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EAP-TLS 1.3: Using the Extensible Authentication Protocol with TLS 1.3

Abstract

The Extensible Authentication Protocol (EAP), defined in RFC 3748, provides a standard mechanism for support of multiple authentication methods. This document specifies the use of EAP-TLS with TLS 1.3 while remaining backwards compatible with existing implementations of EAP-TLS. TLS 1.3 provides significantly improved security and privacy, and reduced latency when compared to earlier versions of TLS. EAP-TLS with TLS 1.3 (EAP-TLS 1.3) further improves security and privacy by always providing forward secrecy, never disclosing the peer identity, and by mandating use of revocation checking when compared to EAP-TLS with earlier versions of TLS. This document also provides guidance on authentication, authorization, and resumption for EAP-TLS in general (regardless of the underlying TLS version used). This document updates RFC 5216.

Status of This Memo

This is an Internet Standards Track document.

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1. Introduction

The Extensible Authentication Protocol (EAP), defined in [RFC3748], provides a standard mechanism for support of multiple authentication methods. EAP-TLS [RFC5216] specifies an EAP authentication method with certificate-based mutual authentication utilizing the TLS handshake protocol for cryptographic algorithms and protocol version negotiation and establishment of shared secret keying material. EAP-TLS is widely supported for authentication and key establishment in IEEE 802.11 [IEEE-802.11] (Wi-Fi) and IEEE 802.1AE [IEEE-802.1AE] (MACsec) networks using IEEE 802.1X [IEEE-802.1X] and it's the default mechanism for certificate-based authentication in 3GPP 5G [TS.33.501] and MulteFire [MulteFire] networks. Many other EAP methods such as Flexible Authentication via Secure Tunneling (EAP-FAST) [RFC4851], Tunneled Transport Layer Security (EAP-TTLS) [RFC5281], the Tunnel Extensible Authentication Protocol (TEAP) [RFC7170], as well as vendor-specific EAP methods such as the

Protected Extensible Authentication Protocol (PEAP) [PEAP], depend on TLS and EAP-TLS.

EAP-TLS [RFC5216] references TLS 1.0 [RFC2246] and TLS 1.1 [RFC4346] but can also work with TLS 1.2 [RFC5246]. TLS 1.0 and 1.1 are formally deprecated and prohibited from being negotiated or used [RFC8996]. Weaknesses found in TLS 1.2 as well as new requirements for security, privacy, and reduced latency have led to the specification of TLS 1.3 [RFC8446], which obsoletes TLS 1.2 [RFC5246]. TLS 1.3 is in large part a complete remodeling of the TLS handshake protocol including a different message flow, different handshake messages, different key schedule, different cipher suites, different resumption mechanism, different privacy protection, and different record padding. This means that significant parts of the normative text in the previous EAP-TLS specification [RFC5216] are not applicable to EAP-TLS with TLS 1.3. Therefore, aspects such as resumption, privacy handling, and key derivation need to be appropriately addressed for EAP-TLS with TLS 1.3.

This document updates [RFC5216] to define how to use EAP-TLS with TLS 1.3. When older TLS versions are negotiated, RFC 5216 applies to maintain backwards compatibility. However, this document does provide additional guidance on authentication, authorization, and resumption for EAP-TLS regardless of the underlying TLS version used. This document only describes differences compared to [RFC5216]. When EAP-TLS is used with TLS 1.3, some references are updated as specified in Appendix A. All message flows are example message flows specific to TLS 1.3 and do not apply to TLS 1.2. Since EAP-TLS couples the TLS handshake state machine with the EAP state machine, it is possible that new versions of TLS will cause incompatibilities that introduce failures or security issues if they are not carefully integrated into the EAP-TLS protocol. Therefore, implementations MUST limit the maximum TLS version they use to 1.3, unless later versions are explicitly enabled by the administrator.

This document specifies EAP-TLS 1.3 and does not specify how other TLS-based EAP methods use TLS 1.3. The specification for how other TLS-based EAP methods use TLS 1.3 is left to other documents such as [TLS-EAP-TYPES].

In addition to the improved security and privacy offered by TLS 1.3, there are other significant benefits of using EAP-TLS with TLS 1.3. Privacy, which in EAP-TLS means that no information about the underlying peer identity is disclosed, is mandatory and achieved without any additional round trips. Revocation checking is mandatory and simplified with Online Certificate Status Protocol (OCSP) stapling, and TLS 1.3 introduces more possibilities to reduce fragmentation when compared to earlier versions of TLS.

1.1. Requirements 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.

Readers are expected to be familiar with the terms and concepts used in EAP-TLS [RFC5216] and TLS [RFC8446]. The term EAP-TLS peer is used for the entity acting as EAP peer and TLS client. The term EAP-TLS server is used for the entity acting as EAP server and TLS server.

This document follows the terminology from [TLS-bis] where the master secret is renamed to the main secret and the exporter_master_secret is renamed to the exporter_secret.

2. Protocol Overview

2.1. Overview of the EAP-TLS Conversation

This section updates Section 2.1 of [RFC5216] by amending it in accordance with the following discussion.

If the TLS implementation correctly implements TLS version negotiation, EAP-TLS will automatically leverage that capability. The EAP-TLS implementation needs to know which version of TLS was negotiated to correctly support EAP-TLS 1.3 as well as to maintain backward compatibility with EAP-TLS 1.2.

TLS 1.3 changes both the message flow and the handshake messages compared to earlier versions of TLS. Therefore, much of Section 2.1 of [RFC5216] does not apply for TLS 1.3. Except for Sections 2.2 and 5.7, this update applies only when TLS 1.3 is negotiated. When TLS 1.2 is negotiated, then [RFC5216] applies.

TLS 1.3 introduces several new handshake messages including HelloRetryRequest, NewSessionTicket, and KeyUpdate. In general, these messages will be handled by the underlying TLS libraries and are not visible to EAP-TLS; however, there are a few things to note:

* The HelloRetryRequest is used by the server to reject the parameters offered in the ClientHello and suggest new parameters. When this message is encountered, it will increase the number of round trips used by the protocol.

* The NewSessionTicket message is used to convey resumption information and is covered in Sections 2.1.2 and 2.1.3.

* The KeyUpdate message is used to update the traffic keys used on a TLS connection. EAP-TLS does not encrypt significant amounts of data so this functionality is not needed. Implementations SHOULD NOT send this message; however, some TLS libraries may automatically generate and process this message.

* Early Data MUST NOT be used in EAP-TLS. EAP-TLS servers MUST NOT send an early_data extension and clients MUST NOT send an EndOfEarlyData message.

* Post-handshake authentication MUST NOT be used in EAP-TLS. Clients MUST NOT send a "post_handshake_auth" extension and Servers MUST NOT request post-handshake client authentication.

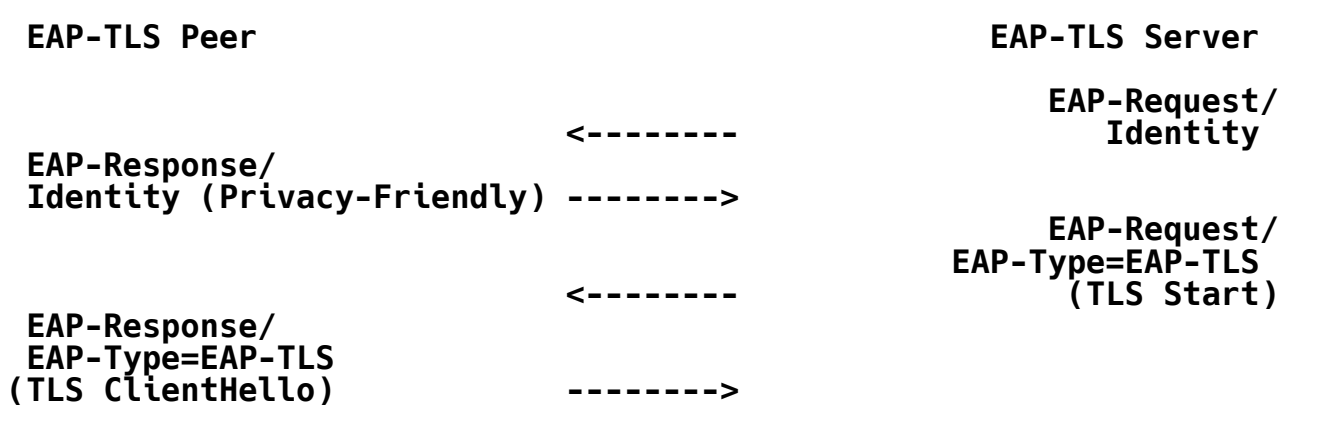
After receiving an EAP-Request packet with EAP-Type=EAP-TLS as described in [RFC5216], the conversation will continue with the TLS handshake protocol encapsulated in the data fields of EAP-Response and EAP-Request packets. When EAP-TLS is used with TLS version 1.3, the formatting and processing of the TLS handshake SHALL be done as specified in version 1.3 of TLS. This update only lists additional and different requirements, restrictions, and processing compared to [RFC8446] and [RFC5216].

2.1.1. Authentication

This section updates Section 2.1.1 of [RFC5216] by amending it in accordance with the following discussion.

