit timeout.

Recommendation: Choosing appropriate timeout values is difficult with infrequent data transmissions, changing network conditions, and large variance in latency. This specification therefore RECOMMENDS an initial timer value of 10 seconds with exponential back off up to no less then 60 seconds. Appendix A provides additional normative text for carrying DTLS over SMS.

14. Random Number Generation

The TLS/DTLS protocol requires random numbers to be available during the protocol run. For example, during the ClientHello and the ServerHello exchange the client and the server exchange random numbers. Also, the use of the Diffie-Hellman exchange requires random numbers during the key pair generation. Special care has to

be paid when generating random numbers in embedded systems as many entropy sources available on desktop operating systems or mobile devices might be missing, as described in [Heninger]. Consequently, if not enough time is given during system start time to fill the entropy pool then the output might be predictable and repeatable, for example leading to the same keys generated again and again.

It is important to note that sources contributing to the randomness pool on laptops, or desktop PCs are not available on many IoT device, such as mouse movement, timing of keystrokes, air turbulence on the movement of hard drive heads, etc. Other sources have to be found or dedicated hardware has to be added.

The ClientHello and the ServerHello messages contains the 'Random' structure, which has two components: gmt_unix_time and a random sequence of 28 random bytes. gmt_unix_time holds the current time and date in standard UNIX 32-bit format (seconds since the midnight starting Jan 1, 1970, GMT). [I-D.mathewson-no-gmtunixtime] argues that the entire ClientHello.Random value (including gmt_unix_time) should be set to a cryptographically random sequence because of privacy concerns regarding device fingerprinting. Since many IoT devices do not have access to a real-time clock this recommendation it is RECOMMENDED to follow the guidance outlined in [I-D.mathewson-no-gmtunixtime] regarding the content of the ClientHello.Random field. However, for the ServerHello.Random structure it is RECOMMENDED to maintain the existing structure with gmt_unix_time followed by a random sequence of 28 random bytes since the client can use the received time information to securely obtain time information.

Recommendation: IoT devices using TLS/DTLS MUST offer ways to generate quality random numbers. Guidelines and requirements for random number generation can be found in RFC 4086 [RFC4086].

15. Truncated MAC and Encrypt-then-MAC Extension

The truncated MAC extension was introduced with RFC 6066 [RFC6066] with the goal to reduce the size of the MAC used at the Record Layer. This extension was developed for TLS ciphersuites that used older modes of operation where the MAC and the encryption operation was performed independently.

The recommended ciphersuites in this document use the newer Authenticated Encryption with Associated Data (AEAD) construct, namely the CBC-MAC mode (CCM) with eight-octet authentication tags, and are therefore not appliable to the truncated MAC extension.

RFC 7366 [RFC7366] introduced the encrypt-then-MAC extension (instead of the previously used MAC-then-encrypt) since the MAC-then-encrypt mechanism has been the subject of a number of security vulnerabilities. RFC 7366 is, however, also not applicable to the AEAD ciphers recommended in this document.

Recommendation: Since this profile only supports AEAD ciphersuites these two extensions are not applicable.

16. Server Name Indication (SNI)

This RFC 6066 extension defines a mechanism for a client to tell a TLS/DTLS server the name of the server it wants to contact. This is a useful extension for many hosting environments where multiple virtual servers are run on single IP address.

Recommendation: Unless it is known that a TLS/DTLS client does not interact with a server in a hosting environment we RECOMMEND clients to implement the SNI extension.

17. Maximum Fragment Length Negotiation

This RFC 6066 extension lowers the maximum fragment length support needed for the Record Layer from 2^14 bytes to 2^9 bytes.

This is a very useful extension that allows the client to indicate to the server how much maximum memory buffers it uses for incoming messages. Ultimately, the main benefit of this extension is it to allows client implementations to lower their RAM requirements since the client does not need to accept packets of large size (such as 16k packets as required by plain TLS/DTLS).

Recommendation: Client implementations MUST support this extension.

