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TLS/DTLS 1.3 Profiles for the Internet of Things  
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## Abstract

RFC 7925 offers guidance to developers on using TLS/DTLS 1.2 for Internet of Things (IoT) devices with resource constraints. This document is a companion to RFC 7925, defining TLS/DTLS 1.3 profiles for IoT devices. Additionally, it updates RFC 7925 with respect to the X.509 certificate profile and ciphersuite requirements.

## Discussion Venues

This note is to be removed before publishing as an RFC.

Source for this draft and an issue tracker can be found at <https://github.com/thomas-fossati/draft-tls13-iot>.

## Status of This Memo

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## 1. Introduction

In the rapidly evolving Internet of Things (IoT) ecosystem, communication security is a critical requirement. The Transport Layer Security (TLS) and Datagram Transport Layer Security (DTLS) protocols have been foundational for ensuring encryption, integrity, and authenticity in communications. However, the constraints of a certain class of IoT devices render conventional, off-the-shelf TLS/DTLS implementations suboptimal for many IoT use cases. This document addresses these limitations by specifying profiles of TLS 1.3 and DTLS 1.3, optimized for resource-constrained IoT devices.

Note that IoT devices vary widely in terms of capabilities. While some are highly resource-constrained, others offer performance comparable to regular desktop computers but operate without end-user interfaces. For a detailed description of the different classes of IoT devices, please refer to [RFC7228] and [I-D.ietf-iotops-7228bis]. It is crucial for developers to thoroughly assess the limitations of their IoT devices and communication technologies to implement the most suitable optimizations. The profiles in this document aim to balance strong security with the hardware and software limitations of IoT devices.

TLS 1.3 has been re-designed and several previously defined extensions are not applicable to the new version of TLS/DTLS anymore. The following features changed with the transition from TLS 1.2 to 1.3:

- \* TLS 1.3 introduced the concept of post-handshake authentication messages, which partially replaced the need for the re-negotiation feature [RFC5746] available in earlier TLS versions. However, rekeying defined in Section 4.6.3 of [TLS13] does not provide forward secrecy and post-handshake authentication defined in Section 4.6.2 of [TLS13] only offers client-to-server authentication. The "Exported Authenticator" specification, see [RFC9261], recently added support for mutual, post-handshake authentication but requires the Certificate, CertificateVerify and the Finished messages to be exchanged by the application layer protocol, as it is exercised for HTTP/2 and HTTP/3 in [I-D.ietf-httpbis-secondary-server-certs].
- \* Rekeying of the application traffic secret does not lead to an update of the exporter secret (see Section 7.5 of [TLS13]) since the derived export secret is based on the exporter\_master\_secret and not on the application traffic secret.
- \* Flight #4, which was used by EAP-TLS 1.2 [RFC5216], does not exist in TLS 1.3. As a consequence, EAP-TLS 1.3 [RFC9190] introduced a dummy message.
- \* [RFC4279] introduced PSK-based authentication to TLS, a feature re-designed in TLS 1.3. The "PSK identity hint" defined in [RFC4279], which is used by the server to help the client in selecting which PSK identity to use, is, however, not available anymore in TLS 1.3.
- \* Finally, ciphersuites were depreciated and the RSA-based key transport is not yet supported in TLS 1.3. As a consequence, only a Diffie-Hellman-based key exchange is available.

The profiles in this specification are designed to be adaptable to the broad spectrum of IoT applications, from low-power consumer devices to large-scale industrial deployments. It provides guidelines for implementing TLS/DTLS 1.3 in diverse networking contexts, including reliable, connection-oriented transport via TCP for TLS, and lightweight, connectionless communication via UDP for DTLS. In particular, DTLS is emphasized for scenarios where low-latency communication is paramount, such as multi-hop mesh networks and low-power wide-area networks, where the amount of data exchanged needs to be minimized.

In conclusion, this document offers comprehensive guidance for deploying secure communication in resource-constrained IoT environments. It outlines best practices for configuring TLS/DTLS 1.3 to meet the unique needs of IoT devices, ensuring robust security without overwhelming their limited processing, memory, and power resources. The document plays a vital role in facilitating secure, efficient IoT deployments, supporting the broad adoption of secure communication standards.

## 2. Conventions and Terminology

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

This document reuses the terms "SHOULD+", "SHOULD-" and "MUST-" from [RFC8221].

## 3. Credential Types

In accordance with the recommendations in [RFC7925], a compliant implementation MUST implement TLS\_AES\_128\_CCM\_8\_SHA256. It SHOULD implement TLS\_CHACHA20\_POLY1305\_SHA256.

Pre-shared key based authentication is integrated into the main TLS/DTLS 1.3 specification and has been harmonized with session resumption.

A compliant implementation supporting authentication based on certificates and raw public keys MUST support digital signatures with ecdsa\_secp256r1\_sha256. A compliant implementation MUST support the key exchange with secp256r1 (NIST P-256) and SHOULD support key exchange with X25519.

A plain PSK-based TLS/DTLS client or server MUST implement the following extensions:

- \* Supported Versions,
- \* Cookie,
- \* Server Name Indication (SNI),
- \* Pre-Shared Key,
- \* PSK Key Exchange Modes, and
- \* Application-Layer Protocol Negotiation (ALPN).

For use of external pre-shared keys [RFC9258] makes the following recommendation:

Applications SHOULD provision separate PSKs for (D)TLS 1.3 and prior versions.

Where possible, the importer interface defined in [RFC9258] MUST be used for external PSKs. This ensures that external PSKs used in (D)TLS 1.3 are bound to a specific key derivation function (KDF) and hash function.

The SNI extension is discussed in this document and the justification for implementing and using the ALPN extension can be found in [RFC9325].

For TLS/DTLS clients and servers implementing raw public keys and/or certificates the guidance for mandatory-to-implement extensions described in Section 9.2 of [RFC8446] MUST be followed.

#### 4. Error Handling

TLS 1.3 simplified the Alert protocol but the underlying challenge in an embedded context remains unchanged, namely what should an IoT device do when it encounters an error situation. The classical approach used in a desktop environment where the user is prompted is often not applicable with unattended devices. Hence, it is more important for a developer to find out from which error cases a device can recover from.

#### 5. Session Resumption

TLS 1.3 has built-in support for session resumption by utilizing PSK-based credentials established in an earlier exchange.

#### 6. Compression

TLS 1.3 does not have support for compression of application data traffic, as offered by previous versions of TLS. Applications are therefore responsible for transmitting payloads that are either compressed or use a more efficient encoding otherwise.

