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Application-Layer TLS
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Abstract

Many clients need to establish secure connections to application services but face challenges establishing these connections due to the presence of middleboxes that terminate TLS connections from the client and reestablish new TLS connections to the service. This document defines a mechanism for transporting TLS records in HTTP message bodies between clients and services. This enables clients and services to establish secure connections using TLS at the application layer, and treat any middleboxes that are intercepting traffic at the network layer as untrusted transport. In short, this mechanism moves the TLS handshake up the OSI stack to the application layer.

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1. Introduction

There are far more classes of clients being deployed on today's networks than at any time previously. This poses challenges for network administrators who need to manage their network and the clients connecting to their network, and poses challenges for client vendors and client software developers who must ensure that their clients can connect to all required services.

One common example is where a client is deployed on a local domain network that protects its perimeter using a TLS terminating middlebox, and the client needs to establish a secure connection to a service in a different network via the middlebox. Traditionally, this has been enabled by the network administrator deploying the necessary certificate authority trusted roots on the client. This can be achieved at scale using standard tools that enable the administrator to automatically push trusted roots out to all client machines in the network from a centralised domain controller. This works for personal computers, laptops and servers running standard Operating Systems that can be centrally managed. This client management process breaks for multiple classes of clients that are being deployed today, there is no standard mechanism for configuring trusted roots on these clients, and there is no standard mechanism for these clients to securely traverse middleboxes.

The TLS over HTTP mechanism defined in this document enables clients to traverse middleboxes that restrict communications to HTTP traffic they have inserted themselves into, and establish secure connections to services across network domain boundaries.

2. Terminology

TLS over HTTP is referred to as ATLS throughout this document i.e. "Application Layer TLS".

3. ATLS Transport Goals

The high level goals driving the design of this mechanism are:

- o reuse existing TLS specifications [RFC5246] [I-D.ietf-tls-tls13] as is without requiring any protocol changes
- o work with all versions of TLS
- o do not require any changes to current TLS software stacks
- o do not mandate constraints on how the TLS stack is configured or used

- o be forward compatible with future TLS versions
- o work with both HTTP and HTTPS transport
- o avoid introducing TLS protocol handling logic or semantics into the HTTP application layer i.e. TLS protocol knowledge and logic is handled by the TLS stack, HTTP is just a dumb transport
- o ensure the client and server software implementations are as simple as possible

4. Architecture Overview

4.1. Network Architecture

A typical network deployment is illustrated in Figure 1. It shows a client connecting to a service via a middlebox. It also shows a TLS terminator deployed in front of the service. The client establishes a transport layer TLS connection with the middlebox (C->M TLS), the middlebox in turn opens a transport layer TLS connection with the TLS terminator deployed in front of the service (M->T TLS). The client can ignore any certificate validation errors when it connects to the middlebox. HTTP messages are transported over this layer between the client and the service. Finally, application layer TLS messages are exchanged inside the HTTP message bodies in order to establish an end-to-end TLS session between the client and the service (C->S TLS).

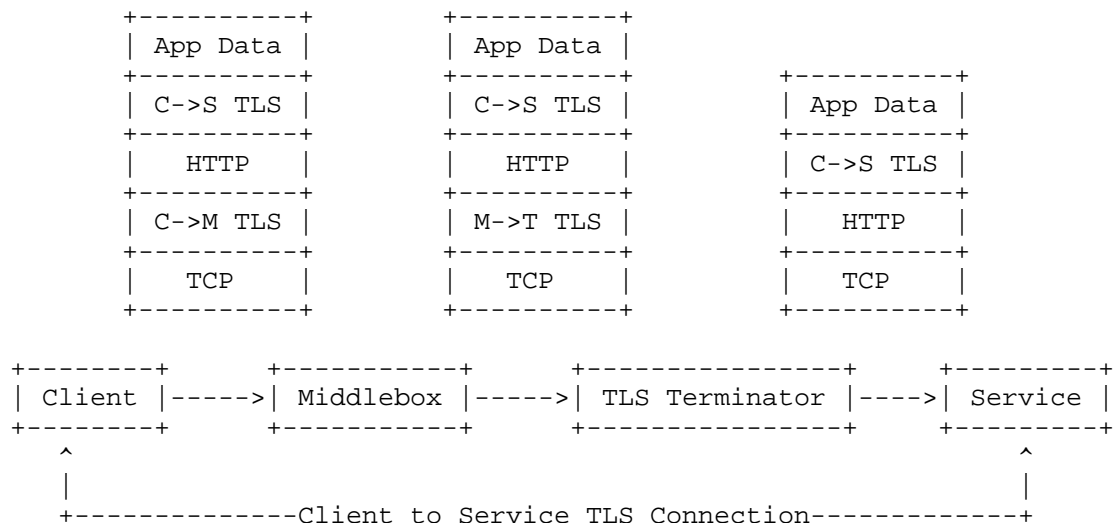


Figure 1: Network Architecture

4.2. Application Architecture

TLS software stacks allow application developers to 'unplug' the default network socket transport layer and read and write TLS records directly from byte buffers. This enables application developers to create application layer TLS sessions, extract the raw TLS record bytes from the bottom of the TLS stack, and transport these bytes over any suitable transport. The TLS software stacks can generate byte streams of full TLS flights which may include multiple TLS records. This is illustrated in Figure 2 below.

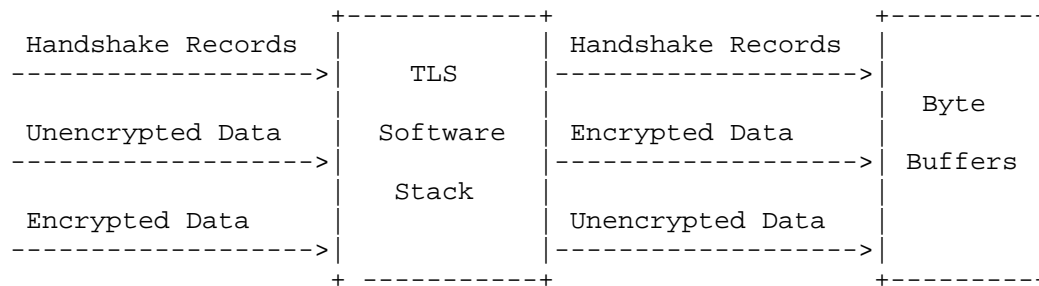


Figure 2: TLS Stack Interfaces

These TLS software stack APIs enable application developers to build the software architecture illustrated in Figure 3. The application creates and interacts with an application layer TLS session in order to generate and consume raw TLS records. The application transports these raw TLS records inside HTTP message bodies using a standard HTTP stack. The HTTP stack may in turn use either TLS or TCP transport to communicate with the peer. The application layer TLS session and network layer TLS session can both leverage a shared, common TLS software stack. This high level architecture is applicable to both clients and services.

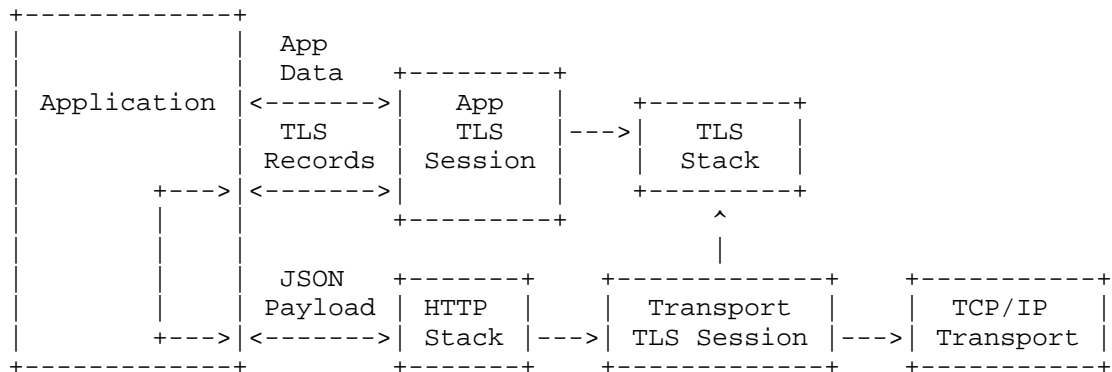


Figure 3: Application Architecture

4.3. Application Architecture Benefits

There are several benefits to using a standard TLS software stack to establish an application layer secure communications channel between a client and a service. These include:

- o no need to define a new cryptographic negotiation and exchange protocol between client and service
- o automatically benefit from new cipher suites by simply upgrading the TLS software stack
- o automatically benefit from new features, bugfixes, etc. in TLS software stack upgrades

4.4. Implementation

Pseudo code illustrating how to read and write TLS records directly from byte buffers using both OpenSSL and Java JSSE is given in the appendices.

5. ATLS Overview

The assumption is that the client will establish a transport layer connection to the server for exchange of HTTP messages. The underlying transport layer connection could be over TCP or TLS. The client will then establish an application layer TLS connection with the server by exchanging TLS records with the server inside HTTP message requests and responses.

5.1. TLS Connections

If the underlying transport layer connection is TLS, this means that the client will establish two independent TLS connections:

- o one at the transport layer which could be directly with the service or could be with a middlebox
- o one at the application layer which will be with the service

As an optimisation, clients may choose to only use ATLS as a fallback mechanism if certificate validation fails on the transport layer TLS connection to the service. For the purposes of establishing a secure connection with the service, the client does not need to perform any certificate checks or validation on the transport layer TLS connection.

Similarly, the service may also establish two independent TLS connections:

- o one at the transport layer which could be directly with the client or could be with a middlebox
- o one at the application layer which will be with the client

Once the application layer TLS connection is established, the client may report to the service the TLS certificates that were presented by the network layer TLS connection but this is application specific behaviour and outside the scope of this specification.

5.2. Protocol Introduction

All application TLS records are transported as base64 encoded payloads inside JSON message bodies over HTTP transport. Each payload contains a full TLS flight made up of one or more TLS records.

The client sends all application TLS records to the server in JSON message bodies in POST requests.

The server sends all TLS records to the client in JSON message bodies in 200 OK responses to the POST requests.

No constraints are placed on the ContentType contained within the transported TLS records. The TLS records may contain handshake, application_data, alert or change_cipher_spec messages. If new ContentType messages are defined in future TLS versions, these may also be transported using this protocol.

If the server is able to handle the application layer TLS records included in the request, the server always responds with a 200 OK and includes any application TLS records in the message body. The server does not, for example, parse the TLS records generated by its TLS software stack for an AlertDescription and attempt to map this to a suitable HTTP error response code.

The server only responds with a non-200 OK message if a server error occurs and it is not capable of handling the application layer TLS message received from the client.

5.3. TLS Session Tracking

The service needs to track multiple client application layer TLS sessions so that it can collerate TLS records received in HTTP message bodies with the appropriate TLS session. It does this by inclusion of an explicit session identifier in the JSON message body.

5.4. Upgrade to Websocket

The HTTP connection between the client and the service may be upgraded to a websocket if required. This would allow a server to send a TLS close request, or any application data, asynchronously to the client. Note that for the majority of use cases, there will be no need to open a websocket between the client and service.

5.5. Service Container Affinity

Application services are typically distributed across multiple containers and virtual machines. As TLS is stateful, it must be ensured that sequences of TLS messages are handled appropriately by the service deployment and the service execution engine has access to all necessary state information. This is explicitly outside the scope of this specification as there are multiple well defined mechanisms for enabling this.

5.6. Keying Material Exporting

This specification does not require, or preclude, the use of [RFC5705]. When the client and service applications detect that the ATLS session is established, the application may use the key exporter functions of the TLS stack to derive shared keys between client and service. The client and service may then use these shared keys to establish an independent cryptographic context and exchange data using any suitable mechanism such as JSON Web Encryption [RFC7516] or Encrypted Content-Encoding for HTTP [RFC8188].

6. Protocol Details

6.1. Message Body

All message bodies are JSON bodies containing one or two parameters:

```
{
  "session": "<session-string>",
  "records": "<base64 encoded TLS records>"
}
```

The following two parameters are defined:

session: This is set by the service and is used to correlate requests across multiple client sessions. This parameter is included in all messages apart from the first first message sent from the client to the service. When a client sends the first request to establish an ATLS session with a service, it **MUST** omit this parameter. When a service handles the first request from a client (and that request will include the ClientHello), and the service creates an internal TLS session object, it **MUST** return a server-generated "<session-string>" to the client. The client **MUST** include that "<session-string>" in all subsequent messages to the server. If the service is unable to find a TLS session that correlates with the "<session-string>" that a client specifies, the server **MUST** return 422 Unprocessable Entity.

records: This parameter is used to transport the base64 encoded TLS records that the client and service applications retrieve from their TLS stack. This parameter is sent in all requests from the client to the service. This parameter may not necessarily be sent in all response messages from the service to the client if the service has no TLS records to send. This can happen with a TLS1.3 handshake.

6.2. HTTP Content-Type

A new HTTP Content-Type is defined:

Content-Type: application/atls+json

6.3. Client Requests

When a client has base64 encoded TLS records to send to a service, it will include the previously received "<session-string>" in the request, or else omit this field for the very first handshake message, and send the following request to the service:

```
POST /atls
Content-Type: application/atls+json

{
  "session": "<session-string>",
  "records": "<base64 encoded TLS records>"
}
```

6.4. Server Responses

When a service has processed the TLS records received from a client and has generated TLS records to reply with, it will send the following reply to the client:

```
200 OK
Content-Type: application/atls+json

{
  "session": "<session-string>",
  "records": "<base64 encoded TLS records>"
}
```

The server MUST respond with one of the following status codes:

200 OK: The server was able to successfully parse the request and process the TLS records using its TLS software stack.

400 Bad Request: The client's request did not contain a JSON object of the form specified above.

422 Unprocessable Entity: The client presented a "<session-string>" that the service is unable to correlate that to an existing TLS session.

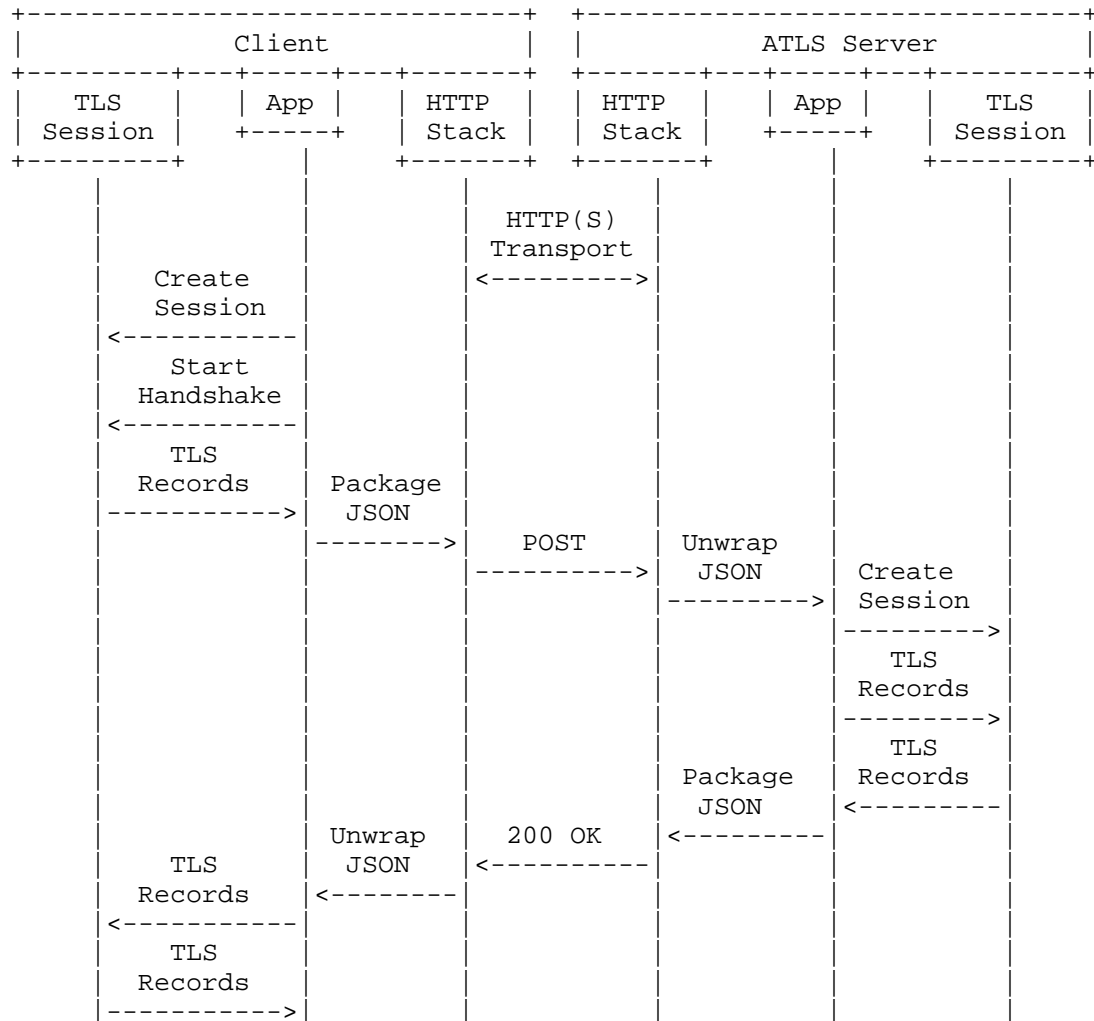
Note that a status code of 200 OK does not indicate that the TLS connection being negotiated is error-free. Alerts produced by TLS will be returned in the encoded TLS records. A 200 OK response simply indicates that the client should provide the records encoded in the response to its TLS stack.

7. ATLS Session Establishment

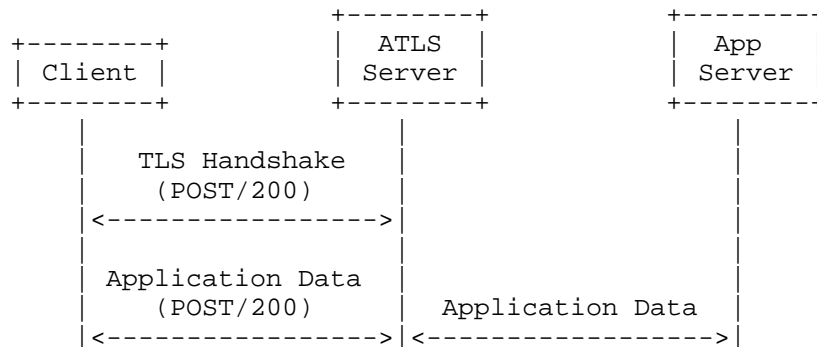
This section describes a typical ATLS session establishment flow.

7.1. ATLS Handshake Message Sequence Flow

The following flow chart shows an illustrative message sequence flow for the first TLS handshake flight between a client and a service.



This process repeats until the handshake completes. Once the application-layer TLS connection is ready to carry application data, the ATLS server relays it to the application server that is ultimately serving the request. That is, a given ATLS server is assumed to be connected to a single application endpoint.



7.2. Detailed ATLS Handshake

- o Client establishes transport layer connection with service

This transport layer session can be established over TCP or TLS. If over TLS, the client does not need to perform certificate validation on the TLS connection, and may ignore any certificate validation errors if it does perform certificate validation.

- o Client creates an application TLS session object

The client application creates a TLS session object that is not bound to any network socket. The client initiates a TLS handshake on the session. This will result in the TLS session generating the TLS record bytes for a full TLS handshake first flight. This will be a ClientHello message. Note that the client application does not explicitly know what the contents of the TLS record bytes are.

- o The client base64 encodes the TLS flight 1 records and sends them in a HTTP POST to the service

POST /atls

Content-Type: application/atls

```
{
  "records": "<base64 encoded flight 1>"
}
```

- o The service creates a TLS session for handling the request

The service notes that there is no "session" in the request and creates an application TLS session object and a suitable "<session-string>" for correlation. The service decodes the received base64 encoded "records" and passes them to the TLS session. The session handles the TLS handshake message and generates a full TLS handshake

response flight. Typically, this will be a ServerHello and additional handshake messages that are TLS version dependent. For TLS1.3, this may include a Finished message. Note that the service application does not explicitly know what the contents of the TLS record bytes are.

- o The service base64 encodes the TLS flight 1 response records and sends them in the response to the client

The service MUST include its generated "session".

200 OK

Content-Type: application/atls

```
{
  "session": "<session-string>",
  "records": "<base64 encoded flight 1 response>"
}
```

- o The client passes the service response to its TLS session

The client decodes the received base64 encoded "records" and passes them to the TLS session. The session handles the TLS handshake message and generates a full TLS handshake second flight. This will be a Finished message, Certificate and CertificateVerify messages if required, and additional handshake messages that are TLS version dependent.

- o The client base64 encodes the TLS flight 2 records and sends them in a HTTP POST to the service

The client MUST include the "<session-string>" it received from the service.

POST /atls

Content-Type: application/atls

```
{
  "session": "<session-string>",
  "records": "<base64 encoded flight 2>"
}
```

- o The service passes the client response to the respective TLS session

The service extracts the "<session-string>" from the request and finds the respective application TLS session object. The service decodes the received base64 encoded "records" and passes them to the

TLS session. The session handles the TLS handshake message and will generate a full TLS handshake response flight where appropriate. For TLS1.2, this will include a Finished and ChangeCipherSpec message. For TLS1.3, there are no TLS records generated.

- o The service base64 encodes the TLS flight 2 response records and sends them in the response to the client

For TLS 1.2:

200 OK

Content-Type: application/atls

```
{
  "session": "<session-string>",
  "records": "<base64 encoded flight 2 response>"
}
```

For TLS1.3:

200 OK

Content-Type: application/atls

```
{
  "session": "<session-string>"
}
```

- o The client passes the service response to its TLS session

If there are TLS records included in the response from the service, the client decodes the received base64 encoded "records" and passes them to its TLS session.

7.3. Application Data Exchange

Application data is exchanged between the client and service inside the TLS tunnel using exactly the same JSON transport payload. When the client has data to send to the service, it encrypts the data using the standard TLS stack methods (e.g. OpenSSL SSL_write() or Java SSLEngine.wrap()), extracts the encrypted TLS records from the bottom of the TLS stack, and sends them as in the JSON "records" parameter to the service. The service injects the TLS records into its stack and reads the decrypted data from the top of its stack.

8. RTT Considerations

The number of RTTs that take place when establishing a TLS session depends on the version of TLS and what capabilities are enabled on the TLS software stack. For example, a 0-RTT exchange is possible with TLS1.3.

If applications wish to ensure a predictable number of RTTs when establishing an application layer TLS connection, this may be achieved by configuring the TLS software stack appropriately. Relevant configuration parameters for OpenSSL and Java SunJSSE stacks are outlined in the appendix.

9. IANA Considerations

[[TODO - New Content-Type must be registered.]]

10. Security Considerations

[[TODO]]

11. Appendix A. TLS Software Stack Configuration

[[EDITOR'S NOTE: We could include details here on how TLS stack configuration items control the number of round trips between the client and server.

And just give two examples: OpenSSL and Java SunJSSE]]

12. Appendix B. Pseudo Code

This appendix gives both C and Java pseudo code illustrating how to inject and extract raw TLS records from a TLS software stack. Please note that this is illustrative, non-functional pseudo code that does not compile. Functioning proof-of-concept code is available on the following public repository [[EDITOR'S NOTE: Add the URL here]].

12.1. B.1 OpenSSL

OpenSSL provides a set of Basic Input/Output (BIO) APIs that can be used to build a custom transport layer for TLS connections. This appendix gives pseudo code on how BIO APIs could be used to build a client application that completes a TLS handshake and exchanges application data with a service.

```
char inbound[MAX];
char outbound[MAX];
int rx_bytes;
SSL_CTX *ctx = SSL_CTX_new();
SSL *ssl = SSL_new(ctx);

// Create in-memory BIOs and plug in to the SSL session
BOI* bio_in = BIO_new(BIO_s_mem());
BOI* bio_out = BIO_new(BIO_s_mem());
SSL_set_bio(ssl, bio_in, bio_out);

// We are a client
SSL_set_connect_state(ssl);

// Loop through TLS flights until we are done
do {
    // Calling SSL_do_handshake() will result in a full
    // TLS flight being written to the BIO buffer
    SSL_do_handshake(ssl);

    // Read the client flight that the TLS session
    // has written to memory
    BIO_read(bio_out, outbound, MAX);

    // POST the outbound bytes to the server using a suitable
    // function. Lets assume that the server response will be
    // written to the 'inbound' buffer
    num_bytes = postTlsRecords(outbound, inbound);

    // Write the server flight to the memory BIO so the TLS session
    // can read it. The next call to SSL_do_handshake() will handle
    // this received server flight
    BIO_write(bio_in, inbound, num_bytes);
} while (!SSL_is_init_finished(ssl));

// Send a message to the server. Calling SSL_write() will run the
// plaintext through the TLS session and write the encrypted TLS
// records to the BIO buffer
SSL_write(ssl, "Hello World", strlen("Hello World"));

// Read the TLS records from the BIO buffer and
// POST them to the server
BIO_read(bio_out, outbound, MAX);
num_bytes = postTlsRecords(outbound, inbound);
```


12.2. B.2 Java JSSE

The Java SSLEngine class "enables secure communications using protocols such as the Secure Sockets Layer (SSL) or IETF RFC 2246 "Transport Layer Security" (TLS) protocols, but is transport independent". This pseudo code illustrates how a server could use the SSLEngine class to handle an inbound client TLS flight and generate an outbound server TLS flight response.

```
SSLEngine sslEngine = SSLContext.getDefault().createSSLEngine();
sslEngine.setUseClientMode(false);
sslEngine.beginHandshake();

// Lets assume 'inbound' has been populated with
// the Client 1st Flight
ByteBuffer inbound;

// 'outbound' will be populated with the
// Server 1st Flight response
ByteBuffer outbound;

// SSLEngine handles one TLS Record per call to unwrap().
// Loop until the engine is finished unwrapping.
while (sslEngine.getHandshakeStatus() ==
        HandshakeStatus.NEED_UNWRAP) {
    SSLEngineResult res = sslEngine.unwrap(inbound, outbound);

    // SSLEngine may need additional tasks run
    if (res.getHandshakeStatus() == NEED_TASK) {
        Runnable run = sslEngine.getDelegatedTask();
        run.run();
    }
}

// The SSLEngine has now finished handling all inbound TLS Records.
// Check if it wants to generate outbound TLS Records. SSLEngine
// generates one TLS Record per call to wrap().
// Loop until the engine is finished wrapping.
while (sslEngine.getHandshakeStatus() ==
        HandshakeStatus.NEED_WRAP) {
    SSLEngineResult res = sslEngine.wrap(inbound, outbound);

    // SSLEngine may need additional tasks run
    if (res.getHandshakeStatus() == NEED_TASK) {
        Runnable run = sslEngine.getDelegatedTask();
        run.run();
    }
}

// outbound ByteBuffer now contains a complete server flight
// containing multiple TLS Records
// Rinse and repeat!
```

13. Appendix C. Example ATLS Handshake

[[EDITOR'S NOTE: For completeness, include a simple full TLS handshake showing the B64 encoded flights in JSON, along with the HTTP request/response/headers. And also the raw hex TLS records showing protocol bits]]

14. Informative References

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The Datagram Transport Layer Security (DTLS) Protocol Version 1.3
draft-ietf-tls-dtls13-43

Abstract

This document specifies Version 1.3 of the Datagram Transport Layer Security (DTLS) protocol. DTLS 1.3 allows client/server applications to communicate over the Internet in a way that is designed to prevent eavesdropping, tampering, and message forgery.

The DTLS 1.3 protocol is intentionally based on the Transport Layer Security (TLS) 1.3 protocol and provides equivalent security guarantees with the exception of order protection/non-replayability. Datagram semantics of the underlying transport are preserved by the DTLS protocol.

This document obsoletes RFC 6347.

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1. Introduction

RFC EDITOR: PLEASE REMOVE THE FOLLOWING PARAGRAPH

The source for this draft is maintained in GitHub. Suggested changes should be submitted as pull requests at <https://github.com/tlswg/dtls13-spec>. Instructions are on that page as well. Editorial changes can be managed in GitHub, but any substantive change should be discussed on the TLS mailing list.

The primary goal of the TLS protocol is to establish an authenticated, confidentiality and integrity protected channel between two communicating peers. The TLS protocol is composed of two layers: the TLS Record Protocol and the TLS Handshake Protocol. However, TLS must run over a reliable transport channel - typically TCP [RFC0793].

There are applications that use UDP [RFC0768] as a transport and to offer communication security protection for those applications the Datagram Transport Layer Security (DTLS) protocol has been developed. DTLS is deliberately designed to be as similar to TLS as possible, both to minimize new security invention and to maximize the amount of code and infrastructure reuse.

DTLS 1.0 [RFC4347] was originally defined as a delta from TLS 1.1 [RFC4346] and DTLS 1.2 [RFC6347] was defined as a series of deltas to TLS 1.2 [RFC5246]. There is no DTLS 1.1; that version number was skipped in order to harmonize version numbers with TLS. This specification describes the most current version of the DTLS protocol as a delta from TLS 1.3 [TLS13]. It obsoletes DTLS 1.2.

Implementations that speak both DTLS 1.2 and DTLS 1.3 can interoperate with those that speak only DTLS 1.2 (using DTLS 1.2 of course), just as TLS 1.3 implementations can interoperate with TLS 1.2 (see Appendix D of [TLS13] for details). While backwards compatibility with DTLS 1.0 is possible the use of DTLS 1.0 is not recommended as explained in Section 3.1.2 of RFC 7525 [RFC7525] and [DEPRECATE].

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.

The following terms are used:

- * **client**: The endpoint initiating the DTLS connection.
- * **association**: Shared state between two endpoints established with a DTLS handshake.
- * **connection**: Synonym for association.
- * **endpoint**: Either the client or server of the connection.
- * **epoch**: one set of cryptographic keys used for encryption and decryption.
- * **handshake**: An initial negotiation between client and server that establishes the parameters of the connection.
- * **peer**: An endpoint. When discussing a particular endpoint, "peer" refers to the endpoint that is remote to the primary subject of discussion.
- * **receiver**: An endpoint that is receiving records.
- * **sender**: An endpoint that is transmitting records.
- * **server**: The endpoint which did not initiate the DTLS connection.
- * **CID**: Connection ID
- * **MSL**: Maximum Segment Lifetime

The reader is assumed to be familiar with [TLS13]. As in TLS 1.3, the HelloRetryRequest has the same format as a ServerHello message, but for convenience we use the term HelloRetryRequest throughout this document as if it were a distinct message.

DTLS 1.3 uses network byte order (big-endian) format for encoding messages based on the encoding format defined in [TLS13] and earlier (D)TLS specifications.

The reader is also assumed to be familiar with [I-D.ietf-tls-dtls-connection-id] as this document applies the CID functionality to DTLS 1.3.

Figures in this document illustrate various combinations of the DTLS protocol exchanges and the symbols have the following meaning:

- * **'+'** indicates noteworthy extensions sent in the previously noted message.

- * `'**'` indicates optional or situation-dependent messages/extensions that are not always sent.
- * `'{}'` indicates messages protected using keys derived from a `[sender]_handshake_traffic_secret`.
- * `'[]'` indicates messages protected using keys derived from `traffic_secret_N`.

3. DTLS Design Rationale and Overview

The basic design philosophy of DTLS is to construct "TLS over datagram transport". Datagram transport does not require nor provide reliable or in-order delivery of data. The DTLS protocol preserves this property for application data. Applications, such as media streaming, Internet telephony, and online gaming use datagram transport for communication due to the delay-sensitive nature of transported data. The behavior of such applications is unchanged when the DTLS protocol is used to secure communication, since the DTLS protocol does not compensate for lost or reordered data traffic. Note that while low-latency streaming and gaming use DTLS to protect data (e.g. for protection of a WebRTC data channel), telephony utilizes DTLS for key establishment, and Secure Real-time Transport Protocol (SRTP) for protection of data [RFC5763].

TLS cannot be used directly over datagram transports the following five reasons:

1. TLS relies on an implicit sequence number on records. If a record is not received, then the recipient will use the wrong sequence number when attempting to remove record protection from subsequent records. DTLS solves this problem by adding sequence numbers to records.
2. The TLS handshake is a lock-step cryptographic protocol. Messages must be transmitted and received in a defined order; any other order is an error. The DTLS handshake includes message sequence numbers to enable fragmented message reassembly and in-order delivery in case datagrams are lost or reordered.
3. During the handshake, messages are implicitly acknowledged by other handshake messages. Some handshake messages, such as the `NewSessionTicket` message, do not result in any direct response that would allow the sender to detect loss. DTLS adds an acknowledgment message to enable better loss recovery.

4. Handshake messages are potentially larger than can be contained in a single datagram. DTLS adds fields to handshake messages to support fragmentation and reassembly.
5. Datagram transport protocols, like UDP, are susceptible to abusive behavior effecting denial of service attacks against nonparticipants. DTLS adds a return-routability check and DTLS 1.3 uses the TLS 1.3 HelloRetryRequest message (see Section 5.1 for details).

3.1. Packet Loss

DTLS uses a simple retransmission timer to handle packet loss. Figure 1 demonstrates the basic concept, using the first phase of the DTLS handshake:

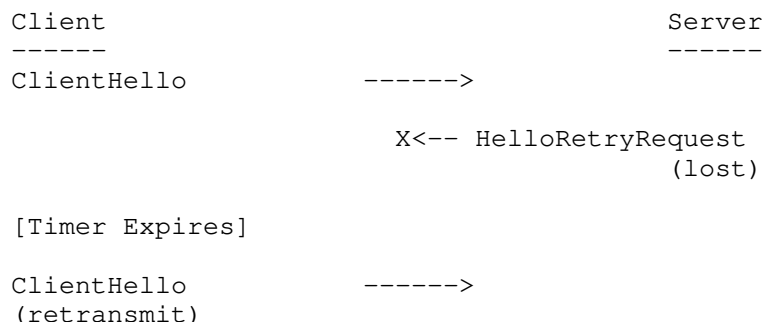


Figure 1: DTLS retransmission example

Once the client has transmitted the ClientHello message, it expects to see a HelloRetryRequest or a ServerHello from the server. However, if the timer expires, the client knows that either the ClientHello or the response from the server has been lost, which causes the the client to retransmit the ClientHello. When the server receives the retransmission, it knows to retransmit its HelloRetryRequest or ServerHello.

The server also maintains a retransmission timer for messages it sends (other than HelloRetryRequest) and retransmits when that timer expires. Not applying retransmissions to the HelloRetryRequest avoids the need to create state on the server. The HelloRetryRequest is designed to be small enough that it will not itself be fragmented, thus avoiding concerns about interleaving multiple HelloRetryRequests.

For more detail on timeouts and retransmission, see Section 5.8.

3.2. Reordering

In DTLS, each handshake message is assigned a specific sequence number. When a peer receives a handshake message, it can quickly determine whether that message is the next message it expects. If it is, then it processes it. If not, it queues it for future handling once all previous messages have been received.

3.3. Fragmentation

TLS and DTLS handshake messages can be quite large (in theory up to $2^{24}-1$ bytes, in practice many kilobytes). By contrast, UDP datagrams are often limited to less than 1500 bytes if IP fragmentation is not desired. In order to compensate for this limitation, each DTLS handshake message may be fragmented over several DTLS records, each of which is intended to fit in a single UDP datagram (see Section 4.4 for guidance). Each DTLS handshake message contains both a fragment offset and a fragment length. Thus, a recipient in possession of all bytes of a handshake message can reassemble the original unfragmented message.

3.4. Replay Detection

DTLS optionally supports record replay detection. The technique used is the same as in IPsec AH/ESP, by maintaining a bitmap window of received records. Records that are too old to fit in the window and records that have previously been received are silently discarded. The replay detection feature is optional, since packet duplication is not always malicious, but can also occur due to routing errors. Applications may conceivably detect duplicate packets and accordingly modify their data transmission strategy.

4. The DTLS Record Layer

The DTLS 1.3 record layer is different from the TLS 1.3 record layer and also different from the DTLS 1.2 record layer.

1. The DTLSCiphertext structure omits the superfluous version number and type fields.
2. DTLS adds an epoch and sequence number to the TLS record header. This sequence number allows the recipient to correctly verify the DTLS MAC. However, the number of bits used for the epoch and sequence number fields in the DTLSCiphertext structure have been reduced from those in previous versions.
3. The DTLSCiphertext structure has a variable length header.

DTLSPlaintext records are used to send unprotected records and DTLSCiphertext records are used to send protected records.

The DTLS record formats are shown below. Unless explicitly stated the meaning of the fields is unchanged from previous TLS / DTLS versions.

```
struct {
    ContentType type;
    ProtocolVersion legacy_record_version;
    uint16 epoch = 0;
    uint48 sequence_number;
    uint16 length;
    opaque fragment[DTLSPlaintext.length];
} DTLSPlaintext;

struct {
    opaque content[DTLSPlaintext.length];
    ContentType type;
    uint8 zeros[length_of_padding];
} DTLSInnerPlaintext;

struct {
    opaque unified_hdr[variable];
    opaque encrypted_record[length];
} DTLSCiphertext;
```

Figure 2: DTLS 1.3 Record Formats

legacy_record_version This value MUST be set to {254, 253} for all records other than the initial ClientHello (i.e., one not generated after a HelloRetryRequest), where it may also be {254, 255} for compatibility purposes. It MUST be ignored for all purposes. See [TLS13]; Appendix D.1 for the rationale for this.

unified_hdr: The unified header (unified_hdr) is a structure of variable length, as shown in Figure 3.

encrypted_record: The AEAD-encrypted form of the serialized DTLSInnerPlaintext structure.

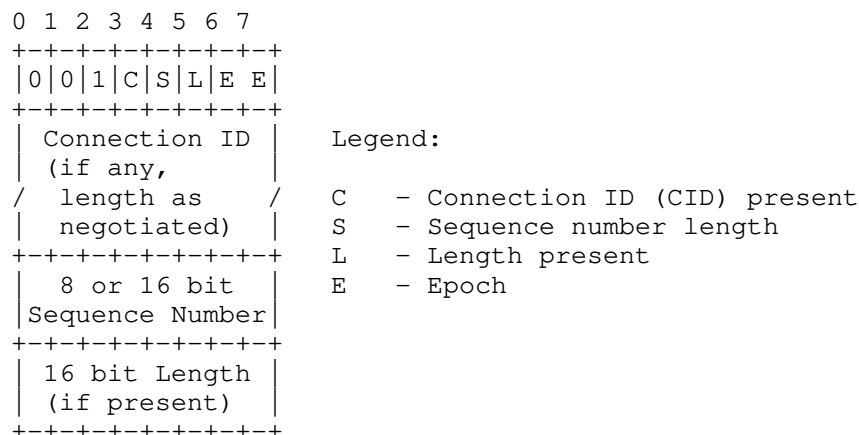


Figure 3: DTLS 1.3 Unified Header

Fixed Bits: The three high bits of the first byte of the unified header are set to 001. This ensures that the value will fit within the DTLS region when multiplexing is performed as described in [RFC7983]. It also ensures that distinguishing encrypted DTLS 1.3 records from encrypted DTLS 1.2 records is possible when they are carried on the same host/port quartet; such multiplexing is only possible when CIDs [I-D.ietf-tls-dtls-connection-id] are in use, in which case DTLS 1.2 records will have the content type `tls12_cid` (25).

C: The C bit (0x10) is set if the Connection ID is present.

S: The S bit (0x08) indicates the size of the sequence number. 0 means an 8-bit sequence number, 1 means 16-bit. Implementations MAY mix sequence numbers of different lengths on the same connection.

L: The L bit (0x04) is set if the length is present.

E: The two low bits (0x03) include the low order two bits of the epoch.

Connection ID: Variable length CID. The CID functionality is described in [I-D.ietf-tls-dtls-connection-id]. An example can be found in Section 9.1.

Sequence Number: The low order 8 or 16 bits of the record sequence number. This value is 16 bits if the S bit is set to 1, and 8 bits if the S bit is 0.

Length: Identical to the length field in a TLS 1.3 record.

As with previous versions of DTLS, multiple DTLSPlaintext and DTLSCiphertext records can be included in the same underlying transport datagram.

Figure 4 illustrates different record headers.

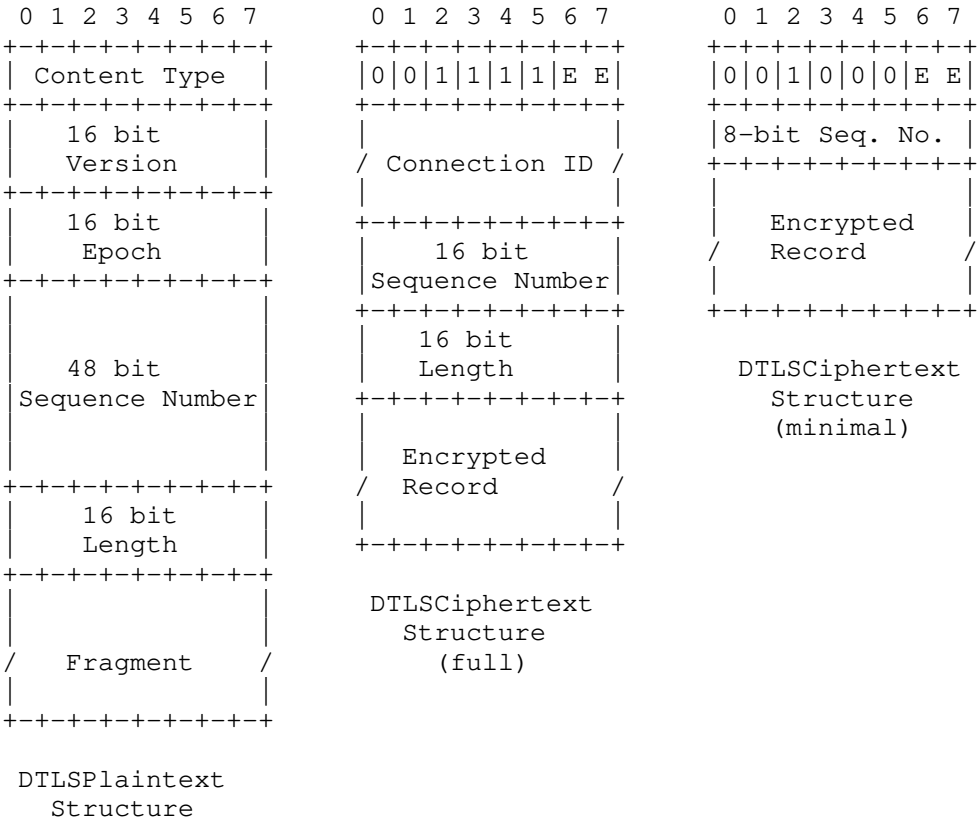


Figure 4: DTLS 1.3 Header Examples

The length field MAY be omitted by clearing the L bit, which means that the record consumes the entire rest of the datagram in the lower level transport. In this case it is not possible to have multiple DTLSCiphertext format records without length fields in the same datagram. Omitting the length field MUST only be used for the last record in a datagram. Implementations MAY mix records with and without length fields on the same connection.

If a Connection ID is negotiated, then it MUST be contained in all datagrams. Sending implementations MUST NOT mix records from multiple DTLS associations in the same datagram. If the second or later record has a connection ID which does not correspond to the same association used for previous records, the rest of the datagram MUST be discarded.

When expanded, the epoch and sequence number can be combined into an unpacked RecordNumber structure, as shown below:

```
struct {  
    uint16 epoch;  
    uint48 sequence_number;  
} RecordNumber;
```

This 64-bit value is used in the ACK message as well as in the "record_sequence_number" input to the AEAD function.

The entire header value shown in Figure 4 (but prior to record number encryption, see Section 4.2.3) is used as the additional data value for the AEAD function. For instance, if the minimal variant is used, the AAD is 2 octets long. Note that this design is different from the additional data calculation for DTLS 1.2 and for DTLS 1.2 with Connection ID.

4.1. Demultiplexing DTLS Records

DTLS 1.3 uses a variable length record format and hence the demultiplexing process is more complex since more header formats need to be distinguished. Implementations can demultiplex DTLS 1.3 records by examining the first byte as follows:

- * If the first byte is alert(21), handshake(22), or ack(proposed, 26), the record MUST be interpreted as a DTLSPlaintext record.
- * If the first byte is any other value, then receivers MUST check to see if the leading bits of the first byte are 001. If so, the implementation MUST process the record as DTLSCiphertext; the true content type will be inside the protected portion.
- * Otherwise, the record MUST be rejected as if it had failed deprotection, as described in Section 4.5.2.

Figure 5 shows this demultiplexing procedure graphically taking DTLS 1.3 and earlier versions of DTLS into account.

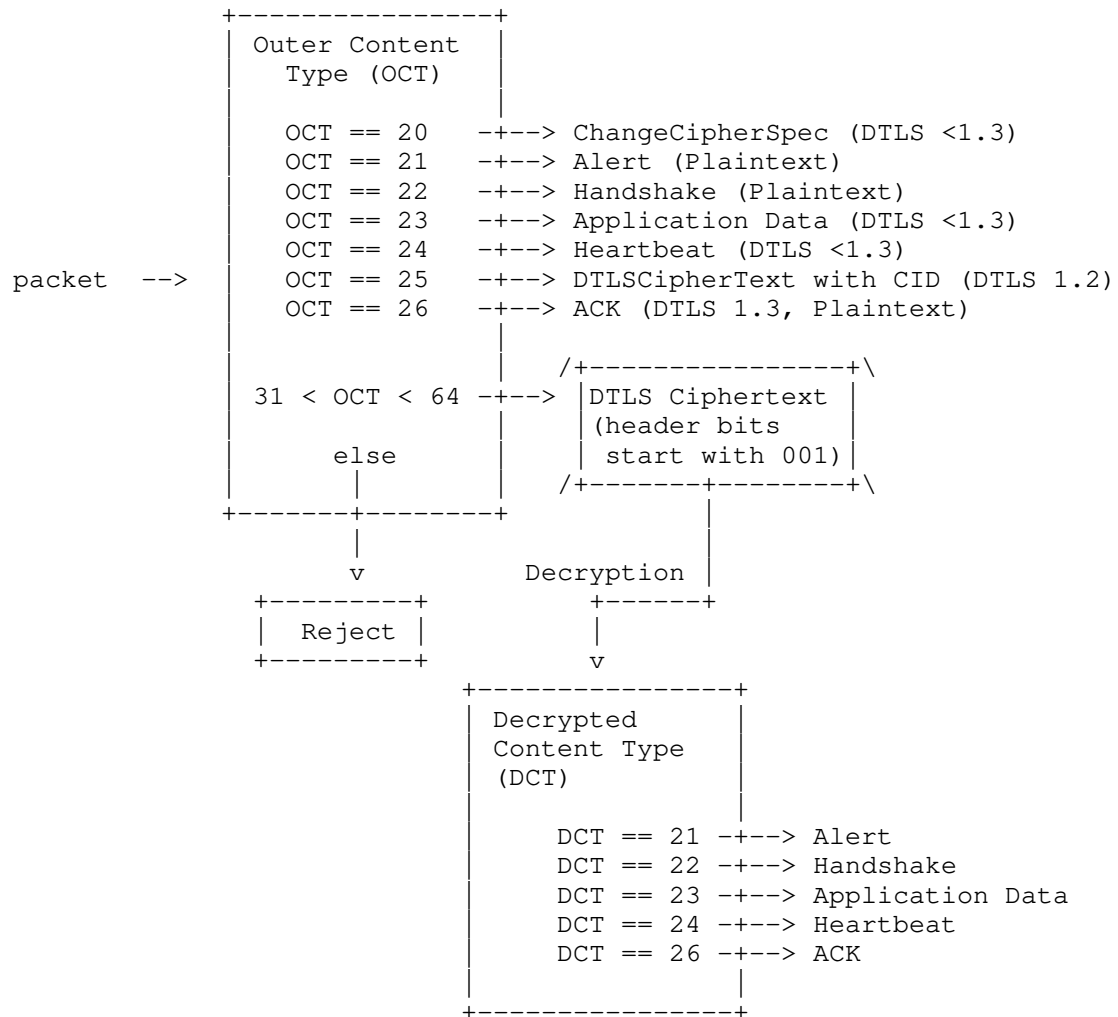


Figure 5: Demultiplexing DTLS 1.2 and DTLS 1.3 Records

Note: The optimized DTLS header format shown in Figure 3, which does not carry the Content Type in the Unified Header format, requires a different demultiplexing strategy compared to what was used in previous DTLS versions where the Content Type was conveyed in every record. As described in Figure 5, the first byte determines how an incoming DTLS record is demultiplexed. The first 3 bits of the first byte distinguish a DTLS 1.3 encrypted record from record types used in previous DTLS versions and plaintext DTLS 1.3 record types. Hence, the range 32 (0b0010 0000) to 63 (0b0011 1111) needs to be excluded from future allocations by IANA to avoid problems while demultiplexing; see Section 14.

4.2. Sequence Number and Epoch

DTLS uses an explicit or partly explicit sequence number, rather than an implicit one, carried in the `sequence_number` field of the record. Sequence numbers are maintained separately for each epoch, with each `sequence_number` initially being 0 for each epoch.

The epoch number is initially zero and is incremented each time keying material changes and a sender aims to rekey. More details are provided in Section 6.1.

4.2.1. Processing Guidelines

Because DTLS records could be reordered, a record from epoch M may be received after epoch N (where $N > M$) has begun. Implementations SHOULD discard records from earlier epochs, but MAY choose to retain keying material from previous epochs for up to the default MSL specified for TCP [RFC0793] to allow for packet reordering. (Note that the intention here is that implementers use the current guidance from the IETF for MSL, as specified in [RFC0793] or successors, not that they attempt to interrogate the MSL that the system TCP stack is using.)

Conversely, it is possible for records that are protected with the new epoch to be received prior to the completion of a handshake. For instance, the server may send its Finished message and then start transmitting data. Implementations MAY either buffer or discard such records, though when DTLS is used over reliable transports (e.g., SCTP [RFC4960]), they SHOULD be buffered and processed once the handshake completes. Note that TLS's restrictions on when records may be sent still apply, and the receiver treats the records as if they were sent in the right order.

Implementations MUST send retransmissions of lost messages using the same epoch and keying material as the original transmission.

Implementations MUST either abandon an association or re-key prior to allowing the sequence number to wrap.

Implementations MUST NOT allow the epoch to wrap, but instead MUST establish a new association, terminating the old association.

4.2.2. Reconstructing the Sequence Number and Epoch

When receiving protected DTLS records, the recipient does not have a full epoch or sequence number value in the record and so there is some opportunity for ambiguity. Because the full epoch and sequence number are used to compute the per-record nonce, failure to reconstruct these values leads to failure to deprotect the record, and so implementations MAY use a mechanism of their choice to determine the full values. This section provides an algorithm which is comparatively simple and which implementations are RECOMMENDED to follow.

If the epoch bits match those of the current epoch, then implementations SHOULD reconstruct the sequence number by computing the full sequence number which is numerically closest to one plus the sequence number of the highest successfully deprotected record in the current epoch.

During the handshake phase, the epoch bits unambiguously indicate the correct key to use. After the handshake is complete, if the epoch bits do not match those from the current epoch implementations SHOULD use the most recent past epoch which has matching bits, and then reconstruct the sequence number for that epoch as described above.

4.2.3. Record Number Encryption

In DTLS 1.3, when records are encrypted, record sequence numbers are also encrypted. The basic pattern is that the underlying encryption algorithm used with the AEAD algorithm is used to generate a mask which is then XORed with the sequence number.

When the AEAD is based on AES, then the Mask is generated by computing AES-ECB on the first 16 bytes of the ciphertext:

```
Mask = AES-ECB(sn_key, Ciphertext[0..15])
```

When the AEAD is based on ChaCha20, then the mask is generated by treating the first 4 bytes of the ciphertext as the block counter and the next 12 bytes as the nonce, passing them to the ChaCha20 block function (Section 2.3 of [CHACHA]):

```
Mask = ChaCha20(sn_key, Ciphertext[0..3], Ciphertext[4..15])
```

The `sn_key` is computed as follows:

```
[sender]_sn_key = HKDF-Expand-Label(Secret, "sn" , "", key_length)
```

[sender] denotes the sending side. The Secret value to be used is described in Section 7.3 of [TLS13]. Note that a new key is used for each epoch: because the epoch is sent in the clear, this does not result in ambiguity.

The encrypted sequence number is computed by XORing the leading bytes of the Mask with the on-the-wire representation of the sequence number. Decryption is accomplished by the same process.

This procedure requires the ciphertext length be at least 16 bytes. Receivers MUST reject shorter records as if they had failed deprotection, as described in Section 4.5.2. Senders MUST pad short plaintexts out (using the conventional record padding mechanism) in order to make a suitable-length ciphertext. Note most of the DTLS AEAD algorithms have a 16-byte authentication tag and need no padding. However, some algorithms such as TLS_AES_128_CCM_8_SHA256 have a shorter authentication tag and may require padding for short inputs.

Future cipher suites, which are not based on AES or ChaCha20, MUST define their own record sequence number encryption in order to be used with DTLS.

Note that sequence number encryption is only applied to the DTLSCiphertext structure and not to the DTLSPlaintext structure, which also contains a sequence number.

4.3. Transport Layer Mapping

DTLS messages MAY be fragmented into multiple DTLS records. Each DTLS record MUST fit within a single datagram. In order to avoid IP fragmentation, clients of the DTLS record layer SHOULD attempt to size records so that they fit within any Path MTU (PMTU) estimates obtained from the record layer. For more information about PMTU issues see Section 4.4.

Multiple DTLS records MAY be placed in a single datagram. Records are encoded consecutively. The length field from DTLS records containing that field can be used to determine the boundaries between records. The final record in a datagram can omit the length field. The first byte of the datagram payload MUST be the beginning of a record. Records MUST NOT span datagrams.

DTLS records without CIDs do not contain any association identifiers and applications must arrange to multiplex between associations. With UDP, the host/port number is used to look up the appropriate security association for incoming records without CIDs.

Some transports, such as DCCP [RFC4340], provide their own sequence numbers. When carried over those transports, both the DTLS and the transport sequence numbers will be present. Although this introduces a small amount of inefficiency, the transport layer and DTLS sequence numbers serve different purposes; therefore, for conceptual simplicity, it is superior to use both sequence numbers.

Some transports provide congestion control for traffic carried over them. If the congestion window is sufficiently narrow, DTLS handshake retransmissions may be held rather than transmitted immediately, potentially leading to timeouts and spurious retransmission. When DTLS is used over such transports, care should be taken not to overrun the likely congestion window. [RFC5238] defines a mapping of DTLS to DCCP that takes these issues into account.

4.4. PMTU Issues

In general, DTLS's philosophy is to leave PMTU discovery to the application. However, DTLS cannot completely ignore PMTU for three reasons:

- * The DTLS record framing expands the datagram size, thus lowering the effective PMTU from the application's perspective.
- * In some implementations, the application may not directly talk to the network, in which case the DTLS stack may absorb ICMP [RFC1191] "Datagram Too Big" indications or ICMPv6 [RFC4443] "Packet Too Big" indications.
- * The DTLS handshake messages can exceed the PMTU.

In order to deal with the first two issues, the DTLS record layer SHOULD behave as described below.

If PMTU estimates are available from the underlying transport protocol, they should be made available to upper layer protocols. In particular:

- * For DTLS over UDP, the upper layer protocol SHOULD be allowed to obtain the PMTU estimate maintained in the IP layer.

- * For DTLS over DCCP, the upper layer protocol SHOULD be allowed to obtain the current estimate of the PMTU.
- * For DTLS over TCP or SCTP, which automatically fragment and reassemble datagrams, there is no PMTU limitation. However, the upper layer protocol MUST NOT write any record that exceeds the maximum record size of 2^{14} bytes.

The DTLS record layer SHOULD also allow the upper layer protocol to discover the amount of record expansion expected by the DTLS processing; alternately it MAY report PMTU estimates minus the estimated expansion from the transport layer and DTLS record framing.

Note that DTLS does not defend against spoofed ICMP messages; implementations SHOULD ignore any such messages that indicate PMTUs below the IPv4 and IPv6 minimums of 576 and 1280 bytes respectively.

If there is a transport protocol indication that the PMTU was exceeded (either via ICMP or via a refusal to send the datagram as in Section 14 of [RFC4340]), then the DTLS record layer MUST inform the upper layer protocol of the error.