The EAP-TLS server MUST authenticate with a certificate and SHOULD require the EAP-TLS peer to authenticate with a certificate. Certificates can be of any type supported by TLS including raw public keys. Pre-Shared Key (PSK) authentication SHALL NOT be used except for resumption. The full handshake in EAP-TLS with TLS 1.3 always provides forward secrecy by exchange of ephemeral "key_share" extensions in the ClientHello and ServerHello (e.g., containing Ephemeral Elliptic Curve Diffie-Hellman (ECDHE) public keys). SessionID is deprecated in TLS 1.3; see Sections 4.1.2 and 4.1.3 of [RFC8446]. TLS 1.3 introduced early application data that like all application data (other than the protected success indication described below) is not used in EAP-TLS; see Section 4.2.10 of [RFC8446] for additional information on the "early_data" extension. Resumption is handled as described in Section 2.1.3. As a protected success indication [RFC3748], the EAP-TLS server always sends TLS application data 0x00; see Section 2.5. Note that a TLS implementation MAY not allow the EAP-TLS layer to control in which order things are sent and the application data MAY therefore be sent before a NewSessionTicket. TLS application data 0x00 is therefore to be interpreted as success after the EAP-Request that contains TLS application data 0x00. After the EAP-TLS server has sent an EAP-Request containing the TLS application data 0x00 and received an EAP-Response packet of EAP-Type=EAP-TLS and no data, the EAP-TLS server sends EAP-Success.

Figure 1 shows an example message flow for a successful EAP-TLS full handshake with mutual authentication (and neither HelloRetryRequest nor post-handshake messages are sent).



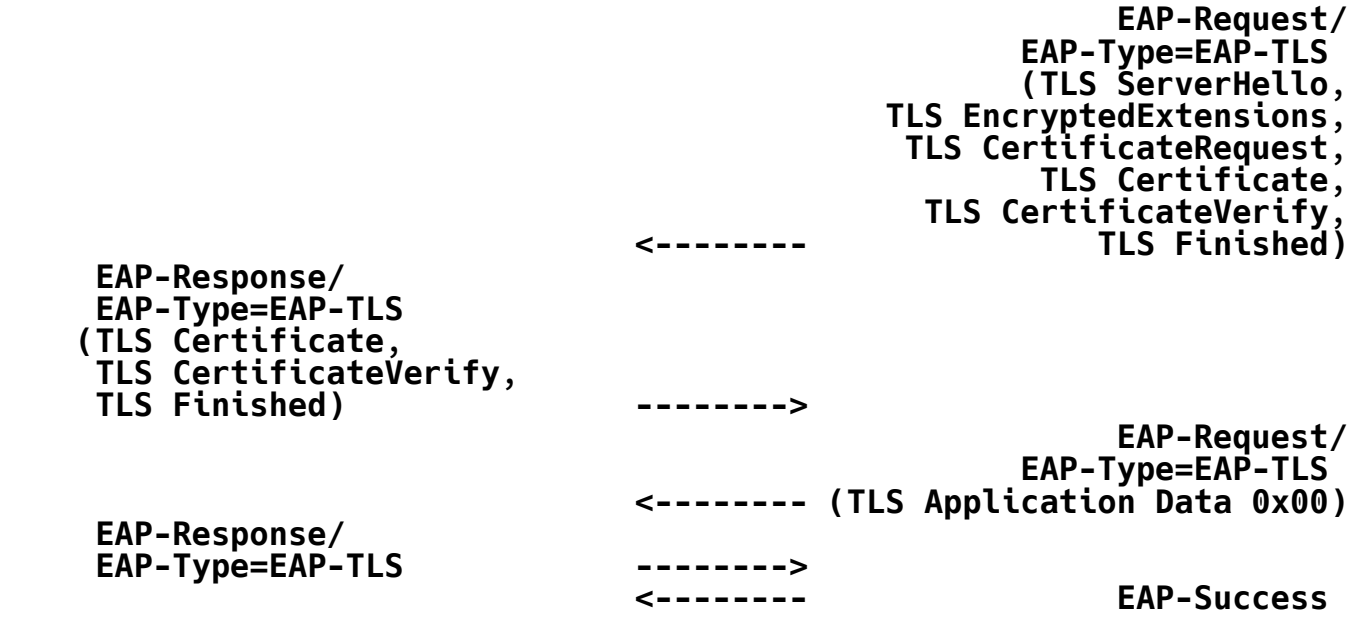


Figure 1: EAP-TLS Mutual Authentication

2.1.2. Ticket Establishment

This is a new section when compared to [RFC5216].

To enable resumption when using EAP-TLS with TLS 1.3, the EAP-TLS server MUST send one or more post-handshake NewSessionTicket messages (each associated with a PSK, a PSK identity, a ticket lifetime, and other parameters) in the initial authentication. Note that TLS 1.3 [RFC8446] limits the ticket lifetime to a maximum of 604800 seconds (7 days) and EAP-TLS servers MUST respect this upper limit when issuing tickets. The NewSessionTicket is sent after the EAP-TLS server has received the client Finished message in the initial authentication. The NewSessionTicket can be sent in the same flight as the TLS server Finished or later. The PSK associated with the ticket depends on the client Finished and cannot be pre-computed (so as to be sent in the same flight as the TLS server Finished) in handshakes with client authentication. The NewSessionTicket message MUST NOT include an "early_data" extension. If the "early_data" extension is received, then it MUST be ignored. Servers should take into account that fewer NewSessionTickets will likely be needed in EAP-TLS than in the usual HTTPS connection scenario. In most cases, a single NewSessionTicket will be sufficient. A mechanism by which clients can specify the desired number of tickets needed for future connections is defined in [TICKET-REQUESTS].

Figure 2 shows an example message flow for a successful EAP-TLS full handshake with mutual authentication and ticket establishment of a single ticket.

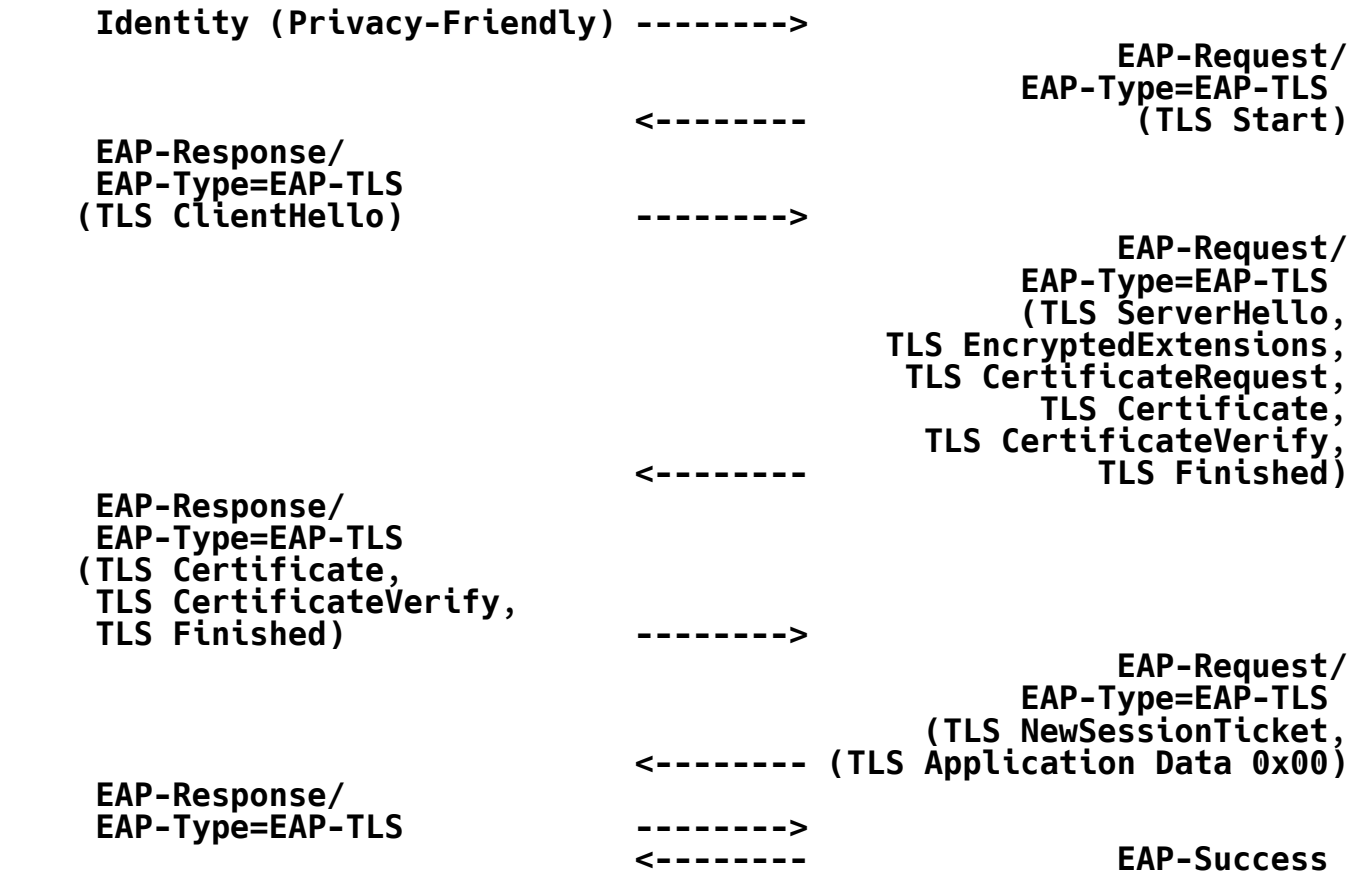


Figure 2: EAP-TLS Ticket Establishment

2.1.3. Resumption

This section updates Section 2.1.2 of [RFC5216] by amending it in accordance with the following discussion.