18. Session Hash

In order to begin connection protection, the Record Protocol requires specification of a suite of algorithms, a master secret, and the client and server random values. The algorithm for computing the master secret is defined in Section 8.1 of RFC 5246 but only includes a small number of parameters exchanged during the handshake and does not include parameters like the client and server identities. This can be utilized by an attacker to mount a man-in-the-middle attack since the master secret is not guaranteed to be unique across sessions, as discovered in the 'Triple Handshake' attack [Tripple-HS].

[I-D.ietf-tls-session-hash] defines a TLS extension that binds the master secret to a log of the full handshake that computes it, thus preventing such attacks.

Recommendation: Client implementations SHOULD implement this extension even though the ciphersuites recommended by this profile are not vulnerable to this attack. For Diffie-Hellman-based ciphersuites the keying material is contributed by both parties and in case of the pre-shared secret key ciphersuite both parties need to be in possession of the shared secret to ensure that the handshake completes successfully. It is, however, possible that some application layer protocols will tunnel other authentication protocols on top of DTLS making this attack relevant again.

19. Re-Negotiation Attacks

TLS/DTLS allows a client and a server who already have a TLS/DTLS connection to negotiate new parameters, generate new keys, etc by using the re-negotiation feature. Renegotiation happens in the existing connection, with the new handshake packets being encrypted along with application data. Upon completion of the re-negotiation procedure the new channel replaces the old channel.

As described in RFC 5746 [RFC5746] there is no cryptographic binding between the two handshakes, although the new handshake is carried out using the cryptographic parameters established by the original handshake.

Recommendation: To prevent the re-negotiation attack [RFC5746] this specification RECOMMENDS to disable the TLS renegotigation feature. Clients MUST respond to server-initiated re-negotiation attempts with an alert message (no_renegotiation) and clients MUST NOT initiate them.

20. Downgrading Attacks

When a client sends a ClientHello with a version higher than the highest version known to the server, the server is supposed to reply with ServerHello.version equal to the highest version known to the server and the handshake can proceed. This behaviour is known as version tolerance. Version-intolerance is when the server (or a middlebox) breaks the handshake when it sees a ClientHello.version higher than what it knows about. This is the behaviour that leads some clients to re-run the handshake with lower version. As a result, a potential security vulnerability is introduced when a system is running an old TLS/SSL version (e.g., because of the need to integrate with legacy systems). In the worst case, this allows an attacker to downgrade the protocol handshake to SSL 3.0. SSL 3.0 is

so broken that there is no secure cipher available for it (see [I-D.ietf-tls-sslv3-diediedie]).

The above-described downgrade vulnerability is solved by the TLS Fallback Signaling Cipher Suite Value (SCSV) [I-D.ietf-tls-downgrade-scsv] extension. However, the solution is not appliable to implementations conforming to this profile since the version negotiation MUST use TLS/DTLS version 1.2 (or higher). More specifically, this implies:

- Clients MUST NOT send a TLS/DTLS version lower than version 1.2 in the ClientHello.
- Clients MUST NOT retry a failed negotiation offering a TLS/DTLS version lower than 1.2.
- Servers MUST fail the handshake by sending a protocol_version fatal alert if a TLS/DTLS version >= 1.2 cannot be negotiated. Note that the aborted connection is non-resumable.

If at some time in the future the TLS/DTLS 1.2 profile reaches the quality of SSL 3.0 a software update mechanism is needed since constrained devices are unlikely to run multiple TLS/DTLS versions due to memory size restrictions.

21. Crypto Agility

This document recommends software and chip manufacturers to implement AES and the CCM mode of operation. This document references the CoAP recommended ciphersuite choices, which have been selected based on implementation and deployment experience from the IoT community. Over time the preference for algorithms will, however, change. Not all components of a ciphersuite are likely to change at the same speed. Changes are more likely expected for ciphers, the mode of operation, and the hash algorithms. The recommended key lengths have to be adjusted over time. Some deployment environments will also be impacted by local regulation, which might dictate a certain cipher and key size. Ongoing discussions regarding the choice of specific ECC curves will also likely to impact implementations.