The DTLS record layer SHOULD NOT interfere with upper layer protocols performing PMTU discovery, whether via [RFC1191] and [RFC4821] for IPv4 or via [RFC8201] for IPv6. In particular:

- * Where allowed by the underlying transport protocol, the upper layer protocol SHOULD be allowed to set the state of the DF bit (in IPv4) or prohibit local fragmentation (in IPv6).
- * If the underlying transport protocol allows the application to request PMTU probing (e.g., DCCP), the DTLS record layer SHOULD honor this request.

The final issue is the DTLS handshake protocol. From the perspective of the DTLS record layer, this is merely another upper layer protocol. However, DTLS handshakes occur infrequently and involve only a few round trips; therefore, the handshake protocol PMTU handling places a premium on rapid completion over accurate PMTU discovery. In order to allow connections under these circumstances, DTLS implementations SHOULD follow the following rules:

- * If the DTLS record layer informs the DTLS handshake layer that a message is too big, the handshake layer SHOULD immediately attempt to fragment the message, using any existing information about the PMTU.

- * If repeated retransmissions do not result in a response, and the PMTU is unknown, subsequent retransmissions SHOULD back off to a smaller record size, fragmenting the handshake message as appropriate. This specification does not specify an exact number of retransmits to attempt before backing off, but 2-3 seems appropriate.

4.5. Record Payload Protection

Like TLS, DTLS transmits data as a series of protected records. The rest of this section describes the details of that format.

4.5.1. Anti-Replay

Each DTLS record contains a sequence number to provide replay protection. Sequence number verification SHOULD be performed using the following sliding window procedure, borrowed from Section 3.4.3 of [RFC4303]. Because each epoch resets the sequence number space, a separate sliding window is needed for each epoch.

The received record counter for an epoch MUST be initialized to zero when that epoch is first used. For each received record, the receiver MUST verify that the record contains a sequence number that does not duplicate the sequence number of any other record received in that epoch during the lifetime of the association. This check SHOULD happen after deprotecting the record; otherwise the record discard might itself serve as a timing channel for the record number. Note that computing the full record number from the partial is still a potential timing channel for the record number, though a less powerful one than whether the record was deprotected.

Duplicates are rejected through the use of a sliding receive window. (How the window is implemented is a local matter, but the following text describes the functionality that the implementation must exhibit.) The receiver SHOULD pick a window large enough to handle any plausible reordering, which depends on the data rate. (The receiver does not notify the sender of the window size.)

The "right" edge of the window represents the highest validated sequence number value received in the epoch. Records that contain sequence numbers lower than the "left" edge of the window are rejected. Records falling within the window are checked against a list of received records within the window. An efficient means for performing this check, based on the use of a bit mask, is described in Section 3.4.3 of [RFC4303]. If the received record falls within the window and is new, or if the record is to the right of the window, then the record is new.

The window **MUST NOT** be updated until the record has been deprotected successfully.

4.5.2. Handling Invalid Records

Unlike TLS, DTLS is resilient in the face of invalid records (e.g., invalid formatting, length, MAC, etc.). In general, invalid records **SHOULD** be silently discarded, thus preserving the association; however, an error **MAY** be logged for diagnostic purposes. Implementations which choose to generate an alert instead, **MUST** generate fatal alerts to avoid attacks where the attacker repeatedly probes the implementation to see how it responds to various types of error. Note that if DTLS is run over UDP, then any implementation which does this will be extremely susceptible to denial-of-service (DoS) attacks because UDP forgery is so easy. Thus, generating fatal alerts is **NOT RECOMMENDED** for such transports, both to increase the reliability of DTLS service and to avoid the risk of spoofing attacks sending traffic to unrelated third parties.

If DTLS is being carried over a transport that is resistant to forgery (e.g., SCTP with SCTP-AUTH), then it is safer to send alerts because an attacker will have difficulty forging a datagram that will not be rejected by the transport layer.

Note that because invalid records are rejected at a layer lower than the handshake state machine, they do not affect pending retransmission timers.

4.5.3. AEAD Limits

Section 5.5 of TLS [TLS13] defines limits on the number of records that can be protected using the same keys. These limits are specific to an AEAD algorithm, and apply equally to DTLS. Implementations **SHOULD NOT** protect more records than allowed by the limit specified for the negotiated AEAD. Implementations **SHOULD** initiate a key update before reaching this limit.

[TLS13] does not specify a limit for AEAD_AES_128_CCM, but the analysis in Appendix B shows that a limit of 2^{23} packets can be used to obtain the same confidentiality protection as the limits specified in TLS.

The usage limits defined in TLS 1.3 exist for protection against attacks on confidentiality and apply to successful applications of AEAD protection. The integrity protections in authenticated encryption also depend on limiting the number of attempts to forge packets. TLS achieves this by closing connections after any record fails an authentication check. In comparison, DTLS ignores any packet that cannot be authenticated, allowing multiple forgery attempts.

Implementations MUST count the number of received packets that fail authentication with each key. If the number of packets that fail authentication exceed a limit that is specific to the AEAD in use, an implementation SHOULD immediately close the connection. Implementations SHOULD initiate a key update with `update_requested` before reaching this limit. Once a key update has been initiated, the previous keys can be dropped when the limit is reached rather than closing the connection. Applying a limit reduces the probability that an attacker is able to successfully forge a packet; see [AEBounds] and [ROBUST].

For AEAD_AES_128_GCM, AEAD_AES_256_GCM, and AEAD_CHACHA20_POLY1305, the limit on the number of records that fail authentication is 2^{36} . Note that the analysis in [AEBounds] supports a higher limit for the AEAD_AES_128_GCM and AEAD_AES_256_GCM, but this specification recommends a lower limit. For AEAD_AES_128_CCM, the limit on the number of records that fail authentication is $2^{23.5}$; see Appendix B.

The AEAD_AES_128_CCM_8 AEAD, as used in TLS_AES_128_CCM_8_SHA256, does not have a limit on the number of records that fail authentication that both limits the probability of forgery by the same amount and does not expose implementations to the risk of denial of service; see Appendix B.3. Therefore, 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.

Any TLS cipher suite that is specified for use with DTLS MUST define limits on the use of the associated AEAD function that preserves margins for both confidentiality and integrity. That is, limits MUST be specified for the number of packets that can be authenticated and for the number of packets that can fail authentication before a key update is required. Providing a reference to any analysis upon which values are based – and any assumptions used in that analysis – allows limits to be adapted to varying usage conditions.

5. The DTLS Handshake Protocol

DTLS 1.3 re-uses the TLS 1.3 handshake messages and flows, with the following changes:

1. To handle message loss, reordering, and fragmentation modifications to the handshake header are necessary.
2. Retransmission timers are introduced to handle message loss.
3. A new ACK content type has been added for reliable message delivery of handshake messages.

Note that TLS 1.3 already supports a cookie extension, which is used to prevent denial-of-service attacks. This DoS prevention mechanism is described in more detail below since UDP-based protocols are more vulnerable to amplification attacks than a connection-oriented transport like TCP that performs return-routability checks as part of the connection establishment.

DTLS implementations do not use the TLS 1.3 "compatibility mode" described in Section D.4 of [TLS13]. DTLS servers MUST NOT echo the "legacy_session_id" value from the client and endpoints MUST NOT send ChangeCipherSpec messages.

With these exceptions, the DTLS message formats, flows, and logic are the same as those of TLS 1.3.

5.1. Denial-of-Service Countermeasures

Datagram security protocols are extremely susceptible to a variety of DoS attacks. Two attacks are of particular concern:

1. An attacker can consume excessive resources on the server by transmitting a series of handshake initiation requests, causing the server to allocate state and potentially to perform expensive cryptographic operations.
2. An attacker can use the server as an amplifier by sending connection initiation messages with a forged source address that belongs to a victim. The server then sends its response to the victim machine, thus flooding it. Depending on the selected parameters this response message can be quite large, as is the case for a Certificate message.

In order to counter both of these attacks, DTLS borrows the stateless cookie technique used by Photuris [RFC2522] and IKE [RFC7296]. When the client sends its ClientHello message to the server, the server

MAY respond with a HelloRetryRequest message. The HelloRetryRequest message, as well as the cookie extension, is defined in TLS 1.3. The HelloRetryRequest message contains a stateless cookie (see [TLS13]; Section 4.2.2). The client MUST send a new ClientHello with the cookie added as an extension. The server then verifies the cookie and proceeds with the handshake only if it is valid. This mechanism forces the attacker/client to be able to receive the cookie, which makes DoS attacks with spoofed IP addresses difficult. This mechanism does not provide any defense against DoS attacks mounted from valid IP addresses.

The DTLS 1.3 specification changes how cookies are exchanged compared to DTLS 1.2. DTLS 1.3 re-uses the HelloRetryRequest message and conveys the cookie to the client via an extension. The client receiving the cookie uses the same extension to place the cookie subsequently into a ClientHello message. DTLS 1.2 on the other hand used a separate message, namely the HelloVerifyRequest, to pass a cookie to the client and did not utilize the extension mechanism. For backwards compatibility reasons, the cookie field in the ClientHello is present in DTLS 1.3 but is ignored by a DTLS 1.3 compliant server implementation.

The exchange is shown in Figure 6. Note that the figure focuses on the cookie exchange; all other extensions are omitted.

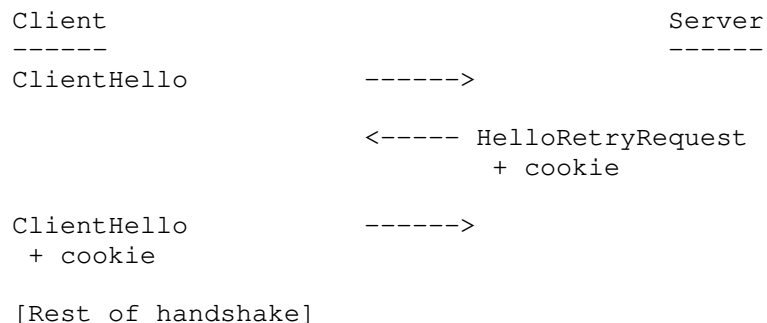


Figure 6: DTLS exchange with HelloRetryRequest containing the "cookie" extension

The cookie extension is defined in Section 4.2.2 of [TLS13]. When sending the initial ClientHello, the client does not have a cookie yet. In this case, the cookie extension is omitted and the legacy_cookie field in the ClientHello message MUST be set to a zero-length vector (i.e., a zero-valued single byte length field).

When responding to a HelloRetryRequest, the client MUST create a new ClientHello message following the description in Section 4.1.2 of [TLS13].

If the HelloRetryRequest message is used, the initial ClientHello and the HelloRetryRequest are included in the calculation of the transcript hash. The computation of the message hash for the HelloRetryRequest is done according to the description in Section 4.4.1 of [TLS13].

The handshake transcript is not reset with the second ClientHello and a stateless server-cookie implementation requires the content or hash of the initial ClientHello (and HelloRetryRequest) to be stored in the cookie. The initial ClientHello is included in the handshake transcript as a synthetic "message_hash" message, so only the hash value is needed for the handshake to complete, though the complete HelloRetryRequest contents are needed.

When the second ClientHello is received, the server can verify that the cookie is valid and that the client can receive packets at the given IP address. If the client's apparent IP address is embedded in the cookie, this prevents an attacker from generating an acceptable ClientHello apparently from another user.

One potential attack on this scheme is for the attacker to collect a number of cookies from different addresses where it controls endpoints and then reuse them to attack the server. The server can defend against this attack by changing the secret value frequently, thus invalidating those cookies. If the server wishes to allow legitimate clients to handshake through the transition (e.g., a client received a cookie with Secret 1 and then sent the second ClientHello after the server has changed to Secret 2), the server can have a limited window during which it accepts both secrets. [RFC7296] suggests adding a key identifier to cookies to detect this case. An alternative approach is simply to try verifying with both secrets. It is RECOMMENDED that servers implement a key rotation scheme that allows the server to manage keys with overlapping lifetime.

Alternatively, the server can store timestamps in the cookie and reject cookies that were generated outside a certain interval of time.

DTLS servers SHOULD perform a cookie exchange whenever a new handshake is being performed. If the server is being operated in an environment where amplification is not a problem, the server MAY be configured not to perform a cookie exchange. The default SHOULD be that the exchange is performed, however. In addition, the server MAY

choose not to do a cookie exchange when a session is resumed or, more generically, when the DTLS handshake uses a PSK-based key exchange and the IP address matches one associated with the PSK. Servers which process 0-RTT requests and send 0.5-RTT responses without a cookie exchange risk being used in an amplification attack if the size of outgoing messages greatly exceeds the size of those that are received. A server SHOULD limit the amount of data it sends toward a client address to three times the amount of data sent by the client before it verifies that the client is able to receive data at that address. A client address is valid after a cookie exchange or handshake completion. Clients MUST be prepared to do a cookie exchange with every handshake. Note that cookies are only valid for the existing handshake and cannot be stored for future handshakes.

If a server receives a ClientHello with an invalid cookie, it MUST terminate the handshake with an "illegal_parameter" alert. This allows the client to restart the connection from scratch without a cookie.

As described in Section 4.1.4 of [TLS13], clients MUST abort the handshake with an "unexpected_message" alert in response to any second HelloRetryRequest which was sent in the same connection (i.e., where the ClientHello was itself in response to a HelloRetryRequest).

DTLS clients which do not want to receive a Connection ID SHOULD still offer the "connection_id" extension unless there is an application profile to the contrary. This permits a server which wants to receive a CID to negotiate one.

5.2. DTLS Handshake Message Format

In order to support message loss, reordering, and message fragmentation, DTLS modifies the TLS 1.3 handshake header:

```
enum {
    client_hello(1),
    server_hello(2),
    new_session_ticket(4),
    end_of_early_data(5),
    encrypted_extensions(8),
    certificate(11),
    certificate_request(13),
    certificate_verify(15),
    finished(20),
    key_update(24),
    message_hash(254),
    (255)
} HandshakeType;

struct {
    HandshakeType msg_type;          /* handshake type */
    uint24 length;                  /* bytes in message */
    uint16 message_seq;              /* DTLS-required field */
    uint24 fragment_offset;          /* DTLS-required field */
    uint24 fragment_length;          /* DTLS-required field */
    select (msg_type) {
        case client_hello:           ClientHello;
        case server_hello:           ServerHello;
        case end_of_early_data:       EndOfEarlyData;
        case encrypted_extensions:    EncryptedExtensions;
        case certificate_request:      CertificateRequest;
        case certificate:              Certificate;
        case certificate_verify:       CertificateVerify;
        case finished:                Finished;
        case new_session_ticket:       NewSessionTicket;
        case key_update:              KeyUpdate;
    } body;
} Handshake;
```

The first message each side transmits in each association always has `message_seq = 0`. Whenever a new message is generated, the `message_seq` value is incremented by one. When a message is retransmitted, the old `message_seq` value is re-used, i.e., not incremented. From the perspective of the DTLS record layer, the retransmission is a new record. This record will have a new `DTLSPlaintext.sequence_number` value.

Note: In DTLS 1.2 the message_seq was reset to zero in case of a rehandshake (i.e., renegotiation). On the surface, a rehandshake in DTLS 1.2 shares similarities with a post-handshake message exchange in DTLS 1.3. However, in DTLS 1.3 the message_seq is not reset to allow distinguishing a retransmission from a previously sent post-handshake message from a newly sent post-handshake message.

DTLS implementations maintain (at least notionally) a next_receive_seq counter. This counter is initially set to zero. When a handshake message is received, if its message_seq value matches next_receive_seq, next_receive_seq is incremented and the message is processed. If the sequence number is less than next_receive_seq, the message MUST be discarded. If the sequence number is greater than next_receive_seq, the implementation SHOULD queue the message but MAY discard it. (This is a simple space/bandwidth tradeoff).

In addition to the handshake messages that are deprecated by the TLS 1.3 specification, DTLS 1.3 furthermore deprecates the HelloVerifyRequest message originally defined in DTLS 1.0. DTLS 1.3-compliant implements MUST NOT use the HelloVerifyRequest to execute a return-routability check. A dual-stack DTLS 1.2/DTLS 1.3 client MUST, however, be prepared to interact with a DTLS 1.2 server.

5.3. ClientHello Message

The format of the ClientHello used by a DTLS 1.3 client differs from the TLS 1.3 ClientHello format as shown below.

```
uint16 ProtocolVersion;
opaque Random[32];

uint8 CipherSuite[2];    /* Cryptographic suite selector */

struct {
    ProtocolVersion legacy_version = { 254,253 }; // DTLSv1.2
    Random random;
    opaque legacy_session_id<0..32>;
    opaque legacy_cookie<0..2^8-1>;                // DTLS
    CipherSuite cipher_suites<2..2^16-2>;
    opaque legacy_compression_methods<1..2^8-1>;
    Extension extensions<8..2^16-1>;
} ClientHello;
```

legacy_version: In previous versions of DTLS, this field was used for version negotiation and represented the highest version number supported by the client. Experience has shown that many servers do not properly implement version negotiation, leading to "version

intolerance" in which the server rejects an otherwise acceptable ClientHello with a version number higher than it supports. In DTLS 1.3, the client indicates its version preferences in the "supported_versions" extension (see Section 4.2.1 of [TLS13]) and the legacy_version field MUST be set to {254, 253}, which was the version number for DTLS 1.2. The supported_versions entries for DTLS 1.0 and DTLS 1.2 are 0xfeff and 0xfefd (to match the wire versions). The value 0xfefc is used to indicate DTLS 1.3.

random: Same as for TLS 1.3, except that the downgrade sentinels described in Section 4.1.3 of [TLS13] when TLS 1.2 and TLS 1.1 and below are negotiated apply to DTLS 1.2 and DTLS 1.0 respectively.

legacy_session_id: Versions of TLS and DTLS before version 1.3 supported a "session resumption" feature which has been merged with pre-shared keys in version 1.3. A client which has a cached session ID set by a pre-DTLS 1.3 server SHOULD set this field to that value. Otherwise, it MUST be set as a zero-length vector (i.e., a zero-valued single byte length field).

legacy_cookie: A DTLS 1.3-only client MUST set the legacy_cookie field to zero length. If a DTLS 1.3 ClientHello is received with any other value in this field, the server MUST abort the handshake with an "illegal_parameter" alert.

cipher_suites: Same as for TLS 1.3; only suites with DTLS-OK=Y may be used.

legacy_compression_methods: Same as for TLS 1.3.

extensions: Same as for TLS 1.3.

5.4. ServerHello Message

The DTLS 1.3 ServerHello message is the same as the TLS 1.3 ServerHello message, except that the legacy_version field is set to 0xfefd, indicating DTLS 1.2.

5.5. Handshake Message Fragmentation and Reassembly

As described in Section 4.3 one or more handshake messages may be carried in a single datagram. However, handshake messages are potentially bigger than the size allowed by the underlying datagram transport. DTLS provides a mechanism for fragmenting a handshake message over a number of records, each of which can be transmitted in separate datagrams, thus avoiding IP fragmentation.

When transmitting the handshake message, the sender divides the message into a series of N contiguous data ranges. The ranges MUST NOT overlap. The sender then creates N handshake messages, all with the same message_seq value as the original handshake message. Each new message is labeled with the fragment_offset (the number of bytes contained in previous fragments) and the fragment_length (the length of this fragment). The length field in all messages is the same as the length field of the original message. An unfragmented message is a degenerate case with fragment_offset=0 and fragment_length=length. Each handshake message fragment that is placed into a record MUST be delivered in a single UDP datagram.

When a DTLS implementation receives a handshake message fragment corresponding to the next expected handshake message sequence number, it MUST buffer it until it has the entire handshake message. DTLS implementations MUST be able to handle overlapping fragment ranges. This allows senders to retransmit handshake messages with smaller fragment sizes if the PMTU estimate changes. Senders MUST NOT change handshake message bytes upon retransmission. Receivers MAY check that retransmitted bytes are identical and SHOULD abort the handshake with an "illegal_parameter" alert if the value of a byte changes.

Note that as with TLS, multiple handshake messages may be placed in the same DTLS record, provided that there is room and that they are part of the same flight. Thus, there are two acceptable ways to pack two DTLS handshake messages into the same datagram: in the same record or in separate records.

5.6. End Of Early Data

The DTLS 1.3 handshake has one important difference from the TLS 1.3 handshake: the EndOfEarlyData message is omitted both from the wire and the handshake transcript: because DTLS records have epochs, EndOfEarlyData is not necessary to determine when the early data is complete, and because DTLS is lossy, attackers can trivially mount the deletion attacks that EndOfEarlyData prevents in TLS. Servers SHOULD NOT accept records from epoch 1 indefinitely once they are able to process records from epoch 3. Though reordering of IP packets can result in records from epoch 1 arriving after records from epoch 3, this is not likely to persist for very long relative to the round trip time. Servers could discard epoch 1 keys after the first epoch 3 data arrives, or retain keys for processing epoch 1 data for a short period. (See Section 6.1 for the definitions of each epoch.)

5.7. DTLS Handshake Flights

DTLS handshake messages are grouped into a series of message flights. A flight starts with the handshake message transmission of one peer and ends with the expected response from the other peer. Table 1 contains a complete list of message combinations that constitute flights.

Note	Client	Server	Handshake Messages
	x		ClientHello
		x	HelloRetryRequest
		x	ServerHello, EncryptedExtensions, CertificateRequest, Certificate, CertificateVerify, Finished
1	x		Certificate, CertificateVerify, Finished
1		x	NewSessionTicket

Table 1: Flight Handshake Message Combinations.

Remarks:

- * Table 1 does not highlight any of the optional messages.
- * Regarding note (1): When a handshake flight is sent without any expected response, as it is the case with the client's final flight or with the NewSessionTicket message, the flight must be acknowledged with an ACK message.

Below are several example message exchange illustrating the flight concept. The notational conventions from [TLS13] are used.

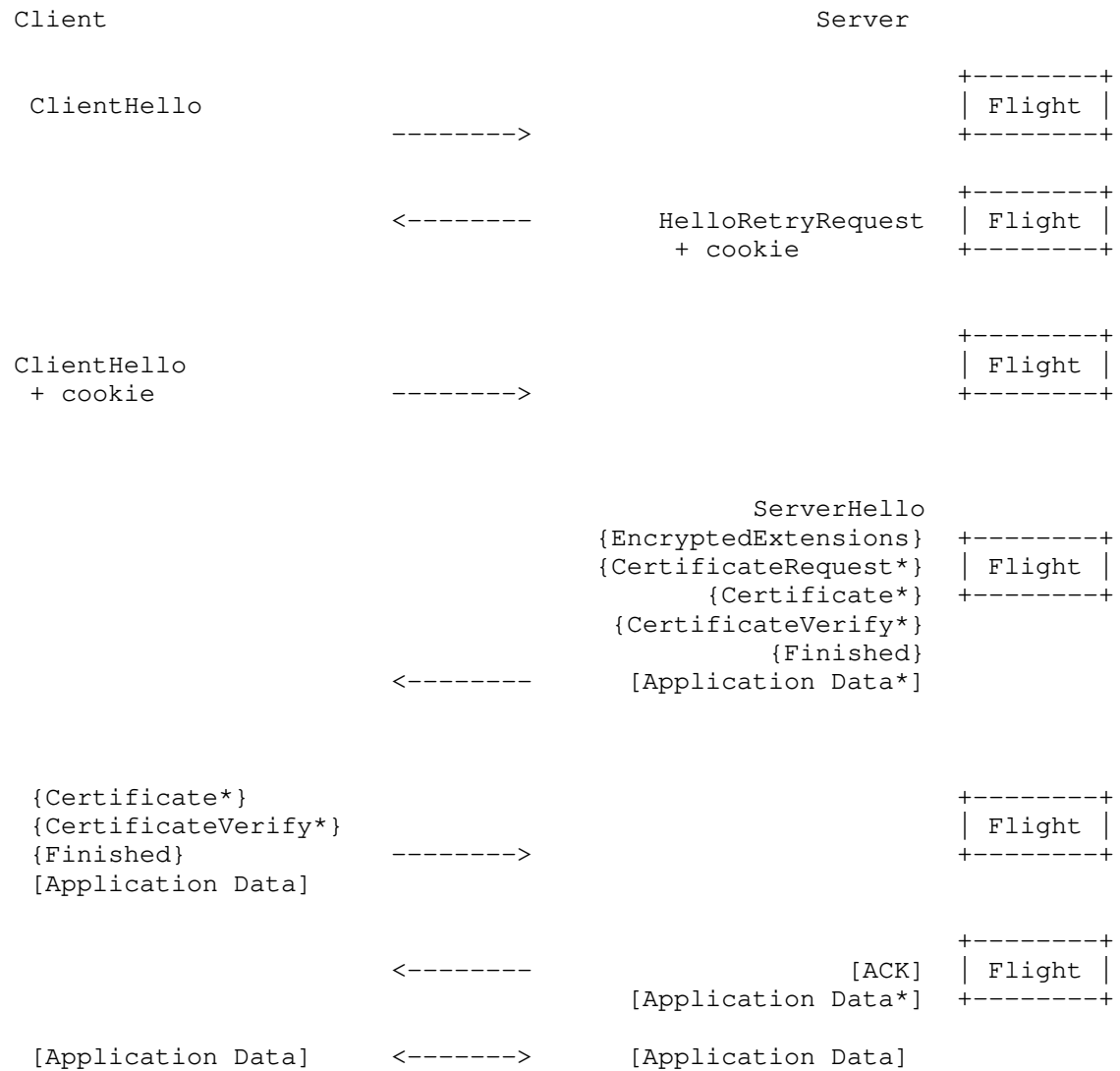


Figure 7: Message flights for a full DTLS Handshake (with cookie exchange)

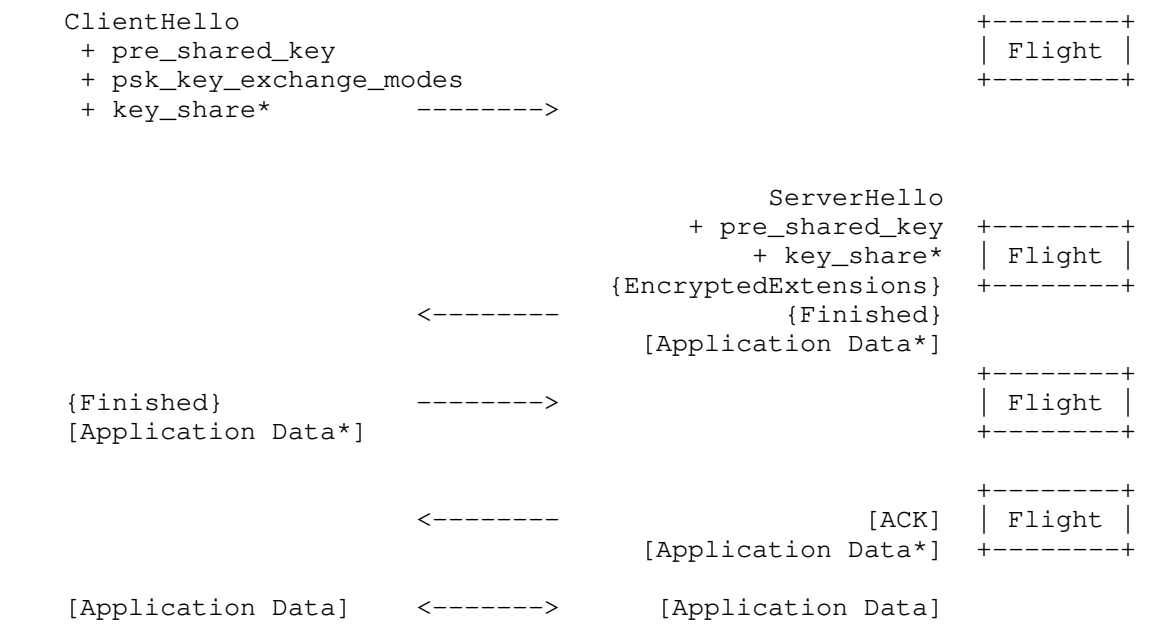


Figure 8: Message flights for resumption and PSK handshake (without cookie exchange)

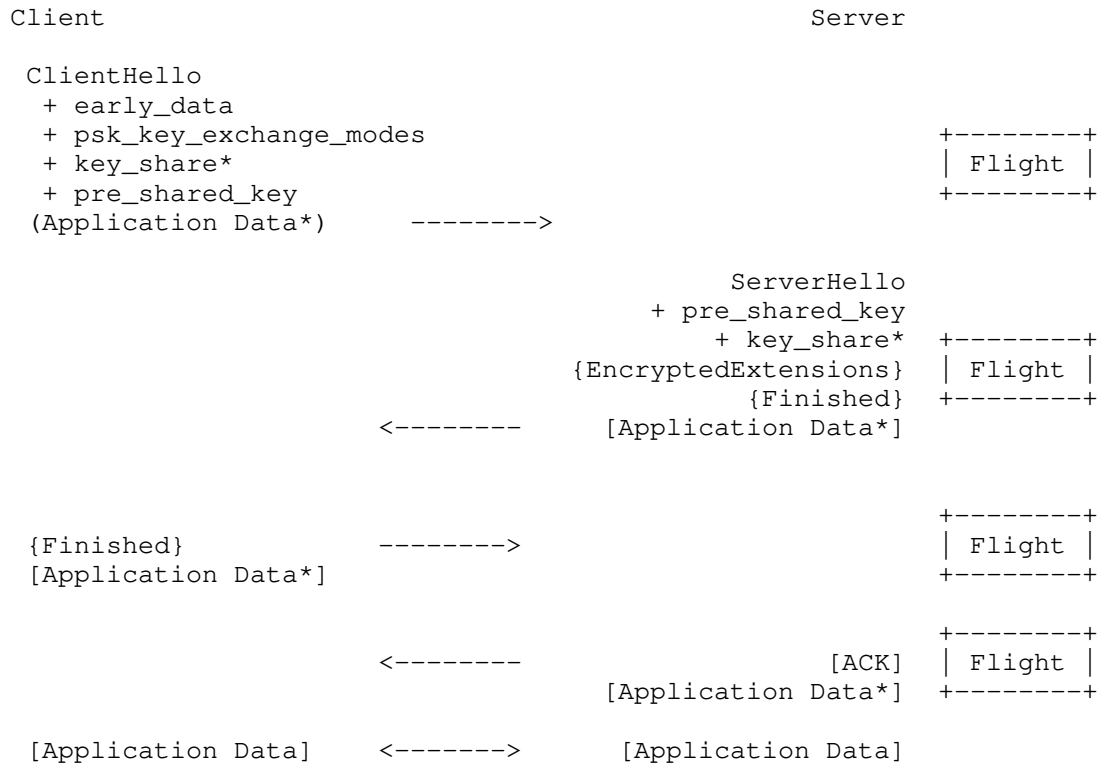
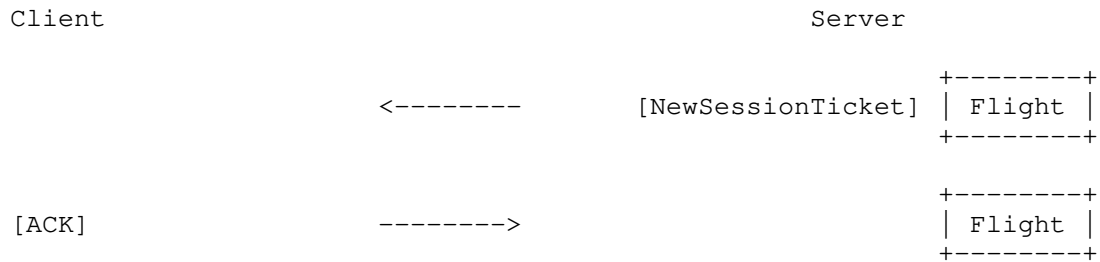


Figure 9: Message flights for the Zero-RTT handshake

Figure 10: Message flights for the `NewSessionTicket` message

`KeyUpdate`, `NewConnectionId` and `RequestConnectionId` follow a similar pattern to `NewSessionTicket`: a single message sent by one side followed by an `ACK` by the other.

5.8. Timeout and Retransmission

5.8.1. State Machine

DTLS uses a simple timeout and retransmission scheme with the state machine shown in Figure 11.

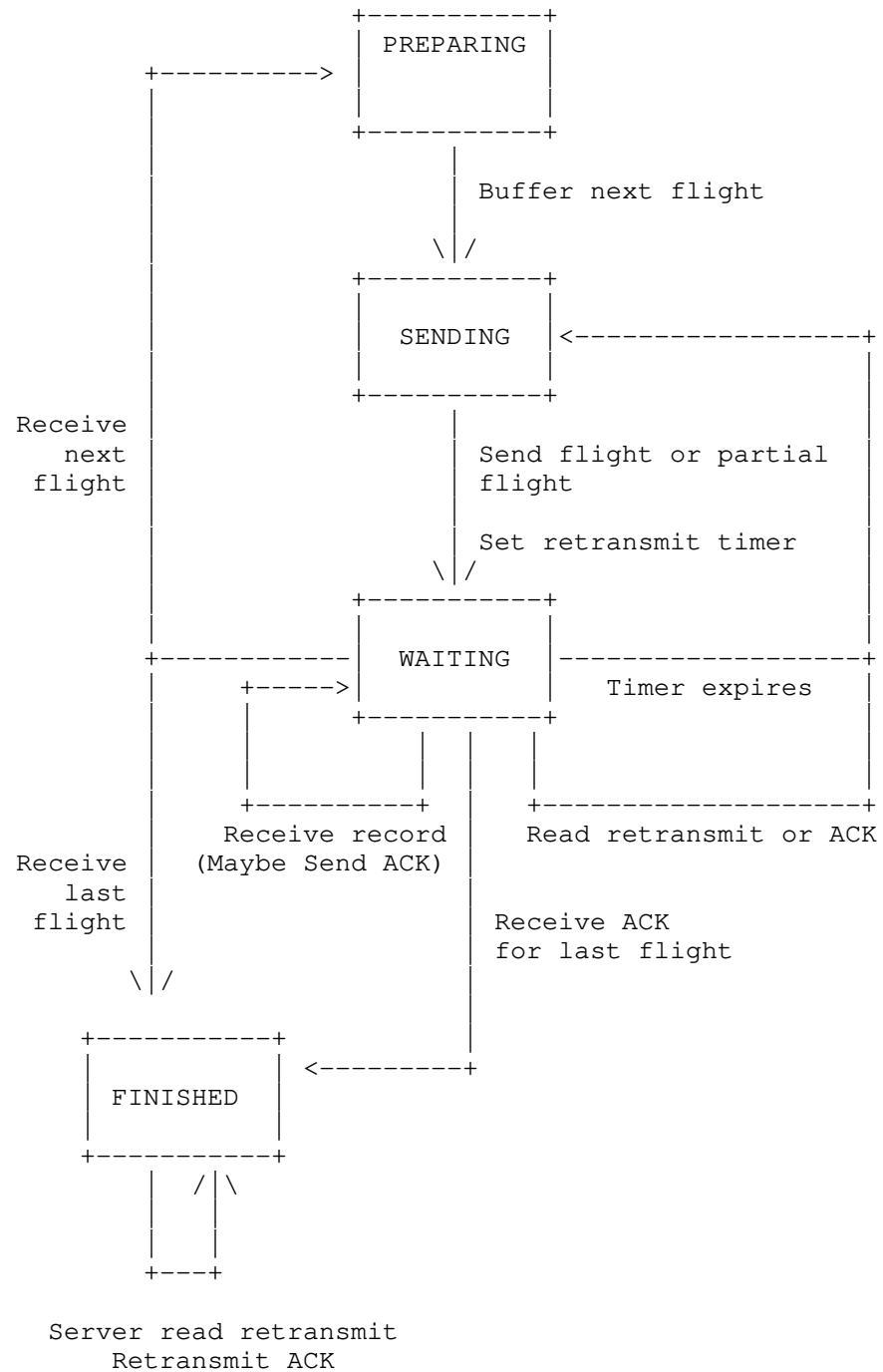


Figure 11: DTLS timeout and retransmission state machine

The state machine has four basic states: PREPARING, SENDING, WAITING, and FINISHED.

In the PREPARING state, the implementation does whatever computations are necessary to prepare the next flight of messages. It then buffers them up for transmission (emptying the transmission buffer first) and enters the SENDING state.

In the SENDING state, the implementation transmits the buffered flight of messages. If the implementation has received one or more ACKs (see Section 7) from the peer, then it SHOULD omit any messages or message fragments which have already been ACKed. Once the messages have been sent, the implementation then sets a retransmit timer and enters the WAITING state.

There are four ways to exit the WAITING state:

1. The retransmit timer expires: the implementation transitions to the SENDING state, where it retransmits the flight, adjusts and re-arms the retransmit timer (see Section 5.8.2), and returns to the WAITING state.
2. The implementation reads an ACK from the peer: upon receiving an ACK for a partial flight (as mentioned in Section 7.1), the implementation transitions to the SENDING state, where it retransmits the unacked portion of the flight, adjusts and re-arms the retransmit timer, and returns to the WAITING state. Upon receiving an ACK for a complete flight, the implementation cancels all retransmissions and either remains in WAITING, or, if the ACK was for the final flight, transitions to FINISHED.
3. The implementation reads a retransmitted flight from the peer: the implementation transitions to the SENDING state, where it retransmits the flight, adjusts and re-arms the retransmit timer, and returns to the WAITING state. The rationale here is that the receipt of a duplicate message is the likely result of timer expiry on the peer and therefore suggests that part of one's previous flight was lost.
4. The implementation receives some or all of the next flight of messages: if this is the final flight of messages, the implementation transitions to FINISHED. If the implementation needs to send a new flight, it transitions to the PREPARING state. Partial reads (whether partial messages or only some of the messages in the flight) may also trigger the implementation to send an ACK, as described in Section 7.1.

Because DTLS clients send the first message (ClientHello), they start in the PREPARING state. DTLS servers start in the WAITING state, but with empty buffers and no retransmit timer.

In addition, for at least twice the default MSL defined for [RFC0793], when in the FINISHED state, the server MUST respond to retransmission of the client's final flight with a retransmit of its ACK.

Note that because of packet loss, it is possible for one side to be sending application data even though the other side has not received the first side's Finished message. Implementations MUST either discard or buffer all application data records for epoch 3 and above until they have received the Finished message from the peer. Implementations MAY treat receipt of application data with a new epoch prior to receipt of the corresponding Finished message as evidence of reordering or packet loss and retransmit their final flight immediately, shortcutting the retransmission timer.

5.8.2. Timer Values

The configuration of timer settings varies with implementations, and certain deployment environments require timer value adjustments. Mishandling of the timer can lead to serious congestion problems, for example if many instances of a DTLS time out early and retransmit too quickly on a congested link.

Unless implementations have deployment-specific and/or external information about the round trip time, implementations SHOULD use an initial timer value of 1000 ms and double the value at each retransmission, up to no less than 60 seconds (the RFC 6298 [RFC6298] maximum). Application specific profiles MAY recommend shorter or longer timer values. For instance:

- * Profiles for specific deployment environments, such as in low-power, multi-hop mesh scenarios as used in some Internet of Things (IoT) networks, MAY specify longer timeouts. See [I-D.ietf-uta-tls13-iot-profile] for more information about one such DTLS 1.3 IoT profile.
- * Real-time protocols MAY specify shorter timeouts. It is RECOMMENDED that for DTLS-SRTP [RFC5764], a default timeout of 400ms be used; because customer experience degrades with one-way latencies of greater than 200ms, real-time deployments are less likely to have long latencies.

In settings where there is external information (for instance from an ICE [RFC8445] handshake, or from previous connections to the same server) about the RTT, implementations SHOULD use 1.5 times that RTT estimate as the retransmit timer.

Implementations SHOULD retain the current timer value until a message is transmitted and acknowledged without having to be retransmitted, at which time the value SHOULD be adjusted to 1.5 times the measured round trip time for that message. After a long period of idleness, no less than 10 times the current timer value, implementations MAY reset the timer to the initial value.

Note that because retransmission is for the handshake and not dataflow, the effect on congestion of shorter timeouts is smaller than in generic protocols such as TCP or QUIC. Experience with DTLS 1.2, which uses a simpler "retransmit everything on timeout" approach, has not shown serious congestion problems in practice.

5.8.3. Large Flight Sizes

DTLS does not have any built-in congestion control or rate control; in general this is not an issue because messages tend to be small. However, in principle, some messages - especially Certificate - can be quite large. If all the messages in a large flight are sent at once, this can result in network congestion. A better strategy is to send out only part of the flight, sending more when messages are acknowledged. Several extensions have been standardized to reduce the size of the certificate message, for example the cached information extension [RFC7924], certificate compression [RFC8879] and [RFC6066], which defines the "client_certificate_url" extension allowing DTLS clients to send a sequence of Uniform Resource Locators (URLs) instead of the client certificate.

DTLS stacks SHOULD NOT send more than 10 records in a single transmission.

5.8.4. State machine duplication for post-handshake messages

DTLS 1.3 makes use of the following categories of post-handshake messages:

1. NewSessionTicket
2. KeyUpdate
3. NewConnectionId
4. RequestConnectionId

5. Post-handshake client authentication

Messages of each category can be sent independently, and reliability is established via independent state machines each of which behaves as described in Section 5.8.1. For example, if a server sends a `NewSessionTicket` and a `CertificateRequest` message, two independent state machines will be created.

As explained in the corresponding sections, sending multiple instances of messages of a given category without having completed earlier transmissions is allowed for some categories, but not for others. Specifically, a server MAY send multiple `NewSessionTicket` messages at once without awaiting ACKs for earlier `NewSessionTicket` first. Likewise, a server MAY send multiple `CertificateRequest` messages at once without having completed earlier client authentication requests before. In contrast, implementations MUST NOT send `KeyUpdate`, `NewConnectionId` or `RequestConnectionId` messages if an earlier message of the same type has not yet been acknowledged.

Note: Except for post-handshake client authentication, which involves handshake messages in both directions, post-handshake messages are single-flight, and their respective state machines on the sender side reduce to waiting for an ACK and retransmitting the original message. In particular, note that a `RequestConnectionId` message does not force the receiver to send a `NewConnectionId` message in reply, and both messages are therefore treated independently.

Creating and correctly updating multiple state machines requires feedback from the handshake logic to the state machine layer, indicating which message belongs to which state machine. For example, if a server sends multiple `CertificateRequest` messages and receives a `Certificate` message in response, the corresponding state machine can only be determined after inspecting the `certificate_request_context` field. Similarly, a server sending a single `CertificateRequest` and receiving a `NewConnectionId` message in response can only decide that the `NewConnectionId` message should be treated through an independent state machine after inspecting the handshake message type.

5.9. CertificateVerify and Finished Messages

CertificateVerify and Finished messages have the same format as in TLS 1.3. Hash calculations include entire handshake messages, including DTLS-specific fields: message_seq, fragment_offset, and fragment_length. However, in order to remove sensitivity to handshake message fragmentation, the CertificateVerify and the Finished messages MUST be computed as if each handshake message had been sent as a single fragment following the algorithm described in Section 4.4.3 and Section 4.4.4 of [TLS13], respectively.

5.10. Cryptographic Label Prefix

Section 7.1 of [TLS13] specifies that HKDF-Expand-Label uses a label prefix of "tls13 ". For DTLS 1.3, that label SHALL be "dtls13". This ensures key separation between DTLS 1.3 and TLS 1.3. Note that there is no trailing space; this is necessary in order to keep the overall label size inside of one hash iteration because "DTLS" is one letter longer than "TLS".

5.11. Alert Messages

Note that Alert messages are not retransmitted at all, even when they occur in the context of a handshake. However, a DTLS implementation which would ordinarily issue an alert SHOULD generate a new alert message if the offending record is received again (e.g., as a retransmitted handshake message). Implementations SHOULD detect when a peer is persistently sending bad messages and terminate the local connection state after such misbehavior is detected. Note that alerts are not reliably transmitted; implementation SHOULD NOT depend on receiving alerts in order to signal errors or connection closure.

5.12. Establishing New Associations with Existing Parameters

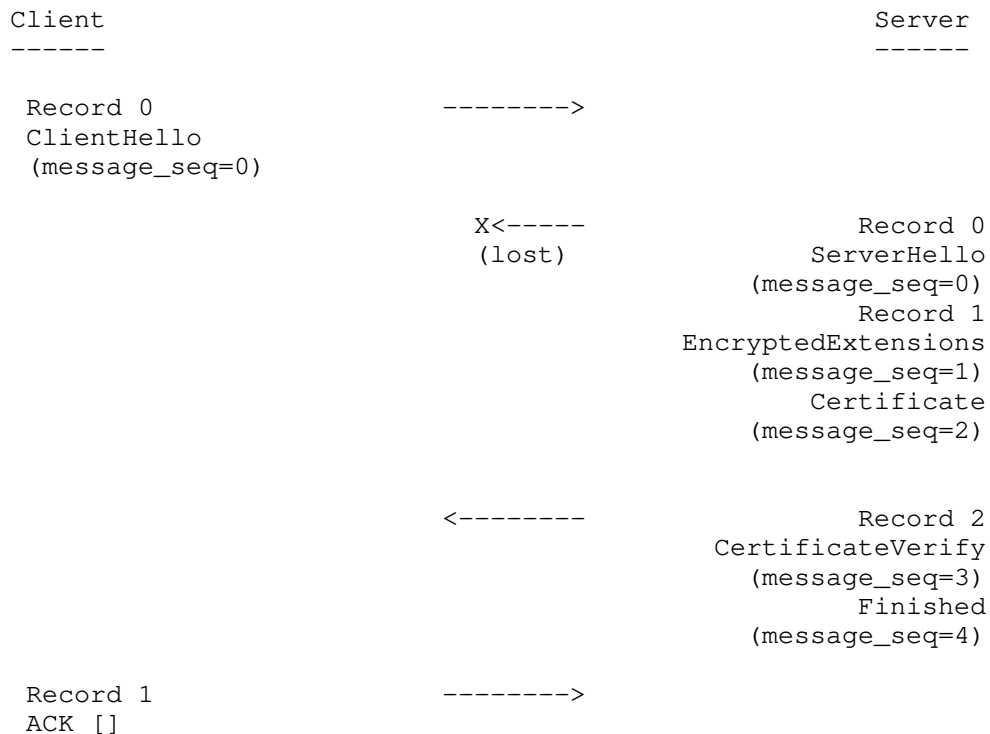
If a DTLS client-server pair is configured in such a way that repeated connections happen on the same host/port quartet, then it is possible that a client will silently abandon one connection and then initiate another with the same parameters (e.g., after a reboot). This will appear to the server as a new handshake with epoch=0. In cases where a server believes it has an existing association on a given host/port quartet and it receives an epoch=0 ClientHello, it SHOULD proceed with a new handshake but MUST NOT destroy the existing association until the client has demonstrated reachability either by completing a cookie exchange or by completing a complete handshake including delivering a verifiable Finished message. After a correct Finished message is received, the server MUST abandon the previous association to avoid confusion between two valid associations with overlapping epochs. The reachability requirement prevents off-path/

blind attackers from destroying associations merely by sending forged ClientHellos.

Note: it is not always possible to distinguish which association a given record is from. For instance, if the client performs a handshake, abandons the connection, and then immediately starts a new handshake, it may not be possible to tell which connection a given protected record is for. In these cases, trial decryption may be necessary, though implementations could use CIDs to avoid the 5-tuple-based ambiguity.

6. Example of Handshake with Timeout and Retransmission

The following is an example of a handshake with lost packets and retransmissions. Note that the client sends an empty ACK message because it can only acknowledge Record 2 sent by the server once it has processed messages in Record 0 needed to establish epoch 2 keys, which are needed to encrypt or decrypt messages found in Record 2. Section 7 provides the necessary background details for this interaction. Note: for simplicity we are not re-setting record numbers in this diagram, so "Record 1" is really "Epoch 2, Record 0, etc.".



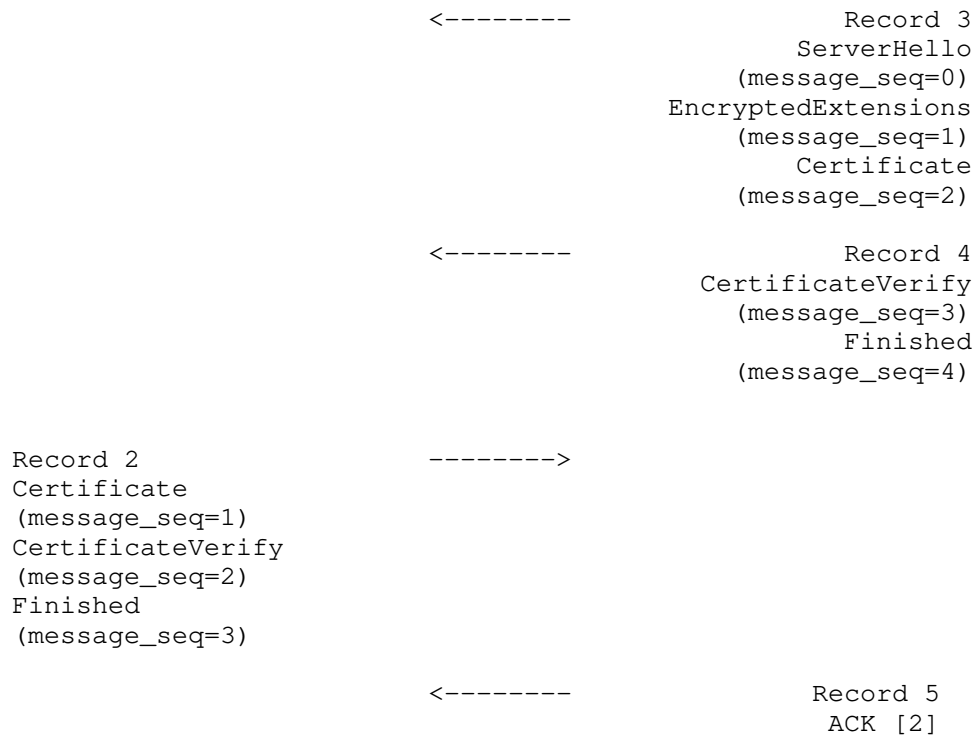


Figure 12: Example DTLS exchange illustrating message loss

6.1. Epoch Values and Rekeying

A recipient of a DTLS message needs to select the correct keying material in order to process an incoming message. With the possibility of message loss and re-ordering, an identifier is needed to determine which cipher state has been used to protect the record payload. The epoch value fulfills this role in DTLS. In addition to the TLS 1.3-defined key derivation steps, see Section 7 of [TLS13], a sender may want to rekey at any time during the lifetime of the connection. It therefore needs to indicate that it is updating its sending cryptographic keys.

This version of DTLS assigns dedicated epoch values to messages in the protocol exchange to allow identification of the correct cipher state:

- * epoch value (0) is used with unencrypted messages. There are three unencrypted messages in DTLS, namely ClientHello, ServerHello, and HelloRetryRequest.

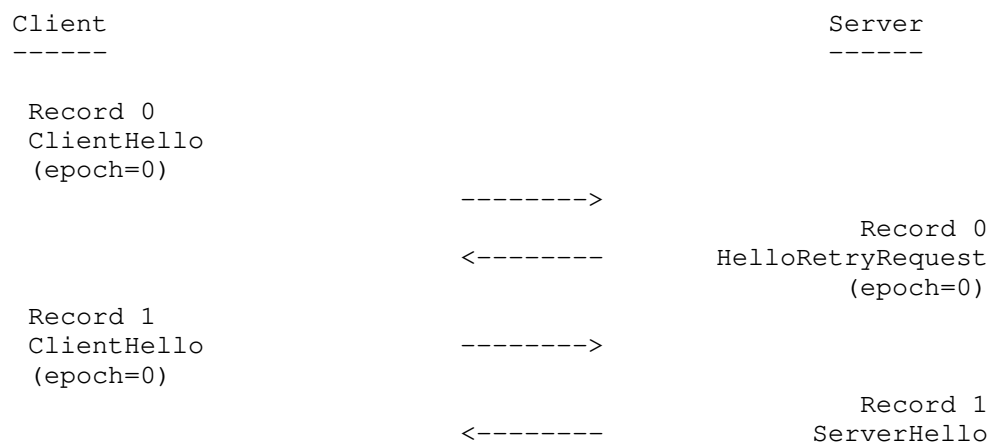
- * epoch value (1) is used for messages protected using keys derived from `client_early_traffic_secret`. Note this epoch is skipped if the client does not offer early data.
- * epoch value (2) is used for messages protected using keys derived from `[sender]_handshake_traffic_secret`. Messages transmitted during the initial handshake, such as `EncryptedExtensions`, `CertificateRequest`, `Certificate`, `CertificateVerify`, and `Finished` belong to this category. Note, however, post-handshake are protected under the appropriate application traffic key and are not included in this category.
- * epoch value (3) is used for payloads protected using keys derived from the initial `[sender]_application_traffic_secret_0`. This may include handshake messages, such as post-handshake messages (e.g., a `NewSessionTicket` message).
- * epoch value (4 to $2^{16}-1$) is used for payloads protected using keys from the `[sender]_application_traffic_secret_N` ($N>0$).

Using these reserved epoch values a receiver knows what cipher state has been used to encrypt and integrity protect a message. Implementations that receive a record with an epoch value for which no corresponding cipher state can be determined SHOULD handle it as a record which fails deprotection.

Note that epoch values do not wrap. If a DTLS implementation would need to wrap the epoch value, it MUST terminate the connection.

The traffic key calculation is described in Section 7.3 of [TLS13].

Figure 13 illustrates the epoch values in an example DTLS handshake.



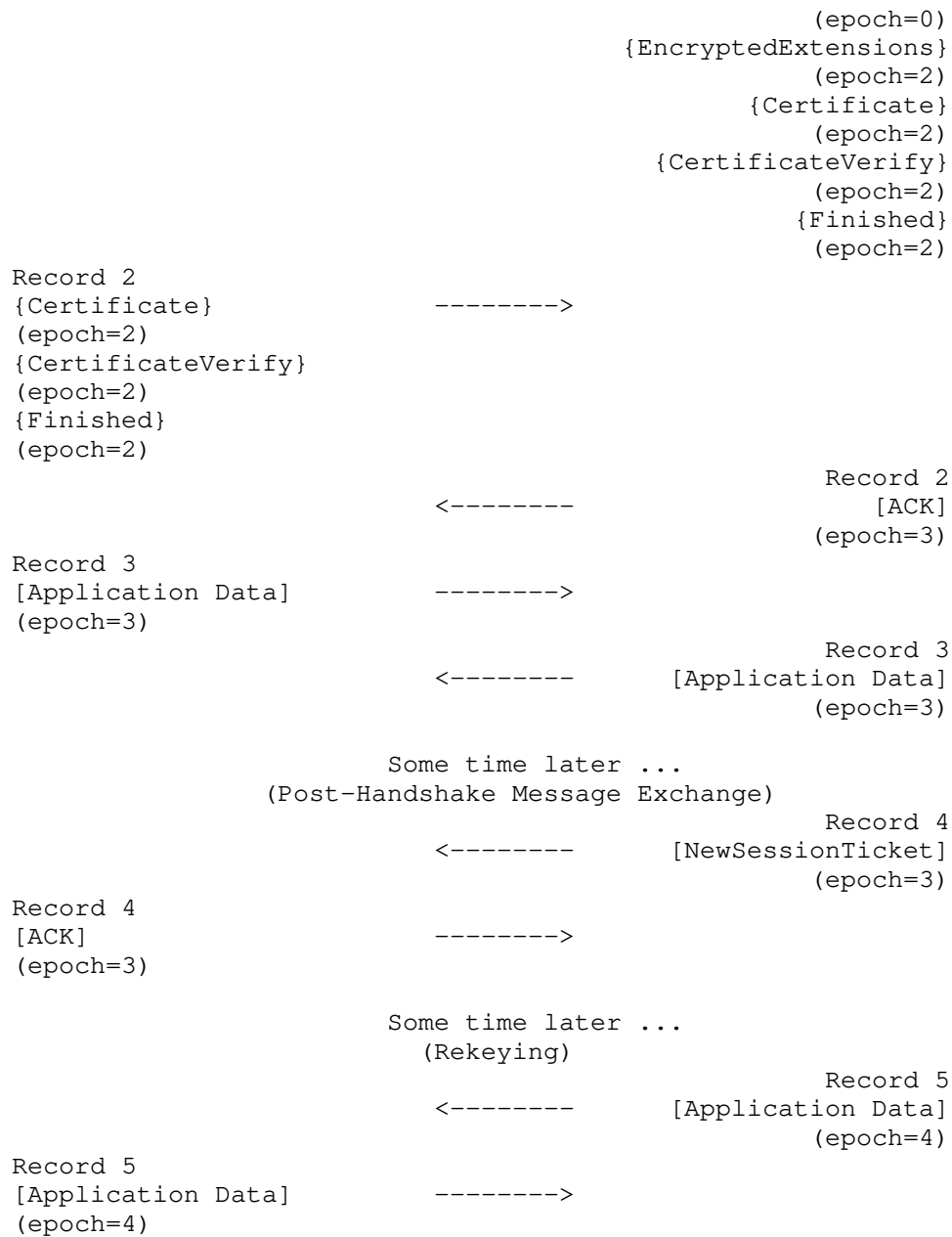


Figure 13: Example DTLS exchange with epoch information

7. ACK Message

The ACK message is used by an endpoint to indicate which handshake records it has received and processed from the other side. ACK is not a handshake message but is rather a separate content type, with code point TBD (proposed, 25). This avoids having ACK being added to the handshake transcript. Note that ACKs can still be sent in the same UDP datagram as handshake records.

```
struct {  
    RecordNumber record_numbers<0..2^16-1>;  
} ACK;
```

record_numbers: a list of the records containing handshake messages in the current flight which the endpoint has received and either processed or buffered, in numerically increasing order.