With regards to the handshake itself, various strategies have been applied to reduce the size of the exchanged payloads. TLS and DTLS 1.3 use less overhead, depending on the type of key confirmations, when compared to previous versions of the protocol. Additionally, the work on Compact TLS (cTLS) [I-D.ietf-tls-ctls] has taken compression of the handshake a step further by utilizing out-of-band knowledge between the communication parties to reduce the amount of data to be transmitted at each individual handshake, among applying other techniques.

#### 7. Forward Secrecy

RFC 8446 has removed Static RSA and Static Diffie-Hellman cipher suites, therefore all public-key-based key exchange mechanisms available in TLS 1.3 provide forward secrecy.

Pre-shared keys (PSKs) can be used with (EC)DHE key exchange to provide forward secrecy or can be used alone, at the cost of losing forward secrecy for the application data.

## 8. Authentication and Integrity-only Cipher Suites

For a few, very specific Industrial IoT use cases [RFC9150] defines two cipher suites that provide data authenticity, but not data confidentiality. Please review the security and privacy considerations about their use detailed in Section 9 of [RFC9150].

## 9. Keep-Alive

The discussion in Section 10 of [RFC7925] is applicable.

## 10. Timers and ACKs

Compared to DTLS 1.2 timeout-based whole flight retransmission, DTLS 1.3 ACKs sensibly decrease the risk of congestion collapse which was the basis for the very conservative recommendations given in Section 11 of [RFC7925].

In general, the recommendations in Section 7.3 of [DTLS13] regarding ACKs apply. In particular, "[w]hen DTLS 1.3 is used in deployments with lossy networks, such as low-power, long-range radio networks as well as low-power mesh networks, the use of ACKs is recommended" to signal any sign of disruption or lack of progress. This allows for selective or early retransmission, which leads to more efficient use of bandwidth and memory resources.

Due to the vast range of network technologies used in IoT deployments, from wired LAN to GSM-SMS, it's not possible to provide a universal recommendation for an initial timeout. Therefore, it is RECOMMENDED that DTLS 1.3 implementations allow developers to explicitly set the initial timer value. Developers SHOULD set the initial timeout to be twice the expected round-trip time (RTT), but no less than 1000ms. For specific application/network combinations, a sub-second initial timeout MAY be set. In cases where no RTT estimates are available, a 1000ms initial timeout is suitable for the general Internet.

For RRC, the recommendations in Section 7.5 of [I-D.ietf-tls-dtls-rrc] apply. Just like the handshake initial timers, it is RECOMMENDED that DTLS 1.2 and 1.3 implementations offer an option for their developers to explicitly set the RRC timer.

## 11. Random Number Generation

The discussion in Section 12 of [RFC7925] is applicable with one exception: the ClientHello and the ServerHello messages in TLS 1.3 do not contain `gmt_unix_time` component anymore.

## 12. Server Name Indication

This specification mandates the implementation of the Server Name Indication (SNI) extension. Where privacy requirements require it, the ECH (Encrypted Client Hello) extension [I-D.ietf-tls-esni] prevents an on-path attacker to determine the domain name the client is trying to connect to.

Since the Encrypted Client Hello extension requires use of Hybrid Public Key Encryption (HPKE) [RFC9180] and additional protocols require further protocol exchanges and cryptographic operations, there is a certain overhead associated with this privacy feature.

Note that in industrial IoT deployments the use of ECH may not be an option because network administrators inspect DNS traffic generated by IoT devices in order to detect malicious behaviour.

Besides, to avoid leaking DNS lookups from network inspection altogether further protocols are needed, including DoH [RFC8484] and DPRIVE [RFC7858] [RFC8094]. For use of such techniques in managed networks, the reader is advised to keep up to date with the protocols defined by the Adaptive DNS Discovery (add) working group [ADD].

## 13. Maximum Fragment Length Negotiation

The Maximum Fragment Length Negotiation (MFL) extension has been superseded by the Record Size Limit (RSL) extension [RFC8449]. Implementations in compliance with this specification MUST implement the RSL extension and SHOULD use it to indicate their RAM limitations.

## 14. Crypto Agility

The recommendations in Section 19 of [RFC7925] are applicable.

## 15. Key Length Recommendations

The recommendations in Section 20 of [RFC7925] are applicable.

## 16. 0-RTT Data

Appendix E.5 of [TLS13] establishes that:

Application protocols MUST NOT use 0-RTT data without a profile that defines its use. That profile needs to identify which messages or interactions are safe to use with 0-RTT and how to handle the situation when the server rejects 0-RTT and falls back to 1-RTT.

At the time of writing, no such profile has been defined for CoAP [CoAP]. Therefore, 0-RTT MUST NOT be used by CoAP applications.

## 17. Certificate Profile

This section contains updates and clarifications to the certificate profile defined in [RFC7925]. The content of Table 1 of [RFC7925] has been split by certificate "type" in order to clarify exactly what requirements and recommendations apply to which entity in the PKI hierarchy.

The content is also better aligned with the IEEE 802.1AR [\_8021AR] specification, which introduces the terms Initial Device Identifier (IDeVID) and Locally Significant Device Identifiers (LDevIDs). IDeVIDs and LDevIDs are Device Identifiers (DevIDs). A DevID consists of

- \* a private key,
- \* a certificate (containing the public key and the identifier certified by the certificate's issuer), and
- \* a certificate chain up to a trust anchor. The trust anchor is usually the root certificate).

Note that the trust anchor does not need to be transmitted in the TLS Certificate message sent by the server. The client MUST NOT use any trust anchor provided in the Certificate message, because the trust anchor is provisioned via out-of-band means. Therefore, transmitting the trust anchor in the Certificate message is a waste of bandwidth. If the trust anchor is not the root CA certificate, the server may be unaware of which trust anchor the client has. In such cases, the client can use the Trusted CA Indication, defined in [RFC6066], to indicate which trust anchors it possesses.

The IDevID is typically provisioned by a manufacturer and signed by the manufacturer CA. It is then used to obtain operational certificates, the LDevIDs, from the operator or owner of the device. Some protocols also introduce an additional hierarchy with application instance certificates, which are obtained for use with specific applications.