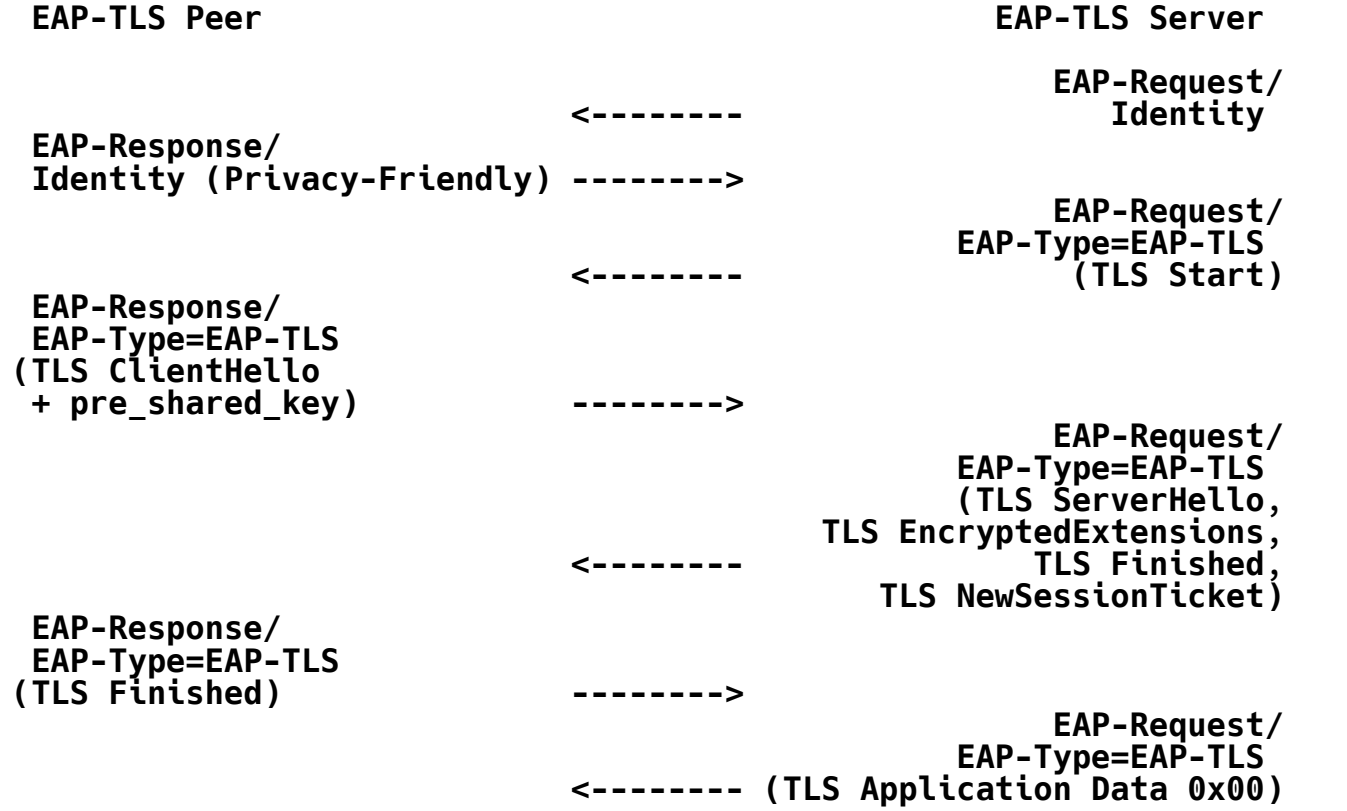
EAP-TLS is typically used with client authentication and typically fragments the TLS flights into a large number of EAP-requests and EAP-responses. Resumption significantly reduces the number of round trips and enables the EAP-TLS server to omit database lookups needed during a full handshake with client authentication. TLS 1.3 replaces the session resumption mechanisms in earlier versions of TLS with a new PSK exchange. When EAP-TLS is used with TLS version 1.3, EAP-TLS SHALL use a resumption mechanism compatible with version 1.3 of TLS.

For TLS 1.3, resumption is described in Section 2.2 of [RFC8446]. If the client has received a NewSessionTicket message from the EAP-TLS server, the client can use the PSK identity associated with the ticket to negotiate the use of the associated PSK. If the EAP-TLS server accepts it, then the resumed session has been deemed to be authenticated and securely associated with the prior authentication or resumption. It is up to the EAP-TLS peer to use resumption, but it is RECOMMENDED that the EAP-TLS peer use resumption if it has a valid ticket that has not been used before. It is left to the EAP-TLS server whether to accept resumption, but it is RECOMMENDED that the EAP-TLS server accept resumption if the ticket that was issued is still valid. However, the EAP-TLS server MAY choose to require a

full handshake. In the case a full handshake is required, the negotiation proceeds as if the session was a new authentication, and the resumption attempt is ignored. The requirements of Sections 2.1.1 and 2.1.2 then apply in their entirety. As described in Appendix C.4 of [RFC8446], reuse of a ticket allows passive observers to correlate different connections. EAP-TLS peers and EAP-TLS servers SHOULD follow the client tracking preventions in Appendix C.4 of [RFC8446].

It is RECOMMENDED to use Network Access Identifiers (NAIs) with the same realm during resumption and the original full handshake. This requirement allows EAP packets to be routed to the same destination as the original full handshake. If this recommendation is not followed, resumption is likely impossible. When NAI reuse can be done without privacy implications, it is RECOMMENDED to use the same NAI in the resumption as was used in the original full handshake [RFC7542]. For example, the NAI @realm can safely be reused since it does not provide any specific information to associate a user's resumption attempt with the original full handshake. However, reusing the NAI P2ZIM2F+OEVAO21nNWg2bVpgNnU=@realm enables an on-path attacker to associate a resumption attempt with the original full handshake. The TLS PSK identity is typically derived by the TLS implementation and may be an opaque blob without a routable realm. The TLS PSK identity on its own is therefore unsuitable as an NAI in the Identity Response.

Figure 3 shows an example message flow for a subsequent successful EAP-TLS resumption handshake where both sides authenticate via a PSK provisioned via an earlier NewSessionTicket and where the server provisions a single new ticket.



```
 EAP-Response/
 EAP-Type=EAP-TLS           -------->
                            <--------              EAP-Success
```

Figure 3: EAP-TLS Resumption

As specified in Section 2.2 of [RFC8446], the EAP-TLS peer SHOULD supply a "key_share" extension when attempting resumption, which allows the EAP-TLS server to potentially decline resumption and fall back to a full handshake. If the EAP-TLS peer did not supply a "key_share" extension when attempting resumption, the EAP-TLS server needs to send a HelloRetryRequest to signal that additional information is needed to complete the handshake, and the EAP-TLS peer needs to send a second ClientHello containing that information. Providing a "key_share" and using the "psk_dhe_ke" pre-shared key exchange mode is also important in order to limit the impact of a key compromise. When using "psk_dhe_ke", TLS 1.3 provides forward secrecy meaning that compromise of the PSK used for resumption does not compromise any earlier connections. The "psk_dh_ke" key exchange mode MUST be used for resumption unless the deployment has a local requirement to allow configuration of other mechanisms.

2.1.4. Termination

This section updates Section 2.1.3 of [RFC5216] by amending it in accordance with the following discussion.

TLS 1.3 changes both the message flow and the handshake messages compared to earlier versions of TLS. Therefore, some normative text in Section 2.1.3 of [RFC5216] does not apply for TLS 1.3. The two paragraphs below replace the corresponding paragraphs in Section 2.1.3 of [RFC5216] when EAP-TLS is used with TLS 1.3. The other paragraphs in Section 2.1.3 of [RFC5216] still apply with the exception that SessionID is deprecated.

> If the EAP-TLS peer authenticates successfully, the EAP-TLS server MUST send an EAP-Request packet with EAP-Type=EAP-TLS containing TLS records conforming to the version of TLS used. The message flow ends with a protected success indication from the EAP-TLS server, followed by an EAP-Response packet of EAP-Type=EAP-TLS and no data from the EAP-TLS peer, followed by EAP-Success from the server.
>
> If the EAP-TLS server authenticates successfully, the EAP-TLS peer MUST send an EAP-Response message with EAP-Type=EAP-TLS containing TLS records conforming to the version of TLS used.

Figures 4, 5, and 6 illustrate message flows in several cases where the EAP-TLS peer or EAP-TLS server sends a TLS Error alert message. In earlier versions of TLS, error alerts could be warnings or fatal. In TLS 1.3, error alerts are always fatal and the only alerts sent at warning level are "close_notify" and "user_canceled", both of which indicate that the connection is not going to continue normally; see [RFC8446].