Implementations **MUST NOT** acknowledge records containing handshake messages or fragments which have not been processed or buffered. Otherwise, deadlock can ensue. As an example, implementations **MUST NOT** send ACKs for handshake messages which they discard because they are not the next expected message.

During the handshake, ACKs only cover the current outstanding flight (this is possible because DTLS is generally a lockstep protocol). In particular, receiving a message from a handshake flight implicitly acknowledges all messages from the previous flight(s). Accordingly, an ACK from the server would not cover both the ClientHello and the client's Certificate, because the ClientHello and client Certificate are in different flights. Implementations can accomplish this by clearing their ACK list upon receiving the start of the next flight.

After the handshake, ACKs **SHOULD** be sent once for each received and processed handshake record (potentially subject to some delay) and **MAY** cover more than one flight. This includes records containing messages which are discarded because a previous copy has been received.

During the handshake, ACK records **MUST** be sent with an epoch that is equal to or higher than the record which is being acknowledged. Note that some care is required when processing flights spanning multiple epochs. For instance, if the client receives only the Server Hello and Certificate and wishes to ACK them in a single record, it must do so in epoch 2, as it is required to use an epoch greater than or equal to 2 and cannot yet send with any greater epoch. Implementations **SHOULD** simply use the highest current sending epoch, which will generally be the highest available. After the handshake, implementations **MUST** use the highest available sending epoch.

7.1. Sending ACKs

When an implementation detects a disruption in the receipt of the current incoming flight, it SHOULD generate an ACK that covers the messages from that flight which it has received and processed so far. Implementations have some discretion about which events to treat as signs of disruption, but it is RECOMMENDED that they generate ACKs under two circumstances:

- * When they receive a message or fragment which is out of order, either because it is not the next expected message or because it is not the next piece of the current message.
- * When they have received part of a flight and do not immediately receive the rest of the flight (which may be in the same UDP datagram). "Immediately" is hard to define. One approach is to set a timer for 1/4 the current retransmit timer value when the first record in the flight is received and then send an ACK when that timer expires. Note: the 1/4 value here is somewhat arbitrary. Given that the round trip estimates in the DTLS handshake are generally very rough (or the default), any value will be an approximation, and there is an inherent compromise due to competition between retransmission due to over-aggressive ACKing and over-aggressive timeout-based retransmission. As a comparison point, QUIC's loss-based recovery algorithms ([I-D.ietf-quic-recovery]; Section 6.1.2) work out to a delay of about 1/3 of the retransmit timer.

In general, flights MUST be ACKed unless they are implicitly acknowledged. In the present specification the following flights are implicitly acknowledged by the receipt of the next flight, which generally immediately follows the flight,

1. Handshake flights other than the client's final flight of the main handshake.
2. The server's post-handshake CertificateRequest.

ACKs SHOULD NOT be sent for these flights unless the responding flight cannot be generated immediately. In this case, implementations MAY send explicit ACKs for the complete received flight even though it will eventually also be implicitly acknowledged through the responding flight. A notable example for this is the case of client authentication in constrained environments, where generating the CertificateVerify message can take considerable time on the client. All other flights MUST be ACKed. Implementations MAY acknowledge the records corresponding to each transmission of each flight or simply acknowledge the most recent one. In general,

implementations SHOULD ACK as many received packets as can fit into the ACK record, as this provides the most complete information and thus reduces the chance of spurious retransmission; if space is limited, implementations SHOULD favor including records which have not yet been acknowledged.

Note: While some post-handshake messages follow a request/response pattern, this does not necessarily imply receipt. For example, a KeyUpdate sent in response to a KeyUpdate with request_update set to 'update_requested' does not implicitly acknowledge the earlier KeyUpdate message because the two KeyUpdate messages might have crossed in flight.

ACKs MUST NOT be sent for other records of any content type other than handshake or for records which cannot be unprotected.

Note that in some cases it may be necessary to send an ACK which does not contain any record numbers. For instance, a client might receive an EncryptedExtensions message prior to receiving a ServerHello. Because it cannot decrypt the EncryptedExtensions, it cannot safely acknowledge it (as it might be damaged). If the client does not send an ACK, the server will eventually retransmit its first flight, but this might take far longer than the actual round trip time between client and server. Having the client send an empty ACK shortcuts this process.

7.2. Receiving ACKs

When an implementation receives an ACK, it SHOULD record that the messages or message fragments sent in the records being ACKed were received and omit them from any future retransmissions. Upon receipt of an ACK that leaves it with only some messages from a flight having been acknowledged an implementation SHOULD retransmit the unacknowledged messages or fragments. Note that this requires implementations to track which messages appear in which records. Once all the messages in a flight have been acknowledged, the implementation MUST cancel all retransmissions of that flight. Implementations MUST treat a record as having been acknowledged if it appears in any ACK; this prevents spurious retransmission in cases where a flight is very large and the receiver is forced to elide acknowledgements for records which have already been ACKed. As noted above, the receipt of any record responding to a given flight MUST be taken as an implicit acknowledgement for the entire flight to which it is responding.

7.3. Design Rationale

ACK messages are used in two circumstances, namely :

- * on sign of disruption, or lack of progress, and
- * to indicate complete receipt of the last flight in a handshake.

In the first case the use of the ACK message is optional because the peer will retransmit in any case and therefore the ACK just allows for selective or early retransmission, as opposed to the timeout-based whole flight retransmission in previous versions of DTLS. When 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.

The use of the ACK for the second case is mandatory for the proper functioning of the protocol. For instance, the ACK message sent by the client in Figure 13, acknowledges receipt and processing of record 4 (containing the NewSessionTicket message) and if it is not sent the server will continue retransmission of the NewSessionTicket indefinitely until its maximum retransmission count is reached.

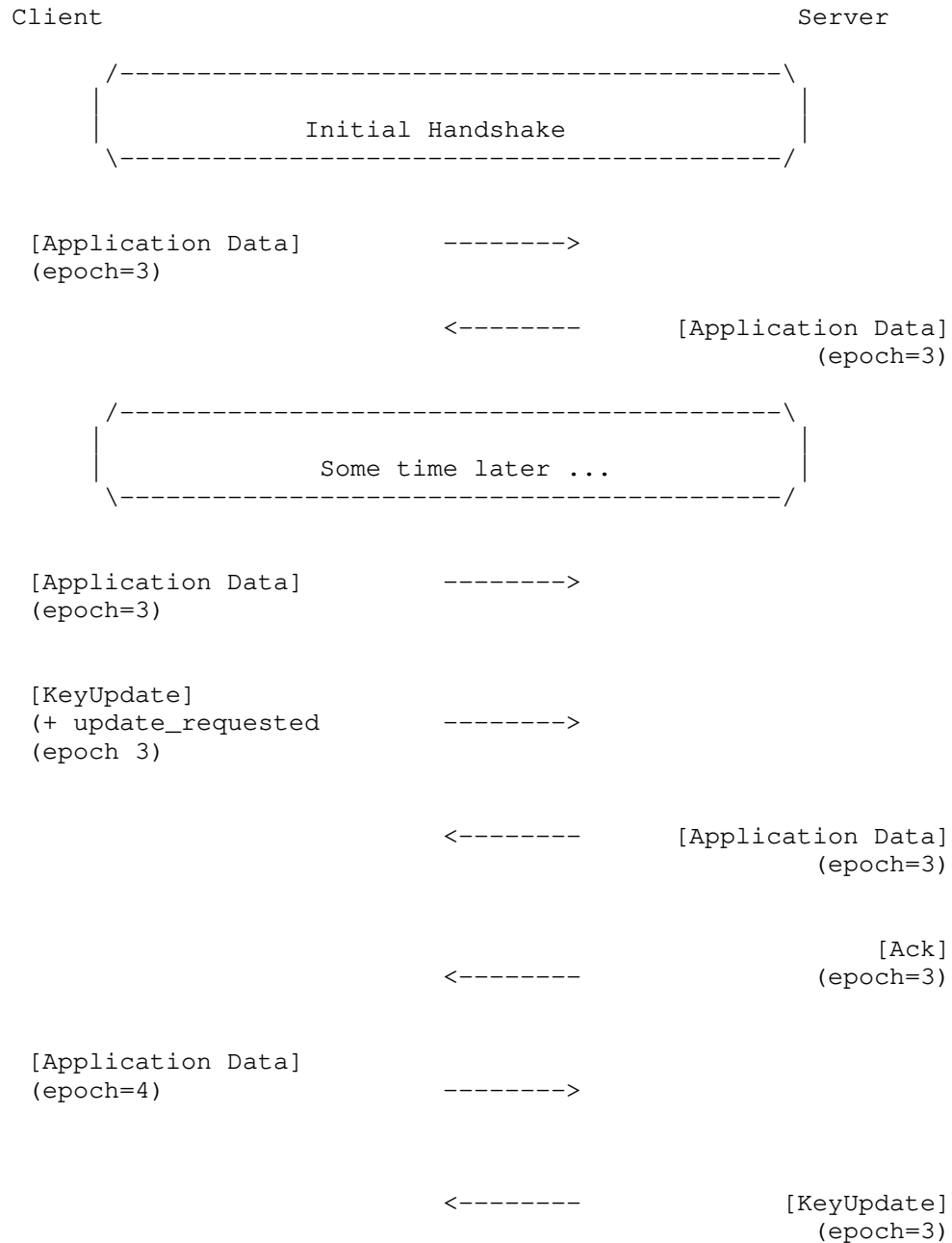
8. Key Updates

As with TLS 1.3, DTLS 1.3 implementations send a KeyUpdate message to indicate that they are updating their sending keys. As with other handshake messages with no built-in response, KeyUpdates MUST be acknowledged. In order to facilitate epoch reconstruction Section 4.2.2 implementations MUST NOT send records with the new keys or send a new KeyUpdate until the previous KeyUpdate has been acknowledged (this avoids having too many epochs in active use).

Due to loss and/or re-ordering, DTLS 1.3 implementations may receive a record with an older epoch than the current one (the requirements above preclude receiving a newer record). They SHOULD attempt to process those records with that epoch (see Section 4.2.2 for information on determining the correct epoch), but MAY opt to discard such out-of-epoch records.

Due to the possibility of an ACK message for a KeyUpdate being lost and thereby preventing the sender of the KeyUpdate from updating its keying material, receivers MUST retain the pre-update keying material until receipt and successful decryption of a message using the new keys.

Figure 14 shows an example exchange illustrating that a successful ACK processing updates the keys of the KeyUpdate message sender, which is reflected in the change of epoch values.



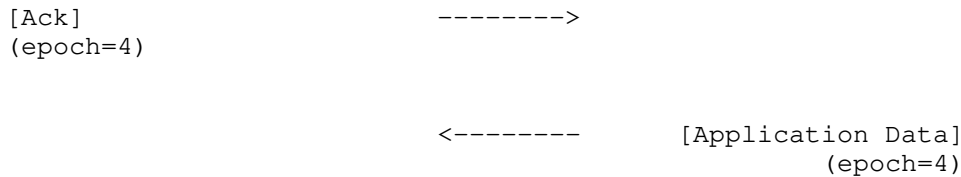


Figure 14: Example DTLS Key Update

9. Connection ID Updates

If the client and server have negotiated the "connection_id" extension [I-D.ietf-tls-dtls-connection-id], either side can send a new CID which it wishes the other side to use in a NewConnectionId message.

```

enum {
    cid_immediate(0), cid_spare(1), (255)
} ConnectionIdUsage;

opaque ConnectionId<0..2^8-1>;

struct {
    ConnectionIds cids<0..2^16-1>;
    ConnectionIdUsage usage;
} NewConnectionId;

```

cid Indicates the set of CIDs which the sender wishes the peer to use.

usage Indicates whether the new CIDs should be used immediately or are spare. If usage is set to "cid_immediate", then one of the new CID MUST be used immediately for all future records. If it is set to "cid_spare", then either existing or new CID MAY be used.

Endpoints SHOULD use receiver-provided CIDs in the order they were provided. Implementations which receive more spare CIDs than they wish to maintain MAY simply discard any extra CIDs. Endpoints MUST NOT have more than one NewConnectionId message outstanding.

Implementations which either did not negotiate the "connection_id" extension or which have negotiated receiving an empty CID MUST NOT send NewConnectionId. Implementations MUST NOT send RequestConnectionId when sending an empty Connection ID. Implementations which detect a violation of these rules MUST terminate the connection with an "unexpected_message" alert.

Implementations SHOULD use a new CID whenever sending on a new path, and SHOULD request new CIDs for this purpose if path changes are anticipated.

```
struct {  
    uint8 num_cids;  
} RequestConnectionId;
```

num_cids The number of CIDs desired.

Endpoints SHOULD respond to RequestConnectionId by sending a NewConnectionId with usage "cid_spare" containing num_cid CIDs soon as possible. Endpoints MUST NOT send a RequestConnectionId message when an existing request is still unfulfilled; this implies that endpoints needs to request new CIDs well in advance. An endpoint MAY handle requests, which it considers excessive, by responding with a NewConnectionId message containing fewer than num_cid CIDs, including no CIDs at all. Endpoints MAY handle an excessive number of RequestConnectionId messages by terminating the connection using a "too_many_cids_requested" (alert number 52) alert.

Endpoints MUST NOT send either of these messages if they did not negotiate a CID. If an implementation receives these messages when CIDs were not negotiated, it MUST abort the connection with an unexpected_message alert.

9.1. Connection ID Example

Below is an example exchange for DTLS 1.3 using a single CID in each direction.

Note: The connection_id extension is defined in [I-D.ietf-tls-dtls-connection-id], which is used in ClientHello and ServerHello messages.

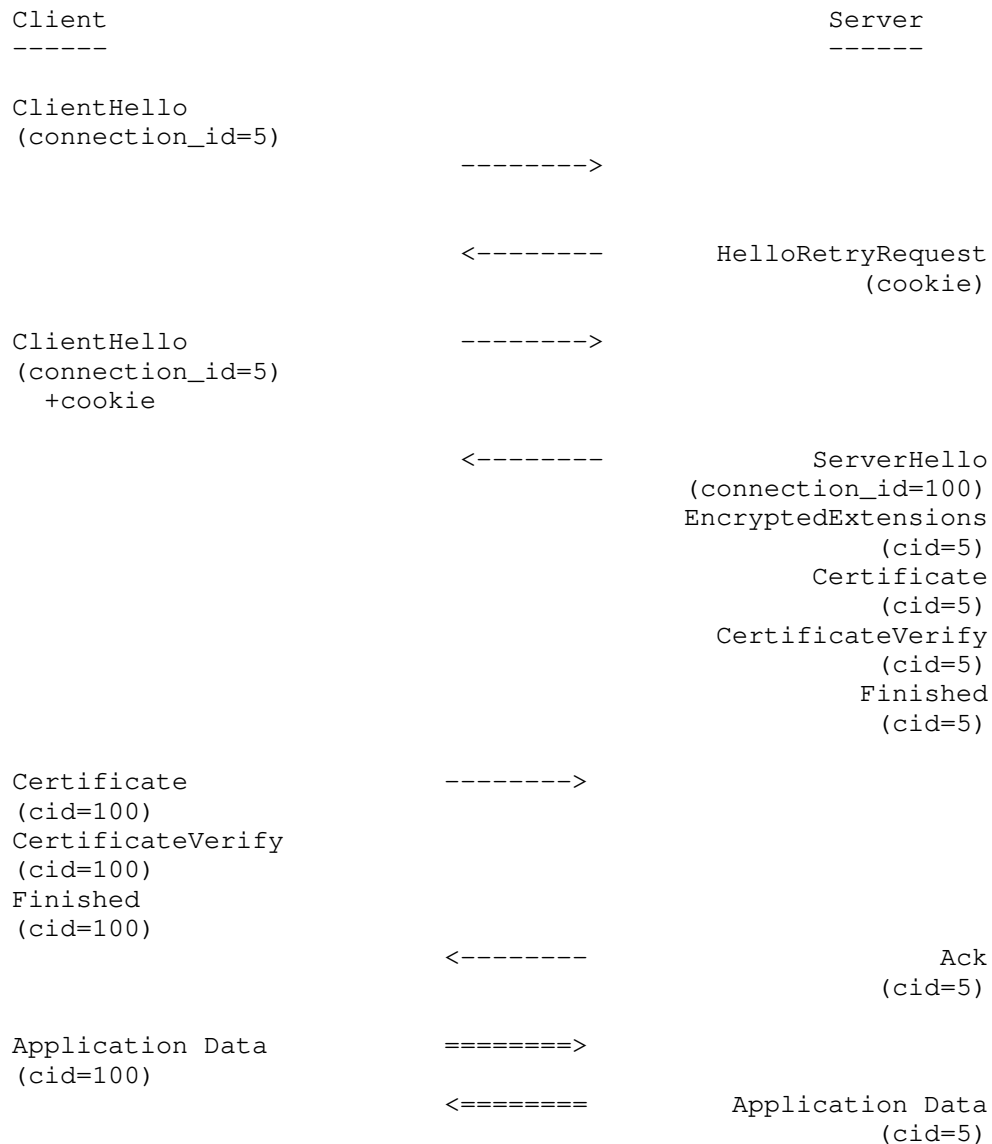


Figure 15: Example DTLS 1.3 Exchange with CIDs

If no CID is negotiated, then the receiver MUST reject any records it receives that contain a CID.

10. Application Data Protocol

Application data messages are carried by the record layer and are split into records and encrypted based on the current connection state. The messages are treated as transparent data to the record layer.

11. Security Considerations

Security issues are discussed primarily in [TLS13].

The primary additional security consideration raised by DTLS is that of denial of service by excessive resource consumption. DTLS includes a cookie exchange designed to protect against denial of service. However, implementations that do not use this cookie exchange are still vulnerable to DoS. In particular, DTLS servers that do not use the cookie exchange may be used as attack amplifiers even if they themselves are not experiencing DoS. Therefore, DTLS servers **SHOULD** use the cookie exchange unless there is good reason to believe that amplification is not a threat in their environment. Clients **MUST** be prepared to do a cookie exchange with every handshake.

Some key properties required of the cookie for the cookie-exchange mechanism to be functional are described in Section 3.3 of [RFC2522]:

- * the cookie **MUST** depend on the client's address.
- * it **MUST NOT** be possible for anyone other than the issuing entity to generate cookies that are accepted as valid by that entity. This typically entails an integrity check based on a secret key.
- * cookie generation and verification are triggered by unauthenticated parties, and as such their resource consumption needs to be restrained in order to avoid having the cookie-exchange mechanism itself serve as a DoS vector.

Although the cookie must allow the server to produce the right handshake transcript, it **SHOULD** be constructed so that knowledge of the cookie is insufficient to reproduce the ClientHello contents. Otherwise, this may create problems with future extensions such as [I-D.ietf-tls-esni].

When cookies are generated using a keyed authentication mechanism it should be possible to rotate the associated secret key, so that temporary compromise of the key does not permanently compromise the integrity of the cookie-exchange mechanism. Though this secret is not as high-value as, e.g., a session-ticket-encryption key, rotating

the cookie-generation key on a similar timescale would ensure that the key-rotation functionality is exercised regularly and thus in working order.

The cookie exchange provides address validation during the initial handshake. DTLS with Connection IDs allows for endpoint addresses to change during the association; any such updated addresses are not covered by the cookie exchange during the handshake. DTLS implementations MUST NOT update the address they send to in response to packets from a different address unless they first perform some reachability test; no such test is defined in this specification. Even with such a test, an active on-path adversary can also black-hole traffic or create a reflection attack against third parties because a DTLS peer has no means to distinguish a genuine address update event (for example, due to a NAT rebinding) from one that is malicious. This attack is of concern when there is a large asymmetry of request/response message sizes.

With the exception of order protection and non-replayability, the security guarantees for DTLS 1.3 are the same as TLS 1.3. While TLS always provides order protection and non-replayability, DTLS does not provide order protection and may not provide replay protection.

Unlike TLS implementations, DTLS implementations SHOULD NOT respond to invalid records by terminating the connection.

TLS 1.3 requires replay protection for 0-RTT data (or rather, for connections that use 0-RTT data; see Section 8 of [TLS13]). DTLS provides an optional per-record replay-protection mechanism, since datagram protocols are inherently subject to message reordering and replay. These two replay-protection mechanisms are orthogonal, and neither mechanism meets the requirements for the other.

The security and privacy properties of the CID for DTLS 1.3 builds on top of what is described for DTLS 1.2 in [I-D.ietf-tls-dtls-connection-id]. There are, however, several differences:

- * In both versions of DTLS extension negotiation is used to agree on the use of the CID feature and the CID values. In both versions the CID is carried in the DTLS record header (if negotiated). However, the way the CID is included in the record header differs between the two versions.
- * The use of the Post-Handshake message allows the client and the server to update their CIDs and those values are exchanged with confidentiality protection.

- * The ability to use multiple CIDs allows for improved privacy properties in multi-homed scenarios. When only a single CID is in use on multiple paths from such a host, an adversary can correlate the communication interaction across paths, which adds further privacy concerns. In order to prevent this, implementations SHOULD attempt to use fresh CIDs whenever they change local addresses or ports (though this is not always possible to detect). The RequestConnectionId message can be used by a peer to ask for new CIDs to ensure that a pool of suitable CIDs is available.
- * The mechanism for encrypting sequence numbers (Section 4.2.3) prevents trivial tracking by on-path adversaries that attempt to correlate the pattern of sequence numbers received on different paths; such tracking could occur even when different CIDs are used on each path, in the absence of sequence number encryption. Switching CIDs based on certain events, or even regularly, helps against tracking by on-path adversaries. Note that sequence number encryption is used for all encrypted DTLS 1.3 records irrespective of whether a CID is used or not. Unlike the sequence number, the epoch is not encrypted because it acts as a key identifier, which may improve correlation of packets from a single connection across different network paths.
- * DTLS 1.3 encrypts handshake messages much earlier than in previous DTLS versions. Therefore, less information identifying the DTLS client, such as the client certificate, is available to an on-path adversary.

12. Changes since DTLS 1.2

Since TLS 1.3 introduces a large number of changes with respect to TLS 1.2, the list of changes from DTLS 1.2 to DTLS 1.3 is equally large. For this reason this section focuses on the most important changes only.

- * New handshake pattern, which leads to a shorter message exchange
- * Only AEAD ciphers are supported. Additional data calculation has been simplified.
- * Removed support for weaker and older cryptographic algorithms
- * HelloRetryRequest of TLS 1.3 used instead of HelloVerifyRequest
- * More flexible ciphersuite negotiation
- * New session resumption mechanism

- * PSK authentication redefined
- * New key derivation hierarchy utilizing a new key derivation construct
- * Improved version negotiation
- * Optimized record layer encoding and thereby its size
- * Added CID functionality
- * Sequence numbers are encrypted.

13. Updates affecting DTLS 1.2

This document defines several changes that optionally affect implementations of DTLS 1.2, including those which do not also support DTLS 1.3.

- * A version downgrade protection mechanism as described in [TLS13]; Section 4.1.3 and applying to DTLS as described in Section 5.3.
- * The updates described in [TLS13]; Section 3.
- * The new compliance requirements described in [TLS13]; Section 9.3.

14. IANA Considerations

IANA is requested to allocate a new value in the "TLS ContentType" registry for the ACK message, defined in Section 7, with content type 26. The value for the "DTLS-OK" column is "Y". IANA is requested to reserve the content type range 32-63 so that content types in this range are not allocated.

IANA is requested to allocate "the too_many_cids_requested" alert in the "TLS Alerts" registry with value 52.

IANA is requested to allocate two values in the "TLS Handshake Type" registry, defined in [TLS13], for RequestConnectionId (TBD), and NewConnectionId (TBD), as defined in this document. The value for the "DTLS-OK" columns are "Y".

IANA is requested to add this RFC as a reference to the TLS Cipher Suite Registry along with the following Note:

Any TLS cipher suite that is specified for use with DTLS MUST define limits on the use of the associated AEAD function that preserves margins for both confidentiality and integrity, as specified in [THIS RFC; Section TODO]

15. References

15.1. Normative References

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Appendix A. Protocol Data Structures and Constant Values

This section provides the normative protocol types and constants definitions.

A.1. Record Layer

```

struct {
    ContentType type;
    ProtocolVersion legacy_record_version;
    uint16 epoch = 0;
    uint48 sequence_number;
    uint16 length;
    opaque fragment[DTLSPlaintext.length];
} DTLSPlaintext;

```

```

struct {
    opaque content[DTLSPlaintext.length];
    ContentType type;
    uint8 zeros[length_of_padding];
} DTLSInnerPlaintext;

```

```

struct {
    opaque unified_hdr[variable];
    opaque encrypted_record[length];
} DTLSCiphertext;

```

```

0 1 2 3 4 5 6 7
+---+---+---+---+---+---+
|0|0|1|C|S|L|E|E|
+---+---+---+---+---+---+
| Connection ID |
| (if any,      |
| / length as   /
| negotiated)   |
+---+---+---+---+---+---+
| 8 or 16 bit   |
| Sequence Number|
+---+---+---+---+---+---+
| 16 bit Length |
| (if present)  |
+---+---+---+---+---+---+

```

Legend:

C - Connection ID (CID) present
 S - Sequence number length
 L - Length present
 E - Epoch

```

struct {
    uint16 epoch;
    uint48 sequence_number;
} RecordNumber;

```

A.2. Handshake Protocol

```
enum {
    hello_request_RESERVED(0),
    client_hello(1),
    server_hello(2),
    hello_verify_request_RESERVED(3),
    new_session_ticket(4),
    end_of_early_data(5),
    hello_retry_request_RESERVED(6),
    encrypted_extensions(8),
    certificate(11),
    server_key_exchange_RESERVED(12),
    certificate_request(13),
    server_hello_done_RESERVED(14),
    certificate_verify(15),
    client_key_exchange_RESERVED(16),
    finished(20),
    certificate_url_RESERVED(21),
    certificate_status_RESERVED(22),
    supplemental_data_RESERVED(23),
    key_update(24),
    message_hash(254),
    (255)
} HandshakeType;

struct {
    HandshakeType msg_type;      /* handshake type */
    uint24 length;              /* bytes in message */
    uint16 message_seq;         /* DTLS-required field */
    uint24 fragment_offset;     /* DTLS-required field */
    uint24 fragment_length;     /* DTLS-required field */
    select (msg_type) {
        case client_hello:      ClientHello;
        case server_hello:      ServerHello;
        case end_of_early_data:  EndOfEarlyData;
        case encrypted_extensions: EncryptedExtensions;
        case certificate_request: CertificateRequest;
        case certificate:        Certificate;
        case certificate_verify:  CertificateVerify;
        case finished:           Finished;
        case new_session_ticket:  NewSessionTicket;
        case key_update:         KeyUpdate;
    } body;
} Handshake;

uint16 ProtocolVersion;
opaque Random[32];

uint8 CipherSuite[2]; /* Cryptographic suite selector */
```

```

struct {
    ProtocolVersion legacy_version = { 254,253 }; // DTLSv1.2
    Random random;
    opaque legacy_session_id<0..32>;
    opaque legacy_cookie<0..2^8-1>; // DTLS
    CipherSuite cipher_suites<2..2^16-2>;
    opaque legacy_compression_methods<1..2^8-1>;
    Extension extensions<8..2^16-1>;
} ClientHello;

```

A.3. ACKs

```

struct {
    RecordNumber record_numbers<0..2^16-1>;
} ACK;

```

A.4. Connection ID Management

```

enum {
    cid_immediate(0), cid_spare(1), (255)
} ConnectionIdUsage;

opaque ConnectionId<0..2^8-1>;

struct {
    ConnectionIds cids<0..2^16-1>;
    ConnectionIdUsage usage;
} NewConnectionId;

struct {
    uint8 num_cids;
} RequestConnectionId;

```

Appendix B. Analysis of Limits on CCM Usage

TLS [TLS13] and [AEBounds] do not specify limits on key usage for AEAD_AES_128_CCM. However, any AEAD that is used with DTLS requires limits on use that ensure that both confidentiality and integrity are preserved. This section documents that analysis for AEAD_AES_128_CCM.

[CCM-ANALYSIS] is used as the basis of this analysis. The results of that analysis are used to derive usage limits that are based on those chosen in [TLS13].

This analysis uses symbols for multiplication (*), division (/), and exponentiation (^), plus parentheses for establishing precedence. The following symbols are also used:

- t: The size of the authentication tag in bits. For this cipher, t is 128.
- n: The size of the block function in bits. For this cipher, n is 128.
- l: The number of blocks in each packet (see below).
- q: The number of genuine packets created and protected by endpoints. This value is the bound on the number of packets that can be protected before updating keys.
- v: The number of forged packets that endpoints will accept. This value is the bound on the number of forged packets that an endpoint can reject before updating keys.

The analysis of AEAD_AES_128_CCM relies on a count of the number of block operations involved in producing each message. For simplicity, and to match the analysis of other AEAD functions in [AEBounds], this analysis assumes a packet length of 2^{10} blocks and a packet size limit of 2^{14} bytes.

For AEAD_AES_128_CCM, the total number of block cipher operations is the sum of: the length of the associated data in blocks, the length of the ciphertext in blocks, and the length of the plaintext in blocks, plus 1. In this analysis, this is simplified to a value of twice the maximum length of a record in blocks (that is, " $2l = 2^{11}$ "). This simplification is based on the associated data being limited to one block.

B.1. Confidentiality Limits

For confidentiality, Theorem 2 in [CCM-ANALYSIS] establishes that an attacker gains a distinguishing advantage over an ideal pseudorandom permutation (PRP) of no more than:

$$(2l * q)^2 / 2^n$$

For a target advantage of 2^{-60} , which matches that used by [TLS13], this results in the relation:

$$q \leq 2^{23}$$

That is, endpoints cannot protect more than 2^{23} packets with the same set of keys without causing an attacker to gain an larger advantage than the target of 2^{-60} .

B.2. Integrity Limits

For integrity, Theorem 1 in [CCM-ANALYSIS] establishes that an attacker gains an advantage over an ideal PRP of no more than:

$$v / 2^t + (2l * (v + q))^2 / 2^n$$

The goal is to limit this advantage to 2^{-57} , to match the target in [TLS13]. As "t" and "n" are both 128, the first term is negligible relative to the second, so that term can be removed without a significant effect on the result. This produces the relation:

$$v + q \leq 2^{24.5}$$

Using the previously-established value of 2^{23} for "q" and rounding, this leads to an upper limit on "v" of $2^{23.5}$. That is, endpoints cannot attempt to authenticate more than $2^{23.5}$ packets with the same set of keys without causing an attacker to gain an larger advantage than the target of 2^{-57} .

B.3. Limits for AEAD_AES_128_CCM_8

The TLS_AES_128_CCM_8_SHA256 cipher suite uses the AEAD_AES_128_CCM_8 function, which uses a short authentication tag (that is, $t=64$).

The confidentiality limits of AEAD_AES_128_CCM_8 are the same as those for AEAD_AES_128_CCM, as this does not depend on the tag length; see Appendix B.1.

The shorter tag length of 64 bits means that the simplification used in Appendix B.2 does not apply to AEAD_AES_128_CCM_8. If the goal is to preserve the same margins as other cipher suites, then the limit on forgeries is largely dictated by the first term of the advantage formula:

$$v \leq 2^7$$

As this represents attempts to fail authentication, applying this limit might be feasible in some environments. However, applying this limit in an implementation intended for general use exposes connections to an inexpensive denial of service attack.

This analysis supports the view that TLS_AES_128_CCM_8_SHA256 is not suitable for general use. Specifically, TLS_AES_128_CCM_8_SHA256 cannot be used without additional measures to prevent forgery of records, or to mitigate the effect of forgeries. This might require understanding the constraints that exist in a particular deployment or application. For instance, it might be possible to set a different target for the advantage an attacker gains based on an understanding of the constraints imposed on a specific usage of DTLS.

Appendix C. Implementation Pitfalls

In addition to the aspects of TLS that have been a source of interoperability and security problems (Section C.3 of [TLS13]), DTLS presents a few new potential sources of issues, noted here.

- * Do you correctly handle messages received from multiple epochs during a key transition? This includes locating the correct key as well as performing replay detection, if enabled.
- * Do you retransmit handshake messages that are not (implicitly or explicitly) acknowledged (Section 5.8)?
- * Do you correctly handle handshake message fragments received, including when they are out of order?
- * Do you correctly handle handshake messages received out of order? This may include either buffering or discarding them.
- * Do you limit how much data you send to a peer before its address is validated?
- * Do you verify that the explicit record length is contained within the datagram in which it is contained?

Appendix D. History

RFC EDITOR: PLEASE REMOVE THE THIS SECTION

(*) indicates a change that may affect interoperability.

IETF Drafts draft-42

- * SHOULD level requirement for the client to offer CID extension.
- * Change the default retransmission timer to 1s and allow people to do otherwise if they have side knowledge.
- * Cap any given flight to 10 records

- * Don't re-set the timer to the initial value but to 1.5 times the measured RTT.
- * A bunch more clarity about the reliability algorithms and timers (including changing reset to re-arm)
- * Update IANA considerations

draft-40

- Clarified encrypted_record structure in DTLS 1.3 record layer
- Added description of the demultiplexing process
- Added text about the DTLS 1.2 and DTLS 1.3 CID mechanism
- Forbid going from an empty CID to a non-empty CID (*)
- Add warning about certificates and congestion
- Use DTLS style version values, even for DTLS 1.3 (*)
- Describe how to distinguish DTLS 1.2 and DTLS 1.3 connections
- Updated examples
- Included editorial improvements from Ben Kaduk
- Removed stale text about out-of-epoch records
- Added clarifications around when ACKs are sent
- Noted that alerts are unreliable
- Clarify when you can reset the timer
- Indicated that records with bogus epochs should be discarded
- Relax age out text
- Updates to cookie text
- Require that cipher suites define a record number encryption algorithm
- Clean up use of connection and association
- Reference tls-old-versions-deprecate

draft-39 - Updated Figure 4 due to misalignment with Figure 3 content

draft-38 - Ban implicit Connection IDs (*) - ACKs are processed as the union.

draft-37: - Fix the other place where we have ACK.

draft-36: - Some editorial changes. - Changed the content type to not conflict with existing allocations (*)

draft-35: - I-D.ietf-tls-dtls-connection-id became a normative reference - Removed duplicate reference to I-D.ietf-tls-dtls-connection-id. - Fix figure 11 to have the right numbers and no cookie in message 1. - Clarify when you can ACK. - Clarify additional data computation.

draft-33: - Key separation between TLS and DTLS. Issue #72.

draft-32: - Editorial improvements and clarifications.

draft-31: - Editorial improvements in text and figures. - Added normative reference to ChaCha20 and Poly1305.

draft-30: - Changed record format - Added text about end of early data - Changed format of the Connection ID Update message - Added Appendix A "Protocol Data Structures and Constant Values"

draft-29: - Added support for sequence number encryption - Update to new record format - Emphasize that compatibility mode isn't used.

draft-28: - Version bump to align with TLS 1.3 pre-RFC version.

draft-27: - Incorporated unified header format. - Added support for CIDs.

draft-04 - 26: - Submissions to align with TLS 1.3 draft versions

draft-03 - Only update keys after KeyUpdate is ACKed.

draft-02 - Shorten the protected record header and introduce an ultra-short version of the record header. - Reintroduce KeyUpdate, which works properly now that we have ACK. - Clarify the ACK rules.

draft-01 - Restructured the ACK to contain a list of records and also be a record rather than a handshake message.

draft-00 - First IETF Draft

Personal Drafts draft-01 - Alignment with version -19 of the TLS 1.3 specification

draft-00

- * Initial version using TLS 1.3 as a baseline.
- * Use of epoch values instead of KeyUpdate message
- * Use of cookie extension instead of cookie field in ClientHello and HelloVerifyRequest messages
- * Added ACK message
- * Text about sequence number handling

Appendix E. Working Group Information

RFC EDITOR: PLEASE REMOVE THIS SECTION.

The discussion list for the IETF TLS working group is located at the e-mail address tls@ietf.org (<mailto:tls@ietf.org>). Information on the group and information on how to subscribe to the list is at <https://www1.ietf.org/mailman/listinfo/tls> (<https://www1.ietf.org/mailman/listinfo/tls>)

Archives of the list can be found at: <https://www.ietf.org/mail-archive/web/tls/current/index.html> (<https://www.ietf.org/mail-archive/web/tls/current/index.html>)

Appendix F. Contributors

Many people have contributed to previous DTLS versions and they are acknowledged in prior versions of DTLS specifications or in the referenced specifications. The sequence number encryption concept is taken from the QUIC specification. We would like to thank the authors of the QUIC specification for their work. Felix Guenther and Martin Thomson contributed the analysis in Appendix B.

In addition, we would like to thank:

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Exported Authenticators in TLS
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Abstract

This document describes a mechanism that builds on Transport Layer Security (TLS) or Datagram Transport Layer Security (DTLS) and enables peers to provide a proof of ownership of an identity, such as an X.509 certificate. This proof can be exported by one peer, transmitted out-of-band to the other peer, and verified by the receiving peer.

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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1. Introduction

This document provides a way to authenticate one party of a Transport Layer Security (TLS) or Datagram Transport Layer Security (DTLS) connection to its peer using authentication messages created after the session has been established. This allows both the client and server to prove ownership of additional identities at any time after the handshake has completed. This proof of authentication can be exported and transmitted out-of-band from one party to be validated by its peer.

This mechanism provides two advantages over the authentication that TLS and DTLS natively provide:

multiple identities - Endpoints that are authoritative for multiple identities - but do not have a single certificate that includes all of the identities - can authenticate additional identities over a single connection.

spontaneous authentication - Endpoints can authenticate after a connection is established, in response to events in a higher-layer protocol, as well as integrating more context (such as context from the application).

Versions of TLS prior to TLS 1.3 used renegotiation as a way to enable post-handshake client authentication given an existing TLS connection. The mechanism described in this document may be used to replace the post-handshake authentication functionality provided by renegotiation. Unlike renegotiation, exported Authenticator-based post-handshake authentication does not require any changes at the TLS layer.

Post-handshake authentication is defined in section 4.6.3 of TLS 1.3 [RFC8446], but it has the disadvantage of requiring additional state to be stored as part of the TLS state machine. Furthermore, the authentication boundaries of TLS 1.3 post-handshake authentication align with TLS record boundaries, which are often not aligned with the authentication boundaries of the higher-layer protocol. For example, multiplexed connection protocols like HTTP/2 [RFC7540] do not have a notion of which TLS record a given message is a part of.

Exported Authenticators are meant to be used as a building block for application protocols. Mechanisms such as those required to advertise support and handle authentication errors are not handled by TLS (or DTLS).

The minimum version of TLS and DTLS required to implement the mechanisms described in this document are TLS 1.2 [RFC6347] and DTLS 1.2 [RFC5246].

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 uses terminology such as client, server, connection, handshake, endpoint, peer that are defined in section 1.1 of [RFC8446]. The term "initial connection" refers to the (D)TLS connection from which the exported authenticator messages are derived.

3. Message Sequences

There are two types of messages defined in this document: Authenticator Requests and Authenticators. These can be combined in the following three sequences:

Client Authentication

- * Server generates Authenticator Request
- * Client generates Authenticator from Server's Authenticator Request
- * Server validates Client's Authenticator

Server Authentication

- * Client generates Authenticator Request
- * Server generates Authenticator from Client's Authenticator Request
- * Client validates Server's Authenticator

Spontaneous Server Authentication

- * Server generates Authenticator
- * Client validates Server's Authenticator

4. Authenticator Request

The authenticator request is a structured message that can be created by either party of a (D)TLS connection using data exported from that connection. It can be transmitted to the other party of the (D)TLS connection at the application layer. The application layer protocol used to send the authenticator request SHOULD use a secure transport channel with equivalent security to TLS, such as QUIC [RFC9001], as its underlying transport to keep the request confidential. The application MAY use the existing (D)TLS connection to transport the authenticator.

An authenticator request message can be constructed by either the client or the server. Server-generated authenticator requests use the `CertificateRequest` message from Section 4.3.2 of [RFC8446]. Client-generated authenticator requests use a new message, called the `ClientCertificateRequest`, which uses the same structure as `CertificateRequest`. (Note that the latter is not a request for a client certificate, but rather a certificate request generated by the client.) These message structures are used even if the connection protocol is TLS 1.2 or DTLS 1.2.

The `CertificateRequest` and `ClientCertificateRequest` messages are used to define the parameters in a request for an authenticator. These are encoded as TLS handshake messages, including length and type fields. They do not include any TLS record layer framing and are not encrypted with a handshake or application-data key.

The structures are defined to be:

```
struct {
    opaque certificate_request_context<0..2^8-1>;
    Extension extensions<2..2^16-1>;
} ClientCertificateRequest;

struct {
    opaque certificate_request_context<0..2^8-1>;
    Extension extensions<2..2^16-1>;
} CertificateRequest;
```

`certificate_request_context`: An opaque string which identifies the authenticator request and which will be echoed in the authenticator message. A `certificate_request_context` value MUST be unique for each authenticator request within the scope of a connection (preventing replay and context confusion). The `certificate_request_context` SHOULD be chosen to be unpredictable to the peer (e.g., by randomly generating it) in order to prevent an attacker who has temporary access to the peer's private key from pre-computing valid authenticators. For example, the application may choose this value to correspond to a value used in an existing datastructure in the software to simplify implementation.

`extensions`: The set of extensions allowed in the `CertificateRequest` structure and the `ClientCertificateRequest` structure are those defined in the TLS ExtensionType Values IANA registry [RFC8447] containing CR in the TLS 1.3 column. In addition, the set of extensions in the `ClientCertificateRequest` structure MAY include the `server_name` [RFC6066] extension.

The uniqueness requirements of the `certificate_request_context` apply only to `CertificateRequest` and `ClientCertificateRequest` messages that are used as part of authenticator requests, but do apply across `CertificateRequest` and `ClientCertificateRequest` messages. A `certificate_request_context` value used in a `ClientCertificateRequest` cannot be used in an authenticator `CertificateRequest` on the same connection, and vice versa. There is no impact if the value of a `certificate_request_context` used in an authenticator request matches the value of a `certificate_request_context` in the handshake or in a post-handshake message.

5. Authenticator

The authenticator is a structured message that can be exported from either party of a (D)TLS connection. It can be transmitted to the other party of the (D)TLS connection at the application layer. The application layer protocol used to send the authenticator SHOULD use a secure transport channel with equivalent security to TLS, such as QUIC [RFC9001], as its underlying transport to keep the authenticator confidential. The application MAY use the existing (D)TLS connection to transport the authenticator.

An authenticator message can be constructed by either the client or the server given an established (D)TLS connection, an identity, such as an X.509 certificate, and a corresponding private key. Clients MUST NOT send an authenticator without a preceding authenticator request; for servers an authenticator request is optional. For authenticators that do not correspond to authenticator requests, the `certificate_request_context` is chosen by the server.

5.1. Authenticator Keys

Each authenticator is computed using a Handshake Context and Finished MAC Key derived from the (D)TLS connection. These values are derived using an exporter as described in Section 4 of [RFC5705] (for (D)TLS 1.2) or Section 7.5 of [RFC8446] (for (D)TLS 1.3). For (D)TLS 1.3, the `exporter_master_secret` MUST be used, not the `early_exporter_master_secret`. These values use different labels depending on the role of the sender:

- * The Handshake Context is an exporter value that is derived using the label "EXPORTER-client authenticator handshake context" or "EXPORTER-server authenticator handshake context" for authenticators sent by the client or server respectively.

- * The Finished MAC Key is an exporter value derived using the label "EXPORTER-client authenticator finished key" or "EXPORTER-server authenticator finished key" for authenticators sent by the client or server respectively.

The context_value used for the exporter is empty (zero length) for all four values. There is no need to include additional context information at this stage since the application-supplied context is included in the authenticator itself. The length of the exported value is equal to the length of the output of the hash function associated with the selected cipher suite (for TLS 1.3) or the hash function used for the pseudorandom function (PRF) (for (D)TLS 1.2). Exported authenticators cannot be used with (D)TLS 1.2 cipher suites that do not use the TLS PRF and with TLS 1.3 cipher suites that do not have an associated hash function. This hash is referred to as the authenticator hash.

To avoid key synchronization attacks, Exported Authenticators MUST NOT be generated or accepted on (D)TLS 1.2 connections that did not negotiate the extended master secret extension [RFC7627].

5.2. Authenticator Construction

An authenticator is formed from the concatenation of TLS 1.3 [RFC8446] Certificate, CertificateVerify, and Finished messages. These messages are encoded as TLS handshake messages, including length and type fields. They do not include any TLS record layer framing and are not encrypted with a handshake or application-data key.

If the peer populating the certificate_request_context field in an authenticator's Certificate message has already created or correctly validated an authenticator with the same value, then no authenticator should be constructed. If there is no authenticator request, the extensions are chosen from those presented in the (D)TLS handshake's ClientHello. Only servers can provide an authenticator without a corresponding request.

ClientHello extensions are used to determine permissible extensions in the server's unsolicited Certificate message in order to follow the general model for extensions in (D)TLS in which extensions can only be included as part of a Certificate message if they were previously sent as part of a CertificateRequest message or ClientHello message. This ensures that the recipient will be able to process such extensions.

5.2.1. Certificate

The Certificate message contains the identity to be used for authentication, such as the end-entity certificate and any supporting certificates in the chain. This structure is defined in [RFC8446], Section 4.4.2.

The Certificate message contains an opaque string called `certificate_request_context`, which is extracted from the authenticator request if present. If no authenticator request is provided, the `certificate_request_context` can be chosen arbitrarily but MUST be unique within the scope of the connection and be unpredictable to the peer.

Certificates chosen in the Certificate message MUST conform to the requirements of a Certificate message in the negotiated version of (D)TLS. In particular, the entries of `certificate_list` MUST be valid for the signature algorithms indicated by the peer in the "signature_algorithms" and "signature_algorithms_cert" extension, as described in Section 4.2.3 of [RFC8446] for (D)TLS 1.3 or from Sections 7.4.2 and 7.4.6 of [RFC5246] for (D)TLS 1.2.

In addition to "signature_algorithms" and "signature_algorithms_cert", the "server_name" [RFC6066], "certificate_authorities" (Section 4.2.4. of [RFC8446]), and "oid_filters" (Section 4.2.5. of [RFC8446]) extensions are used to guide certificate selection.

Only the X.509 certificate type defined in [RFC8446] is supported. Alternative certificate formats such as [RFC7250] Raw Public Keys are not supported in this version of the specification and their use in this context has not yet been analysed.

If an authenticator request was provided, the Certificate message MUST contain only extensions present in the authenticator request. Otherwise, the Certificate message MUST contain only extensions present in the (D)TLS ClientHello. Unrecognized extensions in the authenticator request MUST be ignored.

5.2.2. CertificateVerify

This message is used to provide explicit proof that an endpoint possesses the private key corresponding to its identity. The format of this message is taken from TLS 1.3:

```
struct {  
    SignatureScheme algorithm;  
    opaque signature<0..2^16-1>;  
} CertificateVerify;
```

The algorithm field specifies the signature algorithm used (see Section 4.2.3 of [RFC8446] for the definition of this field). The signature is a digital signature using that algorithm.

The signature scheme MUST be a valid signature scheme for TLS 1.3. This excludes all RSASSA-PKCS1-v1_5 algorithms and combinations of ECDSA and hash algorithms that are not supported in TLS 1.3.

If an authenticator request is present, the signature algorithm MUST be chosen from one of the signature schemes present in the "signature_algorithms" extension of the authenticator request. Otherwise, with spontaneous server authentication, the signature algorithm used MUST be chosen from the "signature_algorithms" sent by the peer in the ClientHello of the (D)TLS handshake. If there are no available signature algorithms, then no authenticator should be constructed.

The signature is computed using the chosen signature scheme over the concatenation of:

- * A string that consists of octet 32 (0x20) repeated 64 times
- * The context string "Exported Authenticator" (which is not NUL-terminated)
- * A single 0 octet which serves as the separator
- * The hashed authenticator transcript

The authenticator transcript is the hash of the concatenated Handshake Context, authenticator request (if present), and Certificate message:

Hash(Handshake Context || authenticator request || Certificate)

Where Hash is the authenticator hash defined in section 4.1. If the authenticator request is not present, it is omitted from this construction, i.e., it is zero-length.

If the party that generates the exported authenticator does so with a different connection than the party that is validating it, then the Handshake Context will not match, resulting in a CertificateVerify message that does not validate. This includes situations in which

the application data is sent via TLS-terminating proxy. Given a failed CertificateVerify validation, it may be helpful for the application to confirm that both peers share the same connection using a value derived from the connection secrets (such as the Handshake Context) before taking a user-visible action.

5.2.3. Finished

An HMAC [HMAC] over the hashed authenticator transcript, which is the concatenation of the Handshake Context, authenticator request (if present), Certificate, and CertificateVerify. The HMAC is computed using the authenticator hash, using the Finished MAC Key as a key.

```
Finished = HMAC(Finished MAC Key, Hash(Handshake Context ||  
    authenticator request || Certificate || CertificateVerify))
```

5.2.4. Authenticator Creation

An endpoint constructs an authenticator by serializing the Certificate, CertificateVerify, and Finished as TLS handshake messages and concatenating the octets:

```
Certificate || CertificateVerify || Finished
```

An authenticator is valid if the CertificateVerify message is correctly constructed given the authenticator request (if used) and the Finished message matches the expected value. When validating an authenticator, constant-time comparisons SHOULD be used for signature and MAC validation.

6. Empty Authenticator

If, given an authenticator request, the endpoint does not have an appropriate identity or does not want to return one, it constructs an authenticated refusal called an empty authenticator. This is a Finished message sent without a Certificate or CertificateVerify. This message is an HMAC over the hashed authenticator transcript with a Certificate message containing no CertificateEntries and the CertificateVerify message omitted. The HMAC is computed using the authenticator hash, using the Finished MAC Key as a key. This message is encoded as a TLS handshake message, including length and type field. It does not include TLS record layer framing and is not encrypted with a handshake or application-data key.

```
Finished = HMAC(Finished MAC Key, Hash(Handshake Context ||  
    authenticator request || Certificate))
```

7. API considerations

The creation and validation of both authenticator requests and authenticators SHOULD be implemented inside the (D)TLS library even if it is possible to implement it at the application layer. (D)TLS implementations supporting the use of exported authenticators SHOULD provide application programming interfaces by which clients and servers may request and verify exported authenticator messages.

Notwithstanding the success conditions described below, all APIs MUST fail if:

- * the connection uses a (D)TLS version of 1.1 or earlier, or
- * the connection is (D)TLS 1.2 and the extended master secret extension [RFC7627] was not negotiated

The following sections describe APIs that are considered necessary to implement exported authenticators. These are informative only.

7.1. The "request" API

The "request" API takes as input:

- * `certificate_request_context` (from 0 to 255 octets)
- * set of extensions to include (this MUST include `signature_algorithms`) and the contents thereof

It returns an authenticator request, which is a sequence of octets that comprises a `CertificateRequest` or `ClientCertificateRequest` message.

7.2. The "get context" API

The "get context" API takes as input:

- * authenticator or authenticator request

It returns the `certificate_request_context`.

7.3. The "authenticate" API

The "authenticate" API takes as input:

- * a reference to the initial connection

- * an identity, such as a set of certificate chains and associated extensions (OCSP [RFC6960], SCT [RFC6962], etc.)
- * a signer (either the private key associated with the identity, or interface to perform private key operations) for each chain
- * an authenticator request or `certificate_request_context` (from 0 to 255 octets)

It returns either the exported authenticator or an empty authenticator as a sequence of octets. It is recommended that the logic for selecting the certificates and extensions to include in the exporter is implemented in the TLS library. Implementing this in the TLS library lets the implementer take advantage of existing extension and certificate selection logic and more easily remember which extensions were sent in the ClientHello.

It is also possible to implement this API outside of the TLS library using TLS exporters. This may be preferable in cases where the application does not have access to a TLS library with these APIs or when TLS is handled independently of the application layer protocol.

7.4. The "validate" API

The "validate" API takes as input:

- * a reference to the initial connection
- * an optional authenticator request
- * an authenticator
- * a function for validating a certificate chain

It returns a status to indicate whether the authenticator is valid or not after applying the function for validating the certificate chain to the chain contained in the authenticator. If validation is successful, it also returns the identity, such as the certificate chain and its extensions.

The API should return a failure if the `certificate_request_context` of the authenticator was used in a different authenticator that was previously validated. Well-formed empty authenticators are returned as invalid.

When validating an authenticator, constant-time comparison should be used.

8. IANA Considerations

8.1. Update of the TLS ExtensionType Registry

IANA is requested to update the entry for `server_name(0)` in the registry for ExtensionType (defined in [RFC8446]) by replacing the value in the "TLS 1.3" column with the value "CH, EE, CR" and adding this document in the "Reference" column.

IANA is also requested to add the following note to the registry:

The addition of the "CR" to the "TLS 1.3" column for the `server_name(0)` extension only marks the extension as valid in a ClientCertificateRequest created as part of client-generated authenticator requests.

8.2. Update of the TLS Exporter Labels Registry

IANA is requested to add the following entries to the registry for Exporter Labels (defined in [RFC5705]): "EXPORTER-client authenticator handshake context", "EXPORTER-server authenticator handshake context", "EXPORTER-client authenticator handshake context", "EXPORTER-client authenticator finished key" and "EXPORTER-server authenticator finished key" with "DTLS-OK" and "Recommended" set to "Y" and this document added to the "Reference" column.

8.3. Update of the TLS HandshakeType Registry

IANA is requested to add the following entry to the registry for HandshakeType (defined in [RFC8446]): "client_certificate_request" with "DTLS-OK" and "Recommended" set to "Y" and this document added to the "Reference" column with the following in the "Note" column: "Used in TLS versions prior to 1.3."

9. Security Considerations

The Certificate/Verify/Finished pattern intentionally looks like the TLS 1.3 pattern which now has been analyzed several times. For example, [SIGMAC] presents a relevant framework for analysis, and section 10. of [RFC8446] contains a comprehensive set of references.

Authenticators are independent and unidirectional. There is no explicit state change inside TLS when an authenticator is either created or validated. The application in possession of a validated authenticator can rely on any semantics associated with data in the `certificate_request_context`.

- * This property makes it difficult to formally prove that a server is jointly authoritative over multiple identities, rather than individually authoritative over each.
- * There is no indication in (D)TLS about which point in time an authenticator was computed. Any feedback about the time of creation or validation of the authenticator should be tracked as part of the application layer semantics if required.

The signatures generated with this API cover the context string "Exported Authenticator" and therefore cannot be transplanted into other protocols.

In TLS 1.3 the client can not explicitly learn from the TLS layer whether its Finished message was accepted. Because the application traffic keys are not dependent on the client's final flight, receiving messages from the server does not prove that the server received the client's Finished. To avoid disagreement between the client and server on the authentication status of EAs, servers MUST verify the client Finished before sending an EA or processing a received EA.

10. Acknowledgements

Comments on this proposal were provided by Martin Thomson.
Suggestions for Section 9 were provided by Karthikeyan Bhargavan.

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IANA Registry Updates for Transport Layer Security (TLS) and Datagram
Transport Layer Security (DTLS)
draft-ietf-tls-iana-registry-updates-05

Abstract

This document describes a number of changes to (D)TLS IANA registries that range from adding notes to the registry all the way to changing the registration policy. These changes were mostly motivated by WG review of the (D)TLS-related registries undertaken as part of the TLS1.3 development process.

This document updates the following RFCs: 3749, 5077, 4680, 5246, 5705, 5878, 6520, 7301.

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1. Process Note

As the authors of this draft are also the WG chairs, the responsible Area Director has agreed to judge consensus.

RFC EDITOR: Please delete section prior to publication.