The following recommendations can be made to chip manufacturers:

- Make any AES hardware-based crypto implementation accessible to developers working on security implementations at higher layers. Sometimes hardware implementatios are added to microcontrollers to offer support for functionality needed at the link layer and are only available to the on-chip link layer protocol implementation.

- Provide flexibility for the use of the crypto function with future extensibility in mind. For example, making an AES-CCM implementation available to developers is a first step but such an implementation may not be usable due to parameter differences between an AES-CCM implementations. AES-CCM in IEEE 802.15.4 and Bluetooth Smart uses a nonce length of 13-octets while DTLS uses a nonce length of 12-octets. Hardware implementations of AES-CCM for IEEE 802.15.4 and Bluetooth Smart are therefore not re-usable by a DTLS stack.

- Offer access to building blocks in addition (or as an alternative) to the complete functionality. For example, a chip manufacturer who gives developers access to an the AES crypto function can use it in functions to build an efficient AES-GCM implementations. Another example is to make a special instruction available that increases the speed of speed-up carryless multiplications.

As a recommendation for developers and product architects we recommend that sufficient headroom is provided to allow an upgrade to a newer cryptographic algorithms over the lifetime of the product. As an example, while AES-CCM is recommended thoughout this specification future products might use the ChaCha20 cipher in combination with the Poly1305 authenticator [I-D.irtf-cfrg-chacha20-poly1305]. The assumption is made that a robust software update mechanism is offered.

22. Key Length Recommendations

RFC 4492 [RFC4492] gives approximate comparable key sizes for symmetric- and asymmetric-key cryptosystems based on the best-known algorithms for attacking them. While other publications suggest slightly different numbers, such as [Keylength], the approximate relationship still holds true. Figure 9 illustrates the comparable key sizes in bits.

At the time of writing the key size recommendations for use with TLS-based ciphers found in [I-D.ietf-uta-tls-bcp] recommend DH key lengths of at least 2048 bit, which corresponds to a 112-bit symmetric key and a 233 bit ECC keys. These recommendations are inline with those from other organizations, such as National Institute of Standards and Technology (NIST) or European Network and Information Security Agency (ENISA). The authors of [ENISA-Report2013] add that a symmetric 80-bit security level is sufficient for legacy applications for the coming years, but a 128-bit security level is the minimum requirement for new systems being deployed. The authors further note that one needs to also take into account the length of time data needs to be kept secure for. The use 80-bit encryption for transactional data may be acceptable

for the near future while one has to insist on 128-bit encryption for long lived data.

Symmetric	ECC	DH/DSA/RSA
80	163	1024
112	233	2048
128	283	3072
192	409	7680
256	571	15360

Figure 9: Comparable Key Sizes (in bits).

23. False Start

A full TLS handshake as specified in [RFC5246] requires two full protocol rounds (four flights) before the handshake is complete and the protocol parties may begin to send application data.

An abbreviated handshake (resuming an earlier TLS session) is complete after three flights, thus adding just one round-trip time if the client sends application data first.

If the conditions outlined in [I-D.bmoeller-tls-falsestart] are met, application data can be transmitted when the sender has sent its own "ChangeCipherSpec" and "Finished" messages. This achieves an improvement of one round-trip time for full handshakes if the client sends application data first, and for abbreviated handshakes if the server sends application data first.

The conditions for using the TLS False Start mechanism are met by the public-key-based ciphersuites in this document. In summary, the conditions are

- Modern symmetric ciphers with an effective key length of 128 bits, such as AES-128-CCM
- Client certificate types, such as ecdsa_sign
- Key exchange methods, such as ECDHE_ECDSA

Based on the improvement over a full roundtrip for the full TLS/DTLS exchange this specification RECOMMENDS the use of the False Start mechanism when clients send application data first.

24. Privacy Considerations

The DTLS handshake exchange conveys various identifiers, which can be observed by an on-path eavesdropper. For example, the DTLS PSK exchange reveals the PSK identity, the supported extensions, the session id, algorithm parameters, etc. When session resumption is used then individual TLS sessions can be correlated by an on-path adversary. With many IoT deployments it is likely that keying material and their identifiers are persistent over a longer period of time due to the cost of updating software on these devices.