In TLS 1.3 [RFC8446], error alerts are not mandatory to send after a

fatal error condition. Failure to send TLS Error alerts means that the peer or server would have no way of determining what went wrong. EAP-TLS 1.3 strengthens this requirement. Whenever an implementation encounters a fatal error condition, it MUST send an appropriate TLS Error alert.

Figure 4 shows an example message flow where the EAP-TLS server rejects the ClientHello with an error alert. The EAP-TLS server can also partly reject the ClientHello with a HelloRetryRequest; see Section 2.1.6.

```
 EAP-TLS Peer                                        EAP-TLS Server

                                                        EAP-Request/
                              <--------                    Identity
 EAP-Response/
 Identity (Privacy-Friendly) -------->
                                                        EAP-Request/
                                                   EAP-Type=EAP-TLS
                              <--------                  (TLS Start)
 EAP-Response/
 EAP-Type=EAP-TLS
(TLS ClientHello)             -------->
                                                        EAP-Request/
                                                   EAP-Type=EAP-TLS
                              <--------            (TLS Error Alert)
 EAP-Response/
 EAP-Type=EAP-TLS             -------->
                              <--------                  EAP-Failure
```

Figure 4: EAP-TLS Server Rejection of ClientHello

Figure 5 shows an example message flow where EAP-TLS server authentication is unsuccessful and the EAP-TLS peer sends a TLS Error alert.

```
 EAP-TLS Peer                                        EAP-TLS Server

                                                        EAP-Request/
                              <--------                    Identity
 EAP-Response/
 Identity (Privacy-Friendly) -------->
                                                        EAP-Request/
                                                   EAP-Type=EAP-TLS
                              <--------                  (TLS Start)
 EAP-Response/
 EAP-Type=EAP-TLS
(TLS ClientHello)             -------->
                                                        EAP-Request/
                                                   EAP-Type=EAP-TLS
                                                   (TLS ServerHello,
                                              TLS EncryptedExtensions,
                                               TLS CertificateRequest,
                                                      TLS Certificate,
                                                TLS CertificateVerify,
                              <--------                 TLS Finished)
```

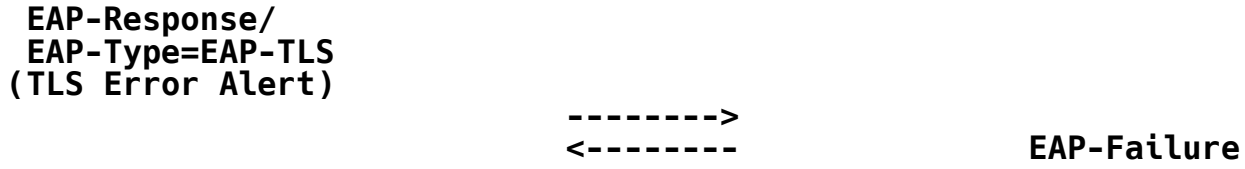


Figure 5: EAP-TLS Unsuccessful EAP-TLS Server Authentication

Figure 6 shows an example message flow where the EAP-TLS server authenticates to the EAP-TLS peer successfully, but the EAP-TLS peer fails to authenticate to the EAP-TLS server and the server sends a TLS Error alert.

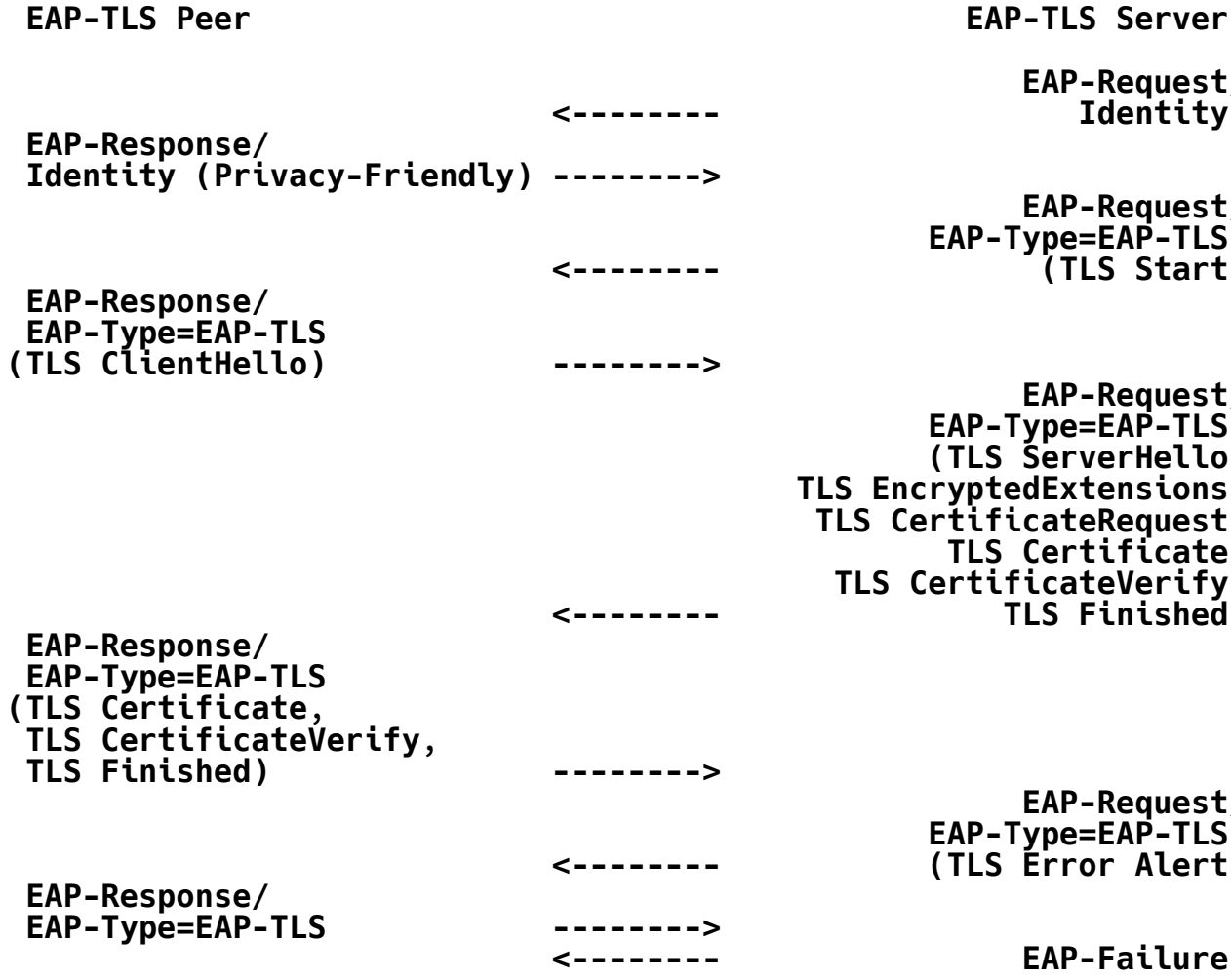


Figure 6: EAP-TLS Unsuccessful Client Authentication

2.1.5. No Peer Authentication

This is a new section when compared to [RFC5216].

Figure 7 shows an example message flow for a successful EAP-TLS full handshake without peer authentication (e.g., emergency services, as described in [RFC7406]).