2. Introduction

This document instructs IANA to make changes to a number of Transport Layer Security and Datagram Transport Layer Security ((D)TLS) related IANA registries. These changes were almost entirely motivated by the development of TLS1.3 [I-D.ietf-tls-tls13].

The changes introduced by this document range from simple, e.g., adding notes, to complex, e.g., changing a registry's registration policy. Instead of listing the changes and their rationale in this, the introductory section, each section provides rationale for the proposed change(s).

This document proposes no changes to the registration policies for TLS Alert [I-D.ietf-tls-tls13], TLS ContentType [I-D.ietf-tls-tls13], TLS HandshakeType [I-D.ietf-tls-tls13], and TLS Certificate Status Types [RFC6961] registries; the existing policies (Standards Action for the first three; IETF Review for the last), are appropriate for these one-byte code points because of their scarcity.

3. 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.

4. Add "TLS" to Registry Names

For consistency amongst TLS registries, IANA [SHALL prepend/has prepended] "TLS" to the following registries:

- o Application-Layer Protocol Negotiation (ALPN) Protocol IDs [RFC7301],
- o ExtensionType Values,
- o Heartbeat Message Types [RFC6520], and
- o Heartbeat Modes [RFC6520].

IANA [SHALL update/has updated] the reference for these four registries to also refer to this document. The remainder of this document will use the registry names with the "TLS" prefix.

5. Aligning with RFC 8126

Many of the TLS-related IANA registries were defined prior to [RFC8126] where "IETF Consensus" was used instead of the RFC8126-defined "IETF Review". To align with the new terminology, IANA [SHALL update/has updated] the following registries to use "IETF Review" in place of "IETF Consensus":

- o TLS Authorization Data Formats [RFC4680]

- o TLS Supplemental Data Formats (SupplementalDataType) [RFC5878]

This is not a universal change as some registries originally defined with "IETF Consensus" are undergoing other changes either as a result of this document or [I-D.ietf-tls-rfc4492bis].

IANA [SHALL update/has updated] the reference for these two registries to also refer to this document.

6. Adding Recommended Column

The instructions in this document add a Recommended column to many of the TLS registries to indicate parameters that are generally recommended for implementations to support. Adding a Recommended parameter to a registry or updating a parameter to Recommended status requires standards action. Not all parameters defined in standards track documents need to be marked as Recommended.

If an item is not marked as Recommended it does not necessarily mean that it is flawed, rather, it indicates that either the item has not been through the IETF consensus process, has limited applicability, or is intended only for specific use cases.

7. Session Ticket TLS Extension

The nomenclature for the registry entries in the TLS ExtensionType Values registry correspond to the presentation language field name except for entry 35. To ensure that the values in the registry are consistently identified in the registry, IANA:

- o [SHALL rename/has renamed] entry 35 to "session_ticket (renamed from "SessionTicket TLS")" [RFC5077].
- o [SHALL add/has added] a reference to this document in the Reference column for entry 35.

8. TLS ExtensionType Values

Experience has shown that the IETF Review registry policy for TLS Extensions was too strict. Based on WG consensus, the decision was taken to change the registration policy to Specification Required [RFC8126] while reserving a small part of the code space for experimental and private use. Therefore, IANA [SHALL update/has updated] the TLS ExtensionType Values registry to:

- o Change the registry policy to:

Values with the first byte in the range 0-254 (decimal) are assigned via Specification Required [RFC8126]. Values with the first byte 255 (decimal) are reserved for Private Use [RFC8126].

- o Update the "Reference" to also refer to this document.

See Section 18 for additional information about the designated expert pool.

Despite wanting to "loosen" the registration policies for TLS Extensions, it is still useful to indicate in the IANA registry which extensions the WG recommends be supported. Therefore, IANA [SHALL update/has updated] the TLS ExtensionType Values registry to:

- o Add a "Recommended" column with the contents as listed below. This table has been generated by marking Standards Track RFCs as "Yes" and all others as "No". Future extensions MUST define the value of the Recommended column. In order to register an extension with the value "Yes", a Standards Track document [RFC8126] is REQUIRED. IESG Approval is REQUIRED for a Yes->No transition.

Extension	Recommended
server_name	Yes
max_fragment_length	Yes
client_certificate_url	Yes
trusted_ca_keys	Yes
truncated_hmac	Yes
status_request	Yes
user_mapping	Yes
client_authz	No
server_authz	No
cert_type	Yes
supported_groups	Yes
ec_point_formats	Yes

srp	No
signature_algorithms	Yes
use_srtp	Yes
heartbeat	Yes
application_layer_protocol_negotiation	Yes
status_request_v2	Yes
signed_certificate_timestamp	No
client_certificate_type	Yes
server_certificate_type	Yes
padding	Yes
encrypt_then_mac	Yes
extended_master_secret	Yes
cached_info	Yes
session_ticket	Yes
renegotiation_info	Yes

IANA [SHALL update/has added] the following notes:

Note: The role of the designation expert is described in [this-RFC]. The designated expert [RFC8126] ensures that the specification is publicly available. An Internet Draft that is posted and never published or a standard in another standards body, industry consortium, university site, etc. suffices. The expert may provide more in depth reviews, but their approval should not be taken as an endorsement of the extension.

Note: As specified in [RFC8126], assignments made in the Private Use space are not generally useful for broad interoperability. It is the responsibility of those making use of the Private Use range to ensure that no conflicts occur (within the intended scope of use). For widespread experiments, temporary reservations are available.

Note: Extensions marked as "Yes" are those allocated via Standards Track RFCs. Extensions marked as "No" are not.

Note: If an item is not marked as Recommended it does not necessarily mean that it is flawed; rather, it indicates that either the item has not been through the IETF consensus process, has limited applicability, or is intended only for specific use cases.

NOTE: token_binding is omitted from the above table; [I-D.ietf-tokbind-negotiation] specifies the Recommended column for this extension.

NOTE: The following is from [I-D.ietf-tls-tls13] and is included here to ensure alignment between these specifications.

[I-D.ietf-tls-tls13] also uses the TLS ExtensionType Registry originally created in [RFC4366]. IANA has updated it to reference this document. The registry and its allocation policy is listed below:

- o IANA [SHALL update/has updated] this registry to include the "key_share", "pre_shared_key", "psk_key_exchange_modes", "early_data", "cookie", "supported_versions", "certificate_authorities", "oid_filters", "post_handshake_auth", and "signature_algorithms_certs", extensions with the values defined in this document and the Recommended value of "Yes".
- o IANA [SHALL update/has updated] this registry to include a "TLS 1.3" column which lists the messages in which the extension may appear. This column [SHALL be/has been] initially populated from the table in Section 4.2 of [I-D.ietf-tls-tls13] with any extension not listed there marked as "-" to indicate that it is not used by TLS 1.3.

9. TLS Cipher Suite Registry

Experience has shown that the IETF Consensus registry policy for TLS Cipher Suites was too strict. Based on WG consensus, the decision was taken to change the TLS Cipher Suite registry's registration policy to Specification Required [RFC8126] while reserving a small part of the code space for experimental and private use. Therefore, IANA [SHALL update/has updated] the TLS Cipher Suite registry's policy as follows:

Values with the first byte in the range 0-254 (decimal) are assigned via Specification Required {{RFC8126}}. Values with the first byte 255 (decimal) are reserved for Private Use {{RFC8126}}.

See Section 18 for additional information about the designated expert pool.

The cipher suite registry has grown significantly and will continue to do so. To better guide those not intimately involved in TLS, IANA [shall update/has updated] the TLS Cipher Suite registry as follows:

- o Add a "Recommended" column to the TLS Cipher Suite registry. The cipher suites that follow in the two tables are marked as "Yes". All other cipher suites are marked as "No". Future cipher suites MUST define the value of the Recommended column. In order to register an extension with the value "Yes, a Standards Track document [RFC8126] is REQUIRED. IESG Approval is REQUIRED for a Yes->No transition.

The cipher suites that follow are standards track server-authenticated (and optionally client-authenticated) cipher suites which are currently available in TLS 1.2.

RFC EDITOR: The previous paragraph is for document reviewers and is not meant for the registry.

Cipher Suite Name	Value
TLS_DHE_RSA_WITH_AES_128_GCM_SHA256	{0x00,0x9E}
TLS_DHE_RSA_WITH_AES_256_GCM_SHA384	{0x00,0x9F}
TLS_ECDHE_ECDSA_WITH_AES_128_GCM_SHA256	{0xC0,0x2B}
TLS_ECDHE_ECDSA_WITH_AES_256_GCM_SHA384	{0xC0,0x2C}
TLS_ECDHE_RSA_WITH_AES_128_GCM_SHA256	{0xC0,0x2F}
TLS_ECDHE_RSA_WITH_AES_256_GCM_SHA384	{0xC0,0x30}
TLS_DHE_RSA_WITH_AES_128_CCM	{0xC0,0x9E}
TLS_DHE_RSA_WITH_AES_256_CCM	{0xC0,0x9F}
TLS_ECDHE_RSA_WITH_CHACHA20_POLY1305_SHA256	{0xCC,0xA8}
TLS_ECDHE_ECDSA_WITH_CHACHA20_POLY1305_SHA256	{0xCC,0xA9}
TLS_DHE_RSA_WITH_CHACHA20_POLY1305_SHA256	{0xCC,0xAA}

The cipher suites that follow are standards track ephemeral pre-shared key cipher suites which are available in TLS 1.2. [RFC6655] is inconsistent with respect to the ordering of components within PSK AES CCM cipher suite names; those names are used here without modification.

RFC EDITOR: The previous paragraph is for document reviewers and is not meant for the registry.

Cipher Suite Name	Value
TLS_DHE_PSK_WITH_AES_128_GCM_SHA256	{0x00,0xAA}
TLS_DHE_PSK_WITH_AES_256_GCM_SHA384	{0x00,0xAB}
TLS_DHE_PSK_WITH_AES_128_CCM	{0xC0,0xA6}
TLS_DHE_PSK_WITH_AES_256_CCM	{0xC0,0xA7}
TLS_ECDHE_PSK_WITH_AES_128_GCM_SHA256	{TBD}
TLS_ECDHE_PSK_WITH_AES_256_GCM_SHA384	{TBD}
TLS_ECDHE_PSK_WITH_AES_128_CCM_SHA256	{TBD}
TLS_ECDHE_PSK_WITH_CHACHA20_POLY1305_SHA256	{0xCC,0xAC}
TLS_DHE_PSK_WITH_CHACHA20_POLY1305_SHA256	{0xCC,0xAD}

Despite the following behavior being misguided, experience has shown that some customers use the IANA registry as checklist against which to measure an implementation's completeness and some implementers blindly implement cipher suites. Therefore, IANA [SHALL add/has added] the following warning to the registry:

WARNING: Cryptographic algorithms and parameters will be broken or weakened over time. Blindly implementing cipher suites listed here is not advised. Implementers and users need to check that the cryptographic algorithms listed continue to provide the expected level of security.

IANA [SHALL add/has added] the following note to ensure that those that focus on IANA registries are aware that TLS 1.3 [I-D.ietf-tls-tls13] uses the same registry but defines ciphers differently:

Note: Although TLS 1.3 uses the same cipher suite space as previous versions of TLS, TLS 1.3 cipher suites are defined differently, only specifying the symmetric ciphers, and cannot be used for TLS 1.2. Similarly, TLS 1.2 and lower cipher suite values cannot be used with TLS 1.3.

IANA [SHALL add/has added] the following notes to document the rules for populating the Recommended column:

Note: Cipher suites marked as "Yes" are those allocated via Standards Track RFCs. Cipher suites marked as "No" are not; cipher suites marked "No" range from "good" to "bad" from a cryptographic standpoint.

Note: CCM_8 cipher suites are not marked as Recommended. These cipher suites have a significantly truncated authentication tag that represents a security trade-off that may not be appropriate for general environments.

Note: If an item is not marked as Recommended it does not necessarily mean that it is flawed; rather, it indicates that either the item has not been through the IETF consensus process, has limited applicability, or is intended only for specific use cases.

IANA [SHALL add/has added] the following notes for additional information:

Note: The role of the signature expert is described in [this-RFC]. The designated expert [RFC8126] ensures that the specification is publicly available. An Internet Draft that is posted and never published or a standard in another standards body, industry consortium, university site, etc. suffices. The expert may provide more in depth reviews, but their approval should not be taken as an endorsement of the cipher suite.

Note: As specified in [RFC8126], assignments made in the Private Use space are not generally useful for broad interoperability. It is the responsibility of those making use of the Private Use range to ensure that no conflicts occur (within the intended scope of use). For widespread experiments, temporary reservations are available.

IANA [SHALL update/has updated] the reference for this registry to also refer to this document.

10. TLS Supported Groups

Similar to cipher suites, supported groups have proliferated over time and some use the registry to measure implementations. Therefore, IANA [SHALL add/has added] a "Recommended" column with a "Yes" for secp256r1, secp384r1, x25519, and x448 while all others are "No". These "Yes" groups are taken from Standards Track RFCs; [I-D.ietf-tls-rfc4492bis] elevates secp256r1 and secp384r1 to Standards Track. Not all groups from [I-D.ietf-tls-rfc4492bis], which is standards track, are marked as "Yes"; these groups apply to TLS 1.3 [I-D.ietf-tls-tls13] and previous versions of TLS. Future supported groups MUST define the value of this column. In order to register an extension with the value "Yes", a Standards Track document [RFC8126] is REQUIRED. IESG Approval is REQUIRED for a Yes->No transition.

IANA [SHALL add/has added] the following note:

Note: Supported Groups marked as "Yes" are those allocated via Standards Track RFCs. Supported Groups marked as "No" are not; supported groups marked "No" range from "good" to "bad" from a cryptographic standpoint.

Note: If an item is not marked as Recommended it does not necessarily mean that it is flawed; rather, it indicates that either the item has not been through the IETF consensus process, has limited applicability, or is intended only for specific use cases.

Note: The role of the designation expert is described in [this-RFC]. The designated expert [RFC8126] ensures that the specification is publicly available. An Internet Draft that is posted and never published or a standard in another standards body, industry consortium, university site, etc. suffices. The expert may provide more in depth reviews, but their approval should not be taken as an endorsement of the supported group.

Despite the following behavior being misguided, experience has shown that some customers use the IANA registry as checklist against which to measure an implementation's completeness and some implementers blindly implement groups supported. Therefore, IANA [SHALL add/has added] the following warning to the registry:

WARNING: Cryptographic algorithms and parameters will be broken or weakened over time. Blindly implementing cipher suites listed here is not advised. Implementers and users need to check that the cryptographic algorithms listed continue to provide the expected level of security.

IANA [SHALL update/has updated] the reference for this registry to also refer to this document.

The value 0 (0x0000) is to be marked as reserved.

11. TLS ClientCertificateType Identifiers

Experience has shown that the IETF Consensus registry policy for TLS ClientCertificateType Identifiers is too strict. Based on WG consensus, the decision was taken to change registration policy to Specification Required [RFC8126] while reserving a small part of the code space for experimental and private use. Therefore, IANA [SHALL update/has updated] the TLS Cipher Suite registry's policy as follows:

Values in the range 0-223 are assigned via Specification Required [RFC8126]. Values 224-255 are reserved for Private Use.

See Section 18 for additional information about the designated expert pool.

IANA [SHALL add/has added] the following notes:

Note: The role of the signature expert is described in [this-RFC]. The designated expert [RFC8126] ensures that the specification is publicly available. An Internet Draft that is posted and never published or a standard in another standards body, industry consortium, university site, etc. suffices. The expert may provide more in depth reviews, but their approval should not be taken as an endorsement of the identifier.

Note: As specified in [RFC8126], assignments made in the Private Use space are not generally useful for broad interoperability. It is the responsibility of those making use of the Private Use range to ensure that no conflicts occur (within the intended scope of use). For widespread experiments, temporary reservations are available.

Note: ClientCertificateType Identifiers marked as "Yes" are those allocated via Standards Track RFCs. ClientCertificateTypes marked as "No" are not.

Note: If an item is not marked as Recommended it does not necessarily mean that it is flawed; rather, it indicates that either the item has not been through the IETF consensus process, has limited applicability, or is intended only for specific use cases.

12. New Session Ticket TLS Handshake Message Type

To align with TLS implementations and to align the naming nomenclature with other Handshake message types, IANA:

- o [SHALL rename/has renamed] entry 4 in the TLS HandshakeType registry to "new_session_ticket (renamed from NewSessionTicket)" [RFC5077].
- o [SHALL add/has added] a reference to this document in the Reference column for entry 4 in the TLS HandshakeType registry.

13. TLS Exporter Label Registry

To aid those reviewers who start with the IANA registry, IANA [SHALL add/has added]:

- o The following note to the TLS Exporter Label Registry:

Note: [RFC5705] defines keying material exporters for TLS in terms of the TLS PRF. [I-D.ietf-tls-tls13] replaced the PRF with HKDF, thus requiring a new construction. The exporter interface remains the same, however the value is computed differently.

- o A "Recommended" column to the TLS Exporter Label registry. The table that follows has been generated by marking Standards Track RFCs as "Yes" and all others as "No". Future exporters MUST define the value of this column. In order to register an extension with the value "Yes", a Standards Track document [RFC8126] is REQUIRED. IESG Approval is REQUIRED for a Yes->No transition.

Exporter Value	Recommended
client finished	Yes
server finished	Yes
master secret	Yes
key expansion	Yes
client EAP encryption	Yes
ttls keying material	Yes
ttls challenge	Yes
EXTRACTOR-dtls_srtp	Yes
EXPORTER_DTLS_OVER_SCTP	Yes
EXPORTER: teap session key seed	Yes

To provide additional information for the designated experts, IANA [SHALL add/has added] the following note:

Note: The role of the designation expert is described in [this-RFC]. The designated expert [RFC8126] ensures that the specification is publicly available. An Internet Draft that is posted and never published or a standard in another standards body, industry consortium, university site, etc. suffices. The expert may provide more in depth reviews, but their approval should not be taken as an endorsement of the exporter. The expert also verifies that the label is a string consisting of printable ASCII characters beginning with "EXPORTER". IANA MUST also verify that one label is not a prefix of any other label. For example, labels "key" or "master secretary" are forbidden.

Note: Exporters Labels marked as "Yes" are those allocated via Standards Track RFCs. Exporter Labels marked as "No" are not.

Note: If an item is not marked as Recommended it does not necessarily mean that it is flawed; rather, it indicates that either the item has not been through the IETF consensus process, has limited applicability, or is intended only for specific use cases.

IANA [SHALL update/has updated] the reference for this registry to also refer to this document.

14. Add Missing Item to TLS Alert Registry

IANA [SHALL add/has added] the following entry to the TLS Alert Registry; the entry was omitted from the IANA instructions in [RFC7301]:

```
120    no_application_protocol    Y    [RFC7301][this-RFC]
```

15. TLS Certificate Types

Experience has shown that the IETF Consensus registry policy for TLS Certificate Types is too strict. Based on WG consensus, the decision was taken to change registration policy to Specification Required [RFC8126] while reserving a small part of the code space for experimental and private use. Therefore, IANA [SHALL change/has changed] the TLS Certificate Types registry to:

- o Change the registry policy to:

Values with the first byte in the range 0-223 (decimal) are assigned via Specification Required [RFC8126]. Values with the first byte 224-255 (decimal) are reserved for Private Use [RFC8126].

- o Add a "Recommended" column to the registry. X.509 and Raw Public Key are "Yes". All others are "No". In order to register an extension with the value "Yes", a Standards Track document [RFC8126] is REQUIRED. Future Certificate Types MUST define the value of this column. A Standards Track document [RFC8126] is REQUIRED to register an entry with the value "Yes". IESG Approval is REQUIRED for a Yes->No transition.

See Section 18 for additional information about the designated expert pool.

IANA [SHALL add/has added] the following note:

Note: The role of the designation expert is described in [this-RFC]. The designated expert [RFC8126] ensures that the specification is publicly available. An Internet Draft that is posted and never published or a standard in another standards body, industry consortium, university site, etc. suffices. The expert may provide more in depth reviews, but their approval should not be taken as an endorsement of the certificate type.

Note: Certificate Types marked as "Yes" are those allocated via Standards Track RFCs. Certificate Types marked as "No" are not.

Note: If an item is not marked as Recommended it does not necessarily mean that it is flawed; rather, it indicates that either the item has not been through the IETF consensus process, has limited applicability, or is intended only for specific use cases.

IANA [SHALL update/has updated] the reference for this registry to also refer this document.

16. Orphaned Extensions

To make it clear that (D)TLS 1.3 has orphaned certain extensions (i.e., some extensions are only applicable to version of (D)TLS prior to 1.3), IANA [SHALL add/has added] the following note to the TLS ExtensionType Values registry:

Note: The following extensions are only applicable to (D)TLS protocol versions prior to 1.3: `trusted_ca_keys`, `truncated_hmac`, `user_mapping`, `cert_type`, `ec_point_formats`, `srp`, `status_request_v2`, `encrypt_then_mac`, `extended_master_secret`, `session_ticket`, and `renegotiation_info`. These extensions are not applicable to (D)TLS 1.3.

17. Orphaned Registries

To make it clear that (D)TLS 1.3 has orphaned certain registries (i.e., they are only applicable to version of (D)TLS protocol versions prior to 1.3), IANA:

- o [SHALL add/has added] the following to the TLS Compression Method Identifiers registry [RFC3749]:

Note: Value 0 (NULL) is the only value in this registry applicable to (D)TLS protocol version 1.3 or later.

- o [SHALL add/has added] the following to the TLS HashAlgorithm [RFC5246] and TLS SignatureAlgorithm registries [RFC5246]:

Note: The values in this registry are only applicable to (D)TLS protocol versions prior to 1.3. (D)TLS 1.3 and later versions' values are registered in the TLS SignatureScheme registry.

- o [SHALL update/has updated] the "Reference" field in the TLS Compression Method Identifiers, TLS HashAlgorithm and TLS SignatureAlgorithm registries to also refer to this document.

- o [SHALL update/has updated] the TLS HashAlgorithm Registry to list values 7 and 9-223 as "Reserved" and the TLS SignatureAlgorithm registry to list values 4-6 and 9-223 as "Reserved".

Despite the fact that the HashAlgorithm and SignatureAlgorithm registries are orphaned, it is still important to warn implementers of pre-TLS1.3 implementations about the dangers of blindly implementing cryptographic algorithms. Therefore, IANA [SHALL add/has added] the following warning to the HashAlgorithm and SignatureAlgorithm:

WARNING: Cryptographic algorithms and parameters will be broken or weakened over time. Blindly implementing the cryptographic algorithms listed here is not advised. Implementers and users need to check that the cryptographic algorithms listed continue to provide the expected level of security.

18. Designated Expert Pool

Specification Required [RFC8126] registry requests are registered after a three-week review period on the `tls-reg-review@ietf.org` mailing list, on the advice of one or more Designated Experts. However, to allow for the allocation of values prior to publication, the Designated Experts may approve registration once they are satisfied that such a specification will be published.

Registration requests sent to the mailing list for review SHOULD use an appropriate subject (e.g., "Request to register value in TLS bar registry").

Within the review period, the Designated Experts will either approve or deny the registration request, communicating this decision to the review list and IANA. Denials SHOULD include an explanation and, if applicable, suggestions as to how to make the request successful. Registration requests that are undetermined for a period longer than 21 days can be brought to the IESG's attention (using the `iesg@ietf.org` mailing list) for resolution.

Criteria that SHOULD be applied by the Designated Experts includes determining whether the proposed registration duplicates existing functionality, whether it is likely to be of general applicability or useful only for a single application, and whether the registration description is clear.

IANA MUST only accept registry updates from the Designated Experts and SHOULD direct all requests for registration to the review mailing list.

It is suggested that multiple Designated Experts be appointed who are able to represent the perspectives of different applications using this specification, in order to enable broadly informed review of registration decisions. In cases where a registration decision could be perceived as creating a conflict of interest for a particular Expert, that Expert SHOULD defer to the judgment of the other Experts.

19. Security Considerations

The change to Specification Required from IETF Review lowers the amount of review provided by the WG for cipher suites and supported groups. This change reflects reality in that the WG essentially provided no cryptographic review of the cipher suites or supported groups. This was especially true of national cipher suites.

Recommended algorithms are regarded as secure for general use at the time of registration, however, cryptographic algorithms and parameters will be broken or weakened over time. It is possible that the Recommended status in the registry lags behind the most recent advances in cryptanalysis. Implementers and users need to check that the cryptographic algorithms listed continue to provide the expected level of security.

Designated experts ensure the specification is publicly available. They may provide more in depth reviews. Their review should not be taken as an endorsement of the cipher suite, extension, supported group, etc.

20. IANA Considerations

This document is entirely about changes to TLS-related IANA registries.

21. References

21.1. Normative References

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March 20, 2018

The Transport Layer Security (TLS) Protocol Version 1.3
draft-ietf-tls-tls13-28

Abstract

This document specifies version 1.3 of the Transport Layer Security (TLS) protocol. TLS allows client/server applications to communicate over the Internet in a way that is designed to prevent eavesdropping, tampering, and message forgery.

This document updates RFCs 4492, 5705, and 6066 and it obsoletes RFCs 5077, 5246, and 6961. This document also specifies new requirements for TLS 1.2 implementations.

Status of This Memo

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1. Introduction

RFC EDITOR: PLEASE REMOVE THE FOLLOWING PARAGRAPH The source for this draft is maintained in GitHub. Suggested changes should be submitted as pull requests at <https://github.com/tlswg/tls13-spec>. Instructions are on that page as well. Editorial changes can be managed in GitHub, but any substantive change should be discussed on the TLS mailing list.

The primary goal of TLS is to provide a secure channel between two communicating peers; the only requirement from the underlying transport is a reliable, in-order, data stream. Specifically, the secure channel should provide the following properties:

- Authentication: The server side of the channel is always authenticated; the client side is optionally authenticated. Authentication can happen via asymmetric cryptography (e.g., RSA [RSA], ECDSA [ECDSA], EdDSA [RFC8032]) or a pre-shared key (PSK).
- Confidentiality: Data sent over the channel after establishment is only visible to the endpoints. TLS does not hide the length of the data it transmits, though endpoints are able to pad TLS records in order to obscure lengths and improve protection against traffic analysis techniques.
- Integrity: Data sent over the channel after establishment cannot be modified by attackers.

These properties should be true even in the face of an attacker who has complete control of the network, as described in [RFC3552]. See Appendix E for a more complete statement of the relevant security properties.

TLS consists of two primary components:

- A handshake protocol (Section 4) that authenticates the communicating parties, negotiates cryptographic modes and parameters, and establishes shared keying material. The handshake protocol is designed to resist tampering; an active attacker should not be able to force the peers to negotiate different parameters than they would if the connection were not under attack.
- A record protocol (Section 5) that uses the parameters established by the handshake protocol to protect traffic between the communicating peers. The record protocol divides traffic up into a series of records, each of which is independently protected using the traffic keys.

TLS is application protocol independent; higher-level protocols can layer on top of TLS transparently. The TLS standard, however, does not specify how protocols add security with TLS; how to initiate TLS handshaking and how to interpret the authentication certificates exchanged are left to the judgment of the designers and implementors of protocols that run on top of TLS.

This document defines TLS version 1.3. While TLS 1.3 is not directly compatible with previous versions, all versions of TLS incorporate a versioning mechanism which allows clients and servers to interoperably negotiate a common version if one is supported by both peers.

This document supersedes and obsoletes previous versions of TLS including version 1.2 [RFC5246]. It also obsoletes the TLS ticket mechanism defined in [RFC5077] and replaces it with the mechanism defined in Section 2.2. Section 4.2.7 updates [RFC4492] by modifying the protocol attributes used to negotiate Elliptic Curves. Because TLS 1.3 changes the way keys are derived, it updates [RFC5705] as described in Section 7.5. It also changes how OCSP messages are carried and therefore updates [RFC6066] and obsoletes [RFC6961] as described in section Section 4.4.2.1.

1.1. 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.

The following terms are used:

client: The endpoint initiating the TLS connection.

connection: A transport-layer connection between two endpoints.

endpoint: Either the client or server of the connection.

handshake: An initial negotiation between client and server that establishes the parameters of their subsequent interactions within TLS.

peer: An endpoint. When discussing a particular endpoint, "peer" refers to the endpoint that is not the primary subject of discussion.

receiver: An endpoint that is receiving records.

sender: An endpoint that is transmitting records.

server: The endpoint which did not initiate the TLS connection.

1.2. Change Log

RFC EDITOR PLEASE DELETE THIS SECTION.

(*) indicates changes to the wire protocol which may require implementations to update.

draft-28

Add a section on exposure of PSK identities.

draft-27

- SHOULD->MUST for being able to process "supported_versions" without 0x0304.
- Much editorial cleanup.

draft-26

- Clarify that you can't negotiate pre-TLS 1.3 with supported_versions.

draft-25

- Add the header to additional data (*)
- Minor clarifications.
- IANA cleanup.

draft-24

- Require that CH2 have version 0303 (*)
- Some clarifications

draft-23

- Renumber key_share (*)
- Add a new extension and new code points to allow negotiating PSS separately for certificates and CertificateVerify (*)

- Slightly restrict when CCS must be accepted to make implementation easier.
- Document protocol invariants
- Add some text on the security of static RSA.

draft-22

- Implement changes for improved middlebox penetration (*)
- Move `server_certificate_type` to encrypted extensions (*)
- Allow resumption with a different SNI (*)
- Padding extension can change on HRR (*)
- Allow an empty `ticket_nonce` (*)
- Remove requirement to immediately respond to `close_notify` with `close_notify` (allowing half-close)

draft-21

- Add a per-ticket nonce so that each ticket is associated with a different PSK (*).
- Clarify that clients should send alerts with the handshake key if possible.
- Update state machine to show rekeying events
- Add discussion of 0-RTT and replay. Recommend that implementations implement some anti-replay mechanism.

draft-20

- Add `"post_handshake_auth"` extension to negotiate post-handshake authentication (*).
- Shorten labels for HKDF-Expand-Label so that we can fit within one compression block (*).
- Define how RFC 7250 works (*).
- Re-enable post-handshake client authentication even when you do PSK. The previous prohibition was editorial error.

- Remove `cert_type` and `user_mapping`, which don't work on TLS 1.3 anyway.
- Added the `no_application_protocol` alert from [RFC7301] to the list of extensions.
- Added discussion of traffic analysis and side channel attacks.

draft-19

- Hash `context_value` input to Exporters (*).
- Add an additional Derive-Secret stage to Exporters (*).
- Hash `ClientHello1` in the transcript when HRR is used. This reduces the state that needs to be carried in cookies. (*)
- Restructure `CertificateRequest` to have the selectors in extensions. This also allowed defining a "certificate_authorities" extension which can be used by the client instead of `trusted_ca_keys` (*).
- Tighten record framing requirements and require checking of them (*).
- Consolidate "ticket_early_data_info" and "early_data" into a single extension (*).
- Change `end_of_early_data` to be a handshake message (*).
- Add pre-extract Derive-Secret stages to key schedule (*).
- Remove spurious requirement to implement "pre_shared_key".
- Clarify location of "early_data" from server (it goes in EE, as indicated by the table in S 10).
- Require peer public key validation
- Add state machine diagram.

draft-18

- Remove unnecessary `resumption_psk` which is the only thing expanded from the resumption master secret. (*)
- Fix `signature_algorithms` entry in extensions table.

- Restate rule from RFC 6066 that you can't resume unless SNI is the same.

draft-17

- Remove 0-RTT Finished and resumption_context, and replace with a psk_binder field in the PSK itself (*)
- Restructure PSK key exchange negotiation modes (*)
- Add max_early_data_size field to TicketEarlyDataInfo (*)
- Add a 0-RTT exporter and change the transcript for the regular exporter (*)
- Merge TicketExtensions and Extensions registry. Changes ticket_early_data_info code point (*)
- Replace Client.key_shares in response to HRR (*)
- Remove redundant labels for traffic key derivation (*)
- Harmonize requirements about cipher suite matching: for resumption you need to match KDF but for 0-RTT you need whole cipher suite. This allows PSKs to actually negotiate cipher suites. (*)
- Move SCT and OCSP into Certificate.extensions (*)
- Explicitly allow non-offered extensions in NewSessionTicket
- Explicitly allow predicting client Finished for NST
- Clarify conditions for allowing 0-RTT with PSK

draft-16

- Revise version negotiation (*)
- Change RSASSA-PSS and EdDSA SignatureScheme codepoints for better backwards compatibility (*)
- Move HelloRetryRequest.selected_group to an extension (*)
- Clarify the behavior of no exporter context and make it the same as an empty context. (*)

- New KeyUpdate format that allows for requesting/not-requesting an answer. This also means changes to the key schedule to support independent updates (*)
- New certificate_required alert (*)
- Forbid CertificateRequest with 0-RTT and PSK.
- Relax requirement to check SNI for 0-RTT.

draft-15

- New negotiation syntax as discussed in Berlin (*)
- Require CertificateRequest.context to be empty during handshake (*)
- Forbid empty tickets (*)
- Forbid application data messages in between post-handshake messages from the same flight (*)
- Clean up alert guidance (*)
- Clearer guidance on what is needed for TLS 1.2.
- Guidance on 0-RTT time windows.
- Rename a bunch of fields.
- Remove old PRNG text.
- Explicitly require checking that handshake records not span key changes.

draft-14

- Allow cookies to be longer (*)
- Remove the "context" from EarlyDataIndication as it was undefined and nobody used it (*)
- Remove 0-RTT EncryptedExtensions and replace the ticket_age extension with an obfuscated version. Also necessitates a change to NewSessionTicket (*).
- Move the downgrade sentinel to the end of ServerHello.Random to accommodate tlsdate (*).

- Define `ecdsa_shal (*)`.
- Allow resumption even after fatal alerts. This matches current practice.
- Remove non-closure warning alerts. Require treating unknown alerts as fatal.
- Make the rules for accepting 0-RTT less restrictive.
- Clarify 0-RTT backward-compatibility rules.
- Clarify how 0-RTT and PSK identities interact.
- Add a section describing the data limits for each cipher.
- Major editorial restructuring.
- Replace the Security Analysis section with a WIP draft.

draft-13

- Allow server to send `SupportedGroups`.
- Remove 0-RTT client authentication
- Remove (EC)DHE 0-RTT.
- Flesh out 0-RTT PSK mode and shrink `EarlyDataIndication`
- Turn PSK-resumption response into an index to save room
- Move `CertificateStatus` to an extension
- Extra fields in `NewSessionTicket`.
- Restructure key schedule and add a `resumption_context` value.
- Require DH public keys and secrets to be zero-padded to the size of the group.
- Remove the redundant length fields in `KeyShareEntry`.
- Define a cookie field for HRR.

draft-12

- Provide a list of the PSK cipher suites.

- Remove the ability for the ServerHello to have no extensions (this aligns the syntax with the text).
- Clarify that the server can send application data after its first flight (0.5 RTT data)
- Revise signature algorithm negotiation to group hash, signature algorithm, and curve together. This is backwards compatible.
- Make ticket lifetime mandatory and limit it to a week.
- Make the purpose strings lower-case. This matches how people are implementing for interop.
- Define exporters.
- Editorial cleanup

draft-11

- Port the CFRG curves & signatures work from RFC4492bis.
- Remove sequence number and version from additional_data, which is now empty.
- Reorder values in HkdfLabel.
- Add support for version anti-downgrade mechanism.
- Update IANA considerations section and relax some of the policies.
- Unify authentication modes. Add post-handshake client authentication.
- Remove early_handshake content type. Terminate 0-RTT data with an alert.
- Reset sequence number upon key change (as proposed by Fournet et al.)

draft-10

- Remove ClientCertificateTypes field from CertificateRequest and add extensions.
- Merge client and server key shares into a single extension.

draft-09

- Change to RSA-PSS signatures for handshake messages.
- Remove support for DSA.
- Update key schedule per suggestions by Hugo, Hoeteck, and Bjoern Tackmann.
- Add support for per-record padding.
- Switch to encrypted record ContentType.
- Change HKDF labeling to include protocol version and value lengths.
- Shift the final decision to abort a handshake due to incompatible certificates to the client rather than having servers abort early.
- Deprecate SHA-1 with signatures.
- Add MTI algorithms.

draft-08

- Remove support for weak and lesser used named curves.
- Remove support for MD5 and SHA-224 hashes with signatures.
- Update lists of available AEAD cipher suites and error alerts.
- Reduce maximum permitted record expansion for AEAD from 2048 to 256 octets.
- Require digital signatures even when a previous configuration is used.
- Merge EarlyDataIndication and KnownConfiguration.
- Change code point for server_configuration to avoid collision with server_hello_done.
- Relax certificate_list ordering requirement to match current practice.

draft-07

- Integration of semi-ephemeral DH proposal.
- Add initial 0-RTT support.

- Remove resumption and replace with PSK + tickets.
- Move ClientKeyShare into an extension.
- Move to HKDF.

draft-06

- Prohibit RC4 negotiation for backwards compatibility.
- Freeze & deprecate record layer version field.
- Update format of signatures with context.
- Remove explicit IV.

draft-05

- Prohibit SSL negotiation for backwards compatibility.
- Fix which MS is used for exporters.

draft-04

- Modify key computations to include session hash.
- Remove ChangeCipherSpec.
- Renumber the new handshake messages to be somewhat more consistent with existing convention and to remove a duplicate registration.
- Remove renegotiation.
- Remove point format negotiation.

draft-03

- Remove GMT time.
- Merge in support for ECC from RFC 4492 but without explicit curves.
- Remove the unnecessary length field from the AD input to AEAD ciphers.
- Rename {Client,Server}KeyExchange to {Client,Server}KeyShare.
- Add an explicit HelloRetryRequest to reject the client's.

draft-02

- Increment version number.
- Rework handshake to provide 1-RTT mode.
- Remove custom DHE groups.
- Remove support for compression.
- Remove support for static RSA and DH key exchange.
- Remove support for non-AEAD ciphers.

1.3. Major Differences from TLS 1.2

The following is a list of the major functional differences between TLS 1.2 and TLS 1.3. It is not intended to be exhaustive and there are many minor differences.

- The list of supported symmetric algorithms has been pruned of all algorithms that are considered legacy. Those that remain all use Authenticated Encryption with Associated Data (AEAD) algorithms. The ciphersuite concept has been changed to separate the authentication and key exchange mechanisms from the record protection algorithm (including secret key length) and a hash to be used with the key derivation function and HMAC.
- A 0-RTT mode was added, saving a round-trip at connection setup for some application data, at the cost of certain security properties.
- Static RSA and Diffie-Hellman cipher suites have been removed; all public-key based key exchange mechanisms now provide forward secrecy.
- All handshake messages after the ServerHello are now encrypted. The newly introduced EncryptedExtension message allows various extensions previously sent in clear in the ServerHello to also enjoy confidentiality protection from active attackers.
- The key derivation functions have been re-designed. The new design allows easier analysis by cryptographers due to their improved key separation properties. The HMAC-based Extract-and-Expand Key Derivation Function (HKDF) is used as an underlying primitive.

- The handshake state machine has been significantly restructured to be more consistent and to remove superfluous messages such as ChangeCipherSpec (except when needed for middlebox compatibility).
- Elliptic curve algorithms are now in the base spec and new signature algorithms, such as ed25519 and ed448, are included. TLS 1.3 removed point format negotiation in favor of a single point format for each curve.
- Other cryptographic improvements including the removal of compression and custom DHE groups, changing the RSA padding to use RSASSA-PSS, and the removal of DSA.
- The TLS 1.2 version negotiation mechanism has been deprecated in favor of a version list in an extension. This increases compatibility with existing servers that incorrectly implemented version negotiation.
- Session resumption with and without server-side state as well as the PSK-based ciphersuites of earlier TLS versions have been replaced by a single new PSK exchange.
- Updated references to point to the updated versions of RFCs, as appropriate (e.g., RFC 5280 rather than RFC 3280).

1.4. Updates Affecting TLS 1.2

This document defines several changes that optionally affect implementations of TLS 1.2, including those which do not also support TLS 1.3:

- A version downgrade protection mechanism is described in Section 4.1.3.
- RSASSA-PSS signature schemes are defined in Section 4.2.3.
- The "supported_versions" ClientHello extension can be used to negotiate the version of TLS to use, in preference to the legacy_version field of the ClientHello.
- The "signature_algorithms_cert" extension allows a client to indicate which signature algorithms it can validate in X.509 certificates

Additionally, this document clarifies some compliance requirements for earlier versions of TLS; see Section 9.3.

2. Protocol Overview

The cryptographic parameters used by the secure channel are produced by the TLS handshake protocol. This sub-protocol of TLS is used by the client and server when first communicating with each other. The handshake protocol allows peers to negotiate a protocol version, select cryptographic algorithms, optionally authenticate each other, and establish shared secret keying material. Once the handshake is complete, the peers use the established keys to protect the application layer traffic.

A failure of the handshake or other protocol error triggers the termination of the connection, optionally preceded by an alert message (Section 6).

TLS supports three basic key exchange modes:

- (EC)DHE (Diffie-Hellman over either finite fields or elliptic curves)
- PSK-only
- PSK with (EC)DHE

Figure 1 below shows the basic full TLS handshake:

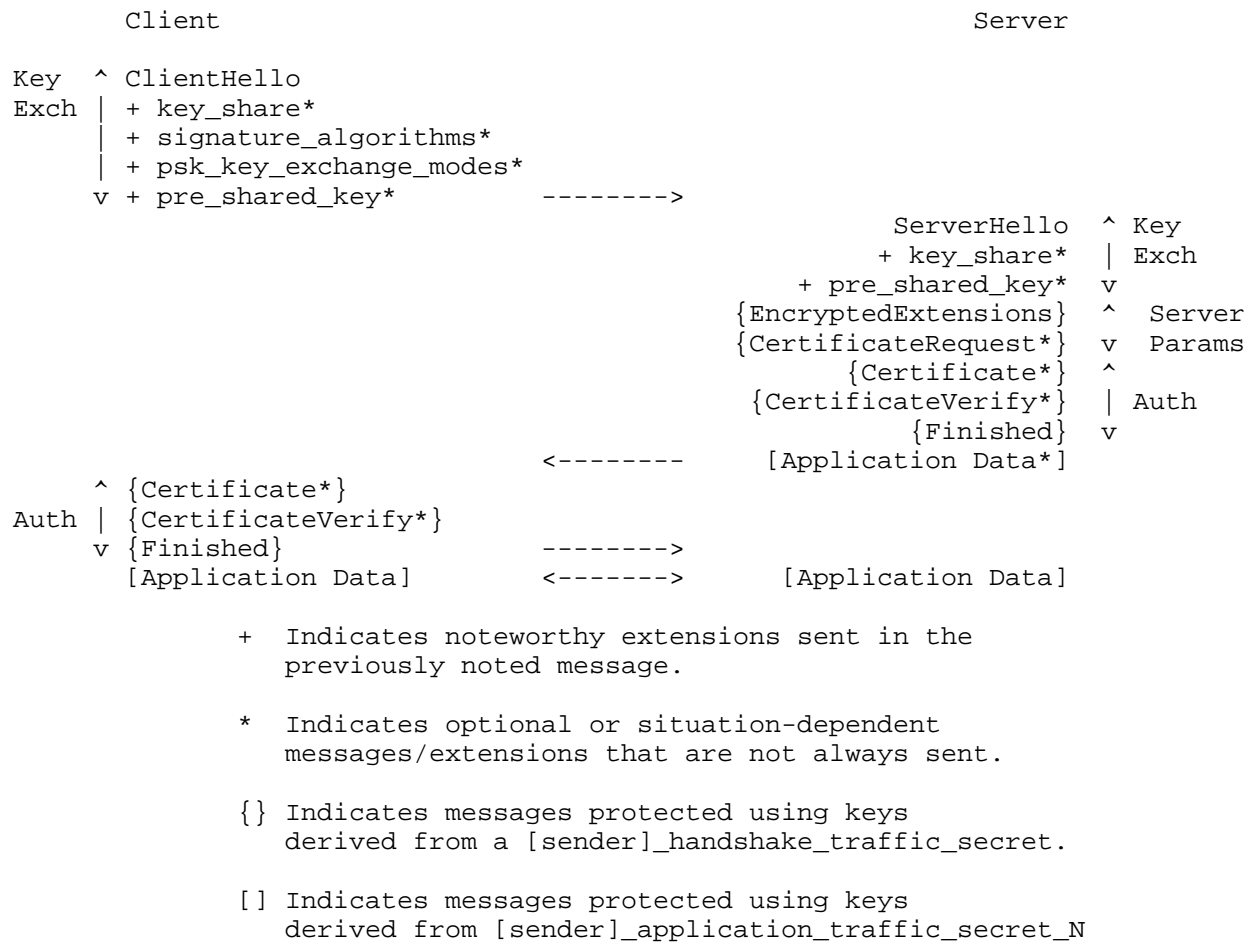


Figure 1: Message flow for full TLS Handshake

The handshake can be thought of as having three phases (indicated in the diagram above):

- Key Exchange: Establish shared keying material and select the cryptographic parameters. Everything after this phase is encrypted.
- Server Parameters: Establish other handshake parameters (whether the client is authenticated, application layer protocol support, etc.).
- Authentication: Authenticate the server (and optionally the client) and provide key confirmation and handshake integrity.

In the Key Exchange phase, the client sends the ClientHello (Section 4.1.2) message, which contains a random nonce (ClientHello.random); its offered protocol versions; a list of symmetric cipher/HKDF hash pairs; either a set of Diffie-Hellman key shares (in the "key_share" extension Section 4.2.8), a set of pre-shared key labels (in the "pre_shared_key" extension Section 4.2.11) or both; and potentially additional extensions. Additional fields and/or messages may also be present for middlebox compatibility.

The server processes the ClientHello and determines the appropriate cryptographic parameters for the connection. It then responds with its own ServerHello (Section 4.1.3), which indicates the negotiated connection parameters. The combination of the ClientHello and the ServerHello determines the shared keys. If (EC)DHE key establishment is in use, then the ServerHello contains a "key_share" extension with the server's ephemeral Diffie-Hellman share; the server's share MUST be in the same group as one of the client's shares. If PSK key establishment is in use, then the ServerHello contains a "pre_shared_key" extension indicating which of the client's offered PSKs was selected. Note that implementations can use (EC)DHE and PSK together, in which case both extensions will be supplied.

The server then sends two messages to establish the Server Parameters:

EncryptedExtensions: responses to ClientHello extensions that are not required to determine the cryptographic parameters, other than those that are specific to individual certificates.
[Section 4.3.1]

CertificateRequest: if certificate-based client authentication is desired, the desired parameters for that certificate. This message is omitted if client authentication is not desired.
[Section 4.3.2]

Finally, the client and server exchange Authentication messages. TLS uses the same set of messages every time that certificate-based authentication is needed. (PSK-based authentication happens as a side effect of key exchange.) Specifically:

Certificate: the certificate of the endpoint and any per-certificate extensions. This message is omitted by the server if not authenticating with a certificate and by the client if the server did not send CertificateRequest (thus indicating that the client should not authenticate with a certificate). Note that if raw public keys [RFC7250] or the cached information extension [RFC7924] are in use, then this message will not contain a

certificate but rather some other value corresponding to the server's long-term key. [Section 4.4.2]

CertificateVerify: a signature over the entire handshake using the private key corresponding to the public key in the Certificate message. This message is omitted if the endpoint is not authenticating via a certificate. [Section 4.4.3]

Finished: a MAC (Message Authentication Code) over the entire handshake. This message provides key confirmation, binds the endpoint's identity to the exchanged keys, and in PSK mode also authenticates the handshake. [Section 4.4.4]

Upon receiving the server's messages, the client responds with its Authentication messages, namely Certificate and CertificateVerify (if requested), and Finished.

At this point, the handshake is complete, and the client and server derive the keying material required by the record layer to exchange application-layer data protected through authenticated encryption. Application data **MUST NOT** be sent prior to sending the Finished message, except as specified in [Section 2.3]. Note that while the server may send application data prior to receiving the client's Authentication messages, any data sent at that point is, of course, being sent to an unauthenticated peer.

2.1. Incorrect DHE Share

If the client has not provided a sufficient "key_share" extension (e.g., it includes only DHE or ECDHE groups unacceptable to or unsupported by the server), the server corrects the mismatch with a HelloRetryRequest and the client needs to restart the handshake with an appropriate "key_share" extension, as shown in Figure 2. If no common cryptographic parameters can be negotiated, the server **MUST** abort the handshake with an appropriate alert.

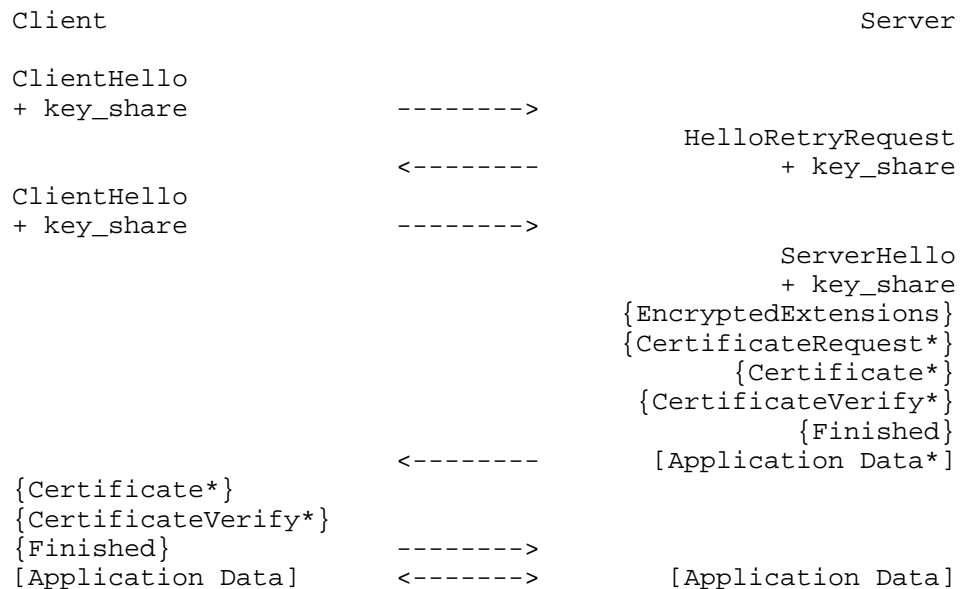


Figure 2: Message flow for a full handshake with mismatched parameters

Note: The handshake transcript incorporates the initial ClientHello/HelloRetryRequest exchange; it is not reset with the new ClientHello.

TLS also allows several optimized variants of the basic handshake, as described in the following sections.

2.2. Resumption and Pre-Shared Key (PSK)

Although TLS PSKs can be established out of band, PSKs can also be established in a previous connection and then used to establish a new connection ("session resumption" or "resuming" with a PSK). Once a handshake has completed, the server can send to the client a PSK identity that corresponds to a unique key derived from the initial handshake (see Section 4.6.1). The client can then use that PSK identity in future handshakes to negotiate the use of the associated PSK. If the server accepts the PSK, then the security context of the new connection is cryptographically tied to the original connection and the key derived from the initial handshake is used to bootstrap the cryptographic state instead of a full handshake. In TLS 1.2 and below, this functionality was provided by "session IDs" and "session tickets" [RFC5077]. Both mechanisms are obsoleted in TLS 1.3.

PSKs can be used with (EC)DHE key exchange in order to provide forward secrecy in combination with shared keys, or can be used

alone, at the cost of losing forward secrecy for the application data.

Figure 3 shows a pair of handshakes in which the first establishes a PSK and the second uses it:

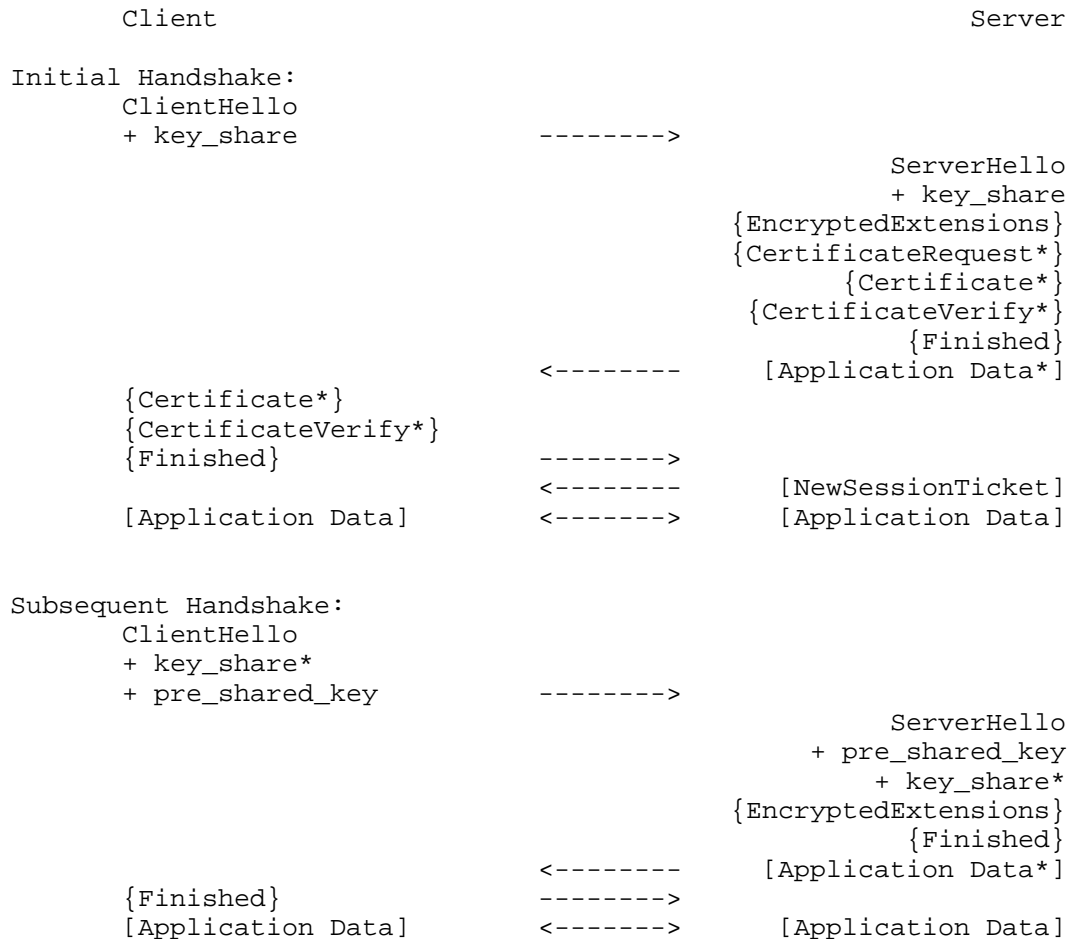


Figure 3: Message flow for resumption and PSK

As the server is authenticating via a PSK, it does not send a Certificate or a CertificateVerify message. When a client offers resumption via PSK, it SHOULD also supply a "key_share" extension to the server to allow the server to decline resumption and fall back to a full handshake, if needed. The server responds with a "pre_shared_key" extension to negotiate use of PSK key establishment

and can (as shown here) respond with a "key_share" extension to do (EC)DHE key establishment, thus providing forward secrecy.

When PSKs are provisioned out of band, the PSK identity and the KDF hash algorithm to be used with the PSK MUST also be provisioned.

Note: When using an out-of-band provisioned pre-shared secret, a critical consideration is using sufficient entropy during the key generation, as discussed in [RFC4086]. Deriving a shared secret from a password or other low-entropy sources is not secure. A low-entropy secret, or password, is subject to dictionary attacks based on the PSK binder. The specified PSK authentication is not a strong password-based authenticated key exchange even when used with Diffie-Hellman key establishment. Specifically, it does not prevent an attacker that can observe the handshake from performing a brute-force attack on the password/pre-shared key.

2.3. 0-RTT Data

When clients and servers share a PSK (either obtained externally or via a previous handshake), TLS 1.3 allows clients to send data on the first flight ("early data"). The client uses the PSK to authenticate the server and to encrypt the early data.

As shown in Figure 4, the 0-RTT data is just added to the 1-RTT handshake in the first flight. The rest of the handshake uses the same messages as for a 1-RTT handshake with PSK resumption.