User participation with many IoT deployments poses a challenge since many of the IoT devices operate unattended, even though they will initially be provisioned by a human. The ability to control data sharing and to configure preference will have to be provided at a system level rather than at the level of the DTLS exchange itself, which is the scope of this document. Quite naturally, the use of DTLS with mutual authentication will allow a TLS server to collect authentication information about the IoT device (likely over a long period of time). While this strong form of authentication will prevent mis-attribution it also allows strong identification. Device-related data collection (e.g., sensor recordings) will be associated with other data to be truly useful and this extra data might include personal data about the owner of the device or data about the environment it senses. Consequently, the data stored on the server-side will be vulnerable to stored data compromise. For the communication between the client and the server this specification prevents eavesdroppers to gain access to the communication content. While the PSK-based ciphersuite does not provide PFS the asymmetric versions do. This prevents an adversary from obtaining past communication content when access to a long-term secret has been gained. Note that no extra effort to make traffic analysis more difficult is provided by the recommendations made in this document.

25. Security Considerations

This entire document is about security.

We would also like to point out that designing a software update mechanism into an IoT system is crucial to ensure that both functionality can be enhanced and that potential vulnerabilities can be fixed. This software update mechanism is also useful for changing configuration information, for example, trust anchors and other keying related information.

26. IANA Considerations

This document includes no request to IANA.

27. Acknowledgements

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Appendix A. Conveying DTLS over SMS

This section is normative for the use of DTLS over SMS. Timer recommendations are already outlined in Section 13 and also applicable to the transport of DTLS over SMS.

This section requires readers to be familiar with the terminology and concepts described in [GSM-SMS], and [WAP-WDP].

The remainder of this section assumes Mobile Stations are capable of producing and consuming 8-bit binary data encoded Transport Protocol Data Units (TPDU).

A.1. Overview

DTLS adds an additional roundtrip to the TLS [RFC5246] handshake to serve as a return-routability test for protection against certain types of DoS attacks. Thus a full blown DTLS handshake comprises up

to 6 "flights" (i.e., logical message exchanges), each of which is then mapped on to one or more DTLS records using the segmentation and reassembly (SaR) scheme described in Section 4.2.3 of [RFC6347]. The overhead for said scheme is 6 bytes per Handshake message which, given a realistic 10+ messages handshake, would amount around 60 bytes across the whole handshake sequence.

Note that the DTLS SaR scheme is defined for handshake messages only. In fact, DTLS records are never fragmented and MUST fit within a single transport layer datagram.

SMS provides an optional segmentation and reassembly scheme as well, known as Concatenated short messages (see Section 9.2.3.24.1 of [GSM-SMS]). However, since the SaR scheme in DTLS cannot be circumvented, the Concatenated short messages mechanism SHOULD NOT be used during handshake to avoid redundant overhead. Before starting the handshake phase (either actively or passively), the DTLS implementation MUST be explicitly configured with the PMTU of the SMS transport in order to correctly instrument its SaR function. The PMTU SHALL be 133 bytes if WDP-based multiplexing is used (see Appendix A.3), 140 bytes otherwise.

It is RECOMMENDED to use the established security context over the longest possible period (possibly until a Closure Alert message is received, or after a very long inactivity timeout) to avoid the expensive re-establishment of the security association.

A.2. Message Segmentation and Re-Assembly

The content of an SMS message is carried in the TP-UserData field, and its size may be up to 140 bytes. As already mentioned in Appendix A.1, longer (i.e., up to 34170 bytes) messages can be sent using Concatenated SMS.

This scheme consumes 6-7 bytes (depending on whether the short or long segmentation format is used) of the TP-UserData field, thus reducing the space available for the actual content of the SMS message to 133-134 bytes per TPDU.