IDevIDs are primarily used with device onboarding or bootstrapping protocols, such as the Bootstrapping Remote Secure Key Infrastructure (BRSKI) protocol [RFC8995] or by LwM2M Bootstrap [LwM2M]. Hence, the use of IDevIDs is limited in purpose even though they have a long lifetime, or do not expire at all. While some bootstrapping protocols use TLS (and therefore make use of the IDevID as part of client authentication) there are other bootstrapping protocols that do not use TLS/DTLS for client authentication, such as FIDO Device Onboarding (FDO) [FDO]. In many cases, a profile for the certificate content is provided by those specifications. For these reasons, this specification focuses on the description of LDevIDs.

While the IEEE 802.1AR terminology is utilized in this document, this specification does not claim conformance to IEEE 802.1AR since such a compliance statement goes beyond the use of the terminology and the certificate content and would include the use of management protocols, fulfillment of certain hardware security requirements, and interfaces to access these hardware security modules. Placing these requirements on network equipment like routers may be appropriate but designers of constrained IoT devices have opted for different protocols and hardware security choices.

## 17.1. All Certificates

To avoid repetition, this section outlines requirements on X.509 certificates applicable to all PKI entities.

### 17.1.1. Version

Certificates MUST be of type X.509 v3. Note that TLS 1.3 allows to convey payloads other than X.509 certificates in the Certificate message. The description in this section only focuses on X.509 v3 certificates and leaves the description of other formats to other sections or even other specifications.

### 17.1.2. Serial Number

CAs MUST generate non-sequential serial numbers greater than or equal to eight (8) octets from a cryptographically secure pseudo-random number generator. [RFC5280] limits this field to a maximum of 20 octets. The serial number MUST be unique for each certificate issued by a given CA (i.e., the issuer name and the serial number uniquely identify a certificate).

This requirement is aligned with [RFC5280].

### 17.1.3. Signature

The signature MUST be ecdsa-with-SHA256 or stronger [RFC5758].

Note: In contrast to IEEE 802.1AR this specification does not require end entity certificates, subordinate CA certificates, and CA certificates to use the same signature algorithm. Furthermore, this specification does not utilize RSA for use with constrained IoT devices and networks.

### 17.1.4. Issuer

The issuer field MUST contain a non-empty distinguished name (DN) of the entity that has signed and issued the certificate in accordance with [RFC5280].

### 17.1.5. Validity

In IoT deployment scenarios it is often expected that the IDevIDs have no maximum validity period. For this purpose the use of a special value for the notAfter date field, the GeneralizedTime value of 99991231235959Z, is utilized. If this is done, then the CA certificates and the certificates of subordinate CAs cannot have a maximum validity period either. Hence, it requires careful consideration whether it is appropriate to issue IDevID certificates with no maximum validity period.

LDevID certificates are, however, issued by the operator or owner, and may be renewed at a regular interval using protocols, such as Enrollment over Secure Transport (EST) [RFC7030] or the Certificate Management Protocol (CMP) [RFC9483]. It is therefore RECOMMENDED to limit the lifetime of these LDevID certificates using the notBefore and notAfter fields, as described in Section 4.1.2.5 of [RFC5280]. Values MUST be expressed in Greenwich Mean Time (Zulu) and MUST include seconds even where the number of seconds is zero.

Note that the validity period is defined as the period of time from notBefore through notAfter, inclusive. This means that a hypothetical certificate with a notBefore date of 9 June 2021 at 03:42:01 and a notAfter date of 7 September 2021 at 03:42:01 becomes valid at the beginning of the :01 second, and only becomes invalid at the :02 second, a period that is 90 days plus 1 second. So for a 90-day, notAfter must actually be 03:42:00.

For devices without a reliable source of time we advise the use of a device management solution, which typically includes a certificate management protocol, to manage the lifetime of all the certificates used by the device. While this approach does not utilize certificates to its widest extent, it is a solution that extends the capabilities offered by a raw public key approach.

#### 17.1.6. Subject Public Key Info

The subjectPublicKeyInfo field indicates the algorithm and any associated parameters for the ECC public key. This profile uses the id-ecPublicKey algorithm identifier for ECDSA signature keys, as defined and specified in [RFC5480]. This specification assumes that devices supported one of the following algorithms:

- \* id-ecPublicKey with secp256r1,
- \* id-ecPublicKey with secp384r1, and
- \* id-ecPublicKey with secp521r1.

There is no requirement to use CA certificates and certificates of subordinate CAs to use the same algorithm as the end entity certificate. Certificates with longer lifetime may well use a cryptographic stronger algorithm.

#### 17.1.7. Certificate Revocation Checks

The guidance in Section 4.4.3 of [RFC7925] still holds: for certificate revocation, neither the Online Certificate Status Protocol (OCSP) nor Certificate Revocation Lists (CRLs) are used by constrained IoT devices.

Since the publication of RFC 7925 the need for firmware update mechanisms has been reinforced and the work on standardizing a secure and interoperable firmware update mechanism has made substantial progress, see [RFC9019]. RFC 7925 recommends to use a software / firmware update mechanism to provision devices with new trust anchors. This approach only addresses the distribution of trust anchors and not end entity certificates or certificates of subordinate CAs.

The use of device management protocols for IoT devices, which often include an onboarding or bootstrapping mechanism, has also seen considerable uptake in deployed devices. These protocols, some of which are standardized, allow for the distribution and updating of certificates on demand. This enables a deployment model where IoT device utilize end entity certificates with shorter lifetime making certificate revocation protocols, like OCSP and CRLs, less relevant. Whenever certificates are updated the TLS stack needs to be informed since the communication endpoints need to be aware of the new certificates. This is particularly important when long-lived TLS connections are used. In such a case, the post-handshake authentication exchange is triggered when the application requires it. TLS 1.3 provides client-to-server post-handshake authentication only. Mutual authentication via post-handshake messages is available by the use of the "Exported Authenticator" [RFC9261] but requires the application layer protocol to carry the payloads.

Hence, instead of performing certificate revocation checks on the IoT device itself this specification recommends to delegate this task to the IoT device operator and to take the necessary action to allow IoT devices to remain operational.

The CRL distribution points extension has been defined in RFC 5280 to identify how CRL information is obtained. The authority information access extension indicates how to access information like the online certificate status service (OCSP). Both extensions SHOULD NOT be set. If set, they MUST NOT be marked critical.

## 17.2. Root CA Certificate

This section outlines the requirements for root CA certificates.

### 17.2.1. Subject

[RFC5280] mandates that Root CA certificates MUST have a non-empty subject field. The subject field MUST contain the `commonName`, the `organizationName`, and the `countryName` attribute and MAY contain an `organizationalUnitName` attribute.