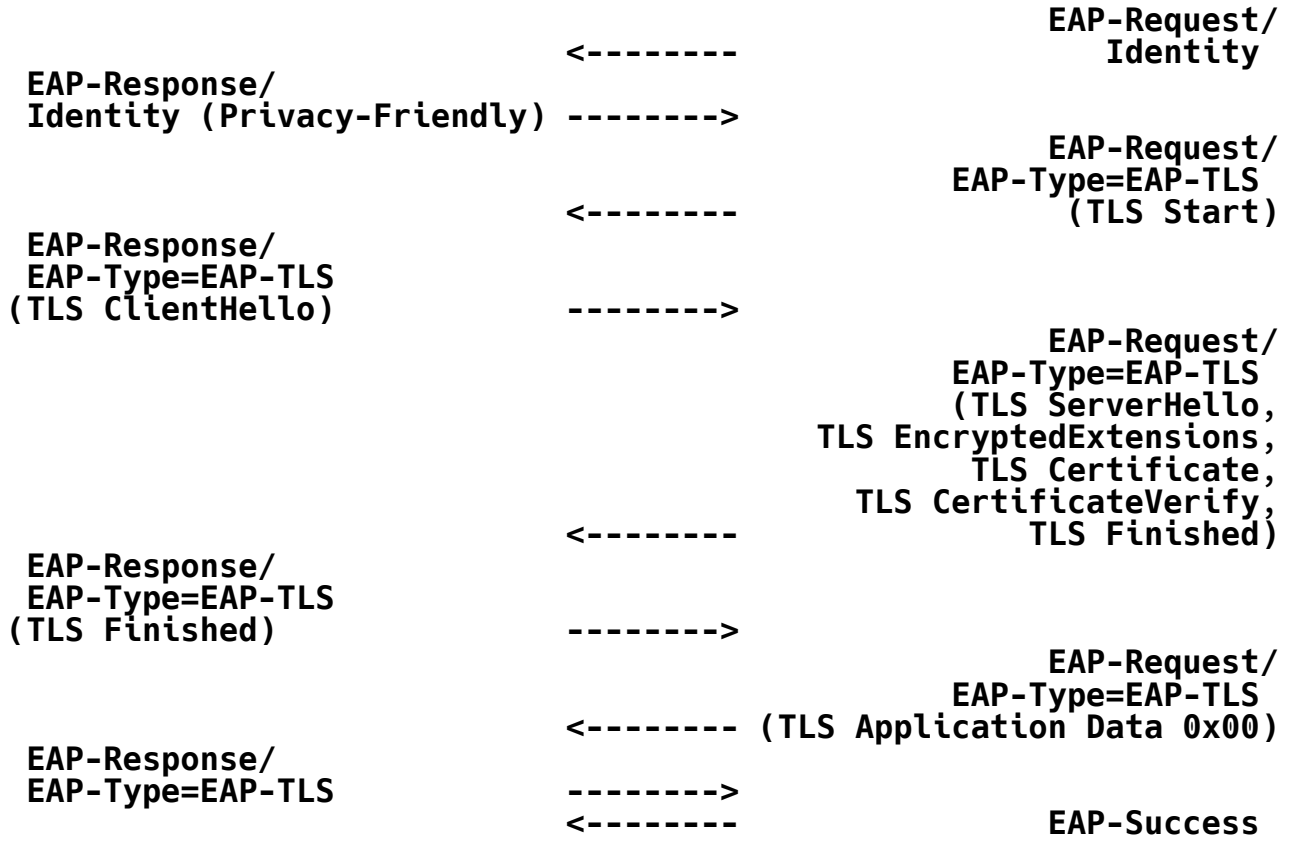


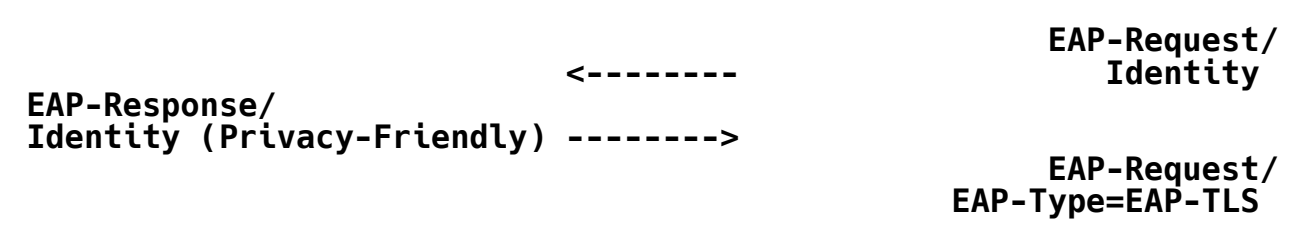
Figure 7: EAP-TLS without Peer Authentication

2.1.6. Hello Retry Request

This is a new section when compared to [RFC5216].

As defined in TLS 1.3 [RFC8446], EAP-TLS servers can send a HelloRetryRequest message in response to a ClientHello if the EAP-TLS server finds an acceptable set of parameters but the initial ClientHello does not contain all the needed information to continue the handshake. One use case is if the EAP-TLS server does not support the groups in the "key_share" extension (or there is no "key_share" extension) but supports one of the groups in the "supported_groups" extension. In this case, the client should send a new ClientHello with a "key_share" that the EAP-TLS server supports.

Figure 8 shows an example message flow for a successful EAP-TLS full handshake with mutual authentication and HelloRetryRequest. Note the extra round trip as a result of the HelloRetryRequest.



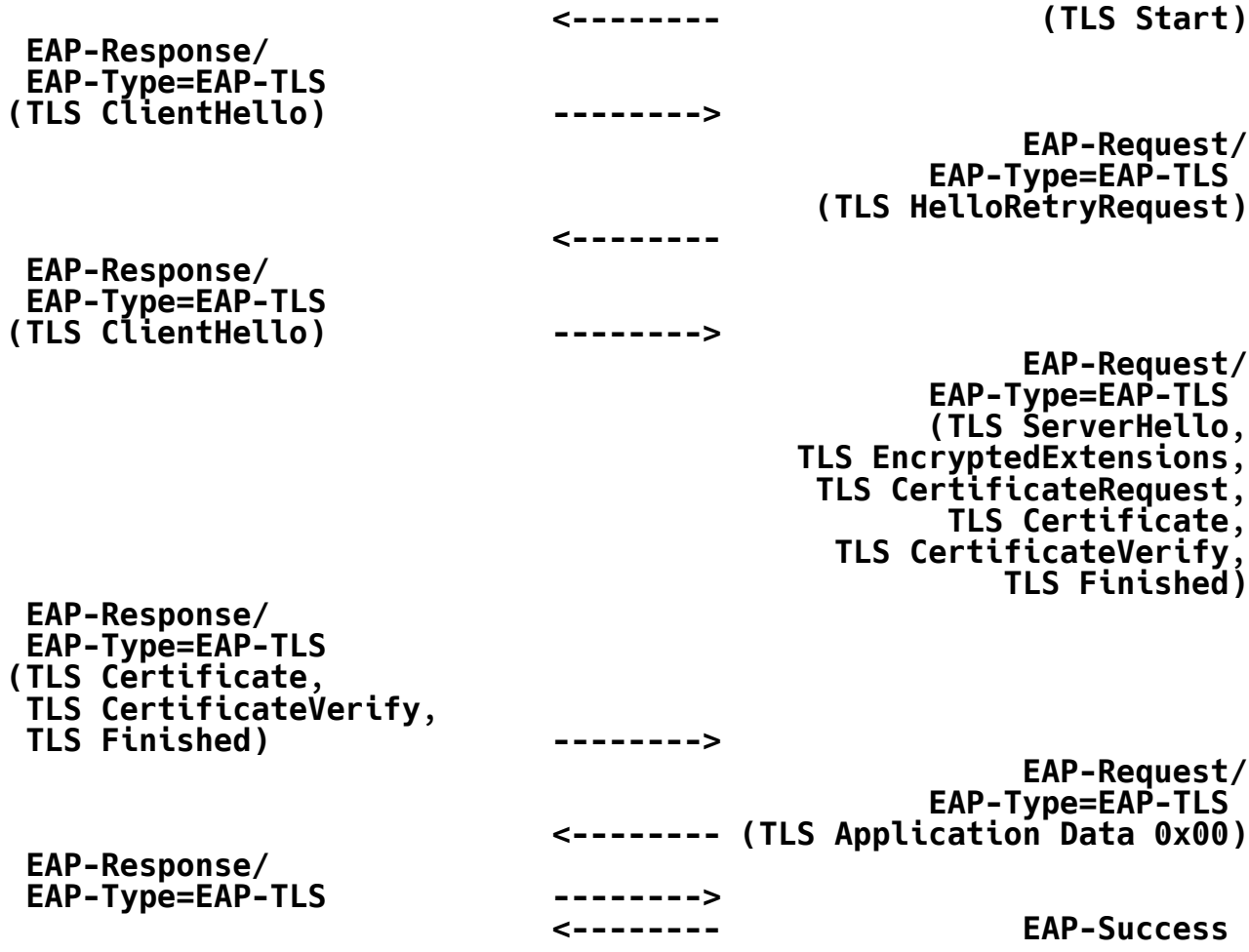


Figure 8: EAP-TLS with Hello Retry Request

2.1.7. Identity

This is a new section when compared to [RFC5216].

It is RECOMMENDED to use anonymous NAIs [RFC7542] in the Identity Response as such identities are routable and privacy-friendly. While opaque blobs are allowed by [RFC3748], such identities are NOT RECOMMENDED as they are not routable and should only be considered in local deployments where the EAP-TLS peer, EAP authenticator, and EAP-TLS server all belong to the same network. Many client certificates contain an identity such as an email address, which is already in NAI format. When the client certificate contains an NAI as subject name or alternative subject name, an anonymous NAI SHOULD be derived from the NAI in the certificate; see Section 2.1.8. More details on identities are described in Sections 2.1.3, 2.1.8, 2.2, and 5.8.

2.1.8. Privacy

This section updates Section 2.1.4 of [RFC5216] by amending it in accordance with the following discussion.

EAP-TLS 1.3 significantly improves privacy when compared to earlier versions of EAP-TLS. EAP-TLS 1.3 forbids cipher suites without

confidentiality, which means that TLS 1.3 is always encrypting large parts of the TLS handshake including the certificate messages.

EAP-TLS peer and server implementations supporting TLS 1.3 MUST support anonymous Network Access Identifiers (NAIs) (Section 2.4 of [RFC7542]). A client supporting TLS 1.3 MUST NOT send its username (or any other permanent identifiers) in cleartext in the Identity Response (or any message used instead of the Identity Response). Following [RFC7542], it is RECOMMENDED to omit the username (i.e., the NAI is @realm), but other constructions such as a fixed username (e.g., anonymous@realm) or an encrypted username (e.g., xCZINCPTK5+7y81CrSYbPg+RKPE3OTrYLn4AQc4AC2U=@realm) are allowed. Note that the NAI MUST be a UTF-8 string as defined by the grammar in Section 2.2 of [RFC7542].