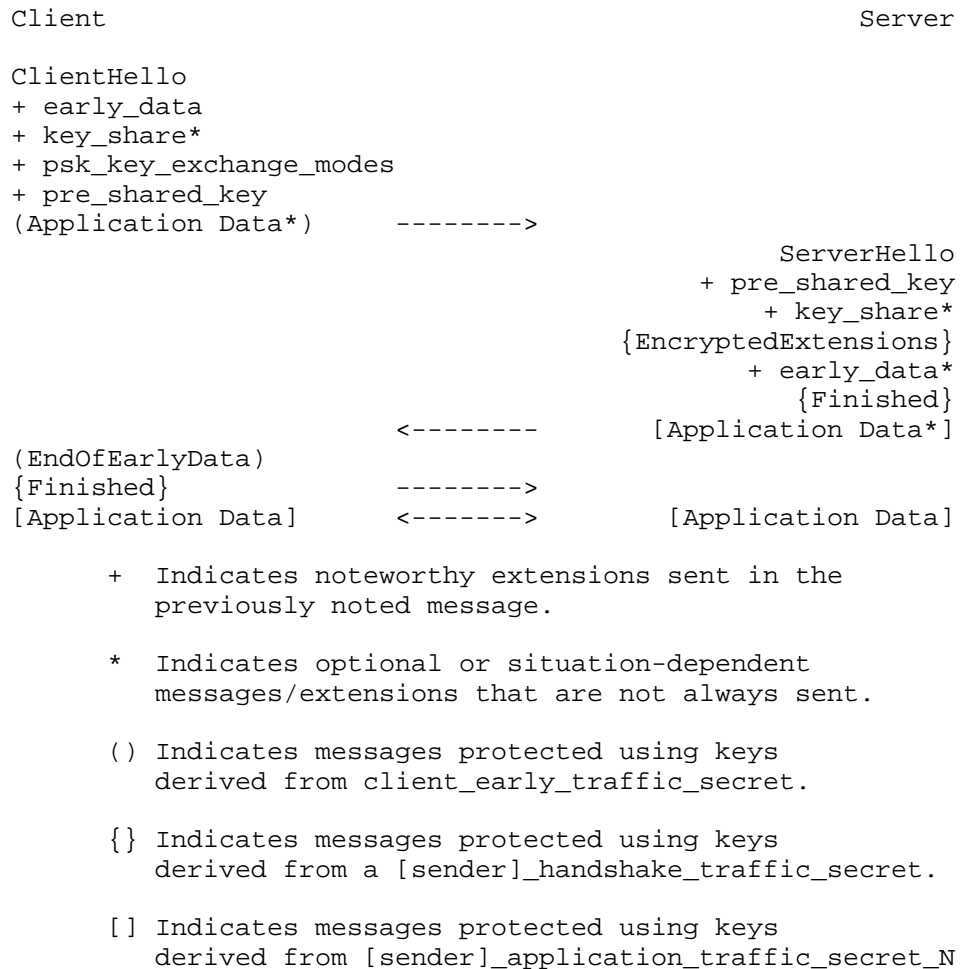


Figure 4: Message flow for a zero round trip handshake

IMPORTANT NOTE: The security properties for 0-RTT data are weaker than those for other kinds of TLS data. Specifically:

1. This data is not forward secret, as it is encrypted solely under keys derived using the offered PSK.
2. There are no guarantees of non-replay between connections. Protection against replay for ordinary TLS 1.3 1-RTT data is provided via the server's Random value, but 0-RTT data does not depend on the ServerHello and therefore has weaker guarantees. This is especially relevant if the data is authenticated either with TLS client authentication or inside the application

protocol. The same warnings apply to any use of the `early_exporter_master_secret`.

0-RTT data cannot be duplicated within a connection (i.e., the server will not process the same data twice for the same connection) and an attacker will not be able to make 0-RTT data appear to be 1-RTT data (because it is protected with different keys.) Appendix E.5 contains a description of potential attacks and Section 8 describes mechanisms which the server can use to limit the impact of replay.

3. Presentation Language

This document deals with the formatting of data in an external representation. The following very basic and somewhat casually defined presentation syntax will be used.

3.1. Basic Block Size

The representation of all data items is explicitly specified. The basic data block size is one byte (i.e., 8 bits). Multiple byte data items are concatenations of bytes, from left to right, from top to bottom. From the byte stream, a multi-byte item (a numeric in the example) is formed (using C notation) by:

```
value = (byte[0] << 8*(n-1)) | (byte[1] << 8*(n-2)) |  
        ... | byte[n-1];
```

This byte ordering for multi-byte values is the commonplace network byte order or big-endian format.

3.2. Miscellaneous

Comments begin with `/*` and end with `*/`.

Optional components are denoted by enclosing them in `"[]"` double brackets.

Single-byte entities containing uninterpreted data are of type `opaque`.

A type alias `T'` for an existing type `T` is defined by:

```
T T';
```


3.3. Numbers

The basic numeric data type is an unsigned byte (uint8). All larger numeric data types are formed from fixed-length series of bytes concatenated as described in Section 3.1 and are also unsigned. The following numeric types are predefined.

```
uint8 uint16[2];
uint8 uint24[3];
uint8 uint32[4];
uint8 uint64[8];
```

All values, here and elsewhere in the specification, are transmitted in network byte (big-endian) order; the uint32 represented by the hex bytes 01 02 03 04 is equivalent to the decimal value 16909060.

3.4. Vectors

A vector (single-dimensioned array) is a stream of homogeneous data elements. The size of the vector may be specified at documentation time or left unspecified until runtime. In either case, the length declares the number of bytes, not the number of elements, in the vector. The syntax for specifying a new type, T', that is a fixed-length vector of type T is

```
T T'[n];
```

Here, T' occupies n bytes in the data stream, where n is a multiple of the size of T. The length of the vector is not included in the encoded stream.

In the following example, Datum is defined to be three consecutive bytes that the protocol does not interpret, while Data is three consecutive Datum, consuming a total of nine bytes.

```
opaque Datum[3];          /* three uninterpreted bytes */
Datum Data[9];             /* 3 consecutive 3-byte vectors */
```

Variable-length vectors are defined by specifying a subrange of legal lengths, inclusively, using the notation <floor..ceiling>. When these are encoded, the actual length precedes the vector's contents in the byte stream. The length will be in the form of a number consuming as many bytes as required to hold the vector's specified maximum (ceiling) length. A variable-length vector with an actual length field of zero is referred to as an empty vector.

```
T T'<floor..ceiling>;
```

In the following example, mandatory is a vector that must contain between 300 and 400 bytes of type opaque. It can never be empty. The actual length field consumes two bytes, a uint16, which is sufficient to represent the value 400 (see Section 3.3). Similarly, longer can represent up to 800 bytes of data, or 400 uint16 elements, and it may be empty. Its encoding will include a two-byte actual length field prepended to the vector. The length of an encoded vector must be an exact multiple of the length of a single element (e.g., a 17-byte vector of uint16 would be illegal).

```
opaque mandatory<300..400>;
    /* length field is 2 bytes, cannot be empty */
uint16 longer<0..800>;
    /* zero to 400 16-bit unsigned integers */
```

3.5. Enumerateds

An additional sparse data type is available called enum or enumerated. Each definition is a different type. Only enumerateds of the same type may be assigned or compared. Every element of an enumerated must be assigned a value, as demonstrated in the following example. Since the elements of the enumerated are not ordered, they can be assigned any unique value, in any order.

```
enum { e1(v1), e2(v2), ... , en(vn) [[, (n)]] } Te;
```

Future extensions or additions to the protocol may define new values. Implementations need to be able to parse and ignore unknown values unless the definition of the field states otherwise.

An enumerated occupies as much space in the byte stream as would its maximal defined ordinal value. The following definition would cause one byte to be used to carry fields of type Color.

```
enum { red(3), blue(5), white(7) } Color;
```

One may optionally specify a value without its associated tag to force the width definition without defining a superfluous element.

In the following example, Taste will consume two bytes in the data stream but can only assume the values 1, 2, or 4 in the current version of the protocol.

```
enum { sweet(1), sour(2), bitter(4), (32000) } Taste;
```

The names of the elements of an enumeration are scoped within the defined type. In the first example, a fully qualified reference to the second element of the enumeration would be Color.blue. Such

qualification is not required if the target of the assignment is well specified.

```
Color color = Color.blue;      /* overspecified, legal */
Color color = blue;           /* correct, type implicit */
```

The names assigned to enumerations do not need to be unique. The numerical value can describe a range over which the same name applies. The value includes the minimum and maximum inclusive values in that range, separated by two period characters. This is principally useful for reserving regions of the space.

```
enum { sad(0), meh(1..254), happy(255) } Mood;
```

3.6. Constructed Types

Structure types may be constructed from primitive types for convenience. Each specification declares a new, unique type. The syntax for definition is much like that of C.

```
struct {
    T1 f1;
    T2 f2;
    ...
    Tn fn;
} T;
```

Fixed- and variable-length vector fields are allowed using the standard vector syntax. Structures V1 and V2 in the variants example below demonstrate this.

The fields within a structure may be qualified using the type's name, with a syntax much like that available for enumerations. For example, T.f2 refers to the second field of the previous declaration.

3.7. Constants

Fields and variables may be assigned a fixed value using "=", as in:

```
struct {
    T1 f1 = 8; /* T.f1 must always be 8 */
    T2 f2;
} T;
```

3.8. Variants

Defined structures may have variants based on some knowledge that is available within the environment. The selector must be an enumerated type that defines the possible variants the structure defines. Each arm of the select specifies the type of that variant's field and an optional field label. The mechanism by which the variant is selected at runtime is not prescribed by the presentation language.

```
struct {  
    T1 f1;  
    T2 f2;  
    ....  
    Tn fn;  
    select (E) {  
        case e1: T1 [[fe1]];  
        case e2: T2 [[fe2]];  
        ....  
        case en: Tn [[fen]];  
    };  
} Tv;
```

For example:

```
enum { apple(0), orange(1) } VariantTag;  
  
struct {  
    uint16 number;  
    opaque string<0..10>; /* variable length */  
} V1;  
  
struct {  
    uint32 number;  
    opaque string[10]; /* fixed length */  
} V2;  
  
struct {  
    VariantTag type;  
    select (VariantRecord.type) {  
        case apple: V1;  
        case orange: V2;  
    };  
} VariantRecord;
```

4. Handshake Protocol

The handshake protocol is used to negotiate the security parameters of a connection. Handshake messages are supplied to the TLS record layer, where they are encapsulated within one or more TLSPlaintext or TLSCiphertext structures, which are processed and transmitted as specified by the current active connection state.

```
enum {
    client_hello(1),
    server_hello(2),
    new_session_ticket(4),
    end_of_early_data(5),
    encrypted_extensions(8),
    certificate(11),
    certificate_request(13),
    certificate_verify(15),
    finished(20),
    key_update(24),
    message_hash(254),
    (255)
} HandshakeType;

struct {
    HandshakeType msg_type;      /* handshake type */
    uint24 length;              /* bytes in message */
    select (Handshake.msg_type) {
        case client_hello:      ClientHello;
        case server_hello:      ServerHello;
        case end_of_early_data:  EndOfEarlyData;
        case encrypted_extensions: EncryptedExtensions;
        case certificate_request: CertificateRequest;
        case certificate:        Certificate;
        case certificate_verify: CertificateVerify;
        case finished:           Finished;
        case new_session_ticket: NewSessionTicket;
        case key_update:         KeyUpdate;
    };
} Handshake;
```

Protocol messages MUST be sent in the order defined in Section 4.4.1 and shown in the diagrams in Section 2. A peer which receives a handshake message in an unexpected order MUST abort the handshake with an "unexpected_message" alert.

New handshake message types are assigned by IANA as described in Section 11.

4.1. Key Exchange Messages

The key exchange messages are used to determine the security capabilities of the client and the server and to establish shared secrets including the traffic keys used to protect the rest of the handshake and the data.

4.1.1. Cryptographic Negotiation

In TLS, the cryptographic negotiation proceeds by the client offering the following four sets of options in its ClientHello:

- A list of cipher suites which indicates the AEAD algorithm/HKDF hash pairs which the client supports.
- A "supported_groups" (Section 4.2.7) extension which indicates the (EC)DHE groups which the client supports and a "key_share" (Section 4.2.8) extension which contains (EC)DHE shares for some or all of these groups.
- A "signature_algorithms" (Section 4.2.3) extension which indicates the signature algorithms which the client can accept.
- A "pre_shared_key" (Section 4.2.11) extension which contains a list of symmetric key identities known to the client and a "psk_key_exchange_modes" (Section 4.2.9) extension which indicates the key exchange modes that may be used with PSKs.

If the server does not select a PSK, then the first three of these options are entirely orthogonal: the server independently selects a cipher suite, an (EC)DHE group and key share for key establishment, and a signature algorithm/certificate pair to authenticate itself to the client. If there is no overlap between the received "supported_groups" and the groups supported by the server then the server MUST abort the handshake with a "handshake_failure" or an "insufficient_security" alert.

If the server selects a PSK, then it MUST also select a key establishment mode from the set indicated by client's "psk_key_exchange_modes" extension (at present, PSK alone or with (EC)DHE). Note that if the PSK can be used without (EC)DHE then non-overlap in the "supported_groups" parameters need not be fatal, as it is in the non-PSK case discussed in the previous paragraph.

If the server selects an (EC)DHE group and the client did not offer a compatible "key_share" extension in the initial ClientHello, the server MUST respond with a HelloRetryRequest (Section 4.1.4) message.

If the server successfully selects parameters and does not require a HelloRetryRequest, it indicates the selected parameters in the ServerHello as follows:

- If PSK is being used, then the server will send a "pre_shared_key" extension indicating the selected key.
- If PSK is not being used, then (EC)DHE and certificate-based authentication are always used.
- When (EC)DHE is in use, the server will also provide a "key_share" extension.
- When authenticating via a certificate, the server will send the Certificate (Section 4.4.2) and CertificateVerify (Section 4.4.3) messages. In TLS 1.3 as defined by this document, either a PSK or a certificate is always used, but not both. Future documents may define how to use them together.

If the server is unable to negotiate a supported set of parameters (i.e., there is no overlap between the client and server parameters), it MUST abort the handshake with either a "handshake_failure" or "insufficient_security" fatal alert (see Section 6).

4.1.2. Client Hello

When a client first connects to a server, it is REQUIRED to send the ClientHello as its first TLS message. The client will also send a ClientHello when the server has responded to its ClientHello with a HelloRetryRequest. In that case, the client MUST send the same ClientHello without modification, except:

- If a "key_share" extension was supplied in the HelloRetryRequest, replacing the list of shares with a list containing a single KeyShareEntry from the indicated group.
- Removing the "early_data" extension (Section 4.2.10) if one was present. Early data is not permitted after HelloRetryRequest.
- Including a "cookie" extension if one was provided in the HelloRetryRequest.
- Updating the "pre_shared_key" extension if present by recomputing the "obfuscated_ticket_age" and binder values and (optionally) removing any PSKs which are incompatible with the server's indicated cipher suite.

- Optionally adding, removing, or changing the length of the "padding" extension [RFC7685].
- Other modifications that may be allowed by an extension defined in the future and present in the HelloRetryRequest.

Because TLS 1.3 forbids renegotiation, if a server has negotiated TLS 1.3 and receives a ClientHello at any other time, it MUST terminate the connection with an "unexpected_message" alert.

If a server established a TLS connection with a previous version of TLS and receives a TLS 1.3 ClientHello in a renegotiation, it MUST retain the previous protocol version. In particular, it MUST NOT negotiate TLS 1.3.

Structure of this message:

```
uint16 ProtocolVersion;
opaque Random[32];

uint8 CipherSuite[2];    /* Cryptographic suite selector */

struct {
    ProtocolVersion legacy_version = 0x0303;    /* TLS v1.2 */
    Random random;
    opaque legacy_session_id<0..32>;
    CipherSuite cipher_suites<2..2^16-2>;
    opaque legacy_compression_methods<1..2^8-1>;
    Extension extensions<8..2^16-1>;
} ClientHello;
```

legacy_version In previous versions of TLS, this field was used for version negotiation and represented the highest version number supported by the client. Experience has shown that many servers do not properly implement version negotiation, leading to "version intolerance" in which the server rejects an otherwise acceptable ClientHello with a version number higher than it supports. In TLS 1.3, the client indicates its version preferences in the "supported_versions" extension (Section 4.2.1) and the legacy_version field MUST be set to 0x0303, which is the version number for TLS 1.2. (See Appendix D for details about backward compatibility.)

random 32 bytes generated by a secure random number generator. See Appendix C for additional information.

legacy_session_id Versions of TLS before TLS 1.3 supported a "session resumption" feature which has been merged with Pre-Shared

Keys in this version (see Section 2.2). A client which has a cached session ID set by a pre-TLS 1.3 server SHOULD set this field to that value. In compatibility mode (see Appendix D.4) this field MUST be non-empty, so a client not offering a pre-TLS 1.3 session MUST generate a new 32-byte value. This value need not be random but SHOULD be unpredictable to avoid implementations fixating on a specific value (also known as ossification). Otherwise, it MUST be set as a zero length vector (i.e., a single zero byte length field).

cipher_suites This is a list of the symmetric cipher options supported by the client, specifically the record protection algorithm (including secret key length) and a hash to be used with HKDF, in descending order of client preference. If the list contains cipher suites that the server does not recognize, support or wish to use, the server MUST ignore those cipher suites and process the remaining ones as usual. Values are defined in Appendix B.4. If the client is attempting a PSK key establishment, it SHOULD advertise at least one cipher suite indicating a Hash associated with the PSK.

legacy_compression_methods Versions of TLS before 1.3 supported compression with the list of supported compression methods being sent in this field. For every TLS 1.3 ClientHello, this vector MUST contain exactly one byte, set to zero, which corresponds to the "null" compression method in prior versions of TLS. If a TLS 1.3 ClientHello is received with any other value in this field, the server MUST abort the handshake with an "illegal_parameter" alert. Note that TLS 1.3 servers might receive TLS 1.2 or prior ClientHellos which contain other compression methods and (if negotiating such a prior version) MUST follow the procedures for the appropriate prior version of TLS. TLS 1.3 ClientHellos are identified as having a legacy_version of 0x0303 and a supported_versions extension present with 0x0304 as the highest version indicated therein.

extensions Clients request extended functionality from servers by sending data in the extensions field. The actual "Extension" format is defined in Section 4.2. In TLS 1.3, use of certain extensions is mandatory, as functionality is moved into extensions to preserve ClientHello compatibility with previous versions of TLS. Servers MUST ignore unrecognized extensions.

All versions of TLS allow an extensions field to optionally follow the compression_methods field. TLS 1.3 ClientHello messages always contain extensions (minimally "supported_versions", otherwise they will be interpreted as TLS 1.2 ClientHello messages). However, TLS 1.3 servers might receive ClientHello messages without an extensions

field from prior versions of TLS. The presence of extensions can be detected by determining whether there are bytes following the `compression_methods` field at the end of the `ClientHello`. Note that this method of detecting optional data differs from the normal TLS method of having a variable-length field, but it is used for compatibility with TLS before extensions were defined. TLS 1.3 servers will need to perform this check first and only attempt to negotiate TLS 1.3 if the "supported_versions" extension is present. If negotiating a version of TLS prior to 1.3, a server **MUST** check that the message either contains no data after `legacy_compression_methods` or that it contains a valid extensions block with no data following. If not, then it **MUST** abort the handshake with a "decode_error" alert.

In the event that a client requests additional functionality using extensions, and this functionality is not supplied by the server, the client **MAY** abort the handshake.

After sending the `ClientHello` message, the client waits for a `ServerHello` or `HelloRetryRequest` message. If early data is in use, the client may transmit early application data (Section 2.3) while waiting for the next handshake message.

4.1.1.3. Server Hello

The server will send this message in response to a `ClientHello` message to proceed with the handshake if it is able to negotiate an acceptable set of handshake parameters based on the `ClientHello`.

Structure of this message:

```
struct {
    ProtocolVersion legacy_version = 0x0303;    /* TLS v1.2 */
    Random random;
    opaque legacy_session_id_echo<0..32>;
    CipherSuite cipher_suite;
    uint8 legacy_compression_method = 0;
    Extension extensions<6..2^16-1>;
} ServerHello;
```

`legacy_version` In previous versions of TLS, this field was used for version negotiation and represented the selected version number for the connection. Unfortunately, some middleboxes fail when presented with new values. In TLS 1.3, the TLS server indicates its version using the "supported_versions" extension (Section 4.2.1), and the `legacy_version` field **MUST** be set to 0x0303, which is the version number for TLS 1.2. (See Appendix D for details about backward compatibility.)

random 32 bytes generated by a secure random number generator. See Appendix C for additional information. The last eight bytes MUST be overwritten as described below if negotiating TLS 1.2 or TLS 1.1, but the remaining bytes MUST be random. This structure is generated by the server and MUST be generated independently of the ClientHello.random.

legacy_session_id_echo The contents of the client's legacy_session_id field. Note that this field is echoed even if the client's value corresponded to a cached pre-TLS 1.3 session which the server has chosen not to resume. A client which receives a legacy_session_id_echo field that does not match what it sent in the ClientHello MUST abort the handshake with an "illegal_parameter" alert.

cipher_suite The single cipher suite selected by the server from the list in ClientHello.cipher_suites. A client which receives a cipher suite that was not offered MUST abort the handshake with an "illegal_parameter" alert.

legacy_compression_method A single byte which MUST have the value 0.

extensions A list of extensions. The ServerHello MUST only include extensions which are required to establish the cryptographic context and negotiate the protocol version. All TLS 1.3 ServerHello messages MUST contain the "supported_versions" extension. Current ServerHello messages additionally contain either the "pre_shared_key" or "key_share" extensions, or both when using a PSK with (EC)DHE key establishment. Other extensions are sent separately in the EncryptedExtensions message.

For reasons of backward compatibility with middleboxes (see Appendix D.4) the HelloRetryRequest message uses the same structure as the ServerHello, but with Random set to the special value of the SHA-256 of "HelloRetryRequest":

```
CF 21 AD 74 E5 9A 61 11 BE 1D 8C 02 1E 65 B8 91
C2 A2 11 16 7A BB 8C 5E 07 9E 09 E2 C8 A8 33 9C
```

Upon receiving a message with type server_hello, implementations MUST first examine the Random value and if it matches this value, process it as described in Section 4.1.4).

TLS 1.3 has a downgrade protection mechanism embedded in the server's random value. TLS 1.3 servers which negotiate TLS 1.2 or below in response to a ClientHello MUST set the last eight bytes of their Random value specially.

If negotiating TLS 1.2, TLS 1.3 servers MUST set the last eight bytes of their Random value to the bytes:

```
44 4F 57 4E 47 52 44 01
```

If negotiating TLS 1.1 or below, TLS 1.3 servers MUST and TLS 1.2 servers SHOULD set the last eight bytes of their Random value to the bytes:

```
44 4F 57 4E 47 52 44 00
```

TLS 1.3 clients receiving a ServerHello indicating TLS 1.2 or below MUST check that the last eight bytes are not equal to either of these values. TLS 1.2 clients SHOULD also check that the last eight bytes are not equal to the second value if the ServerHello indicates TLS 1.1 or below. If a match is found, the client MUST abort the handshake with an "illegal_parameter" alert. This mechanism provides limited protection against downgrade attacks over and above what is provided by the Finished exchange: because the ServerKeyExchange, a message present in TLS 1.2 and below, includes a signature over both random values, it is not possible for an active attacker to modify the random values without detection as long as ephemeral ciphers are used. It does not provide downgrade protection when static RSA is used.

Note: This is a change from [RFC5246], so in practice many TLS 1.2 clients and servers will not behave as specified above.

A legacy TLS client performing renegotiation with TLS 1.2 or prior and which receives a TLS 1.3 ServerHello during renegotiation MUST abort the handshake with a "protocol_version" alert. Note that renegotiation is not possible when TLS 1.3 has been negotiated.

RFC EDITOR: PLEASE REMOVE THE FOLLOWING PARAGRAPH Implementations of draft versions (see Section 4.2.1.1) of this specification SHOULD NOT implement this mechanism on either client and server. A pre-RFC client connecting to RFC servers, or vice versa, will appear to downgrade to TLS 1.2. With the mechanism enabled, this will cause an interoperability failure.

4.1.4. Hello Retry Request

The server will send this message in response to a ClientHello message if it is able to find an acceptable set of parameters but the ClientHello does not contain sufficient information to proceed with the handshake. As discussed in Section 4.1.3, the HelloRetryRequest has the same format as a ServerHello message, and the legacy_version, legacy_session_id_echo, cipher_suite, and legacy_compression methods

fields have the same meaning. However, for convenience we discuss HelloRetryRequest throughout this document as if it were a distinct message.

The server's extensions MUST contain "supported_versions" and otherwise the server SHOULD send only the extensions necessary for the client to generate a correct ClientHello pair. As with ServerHello, a HelloRetryRequest MUST NOT contain any extensions that were not first offered by the client in its ClientHello, with the exception of optionally the "cookie" (see Section 4.2.2) extension.

Upon receipt of a HelloRetryRequest, the client MUST check the legacy_version, legacy_session_id_echo, cipher_suite, and legacy_compression_method as specified in Section 4.1.3 and then process the extensions, starting with determining the version using "supported_versions". Clients MUST abort the handshake with an "illegal_parameter" alert if the HelloRetryRequest would not result in any change in the ClientHello. If a client receives a second HelloRetryRequest in the same connection (i.e., where the ClientHello was itself in response to a HelloRetryRequest), it MUST abort the handshake with an "unexpected_message" alert.

Otherwise, the client MUST process all extensions in the HelloRetryRequest and send a second updated ClientHello. The HelloRetryRequest extensions defined in this specification are:

- supported_versions (see Section 4.2.1)
- cookie (see Section 4.2.2)
- key_share (see Section 4.2.8)

In addition, in its updated ClientHello, the client SHOULD NOT offer any pre-shared keys associated with a hash other than that of the selected cipher suite. This allows the client to avoid having to compute partial hash transcripts for multiple hashes in the second ClientHello. A client which receives a cipher suite that was not offered MUST abort the handshake. Servers MUST ensure that they negotiate the same cipher suite when receiving a conformant updated ClientHello (if the server selects the cipher suite as the first step in the negotiation, then this will happen automatically). Upon receiving the ServerHello, clients MUST check that the cipher suite supplied in the ServerHello is the same as that in the HelloRetryRequest and otherwise abort the handshake with an "illegal_parameter" alert.

The value of selected_version in the HelloRetryRequest "supported_versions" extension MUST be retained in the ServerHello,

and a client MUST abort the handshake with an "illegal_parameter" alert if the value changes.

4.2. Extensions

A number of TLS messages contain tag-length-value encoded extensions structures.

```
struct {
    ExtensionType extension_type;
    opaque extension_data<0..2^16-1>;
} Extension;

enum {
    server_name(0),                /* RFC 6066 */
    max_fragment_length(1),        /* RFC 6066 */
    status_request(5),             /* RFC 6066 */
    supported_groups(10),          /* RFC 4492, 7919 */
    signature_algorithms(13),      /* [[this document]] */
    use_srtp(14),                 /* RFC 5764 */
    heartbeat(15),                /* RFC 6520 */
    application_layer_protocol_negotiation(16), /* RFC 7301 */
    signed_certificate_timestamp(18), /* RFC 6962 */
    client_certificate_type(19),    /* RFC 7250 */
    server_certificate_type(20),    /* RFC 7250 */
    padding(21),                  /* RFC 7685 */
    pre_shared_key(41),           /* [[this document]] */
    early_data(42),               /* [[this document]] */
    supported_versions(43),       /* [[this document]] */
    cookie(44),                   /* [[this document]] */
    psk_key_exchange_modes(45),    /* [[this document]] */
    certificate_authorities(47),   /* [[this document]] */
    oid_filters(48),              /* [[this document]] */
    post_handshake_auth(49),       /* [[this document]] */
    signature_algorithms_cert(50), /* [[this document]] */
    key_share(51),                /* [[this document]] */
    (65535)
} ExtensionType;
```

Here:

- "extension_type" identifies the particular extension type.
- "extension_data" contains information specific to the particular extension type.

The list of extension types is maintained by IANA as described in Section 11.

Extensions are generally structured in a request/response fashion, though some extensions are just indications with no corresponding response. The client sends its extension requests in the ClientHello message and the server sends its extension responses in the ServerHello, EncryptedExtensions, HelloRetryRequest and Certificate messages. The server sends extension requests in the CertificateRequest message which a client MAY respond to with a Certificate message. The server MAY also send unsolicited extensions in the NewSessionTicket, though the client does not respond directly to these.

Implementations MUST NOT send extension responses if the remote endpoint did not send the corresponding extension requests, with the exception of the "cookie" extension in HelloRetryRequest. Upon receiving such an extension, an endpoint MUST abort the handshake with an "unsupported_extension" alert.

The table below indicates the messages where a given extension may appear, using the following notation: CH (ClientHello), SH (ServerHello), EE (EncryptedExtensions), CT (Certificate), CR (CertificateRequest), NST (NewSessionTicket) and HRR (HelloRetryRequest). If an implementation receives an extension which it recognizes and which is not specified for the message in which it appears it MUST abort the handshake with an "illegal_parameter" alert.

Extension	TLS 1.3
server_name [RFC6066]	CH, EE
max_fragment_length [RFC6066]	CH, EE
status_request [RFC6066]	CH, CR, CT
supported_groups [RFC7919]	CH, EE
signature_algorithms [RFC5246]	CH, CR
use_srtp [RFC5764]	CH, EE
heartbeat [RFC6520]	CH, EE
application_layer_protocol_negotiation [RFC7301]	CH, EE
signed_certificate_timestamp [RFC6962]	CH, CR, CT
client_certificate_type [RFC7250]	CH, EE
server_certificate_type [RFC7250]	CH, EE
padding [RFC7685]	CH
key_share [[this document]]	CH, SH, HRR
pre_shared_key [[this document]]	CH, SH
psk_key_exchange_modes [[this document]]	CH
early_data [[this document]]	CH, EE, NST
cookie [[this document]]	CH, HRR
supported_versions [[this document]]	CH, SH, HRR
certificate_authorities [[this document]]	CH, CR
oid_filters [[this document]]	CR
post_handshake_auth [[this document]]	CH
signature_algorithms_cert [[this document]]	CH, CR

When multiple extensions of different types are present, the extensions MAY appear in any order, with the exception of "pre_shared_key" Section 4.2.11 which MUST be the last extension in the ClientHello. There MUST NOT be more than one extension of the same type in a given extension block.

In TLS 1.3, unlike TLS 1.2, extensions are negotiated for each handshake even when in resumption-PSK mode. However, 0-RTT parameters are those negotiated in the previous handshake; mismatches may require rejecting 0-RTT (see Section 4.2.10).

There are subtle (and not so subtle) interactions that may occur in this protocol between new features and existing features which may result in a significant reduction in overall security. The following considerations should be taken into account when designing new extensions:

- Some cases where a server does not agree to an extension are error conditions (e.g., the handshake cannot continue), and some are simply refusals to support particular features. In general, error alerts should be used for the former and a field in the server extension response for the latter.
- Extensions should, as far as possible, be designed to prevent any attack that forces use (or non-use) of a particular feature by manipulation of handshake messages. This principle should be followed regardless of whether the feature is believed to cause a security problem. Often the fact that the extension fields are included in the inputs to the Finished message hashes will be sufficient, but extreme care is needed when the extension changes the meaning of messages sent in the handshake phase. Designers and implementors should be aware of the fact that until the handshake has been authenticated, active attackers can modify messages and insert, remove, or replace extensions.

4.2.1. Supported Versions

```
struct {
    select (Handshake.msg_type) {
        case client_hello:
            ProtocolVersion versions<2..254>;

        case server_hello: /* and HelloRetryRequest */
            ProtocolVersion selected_version;
    };
} SupportedVersions;
```

The "supported_versions" extension is used by the client to indicate which versions of TLS it supports and by the server to indicate which version it is using. The extension contains a list of supported versions in preference order, with the most preferred version first. Implementations of this specification MUST send this extension in the ClientHello containing all versions of TLS which they are prepared to negotiate (for this specification, that means minimally 0x0304, but if previous versions of TLS are allowed to be negotiated, they MUST be present as well).

If this extension is not present, servers which are compliant with this specification, and which also support TLS 1.2, MUST negotiate TLS 1.2 or prior as specified in [RFC5246], even if ClientHello.legacy_version is 0x0304 or later. Servers MAY abort the handshake upon receiving a ClientHello with legacy_version 0x0304 or later.

If this extension is present in the ClientHello, servers MUST NOT use the ClientHello.legacy_version value for version negotiation and MUST use only the "supported_versions" extension to determine client preferences. Servers MUST only select a version of TLS present in that extension and MUST ignore any unknown versions that are present in that extension. Note that this mechanism makes it possible to negotiate a version prior to TLS 1.2 if one side supports a sparse range. Implementations of TLS 1.3 which choose to support prior versions of TLS SHOULD support TLS 1.2. Servers MUST be prepared to receive ClientHellos that include this extension but do not include 0x0304 in the list of versions.

A server which negotiates a version of TLS prior to TLS 1.3 MUST set ServerHello.version and MUST NOT send the "supported_versions" extension. A server which negotiates TLS 1.3 MUST respond by sending a "supported_versions" extension containing the selected version value (0x0304). It MUST set the ServerHello.legacy_version field to 0x0303 (TLS 1.2). Clients MUST check for this extension prior to processing the rest of the ServerHello (although they will have to parse the ServerHello in order to read the extension). If this extension is present, clients MUST ignore the ServerHello.legacy_version value and MUST use only the "supported_versions" extension to determine the selected version. If the "supported_versions" extension in the ServerHello contains a version not offered by the client or contains a version prior to TLS 1.3, the client MUST abort the handshake with an "illegal_parameter" alert.

4.2.1.1. Draft Version Indicator

RFC EDITOR: PLEASE REMOVE THIS SECTION

While the eventual version indicator for the RFC version of TLS 1.3 will be 0x0304, implementations of draft versions of this specification SHOULD instead advertise 0x7f00 | draft_version in the ServerHello and HelloRetryRequest "supported_versions" extension. For instance, draft-17 would be encoded as the 0x7f11. This allows pre-RFC implementations to safely negotiate with each other, even if they would otherwise be incompatible.

4.2.2. Cookie

```
struct {  
    opaque cookie<1..2^16-1>;  
} Cookie;
```

Cookies serve two primary purposes:

- Allowing the server to force the client to demonstrate reachability at their apparent network address (thus providing a measure of DoS protection). This is primarily useful for non-connection-oriented transports (see [RFC6347] for an example of this).
- Allowing the server to offload state to the client, thus allowing it to send a HelloRetryRequest without storing any state. The server can do this by storing the hash of the ClientHello in the HelloRetryRequest cookie (protected with some suitable integrity algorithm).

When sending a HelloRetryRequest, the server MAY provide a "cookie" extension to the client (this is an exception to the usual rule that the only extensions that may be sent are those that appear in the ClientHello). When sending the new ClientHello, the client MUST copy the contents of the extension received in the HelloRetryRequest into a "cookie" extension in the new ClientHello. Clients MUST NOT use cookies in their initial ClientHello in subsequent connections.

When a server is operating statelessly it may receive an unprotected record of type change_cipher_spec between the first and second ClientHello (see Section 5). Since the server is not storing any state this will appear as if it were the first message to be received. Servers operating statelessly MUST ignore these records.

4.2.3. Signature Algorithms

TLS 1.3 provides two extensions for indicating which signature algorithms may be used in digital signatures. The "signature_algorithms_cert" extension applies to signatures in certificates and the "signature_algorithms" extension, which originally appeared in TLS 1.2, applies to signatures in CertificateVerify messages. The keys found in certificates MUST also be of appropriate type for the signature algorithms they are used with. This is a particular issue for RSA keys and PSS signatures, as described below. If no "signature_algorithms_cert" extension is present, then the "signature_algorithms" extension also applies to signatures appearing in certificates. Clients which desire the server to authenticate itself via a certificate MUST send "signature_algorithms". If a server is authenticating via a certificate and the client has not sent a "signature_algorithms" extension, then the server MUST abort the handshake with a "missing_extension" alert (see Section 9.2).

The "signature_algorithms_cert" extension was added to allow implementations which supported different sets of algorithms for certificates and in TLS itself to clearly signal their capabilities. TLS 1.2 implementations SHOULD also process this extension. Implementations which have the same policy in both cases MAY omit the "signature_algorithms_cert" extension.

The "extension_data" field of these extensions contains a SignatureSchemeList value:

```

enum {
    /* RSASSA-PKCS1-v1_5 algorithms */
    rsa_pkcs1_sha256(0x0401),
    rsa_pkcs1_sha384(0x0501),
    rsa_pkcs1_sha512(0x0601),

    /* ECDSA algorithms */
    ecdsa_secp256r1_sha256(0x0403),
    ecdsa_secp384r1_sha384(0x0503),
    ecdsa_secp521r1_sha512(0x0603),

    /* RSASSA-PSS algorithms with public key OID rsaEncryption */
    rsa_pss_rsae_sha256(0x0804),
    rsa_pss_rsae_sha384(0x0805),
    rsa_pss_rsae_sha512(0x0806),

    /* EdDSA algorithms */
    ed25519(0x0807),
    ed448(0x0808),

    /* RSASSA-PSS algorithms with public key OID RSASSA-PSS */
    rsa_pss_pss_sha256(0x0809),
    rsa_pss_pss_sha384(0x080a),
    rsa_pss_pss_sha512(0x080b),

    /* Legacy algorithms */
    rsa_pkcs1_shal(0x0201),
    ecdsa_shal(0x0203),

    /* Reserved Code Points */
    private_use(0xFE00..0xFFFF),
    (0xFFFF)
} SignatureScheme;

struct {
    SignatureScheme supported_signature_algorithms<2..2^16-2>;
} SignatureSchemeList;

```

Note: This enum is named "SignatureScheme" because there is already a "SignatureAlgorithm" type in TLS 1.2, which this replaces. We use the term "signature algorithm" throughout the text.

Each SignatureScheme value lists a single signature algorithm that the client is willing to verify. The values are indicated in descending order of preference. Note that a signature algorithm takes as input an arbitrary-length message, rather than a digest. Algorithms which traditionally act on a digest should be defined in TLS to first hash the input with a specified hash algorithm and then

proceed as usual. The code point groups listed above have the following meanings:

RSASSA-PKCS1-v1_5 algorithms Indicates a signature algorithm using RSASSA-PKCS1-v1_5 [RFC8017] with the corresponding hash algorithm as defined in [SHS]. These values refer solely to signatures which appear in certificates (see Section 4.4.2.2) and are not defined for use in signed TLS handshake messages, although they MAY appear in "signature_algorithms" and "signature_algorithms_cert" for backward compatibility with TLS 1.2,

ECDSA algorithms Indicates a signature algorithm using ECDSA [ECDSA], the corresponding curve as defined in ANSI X9.62 [X962] and FIPS 186-4 [DSS], and the corresponding hash algorithm as defined in [SHS]. The signature is represented as a DER-encoded [X690] ECDSA-Sig-Value structure.

RSASSA-PSS RSAE algorithms Indicates a signature algorithm using RSASSA-PSS [RFC8017] with mask generation function 1. The digest used in the mask generation function and the digest being signed are both the corresponding hash algorithm as defined in [SHS]. The length of the salt MUST be equal to the length of the output of the digest algorithm. If the public key is carried in an X.509 certificate, it MUST use the rsaEncryption OID [RFC5280].

EdDSA algorithms Indicates a signature algorithm using EdDSA as defined in [RFC8032] or its successors. Note that these correspond to the "PureEdDSA" algorithms and not the "prehash" variants.

RSASSA-PSS PSS algorithms Indicates a signature algorithm using RSASSA-PSS [RFC8017] with mask generation function 1. The digest used in the mask generation function and the digest being signed are both the corresponding hash algorithm as defined in [SHS]. The length of the salt MUST be equal to the length of the digest algorithm. If the public key is carried in an X.509 certificate, it MUST use the RSASSA-PSS OID [RFC5756]. When used in certificate signatures, the algorithm parameters MUST be DER encoded. If the corresponding public key's parameters are present, then the parameters in the signature MUST be identical to those in the public key.

Legacy algorithms Indicates algorithms which are being deprecated because they use algorithms with known weaknesses, specifically SHA-1 which is used in this context with either with RSA using RSASSA-PKCS1-v1_5 or ECDSA. These values refer solely to signatures which appear in certificates (see Section 4.4.2.2) and

are not defined for use in signed TLS handshake messages, although they MAY appear in "signature_algorithms" and "signature_algorithms_cert" for backward compatibility with TLS 1.2, Endpoints SHOULD NOT negotiate these algorithms but are permitted to do so solely for backward compatibility. Clients offering these values MUST list them as the lowest priority (listed after all other algorithms in SignatureSchemeList). TLS 1.3 servers MUST NOT offer a SHA-1 signed certificate unless no valid certificate chain can be produced without it (see Section 4.4.2.2).

The signatures on certificates that are self-signed or certificates that are trust anchors are not validated since they begin a certification path (see [RFC5280], Section 3.2). A certificate that begins a certification path MAY use a signature algorithm that is not advertised as being supported in the "signature_algorithms" extension.

Note that TLS 1.2 defines this extension differently. TLS 1.3 implementations willing to negotiate TLS 1.2 MUST behave in accordance with the requirements of [RFC5246] when negotiating that version. In particular:

- TLS 1.2 ClientHellos MAY omit this extension.
- In TLS 1.2, the extension contained hash/signature pairs. The pairs are encoded in two octets, so SignatureScheme values have been allocated to align with TLS 1.2's encoding. Some legacy pairs are left unallocated. These algorithms are deprecated as of TLS 1.3. They MUST NOT be offered or negotiated by any implementation. In particular, MD5 [SLOTH], SHA-224, and DSA MUST NOT be used.
- ECDSA signature schemes align with TLS 1.2's ECDSA hash/signature pairs. However, the old semantics did not constrain the signing curve. If TLS 1.2 is negotiated, implementations MUST be prepared to accept a signature that uses any curve that they advertised in the "supported_groups" extension.
- Implementations that advertise support for RSASSA-PSS (which is mandatory in TLS 1.3), MUST be prepared to accept a signature using that scheme even when TLS 1.2 is negotiated. In TLS 1.2, RSASSA-PSS is used with RSA cipher suites.

4.2.4. Certificate Authorities

The "certificate_authorities" extension is used to indicate the certificate authorities which an endpoint supports and which SHOULD be used by the receiving endpoint to guide certificate selection.

The body of the "certificate_authorities" extension consists of a CertificateAuthoritiesExtension structure.

```
opaque DistinguishedName<1..2^16-1>;

struct {
    DistinguishedName authorities<3..2^16-1>;
} CertificateAuthoritiesExtension;
```

authorities A list of the distinguished names [X501] of acceptable certificate authorities, represented in DER-encoded [X690] format. These distinguished names specify a desired distinguished name for trust anchor or subordinate CA; thus, this message can be used to describe known trust anchors as well as a desired authorization space.

The client MAY send the "certificate_authorities" extension in the ClientHello message. The server MAY send it in the CertificateRequest message.

The "trusted_ca_keys" extension, which serves a similar purpose [RFC6066], but is more complicated, is not used in TLS 1.3 (although it may appear in ClientHello messages from clients which are offering prior versions of TLS).

4.2.5. OID Filters

The "oid_filters" extension allows servers to provide a set of OID/value pairs which it would like the client's certificate to match. This extension, if provided by the server, MUST only be sent in the CertificateRequest message.

```
struct {
    opaque certificate_extension_oid<1..2^8-1>;
    opaque certificate_extension_values<0..2^16-1>;
} OIDFilter;

struct {
    OIDFilter filters<0..2^16-1>;
} OIDFilterExtension;
```


filters A list of certificate extension OIDs [RFC5280] with their allowed value(s) and represented in DER-encoded [X690] format. Some certificate extension OIDs allow multiple values (e.g., Extended Key Usage). If the server has included a non-empty filters list, the client certificate included in the response MUST contain all of the specified extension OIDs that the client recognizes. For each extension OID recognized by the client, all of the specified values MUST be present in the client certificate (but the certificate MAY have other values as well). However, the client MUST ignore and skip any unrecognized certificate extension OIDs. If the client ignored some of the required certificate extension OIDs and supplied a certificate that does not satisfy the request, the server MAY at its discretion either continue the connection without client authentication, or abort the handshake with an "unsupported_certificate" alert. Any given OID MUST NOT appear more than once in the filters list.

PKIX RFCs define a variety of certificate extension OIDs and their corresponding value types. Depending on the type, matching certificate extension values are not necessarily bitwise-equal. It is expected that TLS implementations will rely on their PKI libraries to perform certificate selection using certificate extension OIDs.

This document defines matching rules for two standard certificate extensions defined in [RFC5280]:

- The Key Usage extension in a certificate matches the request when all key usage bits asserted in the request are also asserted in the Key Usage certificate extension.
- The Extended Key Usage extension in a certificate matches the request when all key purpose OIDs present in the request are also found in the Extended Key Usage certificate extension. The special anyExtendedKeyUsage OID MUST NOT be used in the request.

Separate specifications may define matching rules for other certificate extensions.

4.2.6. Post-Handshake Client Authentication

The "post_handshake_auth" extension is used to indicate that a client is willing to perform post-handshake authentication (Section 4.6.2). Servers MUST NOT send a post-handshake CertificateRequest to clients which do not offer this extension. Servers MUST NOT send this extension.

```
struct {} PostHandshakeAuth;
```

The "extension_data" field of the "post_handshake_auth" extension is zero length.

4.2.7. Negotiated Groups

When sent by the client, the "supported_groups" extension indicates the named groups which the client supports for key exchange, ordered from most preferred to least preferred.

Note: In versions of TLS prior to TLS 1.3, this extension was named "elliptic_curves" and only contained elliptic curve groups. See [RFC4492] and [RFC7919]. This extension was also used to negotiate ECDSA curves. Signature algorithms are now negotiated independently (see Section 4.2.3).

The "extension_data" field of this extension contains a "NamedGroupList" value:

```
enum {  
    /* Elliptic Curve Groups (ECDHE) */  
    secp256r1(0x0017), secp384r1(0x0018), secp521r1(0x0019),  
    x25519(0x001D), x448(0x001E),  
  
    /* Finite Field Groups (DHE) */  
    ffdhe2048(0x0100), ffdhe3072(0x0101), ffdhe4096(0x0102),  
    ffdhe6144(0x0103), ffdhe8192(0x0104),  
  
    /* Reserved Code Points */  
    ffdhe_private_use(0x01FC..0x01FF),  
    ecdhe_private_use(0xFE00..0xFEFF),  
    (0xFFFF)  
} NamedGroup;  
  
struct {  
    NamedGroup named_group_list<2..2^16-1>;  
} NamedGroupList;
```

Elliptic Curve Groups (ECDHE) Indicates support for the corresponding named curve, defined either in FIPS 186-4 [DSS] or in [RFC7748]. Values 0xFE00 through 0xFEFF are reserved for private use.

Finite Field Groups (DHE) Indicates support of the corresponding finite field group, defined in [RFC7919]. Values 0x01FC through 0x01FF are reserved for private use.

Items in `named_group_list` are ordered according to the client's preferences (most preferred choice first).

As of TLS 1.3, servers are permitted to send the "supported_groups" extension to the client. Clients MUST NOT act upon any information found in "supported_groups" prior to successful completion of the handshake but MAY use the information learned from a successfully completed handshake to change what groups they use in their "key_share" extension in subsequent connections. If the server has a group it prefers to the ones in the "key_share" extension but is still willing to accept the ClientHello, it SHOULD send "supported_groups" to update the client's view of its preferences; this extension SHOULD contain all groups the server supports, regardless of whether they are currently supported by the client.

4.2.8. Key Share

The "key_share" extension contains the endpoint's cryptographic parameters.

Clients MAY send an empty `client_shares` vector in order to request group selection from the server at the cost of an additional round trip. (see Section 4.1.4)

```
struct {  
    NamedGroup group;  
    opaque key_exchange<1..2^16-1>;  
} KeyShareEntry;
```

`group` The named group for the key being exchanged.

`key_exchange` Key exchange information. The contents of this field are determined by the specified group and its corresponding definition. Finite Field Diffie-Hellman [DH] parameters are described in Section 4.2.8.1; Elliptic Curve Diffie-Hellman parameters are described in Section 4.2.8.2.

In the ClientHello message, the "extension_data" field of this extension contains a "KeyShareClientHello" value:

```
struct {  
    KeyShareEntry client_shares<0..2^16-1>;  
} KeyShareClientHello;
```

`client_shares` A list of offered KeyShareEntry values in descending order of client preference.

This vector MAY be empty if the client is requesting a HelloRetryRequest. Each KeyShareEntry value MUST correspond to a group offered in the "supported_groups" extension and MUST appear in the same order. However, the values MAY be a non-contiguous subset of the "supported_groups" extension and MAY omit the most preferred groups. Such a situation could arise if the most preferred groups are new and unlikely to be supported in enough places to make pregenerating key shares for them efficient.

Clients can offer as many KeyShareEntry values as the number of supported groups it is offering, each representing a single set of key exchange parameters. For instance, a client might offer shares for several elliptic curves or multiple FFDHE groups. The key_exchange values for each KeyShareEntry MUST be generated independently. Clients MUST NOT offer multiple KeyShareEntry values for the same group. Clients MUST NOT offer any KeyShareEntry values for groups not listed in the client's "supported_groups" extension. Servers MAY check for violations of these rules and abort the handshake with an "illegal_parameter" alert if one is violated.

In a HelloRetryRequest message, the "extension_data" field of this extension contains a KeyShareHelloRetryRequest value:

```
struct {  
    NamedGroup selected_group;  
} KeyShareHelloRetryRequest;
```

`selected_group` The mutually supported group the server intends to negotiate and is requesting a retried ClientHello/KeyShare for.

Upon receipt of this extension in a HelloRetryRequest, the client MUST verify that (1) the `selected_group` field corresponds to a group which was provided in the "supported_groups" extension in the original ClientHello; and (2) the `selected_group` field does not correspond to a group which was provided in the "key_share" extension in the original ClientHello. If either of these checks fails, then the client MUST abort the handshake with an "illegal_parameter" alert. Otherwise, when sending the new ClientHello, the client MUST replace the original "key_share" extension with one containing only a new KeyShareEntry for the group indicated in the `selected_group` field of the triggering HelloRetryRequest.

In a ServerHello message, the "extension_data" field of this extension contains a KeyShareServerHello value:

```
struct {  
    KeyShareEntry server_share;  
} KeyShareServerHello;
```

`server_share` A single `KeyShareEntry` value that is in the same group as one of the client's shares.

If using (EC)DHE key establishment, servers offer exactly one `KeyShareEntry` in the `ServerHello`. This value MUST be in the same group as the `KeyShareEntry` value offered by the client that the server has selected for the negotiated key exchange. Servers MUST NOT send a `KeyShareEntry` for any group not indicated in the `"supported_groups"` extension and MUST NOT send a `KeyShareEntry` when using the `"psk_ke"` `PskKeyExchangeMode`. If using (EC)DHE key establishment, and a `HelloRetryRequest` containing a `"key_share"` extension was received by the client, the client MUST verify that the selected `NamedGroup` in the `ServerHello` is the same as that in the `HelloRetryRequest`. If this check fails, the client MUST abort the handshake with an `"illegal_parameter"` alert.

4.2.8.1. Diffie-Hellman Parameters

Diffie-Hellman [DH] parameters for both clients and servers are encoded in the opaque `key_exchange` field of a `KeyShareEntry` in a `KeyShare` structure. The opaque value contains the Diffie-Hellman public value ($Y = g^X \bmod p$) for the specified group (see [RFC7919] for group definitions) encoded as a big-endian integer and padded to the left with zeros to the size of `p` in bytes.

Note: For a given Diffie-Hellman group, the padding results in all public keys having the same length.

Peers MUST validate each other's public key `Y` by ensuring that $1 < Y < p-1$. This check ensures that the remote peer is properly behaved and isn't forcing the local system into a small subgroup.

4.2.8.2. ECDHE Parameters

ECDHE parameters for both clients and servers are encoded in the opaque `key_exchange` field of a `KeyShareEntry` in a `KeyShare` structure.

For `secp256r1`, `secp384r1` and `secp521r1`, the contents are the serialized value of the following struct:

```
struct {
    uint8 legacy_form = 4;
    opaque X[coordinate_length];
    opaque Y[coordinate_length];
} UncompressedPointRepresentation;
```

`X` and `Y` respectively are the binary representations of the `x` and `y` values in network byte order. There are no internal length markers,

so each number representation occupies as many octets as implied by the curve parameters. For P-256 this means that each of X and Y use 32 octets, padded on the left by zeros if necessary. For P-384 they take 48 octets each, and for P-521 they take 66 octets each.

For the curves `secp256r1`, `secp384r1` and `secp521r1`, peers MUST validate each other's public value Q by ensuring that the point is a valid point on the elliptic curve. The appropriate validation procedures are defined in Section 4.3.7 of [X962] and alternatively in Section 5.6.2.3 of [KEYAGREEMENT]. This process consists of three steps: (1) verify that Q is not the point at infinity (O), (2) verify that for Q = (x, y) both integers x and y are in the correct interval, (3) ensure that (x, y) is a correct solution to the elliptic curve equation. For these curves, implementers do not need to verify membership in the correct subgroup.

For X25519 and X448, the contents of the public value are the byte string inputs and outputs of the corresponding functions defined in [RFC7748], 32 bytes for X25519 and 56 bytes for X448.

Note: Versions of TLS prior to 1.3 permitted point format negotiation; TLS 1.3 removes this feature in favor of a single point format for each curve.

4.2.9. Pre-Shared Key Exchange Modes

In order to use PSKs, clients MUST also send a "psk_key_exchange_modes" extension. The semantics of this extension are that the client only supports the use of PSKs with these modes, which restricts both the use of PSKs offered in this ClientHello and those which the server might supply via NewSessionTicket.

A client MUST provide a "psk_key_exchange_modes" extension if it offers a "pre_shared_key" extension. If clients offer "pre_shared_key" without a "psk_key_exchange_modes" extension, servers MUST abort the handshake. Servers MUST NOT select a key exchange mode that is not listed by the client. This extension also restricts the modes for use with PSK resumption; servers SHOULD NOT send NewSessionTicket with tickets that are not compatible with the advertised modes; however, if a server does so, the impact will just be that the client's attempts at resumption fail.

The server MUST NOT send a "psk_key_exchange_modes" extension.

```
enum { psk_ke(0), psk_dhe_ke(1), (255) } PskKeyExchangeMode;

struct {
    PskKeyExchangeMode ke_modes<1..255>;
} PskKeyExchangeModes;
```

psk_ke PSK-only key establishment. In this mode, the server MUST NOT supply a "key_share" value.

psk_dhe_ke PSK with (EC)DHE key establishment. In this mode, the client and server MUST supply "key_share" values as described in Section 4.2.8.

Any future values that are allocated must ensure that the transmitted protocol messages unambiguously identify which mode was selected by the server; at present, this is indicated by the presence of the "key_share" in the ServerHello.

4.2.10. Early Data Indication

When a PSK is used and early data is allowed for that PSK, the client can send application data in its first flight of messages. If the client opts to do so, it MUST supply both the "early_data" extension as well as the "pre_shared_key" extension.

The "extension_data" field of this extension contains an "EarlyDataIndication" value.

```
struct {} Empty;

struct {
    select (Handshake.msg_type) {
        case new_session_ticket:    uint32 max_early_data_size;
        case client_hello:          Empty;
        case encrypted_extensions: Empty;
    };
} EarlyDataIndication;
```

See Section 4.6.1 for the use of the max_early_data_size field.

The parameters for the 0-RTT data (version, symmetric cipher suite, ALPN protocol, etc.) are those associated with the PSK in use. For externally provisioned PSKs, the associated values are those provisioned along with the key. For PSKs established via a NewSessionTicket message, the associated values are those which were negotiated in the connection which established the PSK. The PSK used to encrypt the early data MUST be the first PSK listed in the client's "pre_shared_key" extension.

For PSKs provisioned via NewSessionTicket, a server MUST validate that the ticket age for the selected PSK identity (computed by subtracting `ticket_age_add` from `PskIdentity.obfuscated_ticket_age` modulo 2^{32}) is within a small tolerance of the time since the ticket was issued (see Section 8). If it is not, the server SHOULD proceed with the handshake but reject 0-RTT, and SHOULD NOT take any other action that assumes that this ClientHello is fresh.

0-RTT messages sent in the first flight have the same (encrypted) content types as messages of the same type sent in other flights (handshake and application_data) but are protected under different keys. After receiving the server's Finished message, if the server has accepted early data, an EndOfEarlyData message will be sent to indicate the key change. This message will be encrypted with the 0-RTT traffic keys.