### 17.2.2. Authority Key Identifier

Section 4.2.1.1 of [RFC5280] defines the Authority Key Identifier as follows: "The authority key identifier extension provides a means of identifying the public key corresponding to the private key used to sign a certificate. This extension is used where an issuer has multiple signing keys."

The Authority Key Identifier extension MAY be omitted. If it is set, it MUST NOT be marked critical, and MUST contain the subjectKeyIdentifier of this certificate.

[Editor's Note: Do we need to set the Authority Key Identifier in the CA certificate?]

### 17.2.3. Subject Key Identifier

Section 4.2.1.2 of [RFC5280] defines the SubjectKeyIdentifier as follows: "The subject key identifier extension provides a means of identifying certificates that contain a particular public key."

The Subject Key Identifier extension MUST be set, MUST NOT be marked critical, and MUST contain the key identifier of the public key contained in the subject public key info field.

The subjectKeyIdentifier is used by path construction algorithms to identify which CA has signed a subordinate certificate.

### 17.2.4. Key Usage

[RFC5280] defines the key usage field as follows: "The key usage extension defines the purpose (e.g., encipherment, signature, certificate signing) of the key contained in the certificate."

The Key Usage extension MAY be set. If it is set, it MUST be marked critical and the keyCertSign or cRLSign purposes MUST be set. Additional key usages MAY be set depending on the intended usage of the public key.

[RFC5280] defines the extended key usage as follows: "This extension indicates one or more purposes for which the certified public key may be used, in addition to or in place of the basic purposes indicated in the key usage extension."

This extendedKeyUsage extension MUST NOT be set in CA certificates.

### 17.2.5. Basic Constraints

[RFC5280] states that "The Basic Constraints extension identifies whether the subject of the certificate is a CA and the maximum depth of valid certification paths that include this certificate. The cA boolean indicates whether the certified public key may be used to verify certificate signatures."

For the pathLenConstraint RFC 5280 makes further statements:

- \* "The pathLenConstraint field is meaningful only if the cA boolean is asserted and the key usage extension, if present, asserts the keyCertSign bit. In this case, it gives the maximum number of non-self-issued intermediate certificates that may follow this certificate in a valid certification path."
- \* "A pathLenConstraint of zero indicates that no non-self-issued intermediate CA certificates may follow in a valid certification path."
- \* "Where pathLenConstraint does not appear, no limit is imposed."
- \* "Conforming CAs MUST include this extension in all CA certificates that contain public keys used to validate digital signatures on certificates and MUST mark the extension as critical in such certificates."

The Basic Constraints extension MUST be set, MUST be marked critical, the cA flag MUST be set to true and the pathLenConstraint MUST be omitted.

[Editor's Note: Should we soften the requirement to: "The pathLenConstraint field SHOULD NOT be present."]

### 17.3. Subordinate CA Certificate

This section outlines the requirements for subordinate CA certificates.

#### 17.3.1. Subject

The subject field MUST be set and MUST contain the commonName, the organizationName, and the countryName attribute and MAY contain an organizationalUnitName attribute.

#### 17.3.2. Authority Key Identifier

The Authority Key Identifier extension MUST be set, MUST NOT be marked critical, and MUST contain the subjectKeyIdentifier of the CA that issued this certificate.

#### 17.3.3. Subject Key Identifier

The Subject Key Identifier extension MUST be set, MUST NOT be marked critical, and MUST contain the key identifier of the public key contained in the subject public key info field.

#### 17.3.4. Key Usage

The Key Usage extension MUST be set, MUST be marked critical, the keyCertSign or cRLSign purposes MUST be set, and the digitalSignature purpose SHOULD be set.

Subordinate certification authorities SHOULD NOT have any extendedKeyUsage. [RFC5280] reserves EKUs to be meaningful only in end entity certificates.

#### 17.3.5. Basic Constraints

The Basic Constraints extension MUST be set, MUST be marked critical, the cA flag MUST be set to true and the pathLenConstraint SHOULD be omitted.

#### 17.3.6. CRL Distribution Point

The CRL Distribution Point extension SHOULD NOT be set. If it is set, it MUST NOT be marked critical and MUST identify the CRL relevant for this certificate.

#### 17.3.7. Authority Information Access

The Authority Information Access extension SHOULD NOT be set. If it is set, it MUST NOT be marked critical and MUST identify the location of the certificate of the CA that issued this certificate and the location it provides an online certificate status service (OCSP).

### 17.4. End Entity Certificate

This section outlines the requirements for end entity certificates.

#### 17.4.1. Subject

This section describes the use of end entity certificate primarily for (D)TLS clients running on IoT devices. Operating (D)TLS servers on IoT devices is possible but less common.

[RFC9525], Section 2 mandates that the subject field not be used to identify a service. However, certain IoT applications (for example, [I-D.ietf-anima-constrained-voucher], [\_8021AR]) use the subject field to encode the device serial number.

The requirement in Section 4.4.2 of [RFC7925] to only use EUI-64 for end entity certificates as a subject field is lifted.

Two fields are typically used to encode a device identifier, namely the Subject and the subjectAltName fields. Protocol specifications tend to offer recommendations about what identifiers to use and the deployment situation is fragmented.

The subject field MAY include a unique device serial number. If the serial number is included, it MUST be encoded in the X520SerialNumber attribute. e.g., [RFC8995] use requires a serial number in IDevID certificates.

[RFC5280] defines: "The subject alternative name extension allows identities to be bound to the subject of the certificate. These identities may be included in addition to or in place of the identity in the subject field of the certificate."

The subject alternative name extension MAY be set. If it is set, it MUST NOT be marked critical, except when the subject DN contains an empty sequence.

If the EUI-64 format is used to identify the subject of an end entity certificate, it MUST be encoded as a Subject DN using the X520SerialNumber attribute. The contents of the field is a string of the form HH-HH-HH-HH-HH-HH-HH where 'H' is one of the symbols '0'-'9' or 'A'-'F'.

Per [RFC9525] domain names MUST NOT be encoded in the subject commonName. Instead they MUST be encoded in a subjectAltName of type DNS-ID. Domain names MUST NOT contain wildcard (\*) characters. The subjectAltName MUST NOT contain multiple names.

Note: The IEEE 802.1AR recommends to encode information about a Trusted Platform Module (TPM), if present, in the HardwareModuleName. This specification does not follow this recommendation.