The HelloRequest message used for privacy in EAP-TLS 1.2 does not exist in TLS 1.3 but as the certificate messages in TLS 1.3 are encrypted, there is no need to send an empty certificate_list and perform a second handshake for privacy (as needed by EAP-TLS with earlier versions of TLS). When EAP-TLS is used with TLS version 1.3, the EAP-TLS peer and EAP-TLS server SHALL follow the processing specified by version 1.3 of TLS. This means that the EAP-TLS peer only sends an empty certificate_list if it does not have an appropriate certificate to send, and the EAP-TLS server MAY treat an empty certificate_list as a terminal condition.

EAP-TLS with TLS 1.3 is always used with privacy. This does not add any extra round trips and the message flow with privacy is just the normal message flow as shown in Figure 1.

2.1.9. Fragmentation

This section updates Section 2.1.5 of [RFC5216] by amending it in accordance with the following discussion.

Including ContentType (1 byte), ProtocolVersion (2 bytes), and length (2 bytes) headers, a single TLS record may be up to 16645 octets in length. EAP-TLS fragmentation support is provided through addition of a flags octet within the EAP-Response and EAP-Request packets, as well as a (conditional) TLS Message Length field of four octets. Implementations MUST NOT set the L bit in unfragmented messages, but they MUST accept unfragmented messages with and without the L bit set.

Some EAP implementations and access networks may limit the number of EAP packet exchanges that can be handled. To avoid fragmentation, it is RECOMMENDED to keep the sizes of EAP-TLS peer, EAP-TLS server, and trust anchor certificates small and the length of the certificate chains short. In addition, it is RECOMMENDED to use mechanisms that reduce the sizes of Certificate messages. For a detailed discussion on reducing message sizes to prevent fragmentation, see [RFC9191].

2.2. Identity Verification

This section replaces Section 2.2 of [RFC5216] with the following discussion. The guidance in this section is relevant for EAP-TLS in

general (regardless of the underlying TLS version used).

The EAP peer identity provided in the EAP-Response/Identity is not authenticated by EAP-TLS. Unauthenticated information MUST NOT be used for accounting purposes or to give authorization. The authenticator and the EAP-TLS server MAY examine the identity presented in EAP-Response/Identity for purposes such as routing and EAP method selection. EAP-TLS servers MAY reject conversations if the identity does not match their policy. Note that this also applies to resumption; see Sections 2.1.3, 5.6, and 5.7.

The EAP server identity in the TLS server certificate is typically a fully qualified domain name (FQDN) in the SubjectAltName (SAN) extension. Since EAP-TLS deployments may use more than one EAP server, each with a different certificate, EAP peer implementations SHOULD allow for the configuration of one or more trusted root certificates (CA certificate) to authenticate the server certificate and one or more server names to match against the SubjectAltName (SAN) extension in the server certificate. If any of the configured names match any of the names in the SAN extension, then the name check passes. To simplify name matching, an EAP-TLS deployment can assign a name to represent an authorized EAP server and EAP Server certificates can include this name in the list of SANs for each certificate that represents an EAP-TLS server. If server name matching is not used, then it degrades the confidence that the EAP server with which it is interacting is authoritative for the given network. If name matching is not used with a public root CA, then effectively any server can obtain a certificate that will be trusted for EAP authentication by the peer. While this guidance to verify domain names is new, and was not mentioned in [RFC5216], it has been widely implemented in EAP-TLS peers. As such, it is believed that this section contains minimal new interoperability or implementation requirements on EAP-TLS peers and can be applied to earlier versions of TLS.

The process of configuring a root CA certificate and a server name is non-trivial; therefore, automated methods of provisioning are RECOMMENDED. For example, the eduroam federation [RFC7593] provides a Configuration Assistant Tool (CAT) to automate the configuration process. In the absence of a trusted root CA certificate (user configured or system-wide), EAP peers MAY implement a trust on first use (TOFU) mechanism where the peer trusts and stores the server certificate during the first connection attempt. The EAP peer ensures that the server presents the same stored certificate on subsequent interactions. Use of a TOFU mechanism does not allow for the server certificate to change without out-of-band validation of the certificate and is therefore not suitable for many deployments including ones where multiple EAP servers are deployed for high availability. TOFU mechanisms increase the susceptibility to traffic interception attacks and should only be used if there are adequate controls in place to mitigate this risk.

2.3. Key Hierarchy

This section updates Section 2.3 of [RFC5216] by replacing it in accordance with the following discussion.

TLS 1.3 replaces the TLS pseudorandom function (PRF) used in earlier versions of TLS with the HMAC-based Key Derivation Function (HKDF) and completely changes the key schedule. The key hierarchies shown in Section 2.3 of [RFC5216] are therefore not correct when EAP-TLS is used with TLS version 1.3. For TLS 1.3 the key schedule is described in Section 7.1 of [RFC8446].

When EAP-TLS is used with TLS version 1.3, the Key_Material and Method-Id SHALL be derived from the exporter_secret using the TLS exporter interface [RFC5705] (for TLS 1.3, this is defined in Section 7.5 of [RFC8446]). Type is the value of the EAP Type field defined in Section 2 of [RFC3748]. For EAP-TLS, the Type field has value 0x0D.

```
Type = 0x0D
Key_Material = TLS-Exporter("EXPORTER_EAP_TLS_Key_Material",
                            Type, 128)
Method-Id    = TLS-Exporter("EXPORTER_EAP_TLS_Method-Id",
                            Type, 64)
Session-Id   = Type || Method-Id
```

The MSK and EMSK are derived from the Key_Material in the same manner as with EAP-TLS [RFC5216], Section 2.3. The definitions are repeated below for simplicity:

```
MSK          = Key_Material(0, 63)
EMSK         = Key_Material(64, 127)
```

Other TLS-based EAP methods can use the TLS exporter in a similar fashion; see [TLS-EAP-TYPES].

[RFC5247] deprecates the use of an Initialization Vector (IV). Thus, RECV-IV and SEND-IV are not exported in EAP-TLS with TLS 1.3. As noted in [RFC5247], lower layers use the MSK in a lower-layer-dependent manner. EAP-TLS with TLS 1.3 exports the MSK and does not specify how it is used by lower layers.

Note that the key derivation MUST use the length values given above. While in TLS 1.2 and earlier it was possible to truncate the output by requesting less data from the TLS-Exporter function, this practice is not possible with TLS 1.3. If an implementation intends to use only a part of the output of the TLS-Exporter function, then it MUST ask for the full output and then only use the desired part. Failure to do so will result in incorrect values being calculated for the above keying material.

By using the TLS exporter, EAP-TLS can use any TLS 1.3 implementation that provides a public API for the exporter. Note that when TLS 1.2 is used with the EAP-TLS exporter [RFC5705] it generates the same key material as in EAP-TLS [RFC5216].

2.4. Parameter Negotiation and Compliance Requirements

This section updates Section 2.4 of [RFC5216] by amending it in accordance with the following discussion.

TLS 1.3 cipher suites are defined differently than in earlier versions of TLS (see Appendix B.4 of [RFC8446]), and the cipher suites discussed in Section 2.4 of [RFC5216] can therefore not be used when EAP-TLS is used with TLS version 1.3.

When EAP-TLS is used with TLS version 1.3, the EAP-TLS peers and EAP-TLS servers MUST comply with the compliance requirements (mandatory-to-implement cipher suites, signature algorithms, key exchange algorithms, extensions, etc.) defined in Section 9 of [RFC8446]. In EAP-TLS with TLS 1.3, only cipher suites with confidentiality SHALL be supported.

While EAP-TLS does not protect any application data except for the 0x00 byte that serves as protected success indication, the negotiated cipher suites and algorithms MAY be used to secure data as done in other TLS-based EAP methods.

2.5. EAP State Machines

This is a new section when compared to [RFC5216] and only applies to TLS 1.3. [RFC4137] offers a proposed state machine for EAP.

TLS 1.3 [RFC8446] introduces post-handshake messages. These post-handshake messages use the handshake content type and can be sent after the main handshake. Examples of post-handshake messages are NewSessionTicket, which is used for resumption and KeyUpdate, which is not useful and not expected in EAP-TLS. After sending TLS Finished, the EAP-TLS server may send any number of post-handshake messages in one or more EAP-Requests.

To provide a protected success result indication and to decrease the uncertainty for the EAP-TLS peer, the following procedure MUST be followed:

When an EAP-TLS server has successfully processed the TLS client Finished and sent its last handshake message (Finished or a post-handshake message), it sends an encrypted TLS record with application data 0x00. The encrypted TLS record with application data 0x00 is a protected success result indication, as defined in [RFC3748]. After sending an EAP-Request that contains the protected success result indication, the EAP-TLS server must not send any more EAP-Requests and may only send an EAP-Success. The EAP-TLS server MUST NOT send an encrypted TLS record with application data 0x00 before it has successfully processed the client Finished and sent its last handshake message.

TLS Error alerts SHOULD be considered a failure result indication, as defined in [RFC3748]. Implementations following [RFC4137] set the alternate indication of failure variable altReject after sending or receiving an error alert. After sending or receiving a TLS Error alert, the EAP-TLS server may only send an EAP-Failure. Protected TLS Error alerts are protected failure result indications, and unprotected TLS Error alerts are not.