A server which receives an "early_data" extension MUST behave in one of three ways:

- Ignore the extension and return a regular 1-RTT response. The server then skips past early data by attempting to deprotect received records using the handshake traffic key, discarding records which fail deprotection (up to the configured `max_early_data_size`). Once a record is deprotected successfully, it is treated as the start of the client's second flight and the server proceeds as with an ordinary 1-RTT handshake.
- Request that the client send another ClientHello by responding with a HelloRetryRequest. A client MUST NOT include the "early_data" extension in its followup ClientHello. The server then ignores early data by skipping all records with external content type of "application_data" (indicating that they are encrypted), up to the configured `max_early_data_size`.
- Return its own "early_data" extension in EncryptedExtensions, indicating that it intends to process the early data. It is not possible for the server to accept only a subset of the early data messages. Even though the server sends a message accepting early data, the actual early data itself may already be in flight by the time the server generates this message.

In order to accept early data, the server MUST have accepted a PSK cipher suite and selected the first key offered in the client's "pre_shared_key" extension. In addition, it MUST verify that the following values are the same as those associated with the selected PSK:

- The TLS version number

- The selected cipher suite
- The selected ALPN [RFC7301] protocol, if any

These requirements are a superset of those needed to perform a 1-RTT handshake using the PSK in question. For externally established PSKs, the associated values are those provisioned along with the key. For PSKs established via a NewSessionTicket message, the associated values are those negotiated in the connection during which the ticket was established.

Future extensions MUST define their interaction with 0-RTT.

If any of these checks fail, the server MUST NOT respond with the extension and must discard all the first flight data using one of the first two mechanisms listed above (thus falling back to 1-RTT or 2-RTT). If the client attempts a 0-RTT handshake but the server rejects it, the server will generally not have the 0-RTT record protection keys and must instead use trial decryption (either with the 1-RTT handshake keys or by looking for a cleartext ClientHello in the case of HelloRetryRequest) to find the first non-0-RTT message.

If the server chooses to accept the "early_data" extension, then it MUST comply with the same error handling requirements specified for all records when processing early data records. Specifically, if the server fails to decrypt a 0-RTT record following an accepted "early_data" extension it MUST terminate the connection with a "bad_record_mac" alert as per Section 5.2.

If the server rejects the "early_data" extension, the client application MAY opt to retransmit the application data previously sent in early data once the handshake has been completed. Note that automatic re-transmission of early data could result in assumptions about the status of the connection being incorrect. For instance, when the negotiated connection selects a different ALPN protocol from what was used for the early data, an application might need to construct different messages. Similarly, if early data assumes anything about the connection state, it might be sent in error after the handshake completes.

A TLS implementation SHOULD NOT automatically re-send early data; applications are in a better position to decide when re-transmission is appropriate. A TLS implementation MUST NOT automatically re-send early data unless the negotiated connection selects the same ALPN protocol.

4.2.11. Pre-Shared Key Extension

The "pre_shared_key" extension is used to negotiate the identity of the pre-shared key to be used with a given handshake in association with PSK key establishment.

The "extension_data" field of this extension contains a "PreSharedKeyExtension" value:

```
struct {
    opaque identity<1..2^16-1>;
    uint32 obfuscated_ticket_age;
} PskIdentity;

opaque PskBinderEntry<32..255>;

struct {
    PskIdentity identities<7..2^16-1>;
    PskBinderEntry binders<33..2^16-1>;
} OfferedPsk;

struct {
    select (Handshake.msg_type) {
        case client_hello: OfferedPsk;
        case server_hello: uint16 selected_identity;
    };
} PreSharedKeyExtension;
```

identity A label for a key. For instance, a ticket defined in Appendix B.3.4 or a label for a pre-shared key established externally.

obfuscated_ticket_age An obfuscated version of the age of the key. Section 4.2.11.1 describes how to form this value for identities established via the NewSessionTicket message. For identities established externally an obfuscated_ticket_age of 0 SHOULD be used, and servers MUST ignore the value.

identities A list of the identities that the client is willing to negotiate with the server. If sent alongside the "early_data" extension (see Section 4.2.10), the first identity is the one used for 0-RTT data.

binders A series of HMAC values, one for each PSK offered in the "pre_shared_keys" extension and in the same order, computed as described below.

`selected_identity` The server's chosen identity expressed as a (0-based) index into the identities in the client's list.

Each PSK is associated with a single Hash algorithm. For PSKs established via the ticket mechanism (Section 4.6.1), this is the KDF Hash algorithm on the connection where the ticket was established. For externally established PSKs, the Hash algorithm **MUST** be set when the PSK is established, or default to SHA-256 if no such algorithm is defined. The server **MUST** ensure that it selects a compatible PSK (if any) and cipher suite.

In TLS versions prior to TLS 1.3, the Server Name Identification (SNI) value was intended to be associated with the session (Section 3 of [RFC6066]), with the server being required to enforce that the SNI value associated with the session matches the one specified in the resumption handshake. However, in reality the implementations were not consistent on which of two supplied SNI values they would use, leading to the consistency requirement being de-facto enforced by the clients. In TLS 1.3, the SNI value is always explicitly specified in the resumption handshake, and there is no need for the server to associate an SNI value with the ticket. Clients, however, **SHOULD** store the SNI with the PSK to fulfill the requirements of Section 4.6.1.

Implementor's note: when session resumption is the primary use case of PSKs the most straightforward way to implement the PSK/cipher suite matching requirements is to negotiate the cipher suite first and then exclude any incompatible PSKs. Any unknown PSKs (e.g., they are not in the PSK database or are encrypted with an unknown key) **SHOULD** simply be ignored. If no acceptable PSKs are found, the server **SHOULD** perform a non-PSK handshake if possible. If backwards compatibility is important, client provided, externally established PSKs **SHOULD** influence cipher suite selection.

Prior to accepting PSK key establishment, the server **MUST** validate the corresponding binder value (see Section 4.2.11.2 below). If this value is not present or does not validate, the server **MUST** abort the handshake. Servers **SHOULD NOT** attempt to validate multiple binders; rather they **SHOULD** select a single PSK and validate solely the binder that corresponds to that PSK. See [Section 8.2] and [Appendix E.6] for the security rationale for this requirement. In order to accept PSK key establishment, the server sends a "pre_shared_key" extension indicating the selected identity.

Clients **MUST** verify that the server's `selected_identity` is within the range supplied by the client, that the server selected a cipher suite indicating a Hash associated with the PSK and that a server "key_share" extension is present if required by the ClientHello

"psk_key_exchange_modes". If these values are not consistent the client MUST abort the handshake with an "illegal_parameter" alert.

If the server supplies an "early_data" extension, the client MUST verify that the server's selected_identity is 0. If any other value is returned, the client MUST abort the handshake with an "illegal_parameter" alert.

The "pre_shared_key" extension MUST be the last extension in the ClientHello (this facilitates implementation as described below). Servers MUST check that it is the last extension and otherwise fail the handshake with an "illegal_parameter" alert.

4.2.11.1. Ticket Age

The client's view of the age of a ticket is the time since the receipt of the NewSessionTicket message. Clients MUST NOT attempt to use tickets which have ages greater than the "ticket_lifetime" value which was provided with the ticket. The "obfuscated_ticket_age" field of each PskIdentity contains an obfuscated version of the ticket age formed by taking the age in milliseconds and adding the "ticket_age_add" value that was included with the ticket (see Section 4.6.1), modulo 2^{32} . This addition prevents passive observers from correlating connections unless tickets are reused. Note that the "ticket_lifetime" field in the NewSessionTicket message is in seconds but the "obfuscated_ticket_age" is in milliseconds. Because ticket lifetimes are restricted to a week, 32 bits is enough to represent any plausible age, even in milliseconds.

4.2.11.2. PSK Binder

The PSK binder value forms a binding between a PSK and the current handshake, as well as a binding between the handshake in which the PSK was generated (if via a NewSessionTicket message) and the current handshake. Each entry in the binders list is computed as an HMAC over a transcript hash (see Section 4.4.1) containing a partial ClientHello up to and including the PreSharedKeyExtension.identities field. That is, it includes all of the ClientHello but not the binders list itself. The length fields for the message (including the overall length, the length of the extensions block, and the length of the "pre_shared_key" extension) are all set as if binders of the correct lengths were present.

The PskBinderEntry is computed in the same way as the Finished message (Section 4.4.4) but with the BaseKey being the binder_key derived via the key schedule from the corresponding PSK which is being offered (see Section 7.1).

If the handshake includes a HelloRetryRequest, the initial ClientHello and HelloRetryRequest are included in the transcript along with the new ClientHello. For instance, if the client sends ClientHello1, its binder will be computed over:

```
Transcript-Hash(Truncate(ClientHello1))
```

Where Truncate() removes the binders list from the ClientHello.

If the server responds with HelloRetryRequest, and the client then sends ClientHello2, its binder will be computed over:

```
Transcript-Hash(ClientHello1,  
                  HelloRetryRequest,  
                  Truncate(ClientHello2))
```

The full ClientHello1/ClientHello2 is included in all other handshake hash computations. Note that in the first flight, Truncate(ClientHello1) is hashed directly, but in the second flight, ClientHello1 is hashed and then reinjected as a "message_hash" message, as described in Section 4.4.1.

4.2.11.3. Processing Order

Clients are permitted to "stream" 0-RTT data until they receive the server's Finished, only then sending the EndOfEarlyData message, followed by the rest of the handshake. In order to avoid deadlocks, when accepting "early_data", servers MUST process the client's ClientHello and then immediately send their flight of messages, rather than waiting for the client's EndOfEarlyData message before sending its ServerHello.

4.3. Server Parameters

The next two messages from the server, EncryptedExtensions and CertificateRequest, contain information from the server that determines the rest of the handshake. These messages are encrypted with keys derived from the server_handshake_traffic_secret.

4.3.1. Encrypted Extensions

In all handshakes, the server MUST send the EncryptedExtensions message immediately after the ServerHello message. This is the first message that is encrypted under keys derived from the server_handshake_traffic_secret.

The EncryptedExtensions message contains extensions that can be protected, i.e., any which are not needed to establish the

cryptographic context, but which are not associated with individual certificates. The client MUST check EncryptedExtensions for the presence of any forbidden extensions and if any are found MUST abort the handshake with an "illegal_parameter" alert.

Structure of this message:

```
struct {  
    Extension extensions<0..2^16-1>;  
} EncryptedExtensions;
```

extensions A list of extensions. For more information, see the table in Section 4.2.

4.3.2. Certificate Request

A server which is authenticating with a certificate MAY optionally request a certificate from the client. This message, if sent, MUST follow EncryptedExtensions.

Structure of this message:

```
struct {  
    opaque certificate_request_context<0..2^8-1>;  
    Extension extensions<2..2^16-1>;  
} CertificateRequest;
```

certificate_request_context An opaque string which identifies the certificate request and which will be echoed in the client's Certificate message. The certificate_request_context MUST be unique within the scope of this connection (thus preventing replay of client CertificateVerify messages). This field SHALL be zero length unless used for the post-handshake authentication exchanges described in Section 4.6.2. When requesting post-handshake authentication, the server SHOULD make the context unpredictable to the client (e.g., by randomly generating it) in order to prevent an attacker who has temporary access to the client's private key from pre-computing valid CertificateVerify messages.

extensions A set of extensions describing the parameters of the certificate being requested. The "signature_algorithms" extension MUST be specified, and other extensions may optionally be included if defined for this message. Clients MUST ignore unrecognized extensions.

In prior versions of TLS, the CertificateRequest message carried a list of signature algorithms and certificate authorities which the server would accept. In TLS 1.3 the former is expressed by sending

the "signature_algorithms" and optionally "signature_algorithms_cert" extensions. The latter is expressed by sending the "certificate_authorities" extension (see Section 4.2.4).

Servers which are authenticating with a PSK MUST NOT send the CertificateRequest message in the main handshake, though they MAY send it in post-handshake authentication (see Section 4.6.2) provided that the client has sent the "post_handshake_auth" extension (see Section 4.2.6).

4.4. Authentication Messages

As discussed in Section 2, TLS generally uses a common set of messages for authentication, key confirmation, and handshake integrity: Certificate, CertificateVerify, and Finished. (The PreSharedKey binders also perform key confirmation, in a similar fashion.) These three messages are always sent as the last messages in their handshake flight. The Certificate and CertificateVerify messages are only sent under certain circumstances, as defined below. The Finished message is always sent as part of the Authentication block. These messages are encrypted under keys derived from [sender]_handshake_traffic_secret.

The computations for the Authentication messages all uniformly take the following inputs:

- The certificate and signing key to be used.
- A Handshake Context consisting of the set of messages to be included in the transcript hash.
- A base key to be used to compute a MAC key.

Based on these inputs, the messages then contain:

Certificate The certificate to be used for authentication, and any supporting certificates in the chain. Note that certificate-based client authentication is not available in PSK (including 0-RTT) flows.

CertificateVerify A signature over the value Transcript-Hash(Handshake Context, Certificate)

Finished A MAC over the value Transcript-Hash(Handshake Context, Certificate, CertificateVerify) using a MAC key derived from the base key.

The following table defines the Handshake Context and MAC Base Key for each scenario:

Mode	Handshake Context	Base Key
Server	ClientHello ... later of EncryptedExtensions/CertificateRequest	server_handshake_traffic_secret
Client	ClientHello ... later of server Finished/EndOfEarlyData	client_handshake_traffic_secret
Post-Handshake	ClientHello ... client Finished + CertificateRequest	client_application_traffic_secret_N

4.4.1. The Transcript Hash

Many of the cryptographic computations in TLS make use of a transcript hash. This value is computed by hashing the concatenation of each included handshake message, including the handshake message header carrying the handshake message type and length fields, but not including record layer headers. I.e.,

$$\text{Transcript-Hash}(M_1, M_2, \dots, M_n) = \text{Hash}(M_1 \parallel M_2 \parallel \dots \parallel M_n)$$

As an exception to this general rule, when the server responds to a ClientHello with a HelloRetryRequest, the value of ClientHello1 is replaced with a special synthetic handshake message of handshake type "message_hash" containing Hash(ClientHello1). I.e.,

```
Transcript-Hash(ClientHello1, HelloRetryRequest, ... Mn) =
  Hash(message_hash || /* Handshake type */
    00 00 Hash.length || /* Handshake message length (bytes) */
    Hash(ClientHello1) || /* Hash of ClientHello1 */
    HelloRetryRequest || ... || Mn)
```

The reason for this construction is to allow the server to do a stateless HelloRetryRequest by storing just the hash of ClientHello1 in the cookie, rather than requiring it to export the entire intermediate hash state (see Section 4.2.2).

For concreteness, the transcript hash is always taken from the following sequence of handshake messages, starting at the first ClientHello and including only those messages that were sent:

ClientHello, HelloRetryRequest, ClientHello, ServerHello, EncryptedExtensions, server CertificateRequest, server Certificate, server CertificateVerify, server Finished, EndOfEarlyData, client Certificate, client CertificateVerify, client Finished.

In general, implementations can implement the transcript by keeping a running transcript hash value based on the negotiated hash. Note, however, that subsequent post-handshake authentications do not include each other, just the messages through the end of the main handshake.

4.4.2. Certificate

This message conveys the endpoint's certificate chain to the peer.

The server MUST send a Certificate message whenever the agreed-upon key exchange method uses certificates for authentication (this includes all key exchange methods defined in this document except PSK).

The client MUST send a Certificate message if and only if the server has requested client authentication via a CertificateRequest message (Section 4.3.2). If the server requests client authentication but no suitable certificate is available, the client MUST send a Certificate message containing no certificates (i.e., with the "certificate_list" field having length 0). A Finished message MUST be sent regardless of whether the Certificate message is empty.

Structure of this message:

```
/* Managed by IANA */
enum {
    X509(0),
    RawPublicKey(2),
    (255)
} CertificateType;

struct {
    select (certificate_type) {
        case RawPublicKey:
            /* From RFC 7250 ASN.1_subjectPublicKeyInfo */
            opaque ASN1_subjectPublicKeyInfo<1..2^24-1>;

        case X509:
            opaque cert_data<1..2^24-1>;
    };
    Extension extensions<0..2^16-1>;
} CertificateEntry;

struct {
    opaque certificate_request_context<0..2^8-1>;
    CertificateEntry certificate_list<0..2^24-1>;
} Certificate;
```

certificate_request_context If this message is in response to a CertificateRequest, the value of **certificate_request_context** in that message. Otherwise (in the case of server authentication), this field SHALL be zero length.

certificate_list This is a sequence (chain) of CertificateEntry structures, each containing a single certificate and set of extensions.

extensions: A set of extension values for the CertificateEntry. The "Extension" format is defined in Section 4.2. Valid extensions for server certificates at present include OCSP Status extension ([RFC6066]) and SignedCertificateTimestamps ([RFC6962]); future extensions may be defined for this message as well. Extensions in the Certificate message from the server MUST correspond to ones from the ClientHello message. Extensions in the Certificate from the client MUST correspond with extensions in the CertificateRequest message from the server. If an extension applies to the entire chain, it SHOULD be included in the first CertificateEntry.

If the corresponding certificate type extension ("server_certificate_type" or "client_certificate_type") was not negotiated in Encrypted Extensions, or the X.509 certificate type was

negotiated, then each CertificateEntry contains a DER-encoded X.509 certificate. The sender's certificate MUST come in the first CertificateEntry in the list. Each following certificate SHOULD directly certify the one immediately preceding it. Because certificate validation requires that trust anchors be distributed independently, a certificate that specifies a trust anchor MAY be omitted from the chain, provided that supported peers are known to possess any omitted certificates.

Note: Prior to TLS 1.3, "certificate_list" ordering required each certificate to certify the one immediately preceding it; however, some implementations allowed some flexibility. Servers sometimes send both a current and deprecated intermediate for transitional purposes, and others are simply configured incorrectly, but these cases can nonetheless be validated properly. For maximum compatibility, all implementations SHOULD be prepared to handle potentially extraneous certificates and arbitrary orderings from any TLS version, with the exception of the end-entity certificate which MUST be first.

If the RawPublicKey certificate type was negotiated, then the certificate_list MUST contain no more than one CertificateEntry, which contains an ASN1_subjectPublicKeyInfo value as defined in [RFC7250], Section 3.

The OpenPGP certificate type [RFC6091] MUST NOT be used with TLS 1.3.

The server's certificate_list MUST always be non-empty. A client will send an empty certificate_list if it does not have an appropriate certificate to send in response to the server's authentication request.

4.4.2.1. OCSP Status and SCT Extensions

[RFC6066] and [RFC6961] provide extensions to negotiate the server sending OCSP responses to the client. In TLS 1.2 and below, the server replies with an empty extension to indicate negotiation of this extension and the OCSP information is carried in a CertificateStatus message. In TLS 1.3, the server's OCSP information is carried in an extension in the CertificateEntry containing the associated certificate. Specifically: The body of the "status_request" extension from the server MUST be a CertificateStatus structure as defined in [RFC6066], which is interpreted as defined in [RFC6960].

Note: status_request_v2 extension ([RFC6961]) is deprecated. TLS 1.3 servers MUST NOT act upon its presence or information in it when processing Client Hello, in particular they MUST NOT send the

status_request_v2 extension in the Encrypted Extensions, Certificate Request or the Certificate messages. TLS 1.3 servers MUST be able to process Client Hello messages that include it, as it MAY be sent by clients that wish to use it in earlier protocol versions.

A server MAY request that a client present an OCSP response with its certificate by sending an empty "status_request" extension in its CertificateRequest message. If the client opts to send an OCSP response, the body of its "status_request" extension MUST be a CertificateStatus structure as defined in [RFC6066].

Similarly, [RFC6962] provides a mechanism for a server to send a Signed Certificate Timestamp (SCT) as an extension in the ServerHello in TLS 1.2 and below. In TLS 1.3, the server's SCT information is carried in an extension in CertificateEntry.

4.4.2.2. Server Certificate Selection

The following rules apply to the certificates sent by the server:

- The certificate type MUST be X.509v3 [RFC5280], unless explicitly negotiated otherwise (e.g., [RFC7250]).
- The server's end-entity certificate's public key (and associated restrictions) MUST be compatible with the selected authentication algorithm from the client's "signature_algorithms" extension (currently RSA, ECDSA, or EdDSA).
- The certificate MUST allow the key to be used for signing (i.e., the digitalSignature bit MUST be set if the Key Usage extension is present) with a signature scheme indicated in the client's "signature_algorithms"/"signature_algorithms_cert" extensions (see Section 4.2.3).
- The "server_name" [RFC6066] and "certificate_authorities" extensions are used to guide certificate selection. As servers MAY require the presence of the "server_name" extension, clients SHOULD send this extension, when applicable.

All certificates provided by the server MUST be signed by a signature algorithm advertised by the client, if it is able to provide such a chain (see Section 4.2.3). Certificates that are self-signed or certificates that are expected to be trust anchors are not validated as part of the chain and therefore MAY be signed with any algorithm.

If the server cannot produce a certificate chain that is signed only via the indicated supported algorithms, then it SHOULD continue the handshake by sending the client a certificate chain of its choice

that may include algorithms that are not known to be supported by the client. This fallback chain SHOULD NOT use the deprecated SHA-1 hash algorithm in general, but MAY do so if the client's advertisement permits it, and MUST NOT do so otherwise.

If the client cannot construct an acceptable chain using the provided certificates and decides to abort the handshake, then it MUST abort the handshake with an appropriate certificate-related alert (by default, "unsupported_certificate"; see Section 6.2 for more).

If the server has multiple certificates, it chooses one of them based on the above-mentioned criteria (in addition to other criteria, such as transport layer endpoint, local configuration and preferences).

4.4.2.3. Client Certificate Selection

The following rules apply to certificates sent by the client:

- The certificate type MUST be X.509v3 [RFC5280], unless explicitly negotiated otherwise (e.g., [RFC7250]).
- If the "certificate_authorities" extension in the CertificateRequest message was present, at least one of the certificates in the certificate chain SHOULD be issued by one of the listed CAs.
- The certificates MUST be signed using an acceptable signature algorithm, as described in Section 4.3.2. Note that this relaxes the constraints on certificate-signing algorithms found in prior versions of TLS.
- If the CertificateRequest message contained a non-empty "oid_filters" extension, the end-entity certificate MUST match the extension OIDs that are recognized by the client, as described in Section 4.2.5.

Note that, as with the server certificate, there are certificates that use algorithm combinations that cannot be currently used with TLS.

4.4.2.4. Receiving a Certificate Message

In general, detailed certificate validation procedures are out of scope for TLS (see [RFC5280]). This section provides TLS-specific requirements.

If the server supplies an empty Certificate message, the client MUST abort the handshake with a "decode_error" alert.

If the client does not send any certificates (i.e., it sends an empty Certificate message), the server MAY at its discretion either continue the handshake without client authentication, or abort the handshake with a "certificate_required" alert. Also, if some aspect of the certificate chain was unacceptable (e.g., it was not signed by a known, trusted CA), the server MAY at its discretion either continue the handshake (considering the client unauthenticated) or abort the handshake.

Any endpoint receiving any certificate which it would need to validate using any signature algorithm using an MD5 hash MUST abort the handshake with a "bad_certificate" alert. SHA-1 is deprecated and it is RECOMMENDED that any endpoint receiving any certificate which it would need to validate using any signature algorithm using a SHA-1 hash abort the handshake with a "bad_certificate" alert. For clarity, this means that endpoints MAY accept these algorithms for certificates that are self-signed or are trust anchors.

All endpoints are RECOMMENDED to transition to SHA-256 or better as soon as possible to maintain interoperability with implementations currently in the process of phasing out SHA-1 support.

Note that a certificate containing a key for one signature algorithm MAY be signed using a different signature algorithm (for instance, an RSA key signed with an ECDSA key).

4.4.3. Certificate Verify

This message is used to provide explicit proof that an endpoint possesses the private key corresponding to its certificate. The CertificateVerify message also provides integrity for the handshake up to this point. Servers MUST send this message when authenticating via a certificate. Clients MUST send this message whenever authenticating via a certificate (i.e., when the Certificate message is non-empty). When sent, this message MUST appear immediately after the Certificate message and immediately prior to the Finished message.

Structure of this message:

```
struct {  
    SignatureScheme algorithm;  
    opaque signature<0..216-1>;  
} CertificateVerify;
```

The algorithm field specifies the signature algorithm used (see Section 4.2.3 for the definition of this field). The signature is a digital signature using that algorithm. The content that is covered

extension unless no valid certificate chain can be produced without unsupported algorithms (see Section 4.2.3).

If sent by a client, the signature algorithm used in the signature MUST be one of those present in the supported_signature_algorithms field of the "signature_algorithms" extension in the CertificateRequest message.

In addition, the signature algorithm MUST be compatible with the key in the sender's end-entity certificate. RSA signatures MUST use an RSASSA-PSS algorithm, regardless of whether RSASSA-PKCS1-v1_5 algorithms appear in "signature_algorithms". The SHA-1 algorithm MUST NOT be used in any signatures of CertificateVerify messages. All SHA-1 signature algorithms in this specification are defined solely for use in legacy certificates and are not valid for CertificateVerify signatures.

The receiver of a CertificateVerify message MUST verify the signature field. The verification process takes as input:

- The content covered by the digital signature
- The public key contained in the end-entity certificate found in the associated Certificate message.
- The digital signature received in the signature field of the CertificateVerify message

If the verification fails, the receiver MUST terminate the handshake with a "decrypt_error" alert.

4.4.4. Finished

The Finished message is the final message in the authentication block. It is essential for providing authentication of the handshake and of the computed keys.

Recipients of Finished messages MUST verify that the contents are correct and if incorrect MUST terminate the connection with a "decrypt_error" alert.

Once a side has sent its Finished message and received and validated the Finished message from its peer, it may begin to send and receive application data over the connection. There are two settings in which it is permitted to send data prior to receiving the peer's Finished:

1. Clients sending 0-RTT data as described in Section 4.2.10.

2. Servers MAY send data after sending their first flight, but because the handshake is not yet complete, they have no assurance of either the peer's identity or of its liveness (i.e., the ClientHello might have been replayed).

The key used to compute the Finished message is computed from the Base key defined in Section 4.4 using HKDF (see Section 7.1). Specifically:

```
finished_key =  
    HKDF-Expand-Label(BaseKey, "finished", "", Hash.length)
```

Structure of this message:

```
struct {  
    opaque verify_data[Hash.length];  
} Finished;
```

The verify_data value is computed as follows:

```
verify_data =  
    HMAC(finished_key,  
        Transcript-Hash(Handshake Context,  
                        Certificate*, CertificateVerify*))
```

* Only included if present.

HMAC [RFC2104] uses the Hash algorithm for the handshake. As noted above, the HMAC input can generally be implemented by a running hash, i.e., just the handshake hash at this point.

In previous versions of TLS, the verify_data was always 12 octets long. In TLS 1.3, it is the size of the HMAC output for the Hash used for the handshake.

Note: Alerts and any other record types are not handshake messages and are not included in the hash computations.

Any records following a Finished message MUST be encrypted under the appropriate application traffic key as described in Section 7.2. In particular, this includes any alerts sent by the server in response to client Certificate and CertificateVerify messages.

4.5. End of Early Data

```
struct {} EndOfEarlyData;
```

If the server sent an "early_data" extension, the client MUST send an EndOfEarlyData message after receiving the server Finished. If the server does not send an "early_data" extension, then the client MUST NOT send an EndOfEarlyData message. This message indicates that all 0-RTT application_data messages, if any, have been transmitted and that the following records are protected under handshake traffic keys. Servers MUST NOT send this message and clients receiving it MUST terminate the connection with an "unexpected_message" alert. This message is encrypted under keys derived from the client_early_traffic_secret.

4.6. Post-Handshake Messages

TLS also allows other messages to be sent after the main handshake. These messages use a handshake content type and are encrypted under the appropriate application traffic key.

4.6.1. New Session Ticket Message

At any time after the server has received the client Finished message, it MAY send a NewSessionTicket message. This message creates a unique association between the ticket value and a secret PSK derived from the resumption master secret (see Section 7).

The client MAY use this PSK for future handshakes by including the ticket value in the "pre_shared_key" extension in its ClientHello (Section 4.2.11). Servers MAY send multiple tickets on a single connection, either immediately after each other or after specific events (see Appendix C.4). For instance, the server might send a new ticket after post-handshake authentication in order to encapsulate the additional client authentication state. Multiple tickets are useful for clients for a variety of purposes, including:

- Opening multiple parallel HTTP connections.
- Performing connection racing across interfaces and address families via, e.g., Happy Eyeballs [RFC8305] or related techniques.

Any ticket MUST only be resumed with a cipher suite that has the same KDF hash algorithm as that used to establish the original connection.

Clients MUST only resume if the new SNI value is valid for the server certificate presented in the original session, and SHOULD only resume if the SNI value matches the one used in the original session. The latter is a performance optimization: normally, there is no reason to expect that different servers covered by a single certificate would be able to accept each other's tickets, hence attempting resumption

in that case would waste a single-use ticket. If such an indication is provided (externally or by any other means), clients MAY resume with a different SNI value.

On resumption, if reporting an SNI value to the calling application, implementations MUST use the value sent in the resumption ClientHello rather than the value sent in the previous session. Note that if a server implementation declines all PSK identities with different SNI values, these two values are always the same.

Note: Although the resumption master secret depends on the client's second flight, servers which do not request client authentication MAY compute the remainder of the transcript independently and then send a NewSessionTicket immediately upon sending its Finished rather than waiting for the client Finished. This might be appropriate in cases where the client is expected to open multiple TLS connections in parallel and would benefit from the reduced overhead of a resumption handshake, for example.

```
struct {  
    uint32 ticket_lifetime;  
    uint32 ticket_age_add;  
    opaque ticket_nonce<0..255>;  
    opaque ticket<1..2^16-1>;  
    Extension extensions<0..2^16-2>;  
} NewSessionTicket;
```

ticket_lifetime Indicates the lifetime in seconds as a 32-bit unsigned integer in network byte order from the time of ticket issuance. Servers MUST NOT use any value greater than 604800 seconds (7 days). The value of zero indicates that the ticket should be discarded immediately. Clients MUST NOT cache tickets for longer than 7 days, regardless of the ticket_lifetime, and MAY delete tickets earlier based on local policy. A server MAY treat a ticket as valid for a shorter period of time than what is stated in the ticket_lifetime.

ticket_age_add A securely generated, random 32-bit value that is used to obscure the age of the ticket that the client includes in the "pre_shared_key" extension. The client-side ticket age is added to this value modulo 2^{32} to obtain the value that is transmitted by the client. The server MUST generate a fresh value for each ticket it sends.

ticket_nonce A per-ticket value that is unique across all tickets issued on this connection.

ticket The value of the ticket to be used as the PSK identity. The ticket itself is an opaque label. It MAY either be a database lookup key or a self-encrypted and self-authenticated value. Section 4 of [RFC5077] describes a recommended ticket construction mechanism.

extensions A set of extension values for the ticket. The "Extension" format is defined in Section 4.2. Clients MUST ignore unrecognized extensions.

The sole extension currently defined for NewSessionTicket is "early_data", indicating that the ticket may be used to send 0-RTT data (Section 4.2.10)). It contains the following value:

max_early_data_size The maximum amount of 0-RTT data that the client is allowed to send when using this ticket, in bytes. Only Application Data payload (i.e., plaintext but not padding or the inner content type byte) is counted. A server receiving more than max_early_data_size bytes of 0-RTT data SHOULD terminate the connection with an "unexpected_message" alert. Note that servers that reject early data due to lack of cryptographic material will be unable to differentiate padding from content, so clients SHOULD NOT depend on being able to send large quantities of padding in early data records.

The PSK associated with the ticket is computed as:

```
HKDF-Expand-Label(resumption_master_secret,  
                  "resumption", ticket_nonce, Hash.length)
```

Because the ticket_nonce value is distinct for each NewSessionTicket message, a different PSK will be derived for each ticket.

Note that in principle it is possible to continue issuing new tickets which indefinitely extend the lifetime of the keying material originally derived from an initial non-PSK handshake (which was most likely tied to the peer's certificate). It is RECOMMENDED that implementations place limits on the total lifetime of such keying material; these limits should take into account the lifetime of the peer's certificate, the likelihood of intervening revocation, and the time since the peer's online CertificateVerify signature.

4.6.2. Post-Handshake Authentication

When the client has sent the "post_handshake_auth" extension (see Section 4.2.6), a server MAY request client authentication at any time after the handshake has completed by sending a CertificateRequest message. The client MUST respond with the

appropriate Authentication messages (see Section 4.4). If the client chooses to authenticate, it MUST send Certificate, CertificateVerify, and Finished. If it declines, it MUST send a Certificate message containing no certificates followed by Finished. All of the client's messages for a given response MUST appear consecutively on the wire with no intervening messages of other types.

A client that receives a CertificateRequest message without having sent the "post_handshake_auth" extension MUST send an "unexpected_message" fatal alert.

Note: Because client authentication could involve prompting the user, servers MUST be prepared for some delay, including receiving an arbitrary number of other messages between sending the CertificateRequest and receiving a response. In addition, clients which receive multiple CertificateRequests in close succession MAY respond to them in a different order than they were received (the certificate_request_context value allows the server to disambiguate the responses).

4.6.3. Key and IV Update

```
enum {  
    update_not_requested(0), update_requested(1), (255)  
} KeyUpdateRequest;  
  
struct {  
    KeyUpdateRequest request_update;  
} KeyUpdate;
```

request_update Indicates whether the recipient of the KeyUpdate should respond with its own KeyUpdate. If an implementation receives any other value, it MUST terminate the connection with an "illegal_parameter" alert.

The KeyUpdate handshake message is used to indicate that the sender is updating its sending cryptographic keys. This message can be sent by either peer after it has sent a Finished message. Implementations that receive a KeyUpdate message prior to receiving a Finished message MUST terminate the connection with an "unexpected_message" alert. After sending a KeyUpdate message, the sender SHALL send all its traffic using the next generation of keys, computed as described in Section 7.2. Upon receiving a KeyUpdate, the receiver MUST update its receiving keys.

If the request_update field is set to "update_requested" then the receiver MUST send a KeyUpdate of its own with request_update set to "update_not_requested" prior to sending its next application data

record. This mechanism allows either side to force an update to the entire connection, but causes an implementation which receives multiple KeyUpdates while it is silent to respond with a single update. Note that implementations may receive an arbitrary number of messages between sending a KeyUpdate with `request_update` set to `update_requested` and receiving the peer's KeyUpdate, because those messages may already be in flight. However, because send and receive keys are derived from independent traffic secrets, retaining the receive traffic secret does not threaten the forward secrecy of data sent before the sender changed keys.

If implementations independently send their own KeyUpdates with `request_update` set to `update_requested`, and they cross in flight, then each side will also send a response, with the result that each side increments by two generations.

Both sender and receiver MUST encrypt their KeyUpdate messages with the old keys. Additionally, both sides MUST enforce that a KeyUpdate with the old key is received before accepting any messages encrypted with the new key. Failure to do so may allow message truncation attacks.

5. Record Protocol

The TLS record protocol takes messages to be transmitted, fragments the data into manageable blocks, protects the records, and transmits the result. Received data is verified, decrypted, reassembled, and then delivered to higher-level clients.

TLS records are typed, which allows multiple higher-level protocols to be multiplexed over the same record layer. This document specifies four content types: handshake, application data, alert, and `change_cipher_spec`. The `change_cipher_spec` record is used only for compatibility purposes (see Appendix D.4).

An implementation may receive an unencrypted record of type `change_cipher_spec` consisting of the single byte value 0x01 at any time after the first ClientHello message has been sent or received and before the peer's Finished message has been received and MUST simply drop it without further processing. Note that this record may appear at a point at the handshake where the implementation is expecting protected records and so it is necessary to detect this condition prior to attempting to deprotect the record. An implementation which receives any other `change_cipher_spec` value or which receives a protected `change_cipher_spec` record MUST abort the handshake with an "unexpected_message" alert. A `change_cipher_spec` record received before the first ClientHello message or after the peer's Finished message MUST be treated as an unexpected record type

(though stateless servers may not be able to distinguish these cases from allowed cases).

Implementations MUST NOT send record types not defined in this document unless negotiated by some extension. If a TLS implementation receives an unexpected record type, it MUST terminate the connection with an "unexpected_message" alert. New record content type values are assigned by IANA in the TLS Content Type Registry as described in Section 11.

5.1. Record Layer

The record layer fragments information blocks into TLSPlaintext records carrying data in chunks of 2^{14} bytes or less. Message boundaries are handled differently depending on the underlying ContentType. Any future content types MUST specify appropriate rules. Note that these rules are stricter than what was enforced in TLS 1.2.

Handshake messages MAY be coalesced into a single TLSPlaintext record or fragmented across several records, provided that:

- Handshake messages MUST NOT be interleaved with other record types. That is, if a handshake message is split over two or more records, there MUST NOT be any other records between them.
- Handshake messages MUST NOT span key changes. Implementations MUST verify that all messages immediately preceding a key change align with a record boundary; if not, then they MUST terminate the connection with an "unexpected_message" alert. Because the ClientHello, EndOfEarlyData, ServerHello, Finished, and KeyUpdate messages can immediately precede a key change, implementations MUST send these messages in alignment with a record boundary.

Implementations MUST NOT send zero-length fragments of Handshake types, even if those fragments contain padding.

Alert messages (Section 6) MUST NOT be fragmented across records and multiple Alert messages MUST NOT be coalesced into a single TLSPlaintext record. In other words, a record with an Alert type MUST contain exactly one message.

Application Data messages contain data that is opaque to TLS. Application Data messages are always protected. Zero-length fragments of Application Data MAY be sent as they are potentially useful as a traffic analysis countermeasure. Application Data fragments MAY be split across multiple records or coalesced into a single record.

```
enum {
    invalid(0),
    change_cipher_spec(20),
    alert(21),
    handshake(22),
    application_data(23),
    (255)
} ContentType;

struct {
    ContentType type;
    ProtocolVersion legacy_record_version;
    uint16 length;
    opaque fragment[TLSPplaintext.length];
} TLSPplaintext;
```

type The higher-level protocol used to process the enclosed fragment.

legacy_record_version This value MUST be set to 0x0303 for all records generated by a TLS 1.3 implementation other than an initial ClientHello (i.e., one not generated after a HelloRetryRequest), where it MAY also be 0x0301 for compatibility purposes. This field is deprecated and MUST be ignored for all purposes. Previous versions of TLS would use other values in this field under some circumstances.

length The length (in bytes) of the following TLSPplaintext.fragment. The length MUST NOT exceed 2^{14} bytes. An endpoint that receives a record that exceeds this length MUST terminate the connection with a "record_overflow" alert.

fragment The data being transmitted. This value is transparent and is treated as an independent block to be dealt with by the higher-level protocol specified by the type field.

This document describes TLS 1.3, which uses the version 0x0304. This version value is historical, deriving from the use of 0x0301 for TLS 1.0 and 0x0300 for SSL 3.0. In order to maximize backwards compatibility, records containing an initial ClientHello SHOULD have version 0x0301 and a record containing a second ClientHello or a ServerHello MUST have version 0x0303, reflecting TLS 1.0 and TLS 1.2 respectively. When negotiating prior versions of TLS, endpoints follow the procedure and requirements in Appendix D.

When record protection has not yet been engaged, TLSPplaintext structures are written directly onto the wire. Once record protection has started, TLSPplaintext records are protected and sent

as described in the following section. Note that application data records MUST NOT be written to the wire unprotected (see Section 2 for details).

5.2. Record Payload Protection

The record protection functions translate a `TLSP Plaintext` structure into a `TLSCiphertext`. The deprotection functions reverse the process. In TLS 1.3, as opposed to previous versions of TLS, all ciphers are modeled as "Authenticated Encryption with Additional Data" (AEAD) [RFC5116]. AEAD functions provide a unified encryption and authentication operation which turns plaintext into authenticated ciphertext and back again. Each encrypted record consists of a plaintext header followed by an encrypted body, which itself contains a type and optional padding.

```
struct {
    opaque content[TLSP Plaintext.length];
    ContentType type;
    uint8 zeros[length_of_padding];
} TLSInnerPlaintext;

struct {
    ContentType opaque_type = application_data; /* 23 */
    ProtocolVersion legacy_record_version = 0x0303; /* TLS v1.2 */
    uint16 length;
    opaque encrypted_record[TLSCiphertext.length];
} TLSCiphertext;
```

`content` The `TLSP Plaintext.fragment` value, containing the byte encoding of a handshake or an alert message, or the raw bytes of the application's data to send.

`type` The `TLSP Plaintext.type` value containing the content type of the record.

`zeros` An arbitrary-length run of zero-valued bytes may appear in the cleartext after the type field. This provides an opportunity for senders to pad any TLS record by a chosen amount as long as the total stays within record size limits. See Section 5.4 for more details.

`opaque_type` The outer `opaque_type` field of a `TLSCiphertext` record is always set to the value 23 (`application_data`) for outward compatibility with middleboxes accustomed to parsing previous versions of TLS. The actual content type of the record is found in `TLSInnerPlaintext.type` after decryption.

`legacy_record_version` The `legacy_record_version` field is always 0x0303. TLS 1.3 TLSCiphertexts are not generated until after TLS 1.3 has been negotiated, so there are no historical compatibility concerns where other values might be received. Note that the handshake protocol including the ClientHello and ServerHello messages authenticates the protocol version, so this value is redundant.

`length` The length (in bytes) of the following TLSCiphertext.encrypted_record, which is the sum of the lengths of the content and the padding, plus one for the inner content type, plus any expansion added by the AEAD algorithm. The length MUST NOT exceed $2^{14} + 256$ bytes. An endpoint that receives a record that exceeds this length MUST terminate the connection with a "record_overflow" alert.

`encrypted_record` The AEAD-encrypted form of the serialized TLSInnerPlaintext structure.

AEAD algorithms take as input a single key, a nonce, a plaintext, and "additional data" to be included in the authentication check, as described in Section 2.1 of [RFC5116]. The key is either the `client_write_key` or the `server_write_key`, the nonce is derived from the sequence number and the `client_write_iv` or `server_write_iv` (see Section 5.3), and the additional data input is the record header. I.e.,

```
additional_data = TLSCiphertext.opaque_type ||
                  TLSCiphertext.legacy_record_version ||
                  TLSCiphertext.length
```

The plaintext input to the AEAD algorithm is the encoded TLSInnerPlaintext structure. Derivation of traffic keys is defined in Section 7.3.

The AEAD output consists of the ciphertext output from the AEAD encryption operation. The length of the plaintext is greater than the corresponding TLSPlaintext.length due to the inclusion of TLSInnerPlaintext.type and any padding supplied by the sender. The length of the AEAD output will generally be larger than the plaintext, but by an amount that varies with the AEAD algorithm. Since the ciphers might incorporate padding, the amount of overhead could vary with different lengths of plaintext. Symbolically,

```
AEADEncrypted =
    AEAD-Encrypt(write_key, nonce, additional_data, plaintext)
```

Then the `encrypted_record` field of `TLSCiphertext` is set to `AEADEncrypted`.

In order to decrypt and verify, the cipher takes as input the key, nonce, additional data, and the `AEADEncrypted` value. The output is either the plaintext or an error indicating that the decryption failed. There is no separate integrity check. That is:

```
plaintext of encrypted_record =  
    AEAD-Decrypt(peer_write_key, nonce, additional_data, AEADEncrypted)
```

If the decryption fails, the receiver MUST terminate the connection with a "bad_record_mac" alert.

An AEAD algorithm used in TLS 1.3 MUST NOT produce an expansion greater than 255 octets. An endpoint that receives a record from its peer with `TLSCiphertext.length` larger than $2^{14} + 256$ octets MUST terminate the connection with a "record_overflow" alert. This limit is derived from the maximum `TLSInnerPlaintext` length of 2^{14} octets + 1 octet for `ContentType` + the maximum AEAD expansion of 255 octets.

5.3. Per-Record Nonce

A 64-bit sequence number is maintained separately for reading and writing records. The appropriate sequence number is incremented by one after reading or writing each record. Each sequence number is set to zero at the beginning of a connection and whenever the key is changed; the first record transmitted under a particular traffic key MUST use sequence number 0.

Because the size of sequence numbers is 64-bit, they should not wrap. If a TLS implementation would need to wrap a sequence number, it MUST either re-key (Section 4.6.3) or terminate the connection.

Each AEAD algorithm will specify a range of possible lengths for the per-record nonce, from `N_MIN` bytes to `N_MAX` bytes of input ([RFC5116]). The length of the TLS per-record nonce (`iv_length`) is set to the larger of 8 bytes and `N_MIN` for the AEAD algorithm (see [RFC5116] Section 4). An AEAD algorithm where `N_MAX` is less than 8 bytes MUST NOT be used with TLS. The per-record nonce for the AEAD construction is formed as follows:

1. The 64-bit record sequence number is encoded in network byte order and padded to the left with zeros to `iv_length`.
2. The padded sequence number is XORed with the static `client_write_iv` or `server_write_iv`, depending on the role.

The resulting quantity (of length `iv_length`) is used as the per-record nonce.

Note: This is a different construction from that in TLS 1.2, which specified a partially explicit nonce.

5.4. Record Padding

All encrypted TLS records can be padded to inflate the size of the `TLSCiphertext`. This allows the sender to hide the size of the traffic from an observer.

When generating a `TLSCiphertext` record, implementations MAY choose to pad. An unpadded record is just a record with a padding length of zero. Padding is a string of zero-valued bytes appended to the `ContentType` field before encryption. Implementations MUST set the padding octets to all zeros before encrypting.

Application Data records may contain a zero-length `TLSInnerPlaintext.content` if the sender desires. This permits generation of plausibly-sized cover traffic in contexts where the presence or absence of activity may be sensitive. Implementations MUST NOT send Handshake or Alert records that have a zero-length `TLSInnerPlaintext.content`; if such a message is received, the receiving implementation MUST terminate the connection with an "unexpected_message" alert.

The padding sent is automatically verified by the record protection mechanism; upon successful decryption of a `TLSCiphertext.encrypted_record`, the receiving implementation scans the field from the end toward the beginning until it finds a non-zero octet. This non-zero octet is the content type of the message. This padding scheme was selected because it allows padding of any encrypted TLS record by an arbitrary size (from zero up to TLS record size limits) without introducing new content types. The design also enforces all-zero padding octets, which allows for quick detection of padding errors.

Implementations MUST limit their scanning to the cleartext returned from the AEAD decryption. If a receiving implementation does not find a non-zero octet in the cleartext, it MUST terminate the connection with an "unexpected_message" alert.

The presence of padding does not change the overall record size limitations - the full encoded `TLSInnerPlaintext` MUST NOT exceed $2^{14} + 1$ octets. If the maximum fragment length is reduced, as for example by the `max_fragment_length` extension from [RFC6066], then the

reduced limit applies to the full plaintext, including the content type and padding.

Selecting a padding policy that suggests when and how much to pad is a complex topic and is beyond the scope of this specification. If the application layer protocol on top of TLS has its own padding, it may be preferable to pad application_data TLS records within the application layer. Padding for encrypted handshake and alert TLS records must still be handled at the TLS layer, though. Later documents may define padding selection algorithms or define a padding policy request mechanism through TLS extensions or some other means.

5.5. Limits on Key Usage

There are cryptographic limits on the amount of plaintext which can be safely encrypted under a given set of keys. [AEAD-LIMITS] provides an analysis of these limits under the assumption that the underlying primitive (AES or ChaCha20) has no weaknesses. Implementations SHOULD do a key update as described in Section 4.6.3 prior to reaching these limits.

For AES-GCM, up to $2^{24.5}$ full-size records (about 24 million) may be encrypted on a given connection while keeping a safety margin of approximately 2^{-57} for Authenticated Encryption (AE) security. For ChaCha20/Poly1305, the record sequence number would wrap before the safety limit is reached.

6. Alert Protocol

One of the content types supported by the TLS record layer is the alert type. Like other messages, alert messages are encrypted as specified by the current connection state.

Alert messages convey a description of the alert and a legacy field that conveyed the severity of the message in previous versions of TLS. Alerts are divided into two classes: closure alerts and error alerts. In TLS 1.3, the severity is implicit in the type of alert being sent, and the 'level' field can safely be ignored. The "close_notify" alert is used to indicate orderly closure of one direction of the connection. Upon receiving such an alert, the TLS implementation SHOULD indicate end-of-data to the application.

Error alerts indicate abortive closure of the connection (see Section 6.2). Upon receiving an error alert, the TLS implementation SHOULD indicate an error to the application and MUST NOT allow any further data to be sent or received on the connection. Servers and clients MUST forget the secret values and keys established in failed

connections, with the exception of the PSKs associated with session tickets, which SHOULD be discarded if possible.

All the alerts listed in Section 6.2 MUST be sent with AlertLevel=fatal and MUST be treated as error alerts regardless of the AlertLevel in the message. Unknown alert types MUST be treated as error alerts.

Note: TLS defines two generic alerts (see Section 6) to use upon failure to parse a message. Peers which receive a message which cannot be parsed according to the syntax (e.g., have a length extending beyond the message boundary or contain an out-of-range length) MUST terminate the connection with a "decode_error" alert. Peers which receive a message which is syntactically correct but semantically invalid (e.g., a DHE share of $p - 1$, or an invalid enum) MUST terminate the connection with an "illegal_parameter" alert.

```
enum { warning(1), fatal(2), (255) } AlertLevel;

enum {
    close_notify(0),
    unexpected_message(10),
    bad_record_mac(20),
    record_overflow(22),
    handshake_failure(40),
    bad_certificate(42),
    unsupported_certificate(43),
    certificate_revoked(44),
    certificate_expired(45),
    certificate_unknown(46),
    illegal_parameter(47),
    unknown_ca(48),
    access_denied(49),
    decode_error(50),
    decrypt_error(51),
    protocol_version(70),
    insufficient_security(71),
    internal_error(80),
    inappropriate_fallback(86),
    user_canceled(90),
    missing_extension(109),
    unsupported_extension(110),
    unrecognized_name(112),
    bad_certificate_status_response(113),
    unknown_psk_identity(115),
    certificate_required(116),
    no_application_protocol(120),
    (255)
} AlertDescription;

struct {
    AlertLevel level;
    AlertDescription description;
} Alert;
```

6.1. Closure Alerts

The client and the server must share knowledge that the connection is ending in order to avoid a truncation attack.

close_notify This alert notifies the recipient that the sender will not send any more messages on this connection. Any data received after a closure alert has been received **MUST** be ignored.

`user_canceled` This alert notifies the recipient that the sender is canceling the handshake for some reason unrelated to a protocol failure. If a user cancels an operation after the handshake is complete, just closing the connection by sending a "close_notify" is more appropriate. This alert SHOULD be followed by a "close_notify". This alert generally has `AlertLevel=warning`.

Either party MAY initiate a close of its write side of the connection by sending a "close_notify" alert. Any data received after a closure alert has been received MUST be ignored. If a transport-level close is received prior to a "close_notify", the receiver cannot know that all the data that was sent has been received.

Each party MUST send a "close_notify" alert before closing its write side of the connection, unless it has already sent some error alert. This does not have any effect on its read side of the connection. Note that this is a change from versions of TLS prior to TLS 1.3 in which implementations were required to react to a "close_notify" by discarding pending writes and sending an immediate "close_notify" alert of their own. That previous requirement could cause truncation in the read side. Both parties need not wait to receive a "close_notify" alert before closing their read side of the connection, though doing so would introduce the possibility of truncation.

If the application protocol using TLS provides that any data may be carried over the underlying transport after the TLS connection is closed, the TLS implementation MUST receive a "close_notify" alert before indicating end-of-data to the application-layer. No part of this standard should be taken to dictate the manner in which a usage profile for TLS manages its data transport, including when connections are opened or closed.

Note: It is assumed that closing the write side of a connection reliably delivers pending data before destroying the transport.

6.2. Error Alerts

Error handling in the TLS Handshake Protocol is very simple. When an error is detected, the detecting party sends a message to its peer. Upon transmission or receipt of a fatal alert message, both parties MUST immediately close the connection.

Whenever an implementation encounters a fatal error condition, it SHOULD send an appropriate fatal alert and MUST close the connection without sending or receiving any additional data. In the rest of this specification, when the phrases "terminate the connection" and "abort the handshake" are used without a specific alert it means that

the implementation SHOULD send the alert indicated by the descriptions below. The phrases "terminate the connection with a X alert" and "abort the handshake with a X alert" mean that the implementation MUST send alert X if it sends any alert. All alerts defined in this section below, as well as all unknown alerts, are universally considered fatal as of TLS 1.3 (see Section 6). The implementation SHOULD provide a way to facilitate logging the sending and receiving of alerts.

The following error alerts are defined:

`unexpected_message` An inappropriate message (e.g., the wrong handshake message, premature application data, etc.) was received. This alert should never be observed in communication between proper implementations.

`bad_record_mac` This alert is returned if a record is received which cannot be deprotected. Because AEAD algorithms combine decryption and verification, and also to avoid side channel attacks, this alert is used for all deprotection failures. This alert should never be observed in communication between proper implementations, except when messages were corrupted in the network.

`record_overflow` A TLSCiphertext record was received that had a length more than $2^{14} + 256$ bytes, or a record decrypted to a TLSPlaintext record with more than 2^{14} bytes (or some other negotiated limit). This alert should never be observed in communication between proper implementations, except when messages were corrupted in the network.

`handshake_failure` Receipt of a "handshake_failure" alert message indicates that the sender was unable to negotiate an acceptable set of security parameters given the options available.

`bad_certificate` A certificate was corrupt, contained signatures that did not verify correctly, etc.

`unsupported_certificate` A certificate was of an unsupported type.

`certificate_revoked` A certificate was revoked by its signer.

`certificate_expired` A certificate has expired or is not currently valid.

`certificate_unknown` Some other (unspecified) issue arose in processing the certificate, rendering it unacceptable.

`illegal_parameter` A field in the handshake was incorrect or inconsistent with other fields. This alert is used for errors which conform to the formal protocol syntax but are otherwise incorrect.

`unknown_ca` A valid certificate chain or partial chain was received, but the certificate was not accepted because the CA certificate could not be located or could not be matched with a known trust anchor.

`access_denied` A valid certificate or PSK was received, but when access control was applied, the sender decided not to proceed with negotiation.

`decode_error` A message could not be decoded because some field was out of the specified range or the length of the message was incorrect. This alert is used for errors where the message does not conform to the formal protocol syntax. This alert should never be observed in communication between proper implementations, except when messages were corrupted in the network.

`decrypt_error` A handshake (not record-layer) cryptographic operation failed, including being unable to correctly verify a signature or validate a Finished message or a PSK binder.

`protocol_version` The protocol version the peer has attempted to negotiate is recognized but not supported. (see Appendix D)

`insufficient_security` Returned instead of "handshake_failure" when a negotiation has failed specifically because the server requires parameters more secure than those supported by the client.

`internal_error` An internal error unrelated to the peer or the correctness of the protocol (such as a memory allocation failure) makes it impossible to continue.

`inappropriate_fallback` Sent by a server in response to an invalid connection retry attempt from a client (see [RFC7507]).

`missing_extension` Sent by endpoints that receive a handshake message not containing an extension that is mandatory to send for the offered TLS version or other negotiated parameters.

`unsupported_extension` Sent by endpoints receiving any handshake message containing an extension known to be prohibited for inclusion in the given handshake message, or including any extensions in a ServerHello or Certificate not first offered in the corresponding ClientHello.

`unrecognized_name` Sent by servers when no server exists identified by the name provided by the client via the "server_name" extension (see [RFC6066]).

`bad_certificate_status_response` Sent by clients when an invalid or unacceptable OCSP response is provided by the server via the "status_request" extension (see [RFC6066]).

`unknown_psk_identity` Sent by servers when PSK key establishment is desired but no acceptable PSK identity is provided by the client. Sending this alert is OPTIONAL; servers MAY instead choose to send a "decrypt_error" alert to merely indicate an invalid PSK identity.

`certificate_required` Sent by servers when a client certificate is desired but none was provided by the client.

`no_application_protocol` Sent by servers when a client "application_layer_protocol_negotiation" extension advertises only protocols that the server does not support (see [RFC7301]).

New Alert values are assigned by IANA as described in Section 11.

7. Cryptographic Computations

The TLS handshake establishes one or more input secrets which are combined to create the actual working keying material, as detailed below. The key derivation process incorporates both the input secrets and the handshake transcript. Note that because the handshake transcript includes the random values from the Hello messages, any given handshake will have different traffic secrets, even if the same input secrets are used, as is the case when the same PSK is used for multiple connections.