Where IoT devices are accepting (D)TLS connections, i.e., they are acting as a server, it is unlikely that there will be a useful name that can go into the SNI. In general, the use of SNI for the purpose of virtual hosting on constrained IoT devices is rare. The IoT device cannot depend on a client providing a correct SNI, and so it MUST ignore the extension. This implies that IoT devices cannot do name-based virtual hosting of TLS connections. In the unlikely event that an IoT device has multiple servers responding with different server certificate, then the server SHOULD use different IP addresses or port numbers.

#### 17.4.2. Authority Key Identifier

The Authority Key Identifier extension MUST be set, MUST NOT be marked critical, and MUST contain the subjectKeyIdentifier of the CA that issued this certificate.

#### 17.4.3. Subject Key Identifier

The Subject Key Identifier MUST NOT be included in end entity certificates, as it can be calculated from the public key, so it just takes up space. End entity certificates are not used in path construction, so there is no ambiguity regarding which certificate chain to use, as there can be with subordinate CAs.

#### 17.4.4. Key Usage

The key usage extension MUST be set and MUST be marked as critical. For signature verification keys the digitalSignature key usage purpose MUST be specified. Other key usages are set according to the intended usage of the key.

If enrollment of new certificates uses server-side key generation, encrypted delivery of the private key is required. In such cases the key usage keyEncipherment or keyAgreement MUST be set because the encrypted delivery of the newly generated key involves encryption or agreement of a symmetric key. On-device key generation is, however, the preferred approach.

In IDevID certificates, the extendedKeyUsage SHOULD NOT be present, as it reduces the utility of the IDevID. In locally assigned LDevID certificates, the extendedKeyUsage, if present, MUST contain at least one of id-kp-serverAuth or id-kp-clientAuth in order to be useable with TLS.

### 18. Certificate Overhead

In a public key-based key exchange, certificates and public keys are a major contributor to the size of the overall handshake. For example, in a regular TLS 1.3 handshake with minimal ECC certificates and no subordinate CA utilizing the secp256r1 curve with mutual authentication, around 40% of the entire handshake payload is consumed by the two exchanged certificates.

Hence, it is not surprising that there is a strong desire to reduce the size of certificates and certificate chains. This has led to various standardization efforts. Below is a brief summary of what options an implementer has to reduce the bandwidth requirements of a public key-based key exchange. Note that many of the standardized extensions are not readily available in TLS/DTLS stacks since optimizations typically get implemented last.

- \* Use elliptic curve cryptography (ECC) instead of RSA-based certificate due to the smaller certificate size. This document recommends the use of elliptic curve cryptography only.
- \* Avoid deep and complex CA hierarchies to reduce the number of subordinate CA certificates that need to be transmitted and processed. See [I-D.irtf-t2trg-taxonomy-manufacturer-anchors] for a discussion about CA hierarchies. Most security requirements can be satisfied with a PKI depth of 3 (root CA, one subordinate CA, and end entity certificates).
- \* Pay attention to the amount of information conveyed inside certificates.
- \* Use session resumption to reduce the number of times a full handshake is needed. Use Connection IDs [RFC9146], when possible, to enable long-lasting connections.
- \* Use the TLS cached info [RFC7924] extension to avoid sending certificates with every full handshake.
- \* Use client certificate URLs [RFC6066] instead of full certificates for clients. When applications perform TLS client authentication via DNS-Based Authentication of Named Entities (DANE) TLSA records then the [I-D.ietf-dance-tls-clientid] specification may be used to reduce the packets on the wire. Note: The term "TLSA" does not stand for anything; it is just the name of the RRtype, as explained in [RFC6698].
- \* Use certificate compression as defined in [RFC8879].
- \* Use alternative certificate formats, where possible, such as raw public keys [RFC7250] or CBOR-encoded certificates [I-D.ietf-cose-cbor-encoded-cert].

The use of certificate handles, as introduced in cTLS [I-D.ietf-tls-ctls], is a form of caching or compressing certificates as well.

Whether to utilize any of the above extensions or a combination of them depends on the anticipated deployment environment, the availability of code, and the constraints imposed by already deployed infrastructure (e.g., CA infrastructure, tool support).

## 19. Ciphersuites

According to Section 4.5.3 of [DTLS13], the use of AES-CCM with 8-octet authentication tags (CCM\_8) is considered unsuitable for general use with DTLS. This is because it has low integrity limits (i.e., high sensitivity to forgeries) which makes endpoints that negotiate ciphersuites based on such AEAD vulnerable to a trivial DoS attack. See also Sections 5.3 and 5.4 of [I-D.irtf-cfrg-aead-limits] for further discussion on this topic, as well as references to the analysis supporting these conclusions.

Specifically, [DTLS13] warns that:

```
> TLS_AES_128_CCM_8_SHA256 MUST NOT be used in DTLS without additional
> safeguards against forgery. Implementations MUST set usage limits for
> AEAD_AES_128_CCM_8 based on an understanding of any additional forgery
> protections that are used.
```

Since all the ciphersuites required by [RFC7925] and [CoAP] rely on CCM\_8, there is no alternate ciphersuite available for applications that aim to eliminate the security and availability threats related to CCM\_8 while retaining interoperability with the larger ecosystem.

In order to ameliorate the situation, it is RECOMMENDED that implementations support the following two ciphersuites for TLS 1.3:

```
* TLS_AES_128_GCM_SHA256
* TLS_AES_128_CCM
```

and offer them as their first choice. These ciphersuites provide confidentiality and integrity limits that are considered acceptable in the most general settings. For the details on the exact bounds of both ciphersuites see Section 4.5.3 of [DTLS13]. Note that the GCM-based ciphersuite offers superior interoperability with cloud services at the cost of a slight increase in the wire and peak RAM footprints.

When the GCM-based ciphersuite is used with TLS 1.2, the recommendations in Section 7.2.1 of [RFC9325] related to deterministic nonce generation apply. In addition, the integrity limits on key usage detailed in Section 4.4 of [RFC9325] also apply.

Table 1 summarizes the recommendations regarding ciphersuites:

Ciphersuite	MTI Requirement
TLS_AES_128_CCM_8_SHA256	MUST-
TLS_AES_128_CCM	SHOULD+
TLS_AES_128_GCM_SHA256	SHOULD+

Table 1: TLS 1.3 Ciphersuite Requirements

## 20. Fault Attacks on Deterministic Signature Schemes

A number of passive side-channel attacks as well as active fault-injection attacks (e.g., [Ambrose2017]) have been demonstrated to be successful in allowing a malicious third party to gain information about the signing key if a fully deterministic signature scheme (e.g., ECDSA [RFC6979] or EdDSA [RFC8032]) is used.