The keying material can be derived after the TLS server Finished has

been sent or received. Implementations following [RFC4137] can then set the eapKeyData and aaaEapKeyData variables.

The keying material can be made available to lower layers and the authenticator after the authenticated success result indication has been sent or received. Implementations following [RFC4137] can set the eapKeyAvailable and aaaEapKeyAvailable variables.

3. Detailed Description of the EAP-TLS Protocol

There are no updates to Section 3 of [RFC5216].

4. IANA Considerations

This section provides guidance to the Internet Assigned Numbers Authority (IANA) regarding registration of values related to EAP-TLS 1.3 in accordance with [RFC8126].

Per this document, IANA has added the following labels to the "TLS Exporter Labels" registry defined by [RFC5705]. These labels are used in derivation of Key_Material and Method-Id as defined in Section 2.3:

Value	DTLS-OK	Recommended	Note
EXPORTER_EAP_TLS_Key_Material	N	Y	
EXPORTER_EAP_TLS_Method-Id	N	Y	

Table 1: TLS Exporter Labels

5. Security Considerations

The security considerations of TLS 1.3 [RFC8446] apply to EAP-TLS 1.3.

5.1. Security Claims

Using EAP-TLS with TLS 1.3 does not change the security claims for EAP-TLS as given in Section 5.1 of [RFC5216]. However, it strengthens several of the claims as described in the following updates to the notes given in Section 5.1 of [RFC5216].

[1] Mutual authentication: By mandating revocation checking of certificates, the authentication in EAP-TLS with TLS 1.3 is stronger as authentication with revoked certificates will always fail.

[2] Confidentiality: The TLS 1.3 handshake offers much better confidentiality than earlier versions of TLS. EAP-TLS with TLS 1.3 mandates use of cipher suites that ensure confidentiality. TLS 1.3 also encrypts certificates and some of the extensions. When using EAP-TLS with TLS 1.3, the use of privacy is mandatory and does not cause any additional round trips.

[3] Cryptographic strength: TLS 1.3 only defines strong algorithms without major weaknesses and EAP-TLS with TLS 1.3 always provides forward secrecy; see [RFC8446]. Weak algorithms such as 3DES, CBC mode, RC4, SHA-1, MD5, P-192, and RSA-1024 have not been registered for use in TLS 1.3.

[4] Cryptographic negotiation: The TLS layer handles the negotiation of cryptographic parameters. When EAP-TLS is used with TLS 1.3, EAP-TLS inherits the cryptographic negotiation of the AEAD algorithm, HKDF hash algorithm, key exchange groups, and signature algorithm; see Section 4.1.1 of [RFC8446].

5.2. Peer and Server Identities

No updates to Section 5.2 of [RFC5216]. Note that Section 2.2 has additional discussion on identities.

5.3. Certificate Validation

No updates to Section 5.3 of [RFC5216]. In addition to Section 5.3 of [RFC5216], guidance on server certificate validation can be found in [RFC6125].

5.4. Certificate Revocation

This section updates Section 5.4 of [RFC5216] by amending it in accordance with the following discussion.

There are a number of reasons (e.g., key compromise, CA compromise, privilege withdrawn, etc.) why EAP-TLS peer, EAP-TLS server, or sub-CA certificates have to be revoked before their expiry date. Revocation of the EAP-TLS server's certificate is complicated by the fact that the EAP-TLS peer may not have Internet connectivity until authentication completes.

When EAP-TLS is used with TLS 1.3, the revocation status of all the certificates in the certificate chains MUST be checked (except the trust anchor). An implementation may use the Certificate Revocation List (CRL), Online Certificate Status Protocol (OSCP), or other standardized/proprietary methods for revocation checking. Examples of proprietary methods are non-standard formats for distribution of revocation lists as well as certificates with very short lifetime.

EAP-TLS servers supporting TLS 1.3 MUST implement Certificate Status Requests (OCSP stapling) as specified in [RFC6066] and Section 4.4.2.1 of [RFC8446]. It is RECOMMENDED that EAP-TLS peers and EAP-TLS servers use OCSP stapling for verifying the status of the EAP-TLS server's certificate chain. When an EAP-TLS peer uses Certificate Status Requests to check the revocation status of the EAP-TLS server's certificate chain, it MUST treat a CertificateEntry (but not the trust anchor) without a valid CertificateStatus extension as invalid and abort the handshake with an appropriate alert. The OCSP status handling in TLS 1.3 is different from earlier versions of TLS; see Section 4.4.2.1 of [RFC8446]. In TLS 1.3, the OCSP information is carried in the CertificateEntry containing the

associated certificate instead of a separate CertificateStatus message as in [RFC6066]. This enables sending OCSP information for all certificates in the certificate chain (except the trust anchor).

To enable revocation checking in situations where EAP-TLS peers do not implement or use OCSP stapling, and where network connectivity is not available prior to authentication completion, EAP-TLS peer implementations MUST also support checking for certificate revocation after authentication completes and network connectivity is available. An EAP peer implementation SHOULD NOT trust the network (and any services) until it has verified the revocation status of the server certificate after receiving network connectivity. An EAP peer MUST use a secure transport to verify the revocation status of the server certificate. An EAP peer SHOULD NOT send any other traffic before revocation checking for the server certificate is complete.

5.5. Packet Modification Attacks

This section updates Section 5.5 of [RFC5216] by amending it in accordance with the following discussion.

As described in [RFC3748] and Section 5.5 of [RFC5216], the only information that is integrity and replay protected in EAP-TLS are the parts of the TLS Data that TLS protects. All other information in the EAP-TLS message exchange including EAP-Request and EAP-Response headers, the identity in the Identity Response, EAP-TLS packet header fields, Type, Flags, EAP-Success, and EAP-Failure can be modified, spoofed, or replayed.

Protected TLS Error alerts are protected failure result indications and enable the EAP-TLS peer and EAP-TLS server to determine that the failure result was not spoofed by an attacker. Protected failure result indications provide integrity and replay protection but MAY be unauthenticated. Protected failure results do not significantly improve availability as TLS 1.3 treats most malformed data as a fatal error.

5.6. Authorization

This is a new section when compared to [RFC5216]. The guidance in this section is relevant for EAP-TLS in general (regardless of the underlying TLS version used).

EAP servers will usually require the EAP peer to provide a valid certificate and will fail the connection if one is not provided. Some deployments may permit no peer authentication for some or all connections. When peer authentication is not used, EAP-TLS server implementations MUST take care to limit network access appropriately for unauthenticated peers, and implementations MUST use resumption with caution to ensure that a resumed session is not granted more privilege than was intended for the original session. An example of limiting network access would be to invoke a vendor's walled garden or quarantine network functionality.

EAP-TLS is typically encapsulated in other protocols such as PPP [RFC1661], RADIUS [RFC2865], Diameter [RFC6733], or the Protocol for

Carrying Authentication for Network Access (PANA) [RFC5191]. The encapsulating protocols can also provide additional, non-EAP information to an EAP-TLS server. This information can include, but is not limited to, information about the authenticator, information about the EAP-TLS peer, or information about the protocol layers above or below EAP (MAC addresses, IP addresses, port numbers, Wi-Fi Service Set Identifiers (SSIDs), etc.). EAP-TLS servers implementing EAP-TLS inside those protocols can make policy decisions and enforce authorization based on a combination of information from the EAP-TLS exchange and non-EAP information.

As noted in Section 2.2, the identity presented in EAP-Response/Identity is not authenticated by EAP-TLS and is therefore trivial for an attacker to forge, modify, or replay. Authorization and accounting MUST be based on authenticated information such as information in the certificate or the PSK identity and cached data provisioned for resumption as described in Section 5.7. Note that the requirements for Network Access Identifiers (NAIs) specified in Section 4 of [RFC7542] still apply and MUST be followed.

EAP-TLS servers MAY reject conversations based on non-EAP information provided by the encapsulating protocol, for example if the MAC address of the authenticator does not match the expected policy.

In addition to allowing configuration of one or more trusted root certificates (CA certificate) to authenticate the server certificate and one or more server names to match against the SubjectAltName (SAN) extension, EAP peer implementations MAY allow binding the configured acceptable SAN to a specific CA (or CAs) that should have issued the server certificate to prevent attacks from rogue or compromised CAs.

5.7. Resumption

This is a new section when compared to [RFC5216]. The guidance in this section is relevant for EAP-TLS in general (regardless of the underlying TLS version used).

There are a number of security issues related to resumption that are not described in [RFC5216]. The problems, guidelines, and requirements in this section therefore apply to EAP-TLS when it is used with any version of TLS.

When resumption occurs, it is based on cached information at the TLS layer. To perform resumption securely, the EAP-TLS peer and EAP-TLS server need to be able to securely retrieve authorization information such as certificate chains from the initial full handshake. This document uses the term "cached data" to describe such information. Authorization during resumption MUST be based on such cached data. The EAP-TLS peer and EAP-TLS server MAY perform fresh revocation checks on the cached certificate data. Any security policies for authorization MUST be followed also for resumption. The certificates may have been revoked since the initial full handshake and the authorizations of the other party may have been reduced. If the cached revocation data is not sufficiently current, the EAP-TLS peer or EAP-TLS server MAY force a full TLS handshake.