7.1. Key Schedule

The key derivation process makes use of the HKDF-Extract and HKDF-Expand functions as defined for HKDF [RFC5869], as well as the functions defined below:

```
HKDF-Expand-Label(Secret, Label, Context, Length) =  
    HKDF-Expand(Secret, HkdfLabel, Length)
```

Where HkdfLabel is specified as:

```
struct {  
    uint16 length = Length;  
    opaque label<7..255> = "tls13 " + Label;  
    opaque context<0..255> = Context;  
} HkdfLabel;
```

```
Derive-Secret(Secret, Label, Messages) =  
    HKDF-Expand-Label(Secret, Label,  
        Transcript-Hash(Messages), Hash.length)
```

The Hash function used by Transcript-Hash and HKDF is the cipher suite hash algorithm. Hash.length is its output length in bytes. Messages is the concatenation of the indicated handshake messages, including the handshake message type and length fields, but not including record layer headers. Note that in some cases a zero-length Context (indicated by "") is passed to HKDF-Expand-Label. The Labels specified in this document are all ASCII strings, and do not include a trailing NUL byte.

Note: with common hash functions, any label longer than 12 characters requires an additional iteration of the hash function to compute. The labels in this specification have all been chosen to fit within this limit.

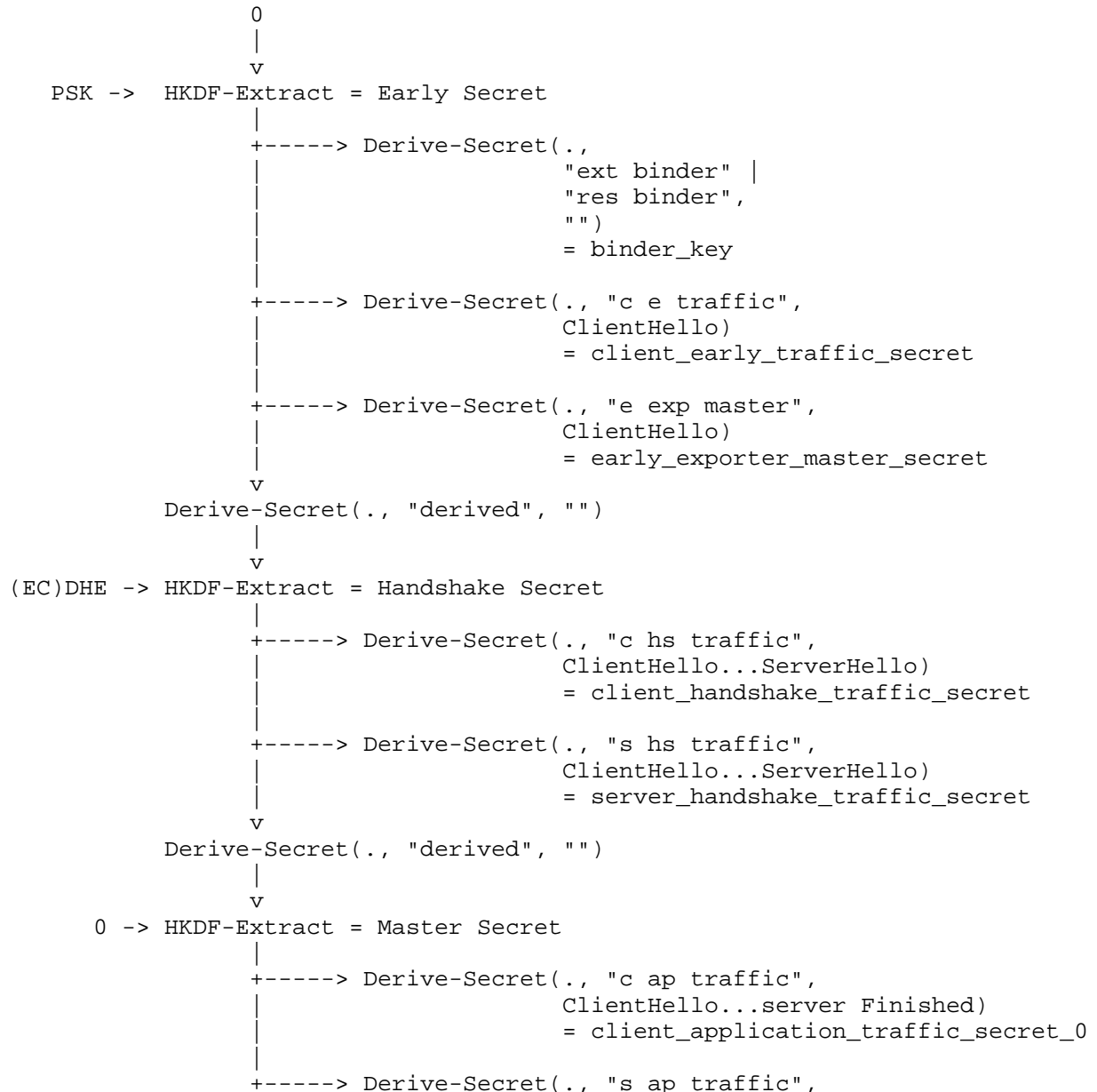
Keys are derived from two input secrets using the HKDF-Extract and Derive-Secret functions. The general pattern for adding a new secret is to use HKDF-Extract with the salt being the current secret state and the IKM being the new secret to be added. In this version of TLS 1.3, the two input secrets are:

- PSK (a pre-shared key established externally or derived from the resumption_master_secret value from a previous connection)
- (EC)DHE shared secret (Section 7.4)

This produces a full key derivation schedule shown in the diagram below. In this diagram, the following formatting conventions apply:

- HKDF-Extract is drawn as taking the Salt argument from the top and the IKM argument from the left, with its output to the bottom and the name of the output on the right.

- Derive-Secret's Secret argument is indicated by the incoming arrow. For instance, the Early Secret is the Secret for generating the client_early_traffic_secret.
- "0" indicates a string of Hash-lengths bytes set to 0.



```

|                                     ClientHello...server Finished)
|                                     = server_application_traffic_secret_0
+-----> Derive-Secret(., "exp master",
|                                     ClientHello...server Finished)
|                                     = exporter_master_secret
+-----> Derive-Secret(., "res master",
|                                     ClientHello...client Finished)
|                                     = resumption_master_secret

```

The general pattern here is that the secrets shown down the left side of the diagram are just raw entropy without context, whereas the secrets down the right side include handshake context and therefore can be used to derive working keys without additional context. Note that the different calls to Derive-Secret may take different Messages arguments, even with the same secret. In a 0-RTT exchange, Derive-Secret is called with four distinct transcripts; in a 1-RTT-only exchange with three distinct transcripts.

If a given secret is not available, then the 0-value consisting of a string of Hash.length bytes set to zeros is used. Note that this does not mean skipping rounds, so if PSK is not in use Early Secret will still be HKDF-Extract(0, 0). For the computation of the binder_secret, the label is "ext binder" for external PSKs (those provisioned outside of TLS) and "res binder" for resumption PSKs (those provisioned as the resumption master secret of a previous handshake). The different labels prevent the substitution of one type of PSK for the other.

There are multiple potential Early Secret values depending on which PSK the server ultimately selects. The client will need to compute one for each potential PSK; if no PSK is selected, it will then need to compute the early secret corresponding to the zero PSK.

Once all the values which are to be derived from a given secret have been computed, that secret SHOULD be erased.

7.2. Updating Traffic Secrets

Once the handshake is complete, it is possible for either side to update its sending traffic keys using the KeyUpdate handshake message defined in Section 4.6.3. The next generation of traffic keys is computed by generating client_/server_application_traffic_secret_N+1 from client_/server_application_traffic_secret_N as described in this section then re-deriving the traffic keys as described in Section 7.3.

The next-generation `application_traffic_secret` is computed as:

```
application_traffic_secret_N+1 =
    HKDF-Expand-Label(application_traffic_secret_N,
                      "traffic upd", "", Hash.length)
```

Once `client/server_application_traffic_secret_N+1` and its associated traffic keys have been computed, implementations **SHOULD** delete `client_/server_application_traffic_secret_N` and its associated traffic keys.

7.3. Traffic Key Calculation

The traffic keying material is generated from the following input values:

- A secret value
- A purpose value indicating the specific value being generated
- The length of the key being generated

The traffic keying material is generated from an input traffic secret value using:

```
[sender]_write_key = HKDF-Expand-Label(Secret, "key", "", key_length)
[sender]_write_iv  = HKDF-Expand-Label(Secret, "iv" , "", iv_length)
```

[sender] denotes the sending side. The Secret value for each record type is shown in the table below.

Record Type	Secret
0-RTT Application	<code>client_early_traffic_secret</code>
Handshake	<code>[sender]_handshake_traffic_secret</code>
Application Data	<code>[sender]_application_traffic_secret_N</code>

All the traffic keying material is recomputed whenever the underlying Secret changes (e.g., when changing from the handshake to application data keys or upon a key update).

7.4. (EC)DHE Shared Secret Calculation

7.4.1. Finite Field Diffie-Hellman

For finite field groups, a conventional Diffie-Hellman [DH76] computation is performed. The negotiated key (Z) is converted to a byte string by encoding in big-endian and left padded with zeros up to the size of the prime. This byte string is used as the shared secret in the key schedule as specified above.

Note that this construction differs from previous versions of TLS which remove leading zeros.

7.4.2. Elliptic Curve Diffie-Hellman

For secp256r1, secp384r1 and secp521r1, ECDH calculations (including parameter and key generation as well as the shared secret calculation) are performed according to [IEEE1363] using the ECKAS-DH1 scheme with the identity map as key derivation function (KDF), so that the shared secret is the x-coordinate of the ECDH shared secret elliptic curve point represented as an octet string. Note that this octet string (Z in IEEE 1363 terminology) as output by FE2OSP, the Field Element to Octet String Conversion Primitive, has constant length for any given field; leading zeros found in this octet string MUST NOT be truncated.

(Note that this use of the identity KDF is a technicality. The complete picture is that ECDH is employed with a non-trivial KDF because TLS does not directly use this secret for anything other than for computing other secrets.)

ECDH functions are used as follows:

- The public key to put into the KeyShareEntry.key_exchange structure is the result of applying the ECDH scalar multiplication function to the secret key of appropriate length (into scalar input) and the standard public basepoint (into u-coordinate point input).
- The ECDH shared secret is the result of applying the ECDH scalar multiplication function to the secret key (into scalar input) and the peer's public key (into u-coordinate point input). The output is used raw, with no processing.

For X25519 and X448, implementations SHOULD use the approach specified in [RFC7748] to calculate the Diffie-Hellman shared secret. Implementations MUST check whether the computed Diffie-Hellman shared secret is the all-zero value and abort if so, as described in

Section 6 of [RFC7748]. If implementors use an alternative implementation of these elliptic curves, they SHOULD perform the additional checks specified in Section 7 of [RFC7748].

7.5. Exporters

[RFC5705] defines keying material exporters for TLS in terms of the TLS pseudorandom function (PRF). This document replaces the PRF with HKDF, thus requiring a new construction. The exporter interface remains the same.

The exporter value is computed as:

```
TLS-Exporter(label, context_value, key_length) =  
    HKDF-Expand-Label(Derive-Secret(Secret, label, ""),  
                      "exporter", Hash(context_value), key_length)
```

Where Secret is either the early_exporter_master_secret or the exporter_master_secret. Implementations MUST use the exporter_master_secret unless explicitly specified by the application. The early_exporter_master_secret is defined for use in settings where an exporter is needed for 0-RTT data. A separate interface for the early exporter is RECOMMENDED; this avoids the exporter user accidentally using an early exporter when a regular one is desired or vice versa.

If no context is provided, the context_value is zero-length. Consequently, providing no context computes the same value as providing an empty context. This is a change from previous versions of TLS where an empty context produced a different output to an absent context. As of this document's publication, no allocated exporter label is used both with and without a context. Future specifications MUST NOT define a use of exporters that permit both an empty context and no context with the same label. New uses of exporters SHOULD provide a context in all exporter computations, though the value could be empty.

Requirements for the format of exporter labels are defined in section 4 of [RFC5705].

8. 0-RTT and Anti-Replay

As noted in Section 2.3 and Appendix E.5, TLS does not provide inherent replay protections for 0-RTT data. There are two potential threats to be concerned with:

- Network attackers who mount a replay attack by simply duplicating a flight of 0-RTT data.

- Network attackers who take advantage of client retry behavior to arrange for the server to receive multiple copies of an application message. This threat already exists to some extent because clients that value robustness respond to network errors by attempting to retry requests. However, 0-RTT adds an additional dimension for any server system which does not maintain globally consistent server state. Specifically, if a server system has multiple zones where tickets from zone A will not be accepted in zone B, then an attacker can duplicate a ClientHello and early data intended for A to both A and B. At A, the data will be accepted in 0-RTT, but at B the server will reject 0-RTT data and instead force a full handshake. If the attacker blocks the ServerHello from A, then the client will complete the handshake with B and probably retry the request, leading to duplication on the server system as a whole.

The first class of attack can be prevented by sharing state to guarantee that the 0-RTT data is accepted at most once. Servers SHOULD provide that level of replay safety, by implementing one of the methods described in this section or by equivalent means. It is understood, however, that due to operational concerns not all deployments will maintain state at that level. Therefore, in normal operation, clients will not know which, if any, of these mechanisms servers actually implement and hence MUST only send early data which they deem safe to be replayed.

In addition to the direct effects of replays, there is a class of attacks where even operations normally considered idempotent could be exploited by a large number of replays (timing attacks, resource limit exhaustion and others described in Appendix E.5). Those can be mitigated by ensuring that every 0-RTT payload can be replayed only a limited number of times. The server MUST ensure that any instance of it (be it a machine, a thread or any other entity within the relevant serving infrastructure) would accept 0-RTT for the same 0-RTT handshake at most once; this limits the number of replays to the number of server instances in the deployment. Such a guarantee can be accomplished by locally recording data from recently-received ClientHellos and rejecting repeats, or by any other method that provides the same or a stronger guarantee. The "at most once per server instance" guarantee is a minimum requirement; servers SHOULD limit 0-RTT replays further when feasible.

The second class of attack cannot be prevented at the TLS layer and MUST be dealt with by any application. Note that any application whose clients implement any kind of retry behavior already needs to implement some sort of anti-replay defense.

8.1. Single-Use Tickets

The simplest form of anti-replay defense is for the server to only allow each session ticket to be used once. For instance, the server can maintain a database of all outstanding valid tickets; deleting each ticket from the database as it is used. If an unknown ticket is provided, the server would then fall back to a full handshake.

If the tickets are not self-contained but rather are database keys, and the corresponding PSKs are deleted upon use, then connections established using PSKs enjoy forward secrecy. This improves security for all 0-RTT data and PSK usage when PSK is used without (EC)DHE.

Because this mechanism requires sharing the session database between server nodes in environments with multiple distributed servers, it may be hard to achieve high rates of successful PSK 0-RTT connections when compared to self-encrypted tickets. Unlike session databases, session tickets can successfully do PSK-based session establishment even without consistent storage, though when 0-RTT is allowed they still require consistent storage for anti-replay of 0-RTT data, as detailed in the following section.

8.2. Client Hello Recording

An alternative form of anti-replay is to record a unique value derived from the ClientHello (generally either the random value or the PSK binder) and reject duplicates. Recording all ClientHellos causes state to grow without bound, but a server can instead record ClientHellos within a given time window and use the "obfuscated_ticket_age" to ensure that tickets aren't reused outside that window.

In order to implement this, when a ClientHello is received, the server first verifies the PSK binder as described Section 4.2.11. It then computes the expected_arrival_time as described in the next section and rejects 0-RTT if it is outside the recording window, falling back to the 1-RTT handshake.

If the expected arrival time is in the window, then the server checks to see if it has recorded a matching ClientHello. If one is found, it either aborts the handshake with an "illegal_parameter" alert or accepts the PSK but reject 0-RTT. If no matching ClientHello is found, then it accepts 0-RTT and then stores the ClientHello for as long as the expected_arrival_time is inside the window. Servers MAY also implement data stores with false positives, such as Bloom filters, in which case they MUST respond to apparent replay by rejecting 0-RTT but MUST NOT abort the handshake.

The server MUST derive the storage key only from validated sections of the ClientHello. If the ClientHello contains multiple PSK identities, then an attacker can create multiple ClientHellos with different binder values for the less-preferred identity on the assumption that the server will not verify it, as recommended by Section 4.2.11. I.e., if the client sends PSKs A and B but the server prefers A, then the attacker can change the binder for B without affecting the binder for A. If the binder for B is part of the storage key, then this ClientHello will not appear as a duplicate, which will cause the ClientHello to be accepted, and may cause side effects such as replay cache pollution, although any 0-RTT data will not be decryptable because it will use different keys. If the validated binder or the ClientHello.random are used as the storage key, then this attack is not possible.

Because this mechanism does not require storing all outstanding tickets, it may be easier to implement in distributed systems with high rates of resumption and 0-RTT, at the cost of potentially weaker anti-replay defense because of the difficulty of reliably storing and retrieving the received ClientHello messages. In many such systems, it is impractical to have globally consistent storage of all the received ClientHellos. In this case, the best anti-replay protection is provided by having a single storage zone be authoritative for a given ticket and refusing 0-RTT for that ticket in any other zone. This approach prevents simple replay by the attacker because only one zone will accept 0-RTT data. A weaker design is to implement separate storage for each zone but allow 0-RTT in any zone. This approach limits the number of replays to once per zone. Application message duplication of course remains possible with either design.

When implementations are freshly started, they SHOULD reject 0-RTT as long as any portion of their recording window overlaps the startup time. Otherwise, they run the risk of accepting replays which were originally sent during that period.

Note: If the client's clock is running much faster than the server's then a ClientHello may be received that is outside the window in the future, in which case it might be accepted for 1-RTT, causing a client retry, and then acceptable later for 0-RTT. This is another variant of the second form of attack described above.

8.3. Freshness Checks

Because the ClientHello indicates the time at which the client sent it, it is possible to efficiently determine whether a ClientHello was likely sent reasonably recently and only accept 0-RTT for such a ClientHello, otherwise falling back to a 1-RTT handshake. This is necessary for the ClientHello storage mechanism described in

Section 8.2 because otherwise the server needs to store an unlimited number of ClientHellos and is a useful optimization for self-contained single-use tickets because it allows efficient rejection of ClientHellos which cannot be used for 0-RTT.

In order to implement this mechanism, a server needs to store the time that the server generated the session ticket, offset by an estimate of the round trip time between client and server. I.e.,

$$\text{adjusted_creation_time} = \text{creation_time} + \text{estimated_RTT}$$

This value can be encoded in the ticket, thus avoiding the need to keep state for each outstanding ticket. The server can determine the client's view of the age of the ticket by subtracting the ticket's "ticket_age_add value" from the "obfuscated_ticket_age" parameter in the client's "pre_shared_key" extension. The server can determine the "expected arrival time" of the ClientHello as:

$$\text{expected_arrival_time} = \text{adjusted_creation_time} + \text{clients_ticket_age}$$

When a new ClientHello is received, the expected_arrival_time is then compared against the current server wall clock time and if they differ by more than a certain amount, 0-RTT is rejected, though the 1-RTT handshake can be allowed to complete.

There are several potential sources of error that might cause mismatches between the expected arrival time and the measured time. Variations in client and server clock rates are likely to be minimal, though potentially the absolute times may be off by large values. Network propagation delays are the most likely causes of a mismatch in legitimate values for elapsed time. Both the NewSessionTicket and ClientHello messages might be retransmitted and therefore delayed, which might be hidden by TCP. For clients on the Internet, this implies windows on the order of ten seconds to account for errors in clocks and variations in measurements; other deployment scenarios may have different needs. Clock skew distributions are not symmetric, so the optimal tradeoff may involve an asymmetric range of permissible mismatch values.

Note that freshness checking alone is not sufficient to prevent replays because it does not detect them during the error window, which, depending on bandwidth and system capacity could include billions of replays in real-world settings. In addition, this freshness checking is only done at the time the ClientHello is received, and not when later early application data records are received. After early data is accepted, records may continue to be streamed to the server over a longer time period.

9. Compliance Requirements

9.1. Mandatory-to-Implement Cipher Suites

In the absence of an application profile standard specifying otherwise, a TLS-compliant application **MUST** implement the TLS_AES_128_GCM_SHA256 [GCM] cipher suite and **SHOULD** implement the TLS_AES_256_GCM_SHA384 [GCM] and TLS_CHACHA20_POLY1305_SHA256 [RFC7539] cipher suites. (see Appendix B.4)

A TLS-compliant application **MUST** support digital signatures with rsa_pkcs1_sha256 (for certificates), rsa_pss_rsae_sha256 (for CertificateVerify and certificates), and ecdsa_secp256r1_sha256. A TLS-compliant application **MUST** support key exchange with secp256r1 (NIST P-256) and **SHOULD** support key exchange with X25519 [RFC7748].

9.2. Mandatory-to-Implement Extensions

In the absence of an application profile standard specifying otherwise, a TLS-compliant application **MUST** implement the following TLS extensions:

- Supported Versions ("supported_versions"; Section 4.2.1)
- Cookie ("cookie"; Section 4.2.2)
- Signature Algorithms ("signature_algorithms"; Section 4.2.3)
- Signature Algorithms Certificate ("signature_algorithms_cert"; Section 4.2.3)
- Negotiated Groups ("supported_groups"; Section 4.2.7)
- Key Share ("key_share"; Section 4.2.8)
- Server Name Indication ("server_name"; Section 3 of [RFC6066])

All implementations **MUST** send and use these extensions when offering applicable features:

- "supported_versions" is **REQUIRED** for all ClientHello, ServerHello and HelloRetryRequest messages.
- "signature_algorithms" is **REQUIRED** for certificate authentication.
- "supported_groups" is **REQUIRED** for ClientHello messages using DHE or ECDHE key exchange.

- "key_share" is REQUIRED for DHE or ECDHE key exchange.
- "pre_shared_key" is REQUIRED for PSK key agreement.
- "psk_key_exchange_modes" is REQUIRED for PSK key agreement.

A client is considered to be attempting to negotiate using this specification if the ClientHello contains a "supported_versions" extension with 0x0304 contained in its body. Such a ClientHello message MUST meet the following requirements:

- If not containing a "pre_shared_key" extension, it MUST contain both a "signature_algorithms" extension and a "supported_groups" extension.
- If containing a "supported_groups" extension, it MUST also contain a "key_share" extension, and vice versa. An empty KeyShare.client_shares vector is permitted.

Servers receiving a ClientHello which does not conform to these requirements MUST abort the handshake with a "missing_extension" alert.

Additionally, all implementations MUST support use of the "server_name" extension with applications capable of using it. Servers MAY require clients to send a valid "server_name" extension. Servers requiring this extension SHOULD respond to a ClientHello lacking a "server_name" extension by terminating the connection with a "missing_extension" alert.

9.3. Protocol Invariants

This section describes invariants that TLS endpoints and middleboxes MUST follow. It also applies to earlier versions of TLS.

TLS is designed to be securely and compatibly extensible. Newer clients or servers, when communicating with newer peers, should negotiate the most preferred common parameters. The TLS handshake provides downgrade protection: Middleboxes passing traffic between a newer client and newer server without terminating TLS should be unable to influence the handshake (see Appendix E.1). At the same time, deployments update at different rates, so a newer client or server MAY continue to support older parameters, which would allow it to interoperate with older endpoints.

For this to work, implementations MUST correctly handle extensible fields:

- A client sending a ClientHello MUST support all parameters advertised in it. Otherwise, the server may fail to interoperate by selecting one of those parameters.
- A server receiving a ClientHello MUST correctly ignore all unrecognized cipher suites, extensions, and other parameters. Otherwise, it may fail to interoperate with newer clients. In TLS 1.3, a client receiving a CertificateRequest or NewSessionTicket MUST also ignore all unrecognized extensions.
- A middlebox which terminates a TLS connection MUST behave as a compliant TLS server (to the original client), including having a certificate which the client is willing to accept, and as a compliant TLS client (to the original server), including verifying the original server's certificate. In particular, it MUST generate its own ClientHello containing only parameters it understands, and it MUST generate a fresh ServerHello random value, rather than forwarding the endpoint's value.

Note that TLS's protocol requirements and security analysis only apply to the two connections separately. Safely deploying a TLS terminator requires additional security considerations which are beyond the scope of this document.

- An middlebox which forwards ClientHello parameters it does not understand MUST NOT process any messages beyond that ClientHello. It MUST forward all subsequent traffic unmodified. Otherwise, it may fail to interoperate with newer clients and servers.

Forwarded ClientHellos may contain advertisements for features not supported by the middlebox, so the response may include future TLS additions the middlebox does not recognize. These additions MAY change any message beyond the ClientHello arbitrarily. In particular, the values sent in the ServerHello might change, the ServerHello format might change, and the TLSCiphertext format might change.

The design of TLS 1.3 was constrained by widely-deployed non-compliant TLS middleboxes (see Appendix D.4), however it does not relax the invariants. Those middleboxes continue to be non-compliant.

10. Security Considerations

Security issues are discussed throughout this memo, especially in Appendix C, Appendix D, and Appendix E.

11. IANA Considerations

This document uses several registries that were originally created in [RFC4346]. IANA [SHALL update/has updated] these to reference this document. The registries and their allocation policies are below:

- TLS Cipher Suite Registry: values with the first byte in the range 0-254 (decimal) are assigned via Specification Required [RFC8126]. Values with the first byte 255 (decimal) are reserved for Private Use [RFC8126].

IANA [SHALL add/has added] the cipher suites listed in Appendix B.4 to the registry. The "Value" and "Description" columns are taken from the table. The "DTLS-OK" and "Recommended" columns are both marked as "Yes" for each new cipher suite. [[This assumes [I-D.ietf-tls-iana-registry-updates] has been applied.]]

- TLS ContentType Registry: Future values are allocated via Standards Action [RFC8126].
- TLS Alert Registry: Future values are allocated via Standards Action [RFC8126]. IANA [SHALL update/has updated] this registry to include values for "missing_extension" and "certificate_required". The "DTLS-OK" column is marked as "Yes" for each new alert.
- TLS HandshakeType Registry: Future values are allocated via Standards Action [RFC8126]. IANA [SHALL update/has updated] this registry to rename item 4 from "NewSessionTicket" to "new_session_ticket" and to add the "hello_retry_request_RESERVED", "encrypted_extensions", "end_of_early_data", "key_update", and "message_hash" values. The "DTLS-OK" are marked as "Yes" for each of these additions.

This document also uses the TLS ExtensionType Registry originally created in [RFC4366]. IANA has updated it to reference this document. Changes to the registry follow:

- IANA [SHALL update/has updated] the registration policy as follows:

Values with the first byte in the range 0-254 (decimal) are assigned via Specification Required [RFC8126]. Values with the first byte 255 (decimal) are reserved for Private Use [RFC8126].

- IANA [SHALL update/has updated] this registry to include the "key_share", "pre_shared_key", "psk_key_exchange_modes",

"early_data", "cookie", "supported_versions",
"certificate_authorities", "oid_filters", "post_handshake_auth",
and "signature_algorithms_cert", extensions with the values
defined in this document and the Recommended value of "Yes".

- IANA [SHALL update/has updated] this registry to include a "TLS 1.3" column which lists the messages in which the extension may appear. This column [SHALL be/has been] initially populated from the table in Section 4.2 with any extension not listed there marked as "-" to indicate that it is not used by TLS 1.3.

In addition, this document defines two new registries to be maintained by IANA:

- TLS SignatureScheme Registry: Values with the first byte in the range 0-253 (decimal) are assigned via Specification Required [RFC8126]. Values with the first byte 254 or 255 (decimal) are reserved for Private Use [RFC8126]. Values with the first byte in the range 0-6 or with the second byte in the range 0-3 that are not currently allocated are reserved for backwards compatibility. This registry SHALL have a "Recommended" column. The registry [shall be/ has been] initially populated with the values described in Section 4.2.3. The following values SHALL be marked as "Recommended": ecdsa_secp256r1_sha256, ecdsa_secp384r1_sha384, rsa_pss_rsae_sha256, rsa_pss_rsae_sha384, rsa_pss_rsae_sha512, rsa_pss_pss_sha256, rsa_pss_pss_sha384, rsa_pss_pss_sha512, and ed25519.
- TLS PskKeyExchangeMode Registry: Values in the range 0-253 (decimal) are assigned via Specification Required [RFC8126]. Values with the first byte 254 or 255 (decimal) are reserved for Private Use [RFC8126]. This registry SHALL have a "Recommended" column. The registry [shall be/ has been] initially populated psk_ke (0) and psk_dhe_ke (1). Both SHALL be marked as "Recommended".

12. References

12.1. Normative References

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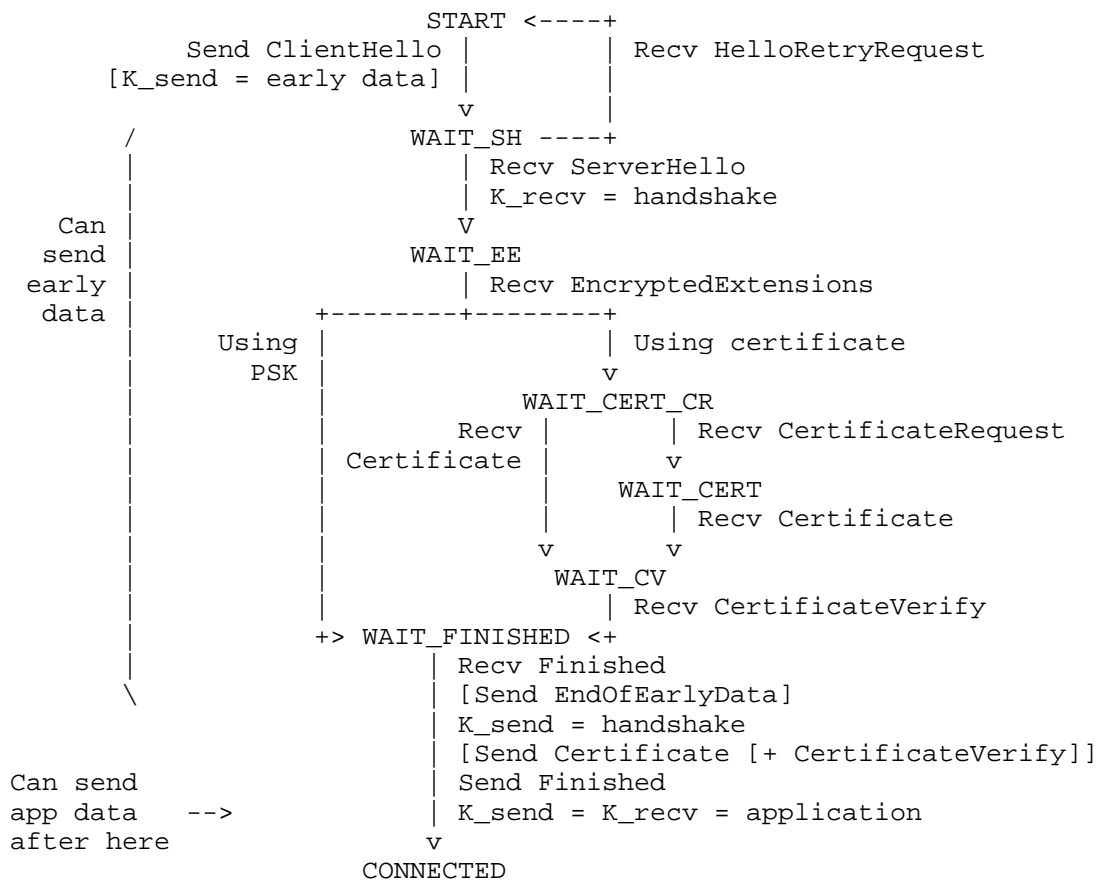
12.3. URIs

- [1] <mailto:tls@ietf.org>

Appendix A. State Machine

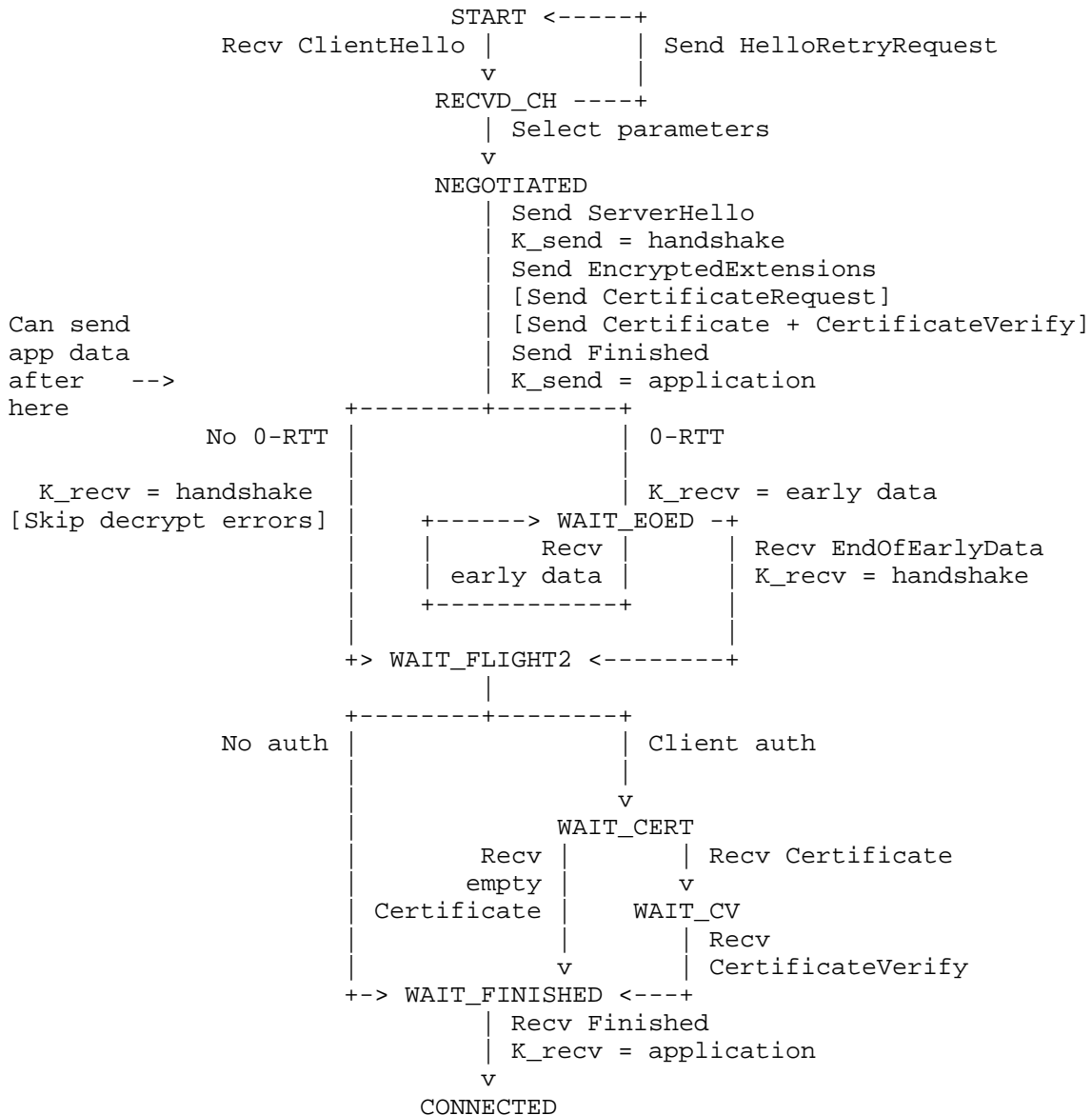
This section provides a summary of the legal state transitions for the client and server handshakes. State names (in all capitals, e.g., START) have no formal meaning but are provided for ease of comprehension. Actions which are taken only in certain circumstances are indicated in []. The notation "K_{send,recv} = foo" means "set the send/recv key to the given key".

A.1. Client



Note that with the transitions as shown above, clients may send alerts that derive from post-ServerHello messages in the clear or with the early data keys. If clients need to send such alerts, they SHOULD first rekey to the handshake keys if possible.

A.2. Server



Appendix B. Protocol Data Structures and Constant Values

This section provides the normative protocol types and constants definitions. Values listed as `_RESERVED` were used in previous versions of TLS and are listed here for completeness. TLS 1.3

implementations MUST NOT send them but might receive them from older TLS implementations.

B.1. Record Layer

```
enum {
    invalid(0),
    change_cipher_spec(20),
    alert(21),
    handshake(22),
    application_data(23),
    (255)
} ContentType;

struct {
    ContentType type;
    ProtocolVersion legacy_record_version;
    uint16 length;
    opaque fragment[TLSPlainText.length];
} TLSPlainText;

struct {
    opaque content[TLSPlainText.length];
    ContentType type;
    uint8 zeros[length_of_padding];
} TLSInnerPlaintext;

struct {
    ContentType opaque_type = application_data; /* 23 */
    ProtocolVersion legacy_record_version = 0x0303; /* TLS v1.2 */
    uint16 length;
    opaque encrypted_record[TLSCiphertext.length];
} TLSCiphertext;
```

B.2. Alert Messages

```
enum { warning(1), fatal(2), (255) } AlertLevel;

enum {
    close_notify(0),
    unexpected_message(10),
    bad_record_mac(20),
    decryption_failed_RESERVED(21),
    record_overflow(22),
    decompression_failure_RESERVED(30),
    handshake_failure(40),
    no_certificate_RESERVED(41),
    bad_certificate(42),
    unsupported_certificate(43),
    certificate_revoked(44),
    certificate_expired(45),
    certificate_unknown(46),
    illegal_parameter(47),
    unknown_ca(48),
    access_denied(49),
    decode_error(50),
    decrypt_error(51),
    export_restriction_RESERVED(60),
    protocol_version(70),
    insufficient_security(71),
    internal_error(80),
    inappropriate_fallback(86),
    user_canceled(90),
    no_renegotiation_RESERVED(100),
    missing_extension(109),
    unsupported_extension(110),
    certificate_unobtainable_RESERVED(111),
    unrecognized_name(112),
    bad_certificate_status_response(113),
    bad_certificate_hash_value_RESERVED(114),
    unknown_psk_identity(115),
    certificate_required(116),
    no_application_protocol(120),
    (255)
} AlertDescription;

struct {
    AlertLevel level;
    AlertDescription description;
} Alert;
```


B.3. Handshake Protocol

```
enum {
    hello_request_RESERVED(0),
    client_hello(1),
    server_hello(2),
    hello_verify_request_RESERVED(3),
    new_session_ticket(4),
    end_of_early_data(5),
    hello_retry_request_RESERVED(6),
    encrypted_extensions(8),
    certificate(11),
    server_key_exchange_RESERVED(12),
    certificate_request(13),
    server_hello_done_RESERVED(14),
    certificate_verify(15),
    client_key_exchange_RESERVED(16),
    finished(20),
    key_update(24),
    message_hash(254),
    (255)
} HandshakeType;

struct {
    HandshakeType msg_type;      /* handshake type */
    uint24 length;              /* bytes in message */
    select (Handshake.msg_type) {
        case client_hello:      ClientHello;
        case server_hello:      ServerHello;
        case end_of_early_data:  EndOfEarlyData;
        case encrypted_extensions: EncryptedExtensions;
        case certificate_request: CertificateRequest;
        case certificate:        Certificate;
        case certificate_verify:  CertificateVerify;
        case finished:           Finished;
        case new_session_ticket:  NewSessionTicket;
        case key_update:         KeyUpdate;
    };
} Handshake;
```

B.3.1. Key Exchange Messages

```
uint16 ProtocolVersion;
opaque Random[32];

uint8 CipherSuite[2];      /* Cryptographic suite selector */

struct {
```

```
    ProtocolVersion legacy_version = 0x0303;    /* TLS v1.2 */
    Random random;
    opaque legacy_session_id<0..32>;
    CipherSuite cipher_suites<2..2^16-2>;
    opaque legacy_compression_methods<1..2^8-1>;
    Extension extensions<8..2^16-1>;
} ClientHello;

struct {
    ProtocolVersion legacy_version = 0x0303;    /* TLS v1.2 */
    Random random;
    opaque legacy_session_id_echo<0..32>;
    CipherSuite cipher_suite;
    uint8 legacy_compression_method = 0;
    Extension extensions<6..2^16-1>;
} ServerHello;

struct {
    ExtensionType extension_type;
    opaque extension_data<0..2^16-1>;
} Extension;

enum {
    server_name(0),                /* RFC 6066 */
    max_fragment_length(1),        /* RFC 6066 */
    status_request(5),             /* RFC 6066 */
    supported_groups(10),          /* RFC 4492, 7919 */
    signature_algorithms(13),      /* [[this document]] */
    use_srtp(14),                  /* RFC 5764 */
    heartbeat(15),                 /* RFC 6520 */
    application_layer_protocol_negotiation(16), /* RFC 7301 */
    signed_certificate_timestamp(18), /* RFC 6962 */
    client_certificate_type(19),    /* RFC 7250 */
    server_certificate_type(20),    /* RFC 7250 */
    padding(21),                   /* RFC 7685 */
    RESERVED(40),                  /* Used but never assigned */
    pre_shared_key(41),            /* [[this document]] */
    early_data(42),                /* [[this document]] */
    supported_versions(43),        /* [[this document]] */
    cookie(44),                    /* [[this document]] */
    psk_key_exchange_modes(45),    /* [[this document]] */
    RESERVED(46),                  /* Used but never assigned */
    certificate_authorities(47),   /* [[this document]] */
    oid_filters(48),               /* [[this document]] */
    post_handshake_auth(49),       /* [[this document]] */
    signature_algorithms_cert(50), /* [[this document]] */
    key_share(51),                 /* [[this document]] */
    (65535)
```

```
    } ExtensionType;

    struct {
        NamedGroup group;
        opaque key_exchange<1..2^16-1>;
    } KeyShareEntry;

    struct {
        KeyShareEntry client_shares<0..2^16-1>;
    } KeyShareClientHello;

    struct {
        NamedGroup selected_group;
    } KeyShareHelloRetryRequest;

    struct {
        KeyShareEntry server_share;
    } KeyShareServerHello;

    struct {
        uint8 legacy_form = 4;
        opaque X[coordinate_length];
        opaque Y[coordinate_length];
    } UncompressedPointRepresentation;

    enum { psk_ke(0), psk_dhe_ke(1), (255) } PskKeyExchangeMode;

    struct {
        PskKeyExchangeMode ke_modes<1..255>;
    } PskKeyExchangeModes;

    struct {} Empty;

    struct {
        select (Handshake.msg_type) {
            case new_session_ticket:    uint32 max_early_data_size;
            case client_hello:          Empty;
            case encrypted_extensions: Empty;
        };
    } EarlyDataIndication;

    struct {
        opaque identity<1..2^16-1>;
        uint32 obfuscated_ticket_age;
    } PskIdentity;

    opaque PskBinderEntry<32..255>;
```

```
struct {
    PskIdentity identities<7..2^16-1>;
    PskBinderEntry binders<33..2^16-1>;
} OfferedPsk;

struct {
    select (Handshake.msg_type) {
        case client_hello: OfferedPsk;
        case server_hello: uint16 selected_identity;
    };
} PreSharedKeyExtension;
```

B.3.1.1. Version Extension

```
struct {
    select (Handshake.msg_type) {
        case client_hello:
            ProtocolVersion versions<2..254>;

        case server_hello: /* and HelloRetryRequest */
            ProtocolVersion selected_version;
    };
} SupportedVersions;
```

B.3.1.2. Cookie Extension

```
struct {
    opaque cookie<1..2^16-1>;
} Cookie;
```

B.3.1.3. Signature Algorithm Extension

```
enum {
    /* RSASSA-PKCS1-v1_5 algorithms */
    rsa_pkcs1_sha256(0x0401),
    rsa_pkcs1_sha384(0x0501),
    rsa_pkcs1_sha512(0x0601),

    /* ECDSA algorithms */
    ecdsa_secp256r1_sha256(0x0403),
    ecdsa_secp384r1_sha384(0x0503),
    ecdsa_secp521r1_sha512(0x0603),

    /* RSASSA-PSS algorithms with public key OID rsaEncryption */
    rsa_pss_rsae_sha256(0x0804),
    rsa_pss_rsae_sha384(0x0805),
    rsa_pss_rsae_sha512(0x0806),

    /* EdDSA algorithms */
    ed25519(0x0807),
    ed448(0x0808),

    /* RSASSA-PSS algorithms with public key OID RSASSA-PSS */
    rsa_pss_pss_sha256(0x0809),
    rsa_pss_pss_sha384(0x080a),
    rsa_pss_pss_sha512(0x080b),

    /* Legacy algorithms */
    rsa_pkcs1_shal(0x0201),
    ecdsa_shal(0x0203),

    /* Reserved Code Points */
    obsolete_RESERVED(0x0000..0x0200),
    dsa_shal_RESERVED(0x0202),
    obsolete_RESERVED(0x0204..0x0400),
    dsa_sha256_RESERVED(0x0402),
    obsolete_RESERVED(0x0404..0x0500),
    dsa_sha384_RESERVED(0x0502),
    obsolete_RESERVED(0x0504..0x0600),
    dsa_sha512_RESERVED(0x0602),
    obsolete_RESERVED(0x0604..0x06FF),
    private_use(0xFE00..0xFFFF),
    (0xFFFF)
} SignatureScheme;

struct {
    SignatureScheme supported_signature_algorithms<2..2^16-2>;
} SignatureSchemeList;
```

B.3.1.4. Supported Groups Extension

```
enum {
    unallocated_RESERVED(0x0000),

    /* Elliptic Curve Groups (ECDHE) */
    obsolete_RESERVED(0x0001..0x0016),
    secp256r1(0x0017), secp384r1(0x0018), secp521r1(0x0019),
    obsolete_RESERVED(0x001A..0x001C),
    x25519(0x001D), x448(0x001E),

    /* Finite Field Groups (DHE) */
    ffdhe2048(0x0100), ffdhe3072(0x0101), ffdhe4096(0x0102),
    ffdhe6144(0x0103), ffdhe8192(0x0104),

    /* Reserved Code Points */
    ffdhe_private_use(0x01FC..0x01FF),
    ecdhe_private_use(0xFE00..0xFEFF),
    obsolete_RESERVED(0xFF01..0xFF02),
    (0xFFFF)
} NamedGroup;

struct {
    NamedGroup named_group_list<2..2^16-1>;
} NamedGroupList;
```

Values within "obsolete_RESERVED" ranges are used in previous versions of TLS and MUST NOT be offered or negotiated by TLS 1.3 implementations. The obsolete curves have various known/theoretical weaknesses or have had very little usage, in some cases only due to unintentional server configuration issues. They are no longer considered appropriate for general use and should be assumed to be potentially unsafe. The set of curves specified here is sufficient for interoperability with all currently deployed and properly configured TLS implementations.

B.3.2. Server Parameters Messages

```
opaque DistinguishedName<1..2^16-1>;

struct {
    DistinguishedName authorities<3..2^16-1>;
} CertificateAuthoritiesExtension;

struct {
    opaque certificate_extension_oid<1..2^8-1>;
    opaque certificate_extension_values<0..2^16-1>;
} OIDFilter;

struct {
    OIDFilter filters<0..2^16-1>;
} OIDFilterExtension;

struct {} PostHandshakeAuth;

struct {
    Extension extensions<0..2^16-1>;
} EncryptedExtensions;

struct {
    opaque certificate_request_context<0..2^8-1>;
    Extension extensions<2..2^16-1>;
} CertificateRequest;
```

B.3.3. Authentication Messages

```
/* Managed by IANA */
enum {
    X509(0),
    OpenPGP_RESERVED(1),
    RawPublicKey(2),
    (255)
} CertificateType;

struct {
    select (certificate_type) {
        case RawPublicKey:
            /* From RFC 7250 ASN.1_subjectPublicKeyInfo */
            opaque ASN1_subjectPublicKeyInfo<1..2^24-1>;

        case X509:
            opaque cert_data<1..2^24-1>;
    };
    Extension extensions<0..2^16-1>;
} CertificateEntry;

struct {
    opaque certificate_request_context<0..2^8-1>;
    CertificateEntry certificate_list<0..2^24-1>;
} Certificate;

struct {
    SignatureScheme algorithm;
    opaque signature<0..2^16-1>;
} CertificateVerify;

struct {
    opaque verify_data[Hash.length];
} Finished;
```

B.3.4. Ticket Establishment

```
struct {
    uint32 ticket_lifetime;
    uint32 ticket_age_add;
    opaque ticket_nonce<0..255>;
    opaque ticket<1..2^16-1>;
    Extension extensions<0..2^16-2>;
} NewSessionTicket;
```


B.3.5. Updating Keys

```

struct {} EndOfEarlyData;

enum {
    update_not_requested(0), update_requested(1), (255)
} KeyUpdateRequest;

struct {
    KeyUpdateRequest request_update;
} KeyUpdate;

```

B.4. Cipher Suites

A symmetric cipher suite defines the pair of the AEAD algorithm and hash algorithm to be used with HKDF. Cipher suite names follow the naming convention:

```
CipherSuite TLS_AEAD_HASH = VALUE;
```

Component	Contents
TLS	The string "TLS"
AEAD	The AEAD algorithm used for record protection
HASH	The hash algorithm used with HKDF
VALUE	The two byte ID assigned for this cipher suite

This specification defines the following cipher suites for use with TLS 1.3.

Description	Value
TLS_AES_128_GCM_SHA256	{0x13,0x01}
TLS_AES_256_GCM_SHA384	{0x13,0x02}
TLS_CHACHA20_POLY1305_SHA256	{0x13,0x03}
TLS_AES_128_CCM_SHA256	{0x13,0x04}
TLS_AES_128_CCM_8_SHA256	{0x13,0x05}

The corresponding AEAD algorithms AEAD_AES_128_GCM, AEAD_AES_256_GCM, and AEAD_AES_128_CCM are defined in [RFC5116]. AEAD_CHACHA20_POLY1305 is defined in [RFC7539]. AEAD_AES_128_CCM_8 is defined in [RFC6655]. The corresponding hash algorithms are defined in [SHS].

Although TLS 1.3 uses the same cipher suite space as previous versions of TLS, TLS 1.3 cipher suites are defined differently, only specifying the symmetric ciphers, and cannot be used for TLS 1.2. Similarly, TLS 1.2 and lower cipher suites cannot be used with TLS 1.3.

New cipher suite values are assigned by IANA as described in Section 11.

Appendix C. Implementation Notes

The TLS protocol cannot prevent many common security mistakes. This section provides several recommendations to assist implementors. [I-D.ietf-tls-tls13-vectors] provides test vectors for TLS 1.3 handshakes.

C.1. Random Number Generation and Seeding

TLS requires a cryptographically secure pseudorandom number generator (CSPRNG). In most cases, the operating system provides an appropriate facility such as /dev/urandom, which should be used absent other (performance) concerns. It is RECOMMENDED to use an existing CSPRNG implementation in preference to crafting a new one. Many adequate cryptographic libraries are already available under favorable license terms. Should those prove unsatisfactory, [RFC4086] provides guidance on the generation of random values.

TLS uses random values both in public protocol fields such as the public Random values in the ClientHello and ServerHello and to generate keying material. With a properly functioning CSPRNG, this does not present a security problem as it is not feasible to determine the CSPRNG state from its output. However, with a broken CSPRNG, it may be possible for an attacker to use the public output to determine the CSPRNG internal state and thereby predict the keying material, as documented in [CHECKOWAY]. Implementations can provide extra security against this form of attack by using separate CSPRNGs to generate public and private values.

C.2. Certificates and Authentication

Implementations are responsible for verifying the integrity of certificates and should generally support certificate revocation messages. Absent a specific indication from an application profile, Certificates should always be verified to ensure proper signing by a trusted Certificate Authority (CA). The selection and addition of trust anchors should be done very carefully. Users should be able to view information about the certificate and trust anchor. Applications SHOULD also enforce minimum and maximum key sizes. For example, certification paths containing keys or signatures weaker than 2048-bit RSA or 224-bit ECDSA are not appropriate for secure applications.

C.3. Implementation Pitfalls

Implementation experience has shown that certain parts of earlier TLS specifications are not easy to understand and have been a source of interoperability and security problems. Many of these areas have been clarified in this document but this appendix contains a short list of the most important things that require special attention from implementors.

TLS protocol issues:

- Do you correctly handle handshake messages that are fragmented to multiple TLS records (see Section 5.1)? Including corner cases like a ClientHello that is split to several small fragments? Do you fragment handshake messages that exceed the maximum fragment size? In particular, the Certificate and CertificateRequest handshake messages can be large enough to require fragmentation.
- Do you ignore the TLS record layer version number in all unencrypted TLS records? (see Appendix D)
- Have you ensured that all support for SSL, RC4, EXPORT ciphers, and MD5 (via the "signature_algorithms" extension) is completely removed from all possible configurations that support TLS 1.3 or later, and that attempts to use these obsolete capabilities fail correctly? (see Appendix D)
- Do you handle TLS extensions in ClientHello correctly, including unknown extensions?
- When the server has requested a client certificate, but no suitable certificate is available, do you correctly send an empty Certificate message, instead of omitting the whole message (see Section 4.4.2.3)?

- When processing the plaintext fragment produced by AEAD-Decrypt and scanning from the end for the ContentType, do you avoid scanning past the start of the cleartext in the event that the peer has sent a malformed plaintext of all-zeros?
- Do you properly ignore unrecognized cipher suites (Section 4.1.2), hello extensions (Section 4.2), named groups (Section 4.2.7), key shares (Section 4.2.8), supported versions (Section 4.2.1), and signature algorithms (Section 4.2.3) in the ClientHello?
- As a server, do you send a HelloRetryRequest to clients which support a compatible (EC)DHE group but do not predict it in the "key_share" extension? As a client, do you correctly handle a HelloRetryRequest from the server?

Cryptographic details:

- What countermeasures do you use to prevent timing attacks [TIMING]?
- When using Diffie-Hellman key exchange, do you correctly preserve leading zero bytes in the negotiated key (see Section 7.4.1)?
- Does your TLS client check that the Diffie-Hellman parameters sent by the server are acceptable, (see Section 4.2.8.1)?
- Do you use a strong and, most importantly, properly seeded random number generator (see Appendix C.1) when generating Diffie-Hellman private values, the ECDSA "k" parameter, and other security-critical values? It is RECOMMENDED that implementations implement "deterministic ECDSA" as specified in [RFC6979].
- Do you zero-pad Diffie-Hellman public key values to the group size (see Section 4.2.8.1)?
- Do you verify signatures after making them to protect against RSA-CRT key leaks? [FW15]

C.4. Client Tracking Prevention

Clients SHOULD NOT reuse a ticket for multiple connections. Reuse of a ticket allows passive observers to correlate different connections. Servers that issue tickets SHOULD offer at least as many tickets as the number of connections that a client might use; for example, a web browser using HTTP/1.1 [RFC7230] might open six connections to a server. Servers SHOULD issue new tickets with every connection. This ensures that clients are always able to use a new ticket when creating a new connection.

C.5. Unauthenticated Operation

Previous versions of TLS offered explicitly unauthenticated cipher suites based on anonymous Diffie-Hellman. These modes have been deprecated in TLS 1.3. However, it is still possible to negotiate parameters that do not provide verifiable server authentication by several methods, including:

- Raw public keys [RFC7250].
- Using a public key contained in a certificate but without validation of the certificate chain or any of its contents.

Either technique used alone is vulnerable to man-in-the-middle attacks and therefore unsafe for general use. However, it is also possible to bind such connections to an external authentication mechanism via out-of-band validation of the server's public key, trust on first use, or a mechanism such as channel bindings (though the channel bindings described in [RFC5929] are not defined for TLS 1.3). If no such mechanism is used, then the connection has no protection against active man-in-the-middle attack; applications **MUST NOT** use TLS in such a way absent explicit configuration or a specific application profile.

Appendix D. Backward Compatibility

The TLS protocol provides a built-in mechanism for version negotiation between endpoints potentially supporting different versions of TLS.

TLS 1.x and SSL 3.0 use compatible ClientHello messages. Servers can also handle clients trying to use future versions of TLS as long as the ClientHello format remains compatible and there is at least one protocol version supported by both the client and the server.

Prior versions of TLS used the record layer version number (TLSPlaintext.legacy_record_version and TLSCiphertext.legacy_record_version) for various purposes. As of TLS 1.3, this field is deprecated. The value of TLSPlaintext.legacy_record_version **MUST** be ignored by all implementations. The value of TLSCiphertext.legacy_record_version is included in the additional data for deprotection but **MAY** otherwise be ignored or **MAY** be validated to match the fixed constant value. Version negotiation is performed using only the handshake versions (ClientHello.legacy_version, ServerHello.legacy_version, as well as the ClientHello, HelloRetryRequest and ServerHello "supported_versions" extensions). In order to maximize interoperability with older endpoints, implementations that negotiate

the use of TLS 1.0-1.2 SHOULD set the record layer version number to the negotiated version for the ServerHello and all records thereafter.