Most of these attacks assume physical access to the device and are therefore especially relevant to smart cards as well as IoT deployments with poor or non-existent physical security.

In this security model, it is recommended to combine both randomness and determinism, for example, as described in [I-D.irtf-cfrg-det-sigs-with-noise].

## 21. Post-Quantum Cryptography (PQC) Considerations

As detailed in [I-D.ietf-pquip-pqc-engineers], the IETF is actively working to address the challenges of adopting PQC in various protocols, including TLS. The document highlights key aspects engineers must consider, such as algorithm selection, performance impacts, and deployment strategies. It emphasizes the importance of gradual integration of PQC to ensure secure communication while accounting for the increased computational, memory, and bandwidth requirements of PQC algorithms. These challenges are especially relevant in the context of IoT, where device constraints limit the adoption of larger key sizes and more complex cryptographic operations [PQC-PERF]. Besides, any choice need to carefully evaluate the associated energy requirements [PQC-ENERGY].

Incorporating PQC into TLS is still ongoing, with key exchange message sizes increasing due to larger public keys. These larger keys demand more flash storage and higher RAM usage, presenting significant obstacles for resource-constrained IoT devices. The transition from classical cryptographic algorithms to PQC will be a

significant challenge for constrained IoT devices, requiring careful planning to select hardware suitable for the task considering the lifetime of an IoT product.

## 22. Open Issues

A list of open issues can be found at <https://github.com/thomas-fossati/draft-tls13-iot/issues>

## 23. Security Considerations

This entire document is about security.

## 24. IANA Considerations

This document makes no requests to IANA.

## 25. References

### 25.1. Normative References

- [DTLS13] Rescorla, E., Tschofenig, H., and N. Modadugu, "The Datagram Transport Layer Security (DTLS) Protocol Version 1.3", RFC 9147, DOI 10.17487/RFC9147, April 2022, <<https://www.rfc-editor.org/rfc/rfc9147>>.
- [I-D.ietf-tls-dtls-rrc] Tschofenig, H., Kraus, A., and T. Fossati, "Return Routability Check for DTLS 1.2 and DTLS 1.3", Work in Progress, Internet-Draft, draft-ietf-tls-dtls-rrc-13, 25 March 2025, <<https://datatracker.ietf.org/doc/html/draft-ietf-tls-dtls-rrc-13>>.
- [RFC2119] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", BCP 14, RFC 2119, DOI 10.17487/RFC2119, March 1997, <<https://www.rfc-editor.org/rfc/rfc2119>>.
- [RFC5280] Cooper, D., Santesson, S., Farrell, S., Boeyen, S., Housley, R., and W. Polk, "Internet X.509 Public Key Infrastructure Certificate and Certificate Revocation List (CRL) Profile", RFC 5280, DOI 10.17487/RFC5280, May 2008, <<https://www.rfc-editor.org/rfc/rfc5280>>.
- [RFC5480] Turner, S., Brown, D., Yiu, K., Housley, R., and T. Polk, "Elliptic Curve Cryptography Subject Public Key Information", RFC 5480, DOI 10.17487/RFC5480, March 2009, <<https://www.rfc-editor.org/rfc/rfc5480>>.

- [RFC5758] Dang, Q., Santesson, S., Moriarty, K., Brown, D., and T. Polk, "Internet X.509 Public Key Infrastructure: Additional Algorithms and Identifiers for DSA and ECDSA", RFC 5758, DOI 10.17487/RFC5758, January 2010, <<https://www.rfc-editor.org/rfc/rfc5758>>.
- [RFC7925] Tschofenig, H., Ed. and T. Fossati, "Transport Layer Security (TLS) / Datagram Transport Layer Security (DTLS) Profiles for the Internet of Things", RFC 7925, DOI 10.17487/RFC7925, July 2016, <<https://www.rfc-editor.org/rfc/rfc7925>>.
- [RFC8174] Leiba, B., "Ambiguity of Uppercase vs Lowercase in RFC 2119 Key Words", BCP 14, RFC 8174, DOI 10.17487/RFC8174, May 2017, <<https://www.rfc-editor.org/rfc/rfc8174>>.
- [RFC8221] Wouters, P., Migault, D., Mattsson, J., Nir, Y., and T. Kivinen, "Cryptographic Algorithm Implementation Requirements and Usage Guidance for Encapsulating Security Payload (ESP) and Authentication Header (AH)", RFC 8221, DOI 10.17487/RFC8221, October 2017, <<https://www.rfc-editor.org/rfc/rfc8221>>.
- [RFC8446] Rescorla, E., "The Transport Layer Security (TLS) Protocol Version 1.3", RFC 8446, DOI 10.17487/RFC8446, August 2018, <<https://www.rfc-editor.org/rfc/rfc8446>>.
- [RFC8449] Thomson, M., "Record Size Limit Extension for TLS", RFC 8449, DOI 10.17487/RFC8449, August 2018, <<https://www.rfc-editor.org/rfc/rfc8449>>.
- [RFC9258] Benjamin, D. and C. A. Wood, "Importing External Pre-Shared Keys (PSKs) for TLS 1.3", RFC 9258, DOI 10.17487/RFC9258, July 2022, <<https://www.rfc-editor.org/rfc/rfc9258>>.
- [RFC9325] Sheffer, Y., Saint-Andre, P., and T. Fossati, "Recommendations for Secure Use of Transport Layer Security (TLS) and Datagram Transport Layer Security (DTLS)", BCP 195, RFC 9325, DOI 10.17487/RFC9325, November 2022, <<https://www.rfc-editor.org/rfc/rfc9325>>.
- [RFC9525] Saint-Andre, P. and R. Salz, "Service Identity in TLS", RFC 9525, DOI 10.17487/RFC9525, November 2023, <<https://www.rfc-editor.org/rfc/rfc9525>>.

- [TLS13] Rescorla, E., "The Transport Layer Security (TLS) Protocol Version 1.3", RFC 8446, DOI 10.17487/RFC8446, August 2018, <<https://www.rfc-editor.org/rfc/rfc8446>>.