Though in principle a PMTU value higher than 140 bytes could be used, which may look like an appealing option given its more efficient use of the transport, there are disadvantages to consider. First, there is an additional overhead of 7 bytes per TPDU to be paid to the SaR function (which is in addition to the overhead introduced by the DTLS SaR mechanism. Second, some networks only partially support the Concatenated SMS function and others do not support it at all.

For these reasons, the Concatenated short messages mechanism SHOULD NOT be used, and it is RECOMMENDED to leave the same PMTU settings used during the handshake phase, i.e., 133 bytes if WDP- based multiplexing is enabled, 140 bytes otherwise.

Note that, after DTLS handshake has completed, any fragmentation and reassembly logic that pertains the application layer (e.g., segmenting CoAP messages into DTLS records and reassembling them after the crypto operations have been successfully performed) needs to be handled by the application that uses the established DTLS tunnel.

A.3. Multiplexing Security Associations

Unlike IPsec ESP/AH, DTLS records do not contain any association identifiers. Applications must arrange to multiplex between associations on the same endpoint which, when using UDP/IP, is usually done with the host/port number.

If the DTLS server allows more than one client to be active at any given time, then the WAP User Datagram Protocol [WAP-WDP] can be used to achieve multiplexing of the different security associations. (The use of WDP provides the additional benefit that upper layer protocols can operate independently of the underlying wireless network, hence achieving application-agnostic transport handover.)

The total overhead cost for encoding the WDP source and destination ports is 7 bytes out of the total available for the SMS content.

The receiving side of the communication gets the source address from the originator address (TP-OA) field of the SMS-DELIVER TPDU. This way an unique 4-tuple identifying the security association can be reconstructed at both ends. (When replying to its DTLS peer, the sender will swaps the TP-OA and TP-DA parameters and the source and destination ports in the WDP.)

A.4. Timeout

If SMS-STATUS-REPORT messages are enabled, their receipt is not to be interpreted as the signal that the specific handshake message has been acted upon by the receiving party. Therefore, it MUST NOT be taken into account by the DTLS timeout and retransmission function.

Handshake messages MUST carry a validity period (TP-VP parameter in a SMS-SUBMIT TPDU) that is not less than the current value of the retransmission timeout. In order to avoid persisting messages in the network that will be discarded by the receiving party, handshake messages SHOULD carry a validity period that is the same as, or just

slightly higher than, the current value of the retransmission timeout.

Appendix B. DTLS Record Layer Per-Packet Overhead

Figure 10 shows the overhead for the DTLS record layer for protecting data traffic when AES-128-CCM with an 8-octet Integrity Check Value (ICV) is used.

```
DTLS Record Layer Header.............13 bytes
Nonce (Explicit).....................8 bytes
ICV..................................8 bytes
-----------------------------------------------
Overhead.............................29 bytes
-----------------------------------------------
```

Figure 10: AES-128-CCM-8 DTLS Record Layer Per-Packet Overhead.

The DTLS record layer header has 13 octets and consists of

- 1 octet content type field,
- 2 octet version field,
- 2 octet epoch field,
- 6 octet sequence number,
- 2 octet length field.

The "nonce" input to the AEAD algorithm is exactly that of [RFC5288], i.e., 12 bytes long. It consists of a 4 octet salt and an 8 octet nonce. The salt is the "implicit" part of the nonce and is not sent in the packet. Since the nonce_explicit may be the 8 octet sequence number and, in DTLS, it is the 8 octet epoch concatenated with the 6 octet sequence number.

RFC 6655 [RFC6655] allows the nonce_explicit to be a sequence number or something else. This document makes this use more restrictive for use with DTLS: the 64-bit none_explicit MUST be the 16-bit epoch concatenated with the 48-bit seq_num. The sequence number component of the nonce_explicit field at the AES-CCM layer is an exact copy of the sequence number in the record layer header field. This leads to a duplication of 8-bytes per record.

To avoid this 8-byte duplication RFC 7400 [RFC7400] provides help with the use of the generic header compression technique for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs). Note that this header compression technique is not available when DTLS is exchanged over transports that do not use IPv6 or 6LoWPAN, such as the SMS transport described in Appendix A.

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