For maximum compatibility with previously non-standard behavior and misconfigured deployments, all implementations SHOULD support validation of certification paths based on the expectations in this document, even when handling prior TLS versions' handshakes. (see Section 4.4.2.2)

TLS 1.2 and prior supported an "Extended Master Secret" [RFC7627] extension which digested large parts of the handshake transcript into the master secret. Because TLS 1.3 always hashes in the transcript up to the server CertificateVerify, implementations which support both TLS 1.3 and earlier versions SHOULD indicate the use of the Extended Master Secret extension in their APIs whenever TLS 1.3 is used.

D.1. Negotiating with an older server

A TLS 1.3 client who wishes to negotiate with servers that do not support TLS 1.3 will send a normal TLS 1.3 ClientHello containing 0x0303 (TLS 1.2) in ClientHello.legacy_version but with the correct version(s) in the "supported_versions" extension. If the server does not support TLS 1.3 it will respond with a ServerHello containing an older version number. If the client agrees to use this version, the negotiation will proceed as appropriate for the negotiated protocol. A client using a ticket for resumption SHOULD initiate the connection using the version that was previously negotiated.

Note that 0-RTT data is not compatible with older servers and SHOULD NOT be sent absent knowledge that the server supports TLS 1.3. See Appendix D.3.

If the version chosen by the server is not supported by the client (or not acceptable), the client MUST abort the handshake with a "protocol_version" alert.

Some legacy server implementations are known to not implement the TLS specification properly and might abort connections upon encountering TLS extensions or versions which they are not aware of. Interoperability with buggy servers is a complex topic beyond the scope of this document. Multiple connection attempts may be required in order to negotiate a backwards compatible connection; however, this practice is vulnerable to downgrade attacks and is NOT RECOMMENDED.

D.2. Negotiating with an older client

A TLS server can also receive a ClientHello indicating a version number smaller than its highest supported version. If the "supported_versions" extension is present, the server MUST negotiate using that extension as described in Section 4.2.1. If the "supported_versions" extension is not present, the server MUST negotiate the minimum of ClientHello.legacy_version and TLS 1.2. For example, if the server supports TLS 1.0, 1.1, and 1.2, and legacy_version is TLS 1.0, the server will proceed with a TLS 1.0 ServerHello. If the "supported_versions" extension is absent and the server only supports versions greater than ClientHello.legacy_version, the server MUST abort the handshake with a "protocol_version" alert.

Note that earlier versions of TLS did not clearly specify the record layer version number value in all cases (TLSPlaintext.legacy_record_version). Servers will receive various TLS 1.x versions in this field, but its value MUST always be ignored.

D.3. 0-RTT backwards compatibility

0-RTT data is not compatible with older servers. An older server will respond to the ClientHello with an older ServerHello, but it will not correctly skip the 0-RTT data and will fail to complete the handshake. This can cause issues when a client attempts to use 0-RTT, particularly against multi-server deployments. For example, a deployment could deploy TLS 1.3 gradually with some servers implementing TLS 1.3 and some implementing TLS 1.2, or a TLS 1.3 deployment could be downgraded to TLS 1.2.

A client that attempts to send 0-RTT data MUST fail a connection if it receives a ServerHello with TLS 1.2 or older. A client that attempts to repair this error SHOULD NOT send a TLS 1.2 ClientHello, but instead send a TLS 1.3 ClientHello without 0-RTT data.

To avoid this error condition, multi-server deployments SHOULD ensure a uniform and stable deployment of TLS 1.3 without 0-RTT prior to enabling 0-RTT.

D.4. Middlebox Compatibility Mode

Field measurements [Ben17a], [Ben17b], [Res17a], [Res17b] have found that a significant number of middleboxes misbehave when a TLS client/server pair negotiates TLS 1.3. Implementations can increase the chance of making connections through those middleboxes by making the TLS 1.3 handshake look more like a TLS 1.2 handshake:

- The client always provides a non-empty session ID in the ClientHello, as described in the legacy_session_id section of Section 4.1.2.
- If not offering early data, the client sends a dummy change_cipher_spec record (see the third paragraph of Section 5.1) immediately before its second flight. This may either be before its second ClientHello or before its encrypted handshake flight. If offering early data, the record is placed immediately after the first ClientHello.
- The server sends a dummy change_cipher_spec record immediately after its first handshake message. This may either be after a ServerHello or a HelloRetryRequest.

When put together, these changes make the TLS 1.3 handshake resemble TLS 1.2 session resumption, which improves the chance of successfully connecting through middleboxes. This "compatibility mode" is partially negotiated: The client can opt to provide a session ID or not and the server has to echo it. Either side can send change_cipher_spec at any time during the handshake, as they must be ignored by the peer, but if the client sends a non-empty session ID, the server MUST send the change_cipher_spec as described in this section.

D.5. Backwards Compatibility Security Restrictions

Implementations negotiating use of older versions of TLS SHOULD prefer forward secret and AEAD cipher suites, when available.

The security of RC4 cipher suites is considered insufficient for the reasons cited in [RFC7465]. Implementations MUST NOT offer or negotiate RC4 cipher suites for any version of TLS for any reason.

Old versions of TLS permitted the use of very low strength ciphers. Ciphers with a strength less than 112 bits MUST NOT be offered or negotiated for any version of TLS for any reason.

The security of SSL 3.0 [SSL3] is considered insufficient for the reasons enumerated in [RFC7568], and it MUST NOT be negotiated for any reason.

The security of SSL 2.0 [SSL2] is considered insufficient for the reasons enumerated in [RFC6176], and it MUST NOT be negotiated for any reason.

Implementations MUST NOT send an SSL version 2.0 compatible CLIENT-HELLO. Implementations MUST NOT negotiate TLS 1.3 or later using an

SSL version 2.0 compatible CLIENT-HELLO. Implementations are NOT RECOMMENDED to accept an SSL version 2.0 compatible CLIENT-HELLO in order to negotiate older versions of TLS.

Implementations MUST NOT send a ClientHello.legacy_version or ServerHello.legacy_version set to 0x0300 or less. Any endpoint receiving a Hello message with ClientHello.legacy_version or ServerHello.legacy_version set to 0x0300 MUST abort the handshake with a "protocol_version" alert.

Implementations MUST NOT send any records with a version less than 0x0300. Implementations SHOULD NOT accept any records with a version less than 0x0300 (but may inadvertently do so if the record version number is ignored completely).

Implementations MUST NOT use the Truncated HMAC extension, defined in Section 7 of [RFC6066], as it is not applicable to AEAD algorithms and has been shown to be insecure in some scenarios.

Appendix E. Overview of Security Properties

A complete security analysis of TLS is outside the scope of this document. In this section, we provide an informal description the desired properties as well as references to more detailed work in the research literature which provides more formal definitions.

We cover properties of the handshake separately from those of the record layer.

E.1. Handshake

The TLS handshake is an Authenticated Key Exchange (AKE) protocol which is intended to provide both one-way authenticated (server-only) and mutually authenticated (client and server) functionality. At the completion of the handshake, each side outputs its view of the following values:

- A set of "session keys" (the various secrets derived from the master secret) from which can be derived a set of working keys.
- A set of cryptographic parameters (algorithms, etc.)
- The identities of the communicating parties.

We assume the attacker to be an active network attacker, which means it has complete control over the network used to communicate between the parties [RFC3552]. Even under these conditions, the handshake should provide the properties listed below. Note that these

properties are not necessarily independent, but reflect the protocol consumers' needs.

Establishing the same session keys. The handshake needs to output the same set of session keys on both sides of the handshake, provided that it completes successfully on each endpoint (See [CK01]; defn 1, part 1).

Secrecy of the session keys. The shared session keys should be known only to the communicating parties and not to the attacker (See [CK01]; defn 1, part 2). Note that in a unilaterally authenticated connection, the attacker can establish its own session keys with the server, but those session keys are distinct from those established by the client.

Peer Authentication. The client's view of the peer identity should reflect the server's identity. If the client is authenticated, the server's view of the peer identity should match the client's identity.

Uniqueness of the session keys: Any two distinct handshakes should produce distinct, unrelated session keys. Individual session keys produced by a handshake should also be distinct and independent.

Downgrade protection. The cryptographic parameters should be the same on both sides and should be the same as if the peers had been communicating in the absence of an attack (See [BBFKZG16]; defns 8 and 9}).

Forward secret with respect to long-term keys. If the long-term keying material (in this case the signature keys in certificate-based authentication modes or the external/resumption PSK in PSK with (EC)DHE modes) is compromised after the handshake is complete, this does not compromise the security of the session key (See [DOW92]), as long as the session key itself has been erased. The forward secrecy property is not satisfied when PSK is used in the "psk_ke" PskKeyExchangeMode.

Key Compromise Impersonation (KCI) resistance. In a mutually-authenticated connection with certificates, compromising the long-term secret of one actor should not break that actor's authentication of their peer in the given connection (see [HGFS15]). For example, if a client's signature key is compromised, it should not be possible to impersonate arbitrary servers to that client in subsequent handshakes.

Protection of endpoint identities. The server's identity (certificate) should be protected against passive attackers. The

client's identity should be protected against both passive and active attackers.

Informally, the signature-based modes of TLS 1.3 provide for the establishment of a unique, secret, shared key established by an (EC)DHE key exchange and authenticated by the server's signature over the handshake transcript, as well as tied to the server's identity by a MAC. If the client is authenticated by a certificate, it also signs over the handshake transcript and provides a MAC tied to both identities. [SIGMA] describes the design and analysis of this type of key exchange protocol. If fresh (EC)DHE keys are used for each connection, then the output keys are forward secret.

The external PSK and resumption PSK bootstrap from a long-term shared secret into a unique per-connection set of short-term session keys. This secret may have been established in a previous handshake. If PSK with (EC)DHE key establishment is used, these session keys will also be forward secret. The resumption PSK has been designed so that the resumption master secret computed by connection N and needed to form connection N+1 is separate from the traffic keys used by connection N, thus providing forward secrecy between the connections. In addition, if multiple tickets are established on the same connection, they are associated with different keys, so compromise of the PSK associated with one ticket does not lead to the compromise of connections established with PSKs associated with other tickets. This property is most interesting if tickets are stored in a database (and so can be deleted) rather than if they are self-encrypted.

The PSK binder value forms a binding between a PSK and the current handshake, as well as between the session where the PSK was established and the current session. This binding transitively includes the original handshake transcript, because that transcript is digested into the values which produce the Resumption Master Secret. This requires that both the KDF used to produce the resumption master secret and the MAC used to compute the binder be collision resistant. See Appendix E.1.1 for more on this. Note: The binder does not cover the binder values from other PSKs, though they are included in the Finished MAC.

Note: TLS does not currently permit the server to send a `certificate_request` message in non-certificate-based handshakes (e.g., PSK). If this restriction were to be relaxed in future, the client's signature would not cover the server's certificate directly. However, if the PSK was established through a `NewSessionTicket`, the client's signature would transitively cover the server's certificate through the PSK binder. [PSK-FINISHED] describes a concrete attack on constructions that do not bind to the server's certificate (see also [Kraw16]). It is unsafe to use certificate-based client

authentication when the client might potentially share the same PSK/key-id pair with two different endpoints. Implementations MUST NOT combine external PSKs with certificate-based authentication of either the client or the server unless negotiated by some extension.

If an exporter is used, then it produces values which are unique and secret (because they are generated from a unique session key). Exporters computed with different labels and contexts are computationally independent, so it is not feasible to compute one from another or the session secret from the exported value. Note: exporters can produce arbitrary-length values. If exporters are to be used as channel bindings, the exported value MUST be large enough to provide collision resistance. The exporters provided in TLS 1.3 are derived from the same handshake contexts as the early traffic keys and the application traffic keys respectively, and thus have similar security properties. Note that they do not include the client's certificate; future applications which wish to bind to the client's certificate may need to define a new exporter that includes the full handshake transcript.

For all handshake modes, the Finished MAC (and where present, the signature), prevents downgrade attacks. In addition, the use of certain bytes in the random nonces as described in Section 4.1.3 allows the detection of downgrade to previous TLS versions. See [BBFKZG16] for more detail on TLS 1.3 and downgrade.

As soon as the client and the server have exchanged enough information to establish shared keys, the remainder of the handshake is encrypted, thus providing protection against passive attackers, even if the computed shared key is not authenticated. Because the server authenticates before the client, the client can ensure that if it authenticates to the server, it only reveals its identity to an authenticated server. Note that implementations must use the provided record padding mechanism during the handshake to avoid leaking information about the identities due to length. The client's proposed PSK identities are not encrypted, nor is the one that the server selects.

E.1.1.1. Key Derivation and HKDF

Key derivation in TLS 1.3 uses the HKDF function defined in [RFC5869] and its two components, HKDF-Extract and HKDF-Expand. The full rationale for the HKDF construction can be found in [Kraw10] and the rationale for the way it is used in TLS 1.3 in [KW16]. Throughout this document, each application of HKDF-Extract is followed by one or more invocations of HKDF-Expand. This ordering should always be followed (including in future revisions of this document), in particular, one SHOULD NOT use an output of HKDF-Extract as an input

to another application of HKDF-Extract without an HKDF-Expand in between. Consecutive applications of HKDF-Expand are allowed as long as these are differentiated via the key and/or the labels.

Note that HKDF-Expand implements a pseudorandom function (PRF) with both inputs and outputs of variable length. In some of the uses of HKDF in this document (e.g., for generating exporters and the `resumption_master_secret`), it is necessary that the application of HKDF-Expand be collision-resistant, namely, it should be infeasible to find two different inputs to HKDF-Expand that output the same value. This requires the underlying hash function to be collision resistant and the output length from HKDF-Expand to be of size at least 256 bits (or as much as needed for the hash function to prevent finding collisions).

E.1.2. Client Authentication

A client that has sent authentication data to a server, either during the handshake or in post-handshake authentication, cannot be sure if the server afterwards considers the client to be authenticated or not. If the client needs to determine if the server considers the connection to be unilaterally or mutually authenticated, this has to be provisioned by the application layer. See [CHHSV17] for details. In addition, the analysis of post-handshake authentication from [Kraw16] shows that the client identified by the certificate sent in the post-handshake phase possesses the traffic key. This party is therefore the client that participated in the original handshake or one to whom the original client delegated the traffic key (assuming that the traffic key has not been compromised).

E.1.3. 0-RTT

The 0-RTT mode of operation generally provides similar security properties as 1-RTT data, with the two exceptions that the 0-RTT encryption keys do not provide full forward secrecy and that the server is not able to guarantee uniqueness of the handshake (non-replayability) without keeping potentially undue amounts of state. See Section 8 for mechanisms to limit the exposure to replay.

E.1.4. Exporter Independence

The `exporter_master_secret` and `early_exporter_master_secret` are derived to be independent of the traffic keys and therefore do not represent a threat to the security of traffic encrypted with those keys. However, because these secrets can be used to compute any exporter value, they SHOULD be erased as soon as possible. If the total set of exporter labels is known, then implementations SHOULD pre-compute the inner Derive-Secret stage of the exporter computation

for all those labels, then erase the [early_exporter_master_secret, followed by each inner values as soon as it is known that it will not be needed again.

E.1.5. Post-Compromise Security

TLS does not provide security for handshakes which take place after the peer's long-term secret (signature key or external PSK) is compromised. It therefore does not provide post-compromise security [CCG16], sometimes also referred to as backwards or future secrecy. This is in contrast to KCI resistance, which describes the security guarantees that a party has after its own long-term secret has been compromised.

E.1.6. External References

The reader should refer to the following references for analysis of the TLS handshake: [DFGS15] [CHSV16] [DFGS16] [KW16] [Kraw16] [FGSW16] [LXZFH16] [FG17] [BBK17].

E.2. Record Layer

The record layer depends on the handshake producing strong traffic secrets which can be used to derive bidirectional encryption keys and nonces. Assuming that is true, and the keys are used for no more data than indicated in Section 5.5 then the record layer should provide the following guarantees:

Confidentiality. An attacker should not be able to determine the plaintext contents of a given record.

Integrity. An attacker should not be able to craft a new record which is different from an existing record which will be accepted by the receiver.

Order protection/non-replayability An attacker should not be able to cause the receiver to accept a record which it has already accepted or cause the receiver to accept record N+1 without having first processed record N.

Length concealment. Given a record with a given external length, the attacker should not be able to determine the amount of the record that is content versus padding.

Forward secrecy after key change. If the traffic key update mechanism described in Section 4.6.3 has been used and the previous generation key is deleted, an attacker who compromises

the endpoint should not be able to decrypt traffic encrypted with the old key.

Informally, TLS 1.3 provides these properties by AEAD-protecting the plaintext with a strong key. AEAD encryption [RFC5116] provides confidentiality and integrity for the data. Non-replayability is provided by using a separate nonce for each record, with the nonce being derived from the record sequence number (Section 5.3), with the sequence number being maintained independently at both sides thus records which are delivered out of order result in AEAD deprotection failures. In order to prevent mass cryptanalysis when the same plaintext is repeatedly encrypted by different users under the same key (as is commonly the case for HTTP), the nonce is formed by mixing the sequence number with a secret per-connection initialization vector derived along with the traffic keys. See [BT16] for analysis of this construction.

The re-keying technique in TLS 1.3 (see Section 7.2) follows the construction of the serial generator in [REKEY], which shows that re-keying can allow keys to be used for a larger number of encryptions than without re-keying. This relies on the security of the HKDF-Expand-Label function as a pseudorandom function (PRF). In addition, as long as this function is truly one way, it is not possible to compute traffic keys from prior to a key change (forward secrecy).

TLS does not provide security for data which is communicated on a connection after a traffic secret of that connection is compromised. That is, TLS does not provide post-compromise security/future secrecy/backward secrecy with respect to the traffic secret. Indeed, an attacker who learns a traffic secret can compute all future traffic secrets on that connection. Systems which want such guarantees need to do a fresh handshake and establish a new connection with an (EC)DHE exchange.

E.2.1. External References

The reader should refer to the following references for analysis of the TLS record layer: [BMMT15] [BT16] [BDFKPPRSZZ16] [BBK17] [Anon18].

E.3. Traffic Analysis

TLS is susceptible to a variety of traffic analysis attacks based on observing the length and timing of encrypted packets [CLINIC] [HCJ16]. This is particularly easy when there is a small set of possible messages to be distinguished, such as for a video server hosting a fixed corpus of content, but still provides usable information even in more complicated scenarios.

TLS does not provide any specific defenses against this form of attack but does include a padding mechanism for use by applications: The plaintext protected by the AEAD function consists of content plus variable-length padding, which allows the application to produce arbitrary length encrypted records as well as padding-only cover traffic to conceal the difference between periods of transmission and periods of silence. Because the padding is encrypted alongside the actual content, an attacker cannot directly determine the length of the padding, but may be able to measure it indirectly by the use of timing channels exposed during record processing (i.e., seeing how long it takes to process a record or trickling in records to see which ones elicit a response from the server). In general, it is not known how to remove all of these channels because even a constant time padding removal function will likely feed the content into data-dependent functions. At minimum, a fully constant time server or client would require close cooperation with the application layer protocol implementation, including making that higher level protocol constant time.

Note: Robust traffic analysis defences will likely lead to inferior performance due to delay in transmitting packets and increased traffic volume.

E.4. Side Channel Attacks

In general, TLS does not have specific defenses against side-channel attacks (i.e., those which attack the communications via secondary channels such as timing) leaving those to the implementation of the relevant cryptographic primitives. However, certain features of TLS are designed to make it easier to write side-channel resistant code:

- Unlike previous versions of TLS which used a composite MAC-then-encrypt structure, TLS 1.3 only uses AEAD algorithms, allowing implementations to use self-contained constant-time implementations of those primitives.
- TLS uses a uniform "bad_record_mac" alert for all decryption errors, which is intended to prevent an attacker from gaining piecewise insight into portions of the message. Additional resistance is provided by terminating the connection on such errors; a new connection will have different cryptographic material, preventing attacks against the cryptographic primitives that require multiple trials.

Information leakage through side channels can occur at layers above TLS, in application protocols and the applications that use them. Resistance to side-channel attacks depends on applications and

application protocols separately ensuring that confidential information is not inadvertently leaked.

E.5. Replay Attacks on 0-RTT

Replayable 0-RTT data presents a number of security threats to TLS-using applications, unless those applications are specifically engineered to be safe under replay (minimally, this means idempotent, but in many cases may also require other stronger conditions, such as constant-time response). Potential attacks include:

- Duplication of actions which cause side effects (e.g., purchasing an item or transferring money) to be duplicated, thus harming the site or the user.
- Attackers can store and replay 0-RTT messages in order to re-order them with respect to other messages (e.g., moving a delete to after a create).
- Exploiting cache timing behavior to discover the content of 0-RTT messages by replaying a 0-RTT message to a different cache node and then using a separate connection to measure request latency, to see if the two requests address the same resource.

If data can be replayed a large number of times, additional attacks become possible, such as making repeated measurements of the speed of cryptographic operations. In addition, they may be able to overload rate-limiting systems. For further description of these attacks, see [Mac17].

Ultimately, servers have the responsibility to protect themselves against attacks employing 0-RTT data replication. The mechanisms described in Section 8 are intended to prevent replay at the TLS layer but do not provide complete protection against receiving multiple copies of client data. TLS 1.3 falls back to the 1-RTT handshake when the server does not have any information about the client, e.g., because it is in a different cluster which does not share state or because the ticket has been deleted as described in Section 8.1. If the application layer protocol retransmits data in this setting, then it is possible for an attacker to induce message duplication by sending the ClientHello to both the original cluster (which processes the data immediately) and another cluster which will fall back to 1-RTT and process the data upon application layer replay. The scale of this attack is limited by the client's willingness to retry transactions and therefore only allows a limited amount of duplication, with each copy appearing as a new connection at the server.

If implemented correctly, the mechanisms described in Section 8.1 and Section 8.2 prevent a replayed ClientHello and its associated 0-RTT data from being accepted multiple times by any cluster with consistent state; for servers which limit the use of 0-RTT to one cluster for a single ticket, then a given ClientHello and its associated 0-RTT data will only be accepted once. However, if state is not completely consistent, then an attacker might be able to have multiple copies of the data be accepted during the replication window. Because clients do not know the exact details of server behavior, they **MUST NOT** send messages in early data which are not safe to have replayed and which they would not be willing to retry across multiple 1-RTT connections.

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.

In addition, to avoid accidental misuse, TLS implementations **MUST NOT** enable 0-RTT (either sending or accepting) unless specifically requested by the application and **MUST NOT** automatically resend 0-RTT data if it is rejected by the server unless instructed by the application. Server-side applications may wish to implement special processing for 0-RTT data for some kinds of application traffic (e.g., abort the connection, request that data be resent at the application layer, or delay processing until the handshake completes). In order to allow applications to implement this kind of processing, TLS implementations **MUST** provide a way for the application to determine if the handshake has completed.

E.5.1. Replay and Exporters

Replays of the ClientHello produce the same early exporter, thus requiring additional care by applications which use these exporters. In particular, if these exporters are used as an authentication channel binding (e.g., by signing the output of the exporter) an attacker who compromises the PSK can transplant authenticators between connections without compromising the authentication key.

In addition, the early exporter **SHOULD NOT** be used to generate server-to-client encryption keys because that would entail the reuse of those keys. This parallels the use of the early application traffic keys only in the client-to-server direction.

E.6. PSK Identity Exposure

Because implementations respond to an invalid PSK binder by aborting the handshake, it may be possible for an attacker to verify whether a given PSK identity is valid. Specifically, if a server accepts both external PSK and certificate-based handshakes, a valid PSK identity will result in a failed handshake, whereas an invalid identity will just be skipped and result in a successful certificate handshake. Servers which solely support PSK handshakes may be able to resist this form of attack by treating the cases where there is no valid PSK identity and where there is an identity but it has an invalid binder identically.

E.7. Attacks on Static RSA

Although TLS 1.3 does not use RSA key transport and so is not directly susceptible to Bleichenbacher-type attacks, if TLS 1.3 servers also support static RSA in the context of previous versions of TLS, then it may be possible to impersonate the server for TLS 1.3 connections [JSS15]. TLS 1.3 implementations can prevent this attack by disabling support for static RSA across all versions of TLS. In principle, implementations might also be able to separate certificates with different keyUsage bits for static RSA decryption and RSA signature, but this technique relies on clients refusing to accept signatures using keys in certificates that do not have the digitalSignature bit set, and many clients do not enforce this restriction.

Appendix F. Working Group Information

The discussion list for the IETF TLS working group is located at the e-mail address tls@ietf.org [1]. Information on the group and information on how to subscribe to the list is at <https://www.ietf.org/mailman/listinfo/tls>

Archives of the list can be found at: <https://www.ietf.org/mail-archive/web/tls/current/index.html>

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The Datagram Transport Layer Security (DTLS) Connection Identifier
draft-rescorla-tls-dtls-connection-id-02

Abstract

This document specifies the "Connection ID" concept for the Datagram Transport Layer Security (DTLS) protocol, version 1.2 and version 1.3.

A Connection ID is an identifier carried in the record layer header that gives the recipient additional information for selecting the appropriate security association. In "classical" DTLS, selecting a security association of an incoming DTLS record is accomplished with the help of the 5-tuple. If the source IP address and/or source port changes during the lifetime of an ongoing DTLS session then the receiver will be unable to locate the correct security context.

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1. Introduction

The Datagram Transport Layer Security (DTLS) protocol was designed for securing connection-less transports, like UDP. DTLS, like TLS, starts with a handshake, which can be computationally demanding (particularly when public key cryptography is used). After a successful handshake, symmetric key cryptography is used to apply data origin authentication, integrity and confidentiality protection. This two-step approach allows to amortize the cost of the initial handshake to subsequent application data protection. Ideally, the second phase where application data is protected lasts over a longer period of time since the established keys will only need to be updated once the key lifetime expires.

In the current version of DTLS, the IP address and port of the peer is used to identify the DTLS association. Unfortunately, in some cases, such as NAT rebinding, these values are insufficient. This is a particular issue in the Internet of Things when the device needs to enter extended sleep periods to increase the battery lifetime and is therefore subject to rebinding. This leads to connection failure, with the resulting cost of a new handshake.

This document defines an extension to DTLS to add a connection ID to each DTLS record. The presence of the connection ID is negotiated via a DTLS extension. It also defines a DTLS 1.3 post-handshake message to change connection ids.

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 RFC 2119 [RFC2119].

The reader is assumed to be familiar with the DTLS specifications since this document defines an extension to DTLS 1.2 and DTLS 1.3.

3. The "connection_id" Extension

This document defines a new extension type (`connection_id(TBD)`), which is used in ClientHello and ServerHello messages.

The extension type is specified as follows.

```
enum {  
    connection_id(TBD), (65535)  
} ExtensionType;
```

The `extension_data` field of this extension, when included in the `ClientHello`, MUST contain the CID structure, which contains the CID which the client wishes the server to use when sending messages towards it. A zero-length value indicates that the client is prepared to send with a connection ID but does not wish the server to use one when sending (alternately, this can be interpreted as the client wishes the server to use a zero-length CID; the result is the same).

```
struct {  
    opaque cid<0..2^8-1>;  
} ConnectionId;
```

A server which is willing to use CIDs will respond with its own "connection_id" extension, containing the CID which it wishes the client to use when sending messages towards it. A zero-length value indicates that the server will send with the client's CID but does not wish the client to use a CID (or again, alternately, to use a zero-length CID).

When a session is resumed, the "connection_id" extension is negotiated afresh, not retained from previous connections in the session.

This is effectively the simplest possible design that will work. Previous design ideas for using cryptographically generated session ids, either using hash chains or public key encryption, were dismissed due to their inefficient designs. Note that a client always has the chance to fall-back to a full handshake or more precisely to a handshake that uses session resumption (DTLS 1.2 language) or to a PSK-based handshake using the ticket-based approach.

Because each party sends in the `extension_data` the value that it will receive as a connection identifier in encrypted records, it is possible for an endpoint to use a globally constant length for such connection identifiers. This can in turn ease parsing and connection lookup, for example by having the length in question be a compile-time constant. Note that such implementations must still be able to send other length connection identifiers to other parties.

In DTLS 1.2, connection ids are exchanged at the beginning of the DTLS session only. There is no dedicated "connection id update" message that allows new connection ids to be established mid-session, because DTLS 1.2 in general does not allow post-handshake messages that do not themselves begin other handshakes. In DTLS 1.3, which does allow such messages, we use post-handshake message to update the connection ID Section 4 and to request new IDs.

DTLS 1.2 peers switch to the new record layer format when encryption is enabled. The same is true for DTLS 1.3 but since the DTLS 1.3 enables encryption early in the handshake phase the connection ID will be enabled earlier. For this reason, the connection ID needs to go in the DTLS 1.3 ServerHello.

4. Post-Handshake Messages

In DTLS 1.3, if the client and server have negotiated the "connection_id" extension, either side can send a new connection ID which it wishes the other side to use in a NewConnectionId message:

```
enum {  
    cid_immediate(0), cid_spare(1), (255)  
} ConnectionIdUsage;  
  
struct {  
    opaque cid<0..2^8-1>;  
    ConnectionIdUsage usage;  
} NewConnectionId;
```

cid Indicates the CID which the sender wishes the peer to use.

usage Indicates whether the new CID should be used immediately or is a spare. If usage is set to "cid_immediate", then the new CID MUST be used immediately for all future records. If it is set to "cid_spare", then either CID MAY be used, as described in Section 7.

If the client and server have negotiated the "connection_id" extension, either side can request a new CID using the RequestConnectionId message.

```
struct {  
} RequestConnectionId;
```

Endpoints SHOULD respond to RequestConnectionId by sending a NewConnectionId with usage "cid_spare" as soon as possible. Note that an endpoint MAY ignore requests which it considers excessive (though they MUST be ACKed as usual).

5. Record Layer Extensions

This extension is applicable for use with DTLS 1.2 and DTLS 1.3. This extension can be used with the optimized DTLS 1.3 record layer format.

Figure 1 and Figure 2 illustrate the record formats of DTLS 1.2 and DTLS 1.3, respectively.

```
struct {
    ContentType type;
    ProtocolVersion version;
    uint16 epoch;
    uint48 sequence_number;
    opaque cid[cid_length];           // New field
    uint16 length;
    select (CipherSpec.cipher_type) {
        case block: GenericBlockCipher;
        case aead:   GenericAEADCipher;
    } fragment;
} DTLSCiphertext;
```

Figure 1: DTLS 1.2 Record Format with Connection ID

```
struct {
    opaque content[DTLSPplaintext.length];
    ContentType type;
    uint8 zeros[length_of_padding];
} DTLSInnerPlaintext;

struct {
    ContentType opaque_type = 23; /* application_data */
    ProtocolVersion legacy_record_version = {254,253}; // DTLSv1.2
    uint16 epoch;                                     // DTLS-related field
    uint48 sequence_number;                           // DTLS-related field
    opaque cid[cid_length];                           // New field
    uint16 length;
    opaque encrypted_record[length];
} DTLSCiphertext;
```

Figure 2: DTLS 1.3 Record Format with Connection ID

Besides the "cid" field, all other fields are defined in the DTLS 1.2 and DTLS 1.3 specifications.

Note that for both record formats, it is not possible to parse the records without knowing if the connection ID is in use and how long it is.

6. Examples

Below is an example exchange for DTLS 1.3 using a single connection id in each direction.


```

Client                                     Server
-----
ClientHello
(connection_id=5)
----->

<----- HelloRetryRequest
          (cookie)

ClientHello
(connection_id=5)
+cookie
----->

<----- ServerHello
          (connection_id=100)
          EncryptedExtensions
            (cid=5)
          Certificate
            (cid=5)
          CertificateVerify
            (cid=5)
          Finished
            (cid=5)

Certificate
(cid=100)
----->
CertificateVerify
(cid=100)
Finished
(cid=100)

<----- Ack
          (cid=5)

Application Data
(cid=100)
=====>

<===== Application Data
          (cid=5)

```

Figure 3: Example DTLS 1.3 Exchange with Connection IDs

Below is an example exchange for DTLS 1.2 using a connection id used uni-directionally from the client to the server.

```

Client                                     Server
-----
ClientHello
(connection_id=empty)
----->

<----- HelloVerifyRequest
          (cookie)

ClientHello
(connection_id=empty)
+cookie
----->

<----- ServerHello
          (connection_id=100)
          Certificate
          ServerKeyExchange
          CertificateRequest
          ServerHelloDone

Certificate
ClientKeyExchange
CertificateVerify
[ChangeCipherSpec]
Finished
(cid=100)
----->

<----- [ChangeCipherSpec]
          Finished

Application Data
(cid=100)
=====>

<===== Application Data

```

Figure 4: Example DTLS 1.2 Exchange with Connection IDs

7. Security and Privacy Considerations

The connection id replaces the previously used 5-tuple and, as such, introduces an identifier that remains persistent during the lifetime of a DTLS connection. Every identifier introduces the risk of linkability, as explained in [RFC6973].

In addition, endpoints can use the connection ID to attach arbitrary metadata to each record they receive. This may be used as a mechanism to communicate per-connection to on-path observers. There is no straightforward way to address this with connection IDs that

contain arbitrary values; implementations concerned about this SHOULD refuse to use connection ids.

An on-path adversary, who is able to observe the DTLS 1.2 protocol exchanges between the DTLS client and the DTLS server, is able to link the observed payloads to all subsequent payloads carrying the same connection id pair (for bi-directional communication). In DTLS 1.3, it is possible to provide new encrypted connection IDs, though of course those IDs are immediately used on the wire. Without multi-homing and mobility the use of the connection id is not different to the use of the 5-tuple.

With multi-homing, an adversary is able to correlate the communication interaction over the two paths, which adds further privacy concerns. In order to prevent this, implementations SHOULD attempt to use fresh connection IDs whenever they change local addresses or ports (though this is not always possible to detect). In DTLS 1.3, The RequestConnectionId message can be used to ask for new IDs in order to ensure that you have a pool of suitable IDs.

This document does not change the security properties of DTLS 1.2 [RFC6347] and DTLS 1.3 [I-D.ietf-tls-dtls13]. It merely provides a more robust mechanism for associating an incoming packet with a stored security context.

[[OPEN ISSUE: Sequence numbers leak connection IDs. We need to update the document to address this. One possibility would be the technique documented in <https://quicwg.github.io/base-drafts/draft-ietf-quic-transport.html#packet-number-gap>.]]

8. IANA Considerations

IANA is requested to allocate an entry to the existing TLS "ExtensionType Values" registry, defined in [RFC5246], for connection_id(TBD) defined in this document.

IANA is requested to allocate two values in the "TLS Handshake Type" registry, defined in [RFC5246], for request_connection_id (TBD), and new_connection_id (TBD), as defined in this document.

9. References

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9.3. URIs

[1] <mailto:tls@ietf.org>

Appendix A. History

RFC EDITOR: PLEASE REMOVE THE THIS SECTION

draft-rescorla-tls-dtls-connection-id-00

- Initial version

Appendix B. Working Group Information

The discussion list for the IETF TLS working group is located at the e-mail address tls@ietf.org [1]. Information on the group and information on how to subscribe to the list is at <https://www1.ietf.org/mailman/listinfo/tls>

Archives of the list can be found at: <https://www.ietf.org/mail-archive/web/tls/current/index.html>

Appendix C. Contributors

Many people have contributed to this specification since the functionality has been highly desired by the IoT community. We would like to thank the following individuals for their contributions in earlier specifications:

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Additionally, we would like to thank Yin Xinxing (Huawei), Tobias Gondrom (Huawei), and the Connection ID task force team members:

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- Christian Huitema (Private Octopus Inc.)
- Jana Iyengar (Google)
- Daniel Kahn Gillmor (ACLU)
- Patrick McManus (Sole Proprietor)
- Ian Swett (Google)
- Mark Nottingham (Fastly)

Finally, we want to thank the IETF TLS working group chairs, Joseph Salowey and Sean Turner, for their patience, support and feedback.

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Extension for protecting (D)TLS handshakes against Denial of Service
draft-tiloca-tls-dos-handshake-02

Abstract

This document describes an extension for TLS and DTLS to protect the server from Denial of Service attacks against the handshake protocol, carried out by an on-path adversary. The extension includes a nonce and a Message Authentication Code (MAC) over that nonce, encoded as a Handshake Token that a Trust Anchor entity computes and provides to the client. The server registered at the Trust Anchor verifies the MAC to determine whether continuing or aborting the handshake.

Status of This Memo

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1. Introduction

Servers running TLS [RFC5246][I-D.ietf-tls-tls13] and DTLS [RFC6347][I-D.ietf-tls-dtls13] are vulnerable to Denial of Service (DoS) attacks during the very first step of the handshake protocol. That is, an adversary can repeatedly send ClientHello messages to the server and induce it to perform computations and execute handshakes, before stopping handshake executions and make the server hold state open.

DTLS 1.2 as well as both TLS 1.3 and DTLS 1.3 provide the optional Cookie exchange as possible solution to mitigate this DoS attack. This mechanism is specifically oriented towards adversaries that are not on-path. That is, the Cookie exchange makes the attack more complicated to mount. However, a well determined and resourceful on-path adversary, able to spoof valid IP addresses, can still

successfully perform the DoS attack, by intercepting the possible server response including the Cookie and then echoing it in the second ClientHello. This is in particular possible if the handshake does not use Pre-Shared Key exchange modes.

More specifically, the handshake protocol is exposed to DoS attacks mounted by an on-path adversary, ranging minimally from a man-on-the-side (i.e. able to read and inject traffic, but not block) to maximally a full active adversary (i.e. able also to block traffic).

Depending on the specific protocol version and the key establishment mode used in the handshake, the attack impact can range from a single reply triggered by invalid ClientHello messages, to the server performing advanced handshake steps with consequent setup of invalid half-open sessions. Especially if performed in a large-scale and distributed manner, this attack can thwart performance and service availability of (D)TLS servers. Moreover, the attack can be particularly effective in application scenarios where servers are resource-constrained devices running DTLS over low-power, low bandwidth and lossy networks.

This specification describes a "dos_protection" extension for TLS and DTLS, included into ClientHello messages in order to mark them as valid and neutralize the DoS attacks mentioned above. In essence, the "dos_protection" extension includes a Handshake Token encoding a nonce and a Message Authentication Code (MAC) computed over that nonce. Upon receiving the ClientHello message, the server checks the MAC conveyed in the Handshake Token, and determines whether to either continue the handshake or to immediately abort it.

The proposed method relies on a Trust Anchor (TA) entity, which is in a trust relation with the server, and authorizes the client to establish a secure session with the server. In particular, the Trust Anchor computes the MAC encoded in the Handshake Token, before providing the latter to the client.

1.1. 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.

Readers are expected to be familiar with terms and concepts related to TLS 1.2 [RFC5246] and DTLS 1.2 [RFC6347], as well as to TLS 1.3 [I-D.ietf-tls-tls13] and DTLS 1.3 [I-D.ietf-tls-dtls13], with particular reference to their respective handshake protocol.

This document refers also to the following terminology.

- o Trust Anchor (TA): a trusted third party with a security association with the (D)TLS server. Compared to each single (D)TLS server it is associated to, the Trust Anchor is usually equipped with significant larger amounts of resources, especially in terms of computing power and memory availability.
- o Master Key (K_M): a long-term symmetric key shared between the Trust Anchor and the server.
- o Handshake Token (T): piece of information provided by the Trust Anchor to a client intending to start a handshake with the server. The Handshake Token is opaque to the client, i.e. the semantics of the Handshake Token are intelligible only to the Trust Anchor and the server.
- o Nonce (N): an unsigned integer value used by the Trust Anchor to produce a fresh Handshake Token. The Trust Anchor maintains a pairwise counter separately for each associated server, in order to produce Nonce values.

2. DoS Protection Extension

2.1. Extension Type

This specification extends the `ExtensionType` enum as follows:

```
enum {  
    ...,  
    dos_protection(TBD),  
    (65535)  
} ExtensionType;
```

2.2. Extension Data

The "extension_data" field of the "dos_protection" extension contains the following information:

```
struct {  
    opaque handshake_token;  
} extension_data_content;
```

The "handshake_token" field is intended to include the Handshake Token generated by the Trust Anchor. The Handshake Token encodes a nonce and a Message Authentication Code (MAC) computed over the nonce.

3. Protocol overview

Before becoming fully operational, the server *S* registers at the TA through a secure communication channel or other out-of-band means. A server is registered at one TA only, while the same TA can be associated to multiple servers.

For each registered server *S*, the TA and *S* maintain a pairwise counter *z_S*, associated to that server and encoded as an unsigned integer. Upon *S*'s registration, *S* and the TA initialize *z_S* to 0 and establish a long-term symmetric key *K_M*. The specific means to establish *K_M* are out of the scope of this specification.

The rest of this document refers to *H* as a hash function and to an HMAC [RFC2104] relying on *H*. The TA and the server **MUST** support the hash function SHA-256.

Figure 1 shows the messages exchanged between the client (*C*), the Trust Anchor (*TA*) and the server (*S*).

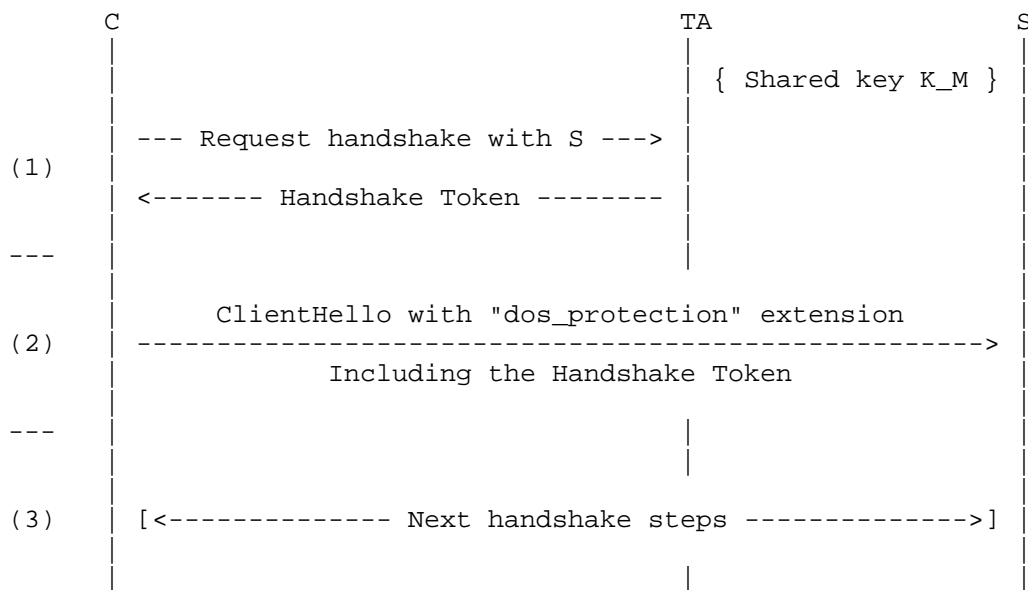


Figure 1: Protocol Overview

Step (1) concerns a client *C* that intends to start a (D)TLS session with the server *S*. That is, *C* contacts the TA and specifies its intention to start a (D)TLS handshake with *S*. The client *C* can rely on services such as [I-D.ietf-core-resource-directory] to know what is the specific TA associated to *S*. All communications between *C* and

the TA must be secured, ensuring integrity, source authentication, confidentiality and replay protection of exchanged messages. The specific means to secure communications between C and the TA are out of the scope of this specification.

The TA must verify that C is authorized to establish a (D)TLS session with S. To this end, the TA can directly authorize the client, or expect the client to upload authorization evidence previously obtained from a trusted entity. Compared with models based on proxies, this approach does not require particular adaptations to the communication between clients and servers. The specific authorization process of clients is out of the scope of this specification.

In case of successful authorization, the TA provides C with a fresh Handshake Token, which encodes a nonce as well as a Message Authentication Code (MAC) computed over the nonce using the key K_M . The Handshake Token is opaque to the client. Besides, the client must consume this Handshake Token right away, and in particular before asking the TA for a new Handshake Token intended for the same server S.

During Step (2), C prepares the ClientHello message addressed to S, including the "dos_protection" extension defined in Section 2. In particular, the extension includes the Handshake Token received by the TA, as content of the field "handshake_token". Then, C sends the ClientHello message to S. The overall content and format of the ClientHello message depend on the specific version of (D)TLS.

Upon receiving the ClientHello message, the server S retrieves the Handshake Token from the "dos_protection" extension. Then, S relies on the nonce included in the Handshake Token to check that the ClientHello message is not a replay. After that, S uses the key K_M to recompute the MAC, and checks it against the MAC encoded in the received Handshake Token.

In case the ClientHello message is fresh and the MAC is valid, S continues to Step (3), i.e., it proceeds with the handshake with C. Otherwise, S discards the ClientHello message and aborts the handshake.

4. Client to Trust Anchor

The client C requests from the TA an authorization to open a new (D)TLS session with the server S. That is, this step does not take place if C intends to resume a (D)TLS session previously established with S. Considerations about session resumption are provided in Section 8.

In case of successful authorization, the TA selects the nonce *N* as the current value of the pairwise counter *z_S* associated to *S*. Then, the TA performs the following actions.

1. It sets the variable *token_nonce* to the nonce *N*.
2. It computes a MAC as the output of $\text{HMAC}(K_M, H(\text{token_nonce}))$.
3. It builds a Handshake Token including *token_nonce* and the MAC.

After that, the TA provides the Handshake Token to *C*, and increments the counter *z_S* by 1.

The TA handles a wrap-around of the counter *z_S* by renewing the Master Key *K_M* as described in Section 9.3.

5. Client to Server

This section considers a client *C* intending to establish a new (D)TLS session with *S*. Considerations about session resumption are provided in Section 8.

Once it has received the Handshake Token from the TA, the client *C* must consume it right away, by including it in a ClientHello message addressed to the server *S*. In particular, the client *C* must consume this Handshake Token before asking the TA for a new one intended for the same server *S*. The client *C* considers the Handshake Token consumed, and hence discards it, once received a valid ServerHello message during the same handshake with the server *S*.

Furthermore, the client discards a Handshake Token also in case of handshake abortion due to too many retransmissions of a same ClientHello message. In such a case, the client must ask the TA for a new, i.e. fresh, Handshake Token and start over a new handshake with the server *S*.

When preparing the ClientHello message, the client *C* proceeds as follows.

1. It builds the "dos_protection" extension defined in Section 2.
2. It includes the Handshake Token received from the TA in the "handshake_token" field of the "dos_protection" extension.
3. It includes the "dos_protection" extension into the ClientHello message, consistently with what is mandated and recommended by the specific version of (D)TLS.

Once the ClientHello message has been completely prepared, C transmits it to S. Note that C retransmits exactly the same "dos_protection" extension from this first ClientHello message, in case it sends a second ClientHello message as a reply to a HelloVerifyRequest in DTLS 1.2 or a HelloRetryRequest in (D)TLS 1.3.

6. Server Processing

This section considers a server S receiving a ClientHello message from C for initiating a new (D)TLS session. Considerations on session resumption are provided in Section 8.

A server MAY require clients to send a valid "dos_protection" extension. A server requiring this MUST respond to a ClientHello lacking a "dos_protection" extension by terminating the handshake, with a "missing_extension" alert if the client has shown support for (D)TLS 1.3, or a "handshake_failure" alert otherwise.

Upon receiving the first ClientHello message from C, the server S retrieves the Handshake Token from the "handshake_token" field of the "dos_protection" extension.

Then, the server S MUST check that the ClientHello message is not a replay. Section 7 of this specification describes a possible method to perform the anti-replay check, based on the nonce encoded in the Handshake Token. If the ClientHello message is found to be not fresh, then S discards it and terminates the handshake with a "handshake_failure" alert.

If the ClientHello message is found to be fresh, then S performs the following actions.

1. It retrieves token_nonce from the Handshake Token.
2. It computes a MAC as the output of HMAC(K_M, H(token_nonce)).

If the computed MAC differs from the MAC encoded in the Handshake Token, S discards the ClientHello message and terminates the handshake with a "handshake_failure" alert. Otherwise, S continues performing the handshake with C.

7. Replay Protection

This section describes a possible method to perform anti-replay checks on received ClientHello messages, based on the nonce encoded in the Handshake Token as token_nonce.

The server *S* maintains a sliding window *W* of size *A*, as a pair $\{w, w_b\}$, where *w* is an *A*-bit vector and *w_b* indicates the current left bound of *W*. That is, *w_b* indicates the lowest value that *S* can accept as the nonce *N* encoded in the Handshake Token as *token_nonce*. Upon startup, *S* sets *w_b* to 0 and all bits in *w* to 0.

Upon receiving a ClientHello message for establishing a new (D)TLS session, the server *S* considers the nonce *N* encoded in the Handshake Token as *token_nonce*, and performs the following checks. As an example, the following considers a 32-bit nonce *N*.

- o If $N < w_b$, then *S* discards the ClientHello message and terminates the handshake.
- o If $w_b \leq N < \min(w_b + A, 2^{32})$, then *S* defines $i = (N - w_b)$, and checks the *i*-th bit of vector *w*. If such bit is set to 1, i.e. the same nonce *N* has been already used, then *S* discards the ClientHello message and terminates the handshake. Instead, if such bit is set to 0, then *S* proceeds with processing the "dos_protection" extension as described in Section 6.
- o If $(w_b + A) \leq N < 2^{32}$, then *S* proceeds with processing the "dos_protection" extension as described in Section 6.

During this handshake execution, *S* discards any possible first ClientHello message including the same nonce *N* encoded in the Handshake Token as *token_nonce*.

Once the handshake has been successfully completed, *S* checks whether the condition $N \geq w_b$ is still valid. In such a case, *S* updates the window *W* as follows.

- o If $w_b \leq N < \min(w_b + A, 2^{32})$, then *S* defines $i = (N - w_b)$ and sets the *i*-th bit of vector *w* to 1, so marking *N* as used. Instead,
- o if $(w_b + A) \leq N < 2^{32}$, then *S* defines $w^* = (N - A + 1)$ and updates vector *w* as $w = w \gg (w^* - w_b)$, where ' \gg ' is the unsigned right bit shift operator. After that, *S* updates *w_b* as $w_b = w^*$. Finally, *S* defines $i = (N - w_b)$ and sets the *i*-th bit of vector *w* to 1, so marking *N* as used.

The window size *A* should be determined based on the expected frequency of new session establishments on the server *S*. Evidently, the larger the window, the more accurate is the replay protection, but the greater the memory overhead on the server side.

Furthermore, the window size A should take into account the time required for a client to request and get a Handshake Token from the TA, as well as to deliver it to the (D)TLS server in the ClientHello message. This is necessary in order to avoid that the sliding window advances too fast, and hence that the (D)TLS server discards such ClientHello messages as stale.

8. Session Resumption

In case a client C sends a ClientHello message asking to resume a session, the server S relies on the existing association with C and hence does not need a further assertion of client's validity from the TA. In addition, S can rely on the Client Hello Recording mechanism described in Section 8 of [I-D.ietf-tls-tls13], in order to perform anti-replay checks on ClientHello messages asking for session resumption.

As a consequence, the "dos_protection" extension defined in Section 2 is not strictly necessary in ClientHello messages sent for session resumption.

However, Section 7.4.1.4 of [RFC5246] states that a client asking for session resumption SHOULD send the same extensions as it would if it was not attempting resumption. At the same time, it states that most extensions are relevant only when a new session is initiated, and hence the server would not process them in case of session resumption.

In accordance with such guidelines, a server S can possibly instruct the TA to also provide requesting clients with a small number R of additional Resumption Tokens.

In order to compute each of the Resumption Tokens for a same request from a given client, the TA MUST use the same nonce value N used to compute the Handshake Token (see Section 4). In particular, the TA computes the i-th Resumption Token, $0 \leq i < R$, as follows.

1. It sets the variable token_nonce to $(N + i)$, where '+' is the concatenate operator.
2. It computes a MAC as the output of $\text{HMAC}(K_M, H(\text{token_nonce}))$.
3. It builds the i-th Resumption Token including token_nonce and the MAC.

Finally, the TA provides the requesting client with the Handshake Token and the additional Resumption Tokens. The client MUST use the Handshake Token during a handshake with S for session initiation, as

described in Section 5. The client MUST use the *i*-th Resumption Token upon attempting the *i*-th resumption of that session. After it has used all the Resumption Tokens received from the TA, the client must assume that S does not support further resumptions of the same session.

Upon receiving a ClientHello message from C asking to resume a session, the server S verifies the MAC encoded in the Resumption Token as described in Section 6. However, S does not rely on the "dos_protection" extension and the token_nonce in the Resumption Token to perform an anti-replay check.

Further details about session resumption are defined in the (D)TLS specifications of the different respective versions.

9. Security Considerations

This specification does not change the intended security properties of TLS and DTLS. Additional security aspects are discussed below.

9.1. Security Effectiveness

The MAC encoded in the "dos_protection" extension as part of the Handshake Token is computed only over the 'token_nonce' part of the same Handshake Token. That is, a server S can actually assert the validity and freshness of the Handshake Token only, rather than of the whole ClientHello message.

As a consequence, an on-path adversary can intercept ClientHello messages sent by legitimate clients, retrieve the "dos_protection" extension, and then use it inside forged ClientHello messages injected and addressed to the server. However, this practically displays negligible consequences in terms of additional impact on the server, as discussed in the following.

On one hand, a man-on-the-side adversary, namely able to intercept and inject traffic but not block, can, with reasonable effort, exploit the limitation above in order to induce the server to negotiate more expensive cipher suites, which is fair to consider as a weak attack achievement. Furthermore, the injection of such forged ClientHello messages including a stolen "dos_protection" extension is anyway rate limited by the number of legitimate clients and the frequency of their handshake executions.

On the other hand, a full active adversary, namely able to also block traffic, would not even bother to inject forged ClientHello messages including a stolen "dos_protection" extension. In fact, (s)he can more easily let the server process handshake messages from legitimate

clients during handshake early phases, and later on block specific client messages during handshake advanced phases, so leaving the server with several half-open sessions and open states. Again, this is anyway rate limited by the number of legitimate clients and the frequency of their handshake executions.

9.2. Trust Anchor as Target

Communications between clients and the TA may be secured by means of (D)TLS, with the TA acting as server. In such a case, the TA becomes also a target for the DoS attack addressed in this specification.

On the other hand, TAs are expected to be equipped with plentiful of resources, i.e. in significant larger amounts than each of the associated (D)TLS servers. That is, given a class of adversary targeting a number of (D)TLS servers, the corresponding TA is practically not a feasible target for that adversary.

Besides, while it is infeasible to expect a considerably high number of (resource-constrained) (D)TLS servers to be robust against DoS by construction, it is instead feasible to have relatively few deployed TAs which are able to endure this attack when carried out against them. This might in turn encourage an adversary to rather target a TA, in order to indirectly make the (D)TLS servers unavailable to serve clients. However, as discussed above, a class of adversary targeting a (D)TLS server is not supposed to have sufficient resources to effectively compromise the availability of the corresponding TA.

Furthermore, a typical starting point for an adversary consists in identifying the set of victim servers, as belonging to the same application/administrative domain(s) or network segment(s). Hence, the adversary would be motivated in targeting the TA(s) associated to the (D)TLS servers in those segments. As an additional deterrent, (D)TLS servers in a same segment or domain can thus be registered at different TAs, in order to further reduce the feasibility and spread the effectiveness of attacks rather addressed against those TAs.

9.3. Renewal of Long-Term Key K_M

While it can practically take a long amount of time, the pairwise counter z_S maintained by the TA and associated to S eventually wraps around. When this happens, the TA MUST revoke the key K_M shared with S , in order to not reuse $\{K_M, N\}$ pairs when building Handshake Tokens for requesting clients.

In particular, when the counter z_S wraps-around, the TA MUST perform the following actions.

1. It stops accepting requests related to S from clients.
2. It securely generates a new long-term key K_M and securely provides it to S.
3. It resumes serving requests related to S from clients, using the new K_M to compute MACs when building Handshake Tokens.

9.4. Rate Limit to Nonce Release

It is RECOMMENDED that the TA does not release Handshake Tokens to clients beyond a maximum rate. This prevents a client with legitimate credentials from quickly consuming the nonce space associated to S, and thus making the TA unable to serve other clients.

10. IANA Considerations

IANA is requested to allocate an entry to the existing TLS "ExtensionType" registry defined in [RFC5246] and originally created in [RFC4366], for dos_protection (TBD) defined in this document.

11. Acknowledgments

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