## 25.2. Informative References

- [ADD] IETF, "Adaptive DNS Discovery (add) Working Group", September 2023, <<https://datatracker.ietf.org/wg/add/about/>>.
- [Ambrose2017] Ambrose, C., Bos, J. W., Fay, B., Joye, M., Lochter, M., and B. Murray, "Differential Attacks on Deterministic Signatures", 2017, <<https://eprint.iacr.org/2017/975.pdf>>.
- [CoAP] Shelby, Z., Hartke, K., and C. Bormann, "The Constrained Application Protocol (CoAP)", RFC 7252, DOI 10.17487/RFC7252, June 2014, <<https://www.rfc-editor.org/rfc/rfc7252>>.
- [FIDO] FIDO Alliance, "FIDO Device Onboard Specification 1.1", April 2022, <<https://fidoalliance.org/specifications/download-iot-specifications/>>.
- [I-D.ietf-anima-constrained-voucher] Richardson, M., Van der Stok, P., Kampanakis, P., and E. Dijk, "Constrained Bootstrapping Remote Secure Key Infrastructure (cBRSKI)", Work in Progress, Internet-Draft, draft-ietf-anima-constrained-voucher-27, 3 March 2025, <<https://datatracker.ietf.org/doc/html/draft-ietf-anima-constrained-voucher-27>>.
- [I-D.ietf-cose-cbor-encoded-cert] Mattsson, J. P., Selander, G., Raza, S., H. H. glund, J., and M. Furuheid, "CBOR Encoded X.509 Certificates (C509 Certificates)", Work in Progress, Internet-Draft, draft-ietf-cose-cbor-encoded-cert-13, 3 March 2025, <<https://datatracker.ietf.org/doc/html/draft-ietf-cose-cbor-encoded-cert-13>>.
- [I-D.ietf-dance-tls-clientid] Huque, S. and V. Dukhovni, "TLS Extension for DANE Client Identity", Work in Progress, Internet-Draft, draft-ietf-dance-tls-clientid-05, 4 May 2025, <<https://datatracker.ietf.org/doc/html/draft-ietf-dance-tls-clientid-05>>.

[I-D.ietf-httpbis-secondary-server-certs]

Gorbaty, E. and M. Bishop, "Secondary Certificate Authentication of HTTP Servers", Work in Progress, Internet-Draft, draft-ietf-httpbis-secondary-server-certs-01, 12 October 2024, <<https://datatracker.ietf.org/doc/html/draft-ietf-httpbis-secondary-server-certs-01>>.

[I-D.ietf-iotops-7228bis]

Bormann, C., Ersue, M., Keränen, A., and C. Gomez, "Terminology for Constrained-Node Networks", Work in Progress, Internet-Draft, draft-ietf-iotops-7228bis-01, 8 January 2025, <<https://datatracker.ietf.org/doc/html/draft-ietf-iotops-7228bis-01>>.

[I-D.ietf-pquip-pqc-engineers]

Banerjee, A., Reddy, K. T., Schoenianakis, D., Hollebeek, T., and M. Ounsworth, "Post-Quantum Cryptography for Engineers", Work in Progress, Internet-Draft, draft-ietf-pquip-pqc-engineers-10, 1 May 2025, <<https://datatracker.ietf.org/doc/html/draft-ietf-pquip-pqc-engineers-10>>.

[I-D.ietf-tls-ctls]

Rescorla, E., Barnes, R., Tschofenig, H., and B. M. Schwartz, "Compact TLS 1.3", Work in Progress, Internet-Draft, draft-ietf-tls-ctls-10, 17 April 2024, <<https://datatracker.ietf.org/doc/html/draft-ietf-tls-ctls-10>>.

[I-D.ietf-tls-esni]

Rescorla, E., Oku, K., Sullivan, N., and C. A. Wood, "TLS Encrypted Client Hello", Work in Progress, Internet-Draft, draft-ietf-tls-esni-24, 20 March 2025, <<https://datatracker.ietf.org/doc/html/draft-ietf-tls-esni-24>>.

[I-D.irtf-cfrg-aead-limits]

Günther, F., Thomson, M., and C. A. Wood, "Usage Limits on AEAD Algorithms", Work in Progress, Internet-Draft, draft-irtf-cfrg-aead-limits-10, 8 April 2025, <<https://datatracker.ietf.org/doc/html/draft-irtf-cfrg-aead-limits-10>>.

- [I-D.irtf-cfrg-det-sigs-with-noise]  
Mattsson, J. P., Thormarker, E., and S. Ruohomaa, "Hedged ECDSA and EdDSA Signatures", Work in Progress, Internet-Draft, draft-irtf-cfrg-det-sigs-with-noise-05, 3 March 2025, <<https://datatracker.ietf.org/doc/html/draft-irtf-cfrg-det-sigs-with-noise-05>>.
- [I-D.irtf-t2trg-taxonomy-manufacturer-anchors]  
Richardson, M., "A Taxonomy of operational security considerations for manufacturer installed keys and Trust Anchors", Work in Progress, Internet-Draft, draft-irtf-t2trg-taxonomy-manufacturer-anchors-07, 29 March 2025, <<https://datatracker.ietf.org/doc/html/draft-irtf-t2trg-taxonomy-manufacturer-anchors-07>>.
- [LwM2M]  
OMA SpecWorks, "Lightweight Machine to Machine (LwM2M) V.1.2.1 Technical Specification: Transport Bindings", December 2022, <[https://openmobilealliance.org/release/LightweightM2M/V1\\_2\\_1-20221209-A/](https://openmobilealliance.org/release/LightweightM2M/V1_2_1-20221209-A/)>.
- [PQC-ENERGY]  
Tasopoulos, G., Dimopoulos, C., Fournaris, A., Zhao, R., Sakzad, A., and R. Steinfeld, "Energy Consumption Evaluation of Post-Quantum TLS 1.3 for Resource-Constrained Embedded Devices", ACM, Proceedings of the 20th ACM International Conference on Computing Frontiers pp. 366-374, DOI 10.1145/3587135.3592821, May 2023, <<https://doi.org/10.1145/3587135.3592821>>.
- [PQC-PERF]  
Tasopoulos, G., Li, J., Fournaris, A., Zhao, R., Sakzad, A., and R. Steinfeld, "Performance Evaluation of Post-Quantum TLS 1.3 on Resource-Constrained Embedded Systems", Springer International Publishing, Lecture Notes in Computer Science pp. 432-451, DOI 10.1007/978-3-031-21280-2\_24, ISBN ["9783031212796", "9783031212802"], 2022, <[https://doi.org/10.1007/978-3-031-21280-2\\_24](https://doi.org/10.1007/978-3-031-21280-2_24)>.
- [RFC4279]  
Eronen, P., Ed. and H. Tschofenig, Ed., "Pre-Shared Key Ciphersuites for Transport Layer Security (TLS)", RFC 4279, DOI 10.17487/RFC4279, December 2005, <<https://www.rfc-editor.org/rfc/rfc4279>>.
- [RFC5216]  
Simon, D., Aboba, B., and R. Hurst, "The EAP-TLS Authentication Protocol", RFC 5216, DOI 10.17487/RFC5216, March 2008, <<https://www.rfc-editor.org/rfc/rfc5216>>.