There are two ways to retrieve the cached data from the original full handshake. The first method is that the EAP-TLS server and client cache the information locally. The cached information is identified by an identifier. For TLS versions before 1.3, the identifier can be the session ID; for TLS 1.3, the identifier is the PSK identity. The second method for retrieving cached information is via [RFC5077] or [RFC8446], where the EAP-TLS server avoids storing information locally and instead encapsulates the information into a ticket that is sent to the client for storage. This ticket is encrypted using a key that only the EAP-TLS server knows. Note that the client still needs to cache the original handshake information locally and will obtain it while determining the session ID or PSK identity to use for resumption. However, the EAP-TLS server is able to decrypt the ticket or PSK to obtain the original handshake information.

The EAP-TLS server or EAP client MUST cache data during the initial full handshake sufficient to allow authorization decisions to be made during resumption. If cached data cannot be retrieved securely, resumption MUST NOT be done.

The above requirements also apply if the EAP-TLS server expects some system to perform accounting for the session. Since accounting must be tied to an authenticated identity, and resumption does not supply such an identity, accounting is impossible without access to cached data. Therefore, systems that expect to perform accounting for the session SHOULD cache an identifier that can be used in subsequent accounting.

As suggested in [RFC8446], EAP-TLS peers MUST NOT store resumption PSKs or tickets (and associated cached data) for longer than 604800 seconds (7 days) regardless of the PSK or ticket lifetime. The EAP-TLS peer MAY delete them earlier based on local policy. The cached data MAY also be removed on the EAP-TLS server or EAP-TLS peer if any certificate in the certificate chain has been revoked or has expired. In all such cases, an attempt at resumption results in a full TLS handshake instead.

Information from the EAP-TLS exchange (e.g., the identity provided in EAP-Response/Identity) as well as non-EAP information (e.g., IP addresses) may change between the initial full handshake and resumption. This change creates a "time-of-check time-of-use" (TOCTOU) security vulnerability. A malicious or compromised user could supply one set of data during the initial authentication, and a different set of data during resumption, potentially allowing them to obtain access that they should not have.

If any authorization, accounting, or policy decisions were made with information that has changed between the initial full handshake and resumption, and if change may lead to a different decision, such decisions MUST be reevaluated. It is RECOMMENDED that authorization, accounting, and policy decisions are reevaluated based on the information given in the resumption. EAP-TLS servers MAY reject resumption where the information supplied during resumption does not match the information supplied during the original authentication. If a safe decision is not possible, EAP-TLS servers SHOULD reject the

resumption and continue with a full handshake.

Sections 2.2 and 4.2.11 of [RFC8446] provide security considerations for TLS 1.3 resumption.

5.8. Privacy Considerations

This is a new section when compared to [RFC5216].

TLS 1.3 offers much better privacy than earlier versions of TLS as discussed in Section 2.1.8. In this section, we only discuss the privacy properties of EAP-TLS with TLS 1.3. For privacy properties of TLS 1.3 itself, see [RFC8446].

EAP-TLS sends the standard TLS 1.3 handshake messages encapsulated in EAP packets. Additionally, the EAP-TLS peer sends an identity in the first EAP-Response. The other fields in the EAP-TLS Request and the EAP-TLS Response packets do not contain any cleartext privacy-sensitive information.

Tracking of users by eavesdropping on Identity Responses or certificates is a well-known problem in many EAP methods. When EAP-TLS is used with TLS 1.3, all certificates are encrypted, and the username part of the Identity Response is not revealed (e.g., using anonymous NAIs). Note that even though all certificates are encrypted, the server's identity is only protected against passive attackers while the client's identity is protected against both passive and active attackers. As with other EAP methods, even when privacy-friendly identifiers or EAP tunneling is used, the domain name (i.e., the realm) in the NAI is still typically visible. How much privacy-sensitive information the domain name leaks is highly dependent on how many other users are using the same domain name in the particular access network. If all EAP-TLS peers have the same domain, no additional information is leaked. If a domain name is used by a small subset of the EAP-TLS peers, it may aid an attacker in tracking or identifying the user.

Without padding, information about the size of the client certificate is leaked from the size of the EAP-TLS packets. The EAP-TLS packets sizes may therefore leak information that can be used to track or identify the user. If all client certificates have the same length, no information is leaked. EAP-TLS peers SHOULD use record padding; see Section 5.4 of [RFC8446] to reduce information leakage of certificate sizes.

If anonymous NAIs are not used, the privacy-friendly identifiers need to be generated with care. The identities MUST be generated in a cryptographically secure way so that it is computationally infeasible for an attacker to differentiate two identities belonging to the same user from two identities belonging to different users in the same realm. This can be achieved, for instance, by using random or pseudo-random usernames such as random byte strings or ciphertexts and only using the pseudo-random usernames a single time. Note that the privacy-friendly usernames also MUST NOT include substrings that can be used to relate the identity to a specific user. Similarly, privacy-friendly usernames MUST NOT be formed by a fixed mapping that

stays the same across multiple different authentications.

An EAP-TLS peer with a policy allowing communication with EAP-TLS servers supporting only TLS 1.2 without privacy and with a static RSA key exchange is vulnerable to disclosure of the EAP-TLS peer username. An active attacker can in this case make the EAP-TLS peer believe that an EAP-TLS server supporting TLS 1.3 only supports TLS 1.2 without privacy. The attacker can simply impersonate the EAP-TLS server and negotiate TLS 1.2 with static RSA key exchange and send a TLS alert message when the EAP-TLS peer tries to use privacy by sending an empty certificate message. Since the attacker (impersonating the EAP-TLS server) does not provide a proof-of-possession of the private key until the Finished message when a static RSA key exchange is used, an EAP-TLS peer may inadvertently disclose its identity (username) to an attacker. Therefore, it is RECOMMENDED for EAP-TLS peers to not use EAP-TLS with TLS 1.2 and static RSA-based cipher suites without privacy. This implies that an EAP-TLS peer SHOULD NOT continue the EAP authentication attempt if a TLS 1.2 EAP-TLS server sends an EAP-TLS/Request with a TLS alert message in response to an empty certificate message from the peer.

5.9. Pervasive Monitoring

This is a new section when compared to [RFC5216].

Pervasive monitoring refers to widespread surveillance of users. In the context of EAP-TLS, pervasive monitoring attacks can target EAP-TLS peer devices for tracking them (and their users) when they join a network. By encrypting more information, mandating the use of privacy, and always providing forward secrecy, EAP-TLS with TLS 1.3 offers much better protection against pervasive monitoring. In addition to the privacy attacks discussed above, surveillance on a large scale may enable tracking of a user over a wide geographical area and across different access networks. Using information from EAP-TLS together with information gathered from other protocols increases the risk of identifying individual users.

In TLS 1.3, the post-handshake key update mechanism provides forward secrecy for the traffic secrets. EAP-TLS 1.3 does not provide a similar mechanism for MSK and EMSK. Implementation using the exported MSK and EMSK can achieve forward secrecy by frequently deriving new keys in a similar way as described in Section 7.2 of [RFC8446].

5.10. Discovered Vulnerabilities

This is a new section when compared to [RFC5216].

Over the years, there have been several serious attacks on earlier versions of Transport Layer Security (TLS), including attacks on its most commonly used ciphers and modes of operation. [RFC7457] summarizes the attacks that were known at the time of publishing, and BCP 195 [RFC7525] [RFC8996] provides recommendations and requirements for improving the security of deployed services that use TLS. However, many of the attacks are less serious for EAP-TLS as EAP-TLS only uses the TLS handshake and does not protect any application

data. EAP-TLS implementations MUST mitigate known attacks. EAP-TLS implementations need to monitor and follow new EAP- and TLS-related security guidance and requirements such as [RFC8447] and [RFC9155].

5.11. Cross-Protocol Attacks

This is a new section when compared to [RFC5216].

Allowing the same certificate to be used in multiple protocols can potentially allow an attacker to authenticate via one protocol and then "resume" that session in another protocol. Section 2.2 suggests that certificates typically have one or more FQDNs in the SAN extension. However, those fields are for EAP validation only and do not indicate that the certificates are suitable for use with HTTPS or other protocols on the named host.

Section 2.1.3 suggests that authorization rules should be reapplied on resumption but does not mandate this behavior. As a result, this cross-protocol resumption could allow the attacker to bypass authorization policies and to obtain undesired access to secured systems. Along with making sure that appropriate authorization information is available and used during resumption, using different certificates and resumption caches for different protocols is RECOMMENDED to help keep different protocol usages separate.

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Appendix A. Updated References

The following references in [RFC5216] are updated as specified below when EAP-TLS is used with TLS 1.3.

* All references to [RFC2560] are updated to refer to [RFC6960].

* All references to [RFC3280] are updated to refer to [RFC5280]. References to Section 4.2.1.13 of [RFC3280] are updated to refer to Section 4.2.1.12 of [RFC5280].

* All references to [RFC4282] are updated to refer to [RFC7542]. References to Section 2.1 of [RFC4282] are updated to refer to Section 2.2 of [RFC7542].

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