- [RFC5746] Rescorla, E., Ray, M., Dispensa, S., and N. Oskov, "Transport Layer Security (TLS) Renegotiation Indication Extension", RFC 5746, DOI 10.17487/RFC5746, February 2010, <<https://www.rfc-editor.org/rfc/rfc5746>>.
- [RFC6066] Eastlake 3rd, D., "Transport Layer Security (TLS) Extensions: Extension Definitions", RFC 6066, DOI 10.17487/RFC6066, January 2011, <<https://www.rfc-editor.org/rfc/rfc6066>>.
- [RFC6698] Hoffman, P. and J. Schlyter, "The DNS-Based Authentication of Named Entities (DANE) Transport Layer Security (TLS) Protocol: TLSA", RFC 6698, DOI 10.17487/RFC6698, August 2012, <<https://www.rfc-editor.org/rfc/rfc6698>>.
- [RFC6979] Pornin, T., "Deterministic Usage of the Digital Signature Algorithm (DSA) and Elliptic Curve Digital Signature Algorithm (ECDSA)", RFC 6979, DOI 10.17487/RFC6979, August 2013, <<https://www.rfc-editor.org/rfc/rfc6979>>.
- [RFC7030] Pritikin, M., Ed., Yee, P., Ed., and D. Harkins, Ed., "Enrollment over Secure Transport", RFC 7030, DOI 10.17487/RFC7030, October 2013, <<https://www.rfc-editor.org/rfc/rfc7030>>.
- [RFC7228] Bormann, C., Ersue, M., and A. Keranen, "Terminology for Constrained-Node Networks", RFC 7228, DOI 10.17487/RFC7228, May 2014, <<https://www.rfc-editor.org/rfc/rfc7228>>.
- [RFC7250] Wouters, P., Ed., Tschofenig, H., Ed., Gilmore, J., Weiler, S., and T. Kivinen, "Using Raw Public Keys in Transport Layer Security (TLS) and Datagram Transport Layer Security (DTLS)", RFC 7250, DOI 10.17487/RFC7250, June 2014, <<https://www.rfc-editor.org/rfc/rfc7250>>.
- [RFC7858] Hu, Z., Zhu, L., Heidemann, J., Mankin, A., Wessels, D., and P. Hoffman, "Specification for DNS over Transport Layer Security (TLS)", RFC 7858, DOI 10.17487/RFC7858, May 2016, <<https://www.rfc-editor.org/rfc/rfc7858>>.
- [RFC7924] Santesson, S. and H. Tschofenig, "Transport Layer Security (TLS) Cached Information Extension", RFC 7924, DOI 10.17487/RFC7924, July 2016, <<https://www.rfc-editor.org/rfc/rfc7924>>.

- [RFC8032] Josefsson, S. and I. Liusvaara, "Edwards-Curve Digital Signature Algorithm (EdDSA)", RFC 8032, DOI 10.17487/RFC8032, January 2017, <<https://www.rfc-editor.org/rfc/rfc8032>>.
- [RFC8094] Reddy, T., Wing, D., and P. Patil, "DNS over Datagram Transport Layer Security (DTLS)", RFC 8094, DOI 10.17487/RFC8094, February 2017, <<https://www.rfc-editor.org/rfc/rfc8094>>.
- [RFC8484] Hoffman, P. and P. McManus, "DNS Queries over HTTPS (DoH)", RFC 8484, DOI 10.17487/RFC8484, October 2018, <<https://www.rfc-editor.org/rfc/rfc8484>>.
- [RFC8879] Ghedini, A. and V. Vasiliev, "TLS Certificate Compression", RFC 8879, DOI 10.17487/RFC8879, December 2020, <<https://www.rfc-editor.org/rfc/rfc8879>>.
- [RFC8995] Pritikin, M., Richardson, M., Eckert, T., Behringer, M., and K. Watsen, "Bootstrapping Remote Secure Key Infrastructure (BRSKI)", RFC 8995, DOI 10.17487/RFC8995, May 2021, <<https://www.rfc-editor.org/rfc/rfc8995>>.
- [RFC9019] Moran, B., Tschofenig, H., Brown, D., and M. Meriac, "A Firmware Update Architecture for Internet of Things", RFC 9019, DOI 10.17487/RFC9019, April 2021, <<https://www.rfc-editor.org/rfc/rfc9019>>.
- [RFC9146] Rescorla, E., Ed., Tschofenig, H., Ed., Fossati, T., and A. Kraus, "Connection Identifier for DTLS 1.2", RFC 9146, DOI 10.17487/RFC9146, March 2022, <<https://www.rfc-editor.org/rfc/rfc9146>>.
- [RFC9150] Cam-Winget, N. and J. Visoky, "TLS 1.3 Authentication and Integrity-Only Cipher Suites", RFC 9150, DOI 10.17487/RFC9150, April 2022, <<https://www.rfc-editor.org/rfc/rfc9150>>.
- [RFC9180] Barnes, R., Bhargavan, K., Lipp, B., and C. Wood, "Hybrid Public Key Encryption", RFC 9180, DOI 10.17487/RFC9180, February 2022, <<https://www.rfc-editor.org/rfc/rfc9180>>.
- [RFC9190] Preu Mattsson, J. and M. Sethi, "EAP-TLS 1.3: Using the Extensible Authentication Protocol with TLS 1.3", RFC 9190, DOI 10.17487/RFC9190, February 2022, <<https://www.rfc-editor.org/rfc/rfc9190>>.

- [RFC9261] Sullivan, N., "Exported Authenticators in TLS", RFC 9261, DOI 10.17487/RFC9261, July 2022, <<https://www.rfc-editor.org/rfc/rfc9261>>.
- [RFC9483] Brockhaus, H., von Oheimb, D., and S. Fries, "Lightweight Certificate Management Protocol (CMP) Profile", RFC 9483, DOI 10.17487/RFC9483, November 2023, <<https://www.rfc-editor.org/rfc/rfc9483>>.
- [\_8021AR] IEEE, "IEEE Standard for Local and metropolitan area networks Secure Device Identity, IEEE 802.1AR-2018", August 2018, <<https://1.ieee802.org/security/802-lar>>.

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