Internet Engineering Task Force (IETF)
Request for Comments: 9329
Obsoletes: 8229
Category: Standards Track
ISSN: 2070-1721

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November 2022

TCP Encapsulation of Internet Key Exchange Protocol (IKE) and IPsec Packets

Abstract

This document describes a method to transport Internet Key Exchange Protocol (IKE) and IPsec packets over a TCP connection for traversing network middleboxes that may block IKE negotiation over UDP. This method, referred to as "TCP encapsulation", involves sending both IKE packets for Security Association (SA) establishment and Encapsulating Security Payload (ESP) packets over a TCP connection. This method is intended to be used as a fallback option when IKE cannot be negotiated over UDP.

TCP encapsulation for IKE and IPsec was defined in RFC 8229. This document clarifies the specification for TCP encapsulation by including additional clarifications obtained during implementation and deployment of this method. This documents obsoletes RFC 8229.

Status of This Memo

This is an Internet Standards Track document.

This document is a product of the Internet Engineering Task Force (IETF). It represents the consensus of the IETF community. It has received public review and has been approved for publication by the Internet Engineering Steering Group (IESG). Further information on Internet Standards is available in Section 2 of RFC 7841.

Information about the current status of this document, any errata, and how to provide feedback on it may be obtained at https://www.rfc-editor.org/info/rfc9329.

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1. Introduction

The Internet Key Exchange Protocol version 2 (IKEv2) [RFC7296] is a protocol for establishing IPsec Security Associations (SAs) using IKE messages over UDP for control traffic and using Encapsulating Security Payload (ESP) messages [RFC4303] for encrypted data traffic. Many network middleboxes that filter traffic on public hotspots block all UDP traffic, including IKE and IPsec, but allow TCP connections through because they appear to be web traffic. Devices on these networks that need to use IPsec (to access private enterprise networks, to route Voice over IP calls to carrier networks because of security policies, etc.) are unable to establish IPsec SAs. This document defines a method for encapsulating IKE control messages as well as ESP data messages within a TCP connection. Note that Authentication Header (AH) is not supported by this specification.

Using TCP as a transport for IPsec packets adds the third option (below) to the list of traditional IPsec transports:

1. Direct. Usually, IKE negotiations begin over UDP port 500. If no Network Address Translation (NAT) device is detected between the Initiator and the Responder, then subsequent IKE packets are sent over UDP port 500 and IPsec data packets are sent using ESP.

2. UDP Encapsulation. Described in [RFC3948]. If a NAT is detected between the Initiator and the Responder, then subsequent IKE packets are sent over UDP port 4500 with 4 bytes of zero at the start of the UDP payload, and ESP packets are sent out over UDP port 4500. Some implementations default to using UDP encapsulation even when no NAT is detected on the path, as some middleboxes do not support IP protocols other than TCP and UDP.

3. TCP Encapsulation. Described in this document. If the other two methods are not available or appropriate, IKE negotiation packets as well as ESP packets can be sent over a single TCP connection to the peer.

Direct use of ESP or UDP encapsulation should be preferred by IKE implementations due to performance concerns when using TCP encapsulation (Section 9). Most implementations should use TCP encapsulation only on networks where negotiation over UDP has been attempted without receiving responses from the peer or if a network is known to not support UDP.

1.1. Prior Work and Motivation

Encapsulating IKE connections within TCP streams is a common approach to solve the problem of UDP packets being blocked by network middleboxes. The specific goals of this document are as follows:

* To promote interoperability by defining a standard method of framing IKE and ESP messages within TCP streams.

* To be compatible with the current IKEv2 standard without requiring modifications or extensions.

* To use IKE over UDP by default to avoid the overhead of other alternatives that always rely on TCP or Transport Layer Security (TLS) [RFC5246] [RFC8446].

Some previous alternatives include:

Cellular Network Access:
: Interworking Wireless LAN (IWLAN) uses IKEv2 to create secure connections to cellular carrier networks for making voice calls and accessing other network services over Wi-Fi networks. 3GPP has recommended that IKEv2 and ESP packets be sent within a TLS connection to be able to establish connections on restrictive networks.

ISAKMP over TCP:
: Various non-standard extensions to the Internet Security Association and Key Management Protocol (ISAKMP) have been deployed that send IPsec traffic over TCP or TCP-like packets.

Secure Sockets Layer (SSL) VPNs:
: Many proprietary VPN solutions use a combination of TLS and IPsec in order to provide reliability. These often run on TCP port 443.

IKEv2 over TCP:
: IKEv2 over TCP as described in [IPSECME-IKE-TCP] is used to avoid UDP fragmentation.

TCP encapsulation for IKE and IPsec was defined in [RFC8229]. This document updates the specification for TCP encapsulation by including additional clarifications obtained during implementation and deployment of this method.

In particular:

* The interpretation of the Length field preceding every message is clarified (Section 3).

* The use of the NAT_DETECTION_*_IP notifications is clarified (Sections 5.1, 6.5, and 7.1).

* Retransmission behavior is clarified (Section 6.2).

* The use of cookies and puzzles is described in more detail (Section 6.3).

* Error handling is clarified (Section 6.4).

* Implications of TCP encapsulation on IPsec SA processing are expanded (Section 6.8).

* Section 7 describing interactions with other IKEv2 extensions is added.

* The interaction of TCP encapsulation with IKEv2 Mobility and Multihoming (MOBIKE) is clarified (Section 7.1).

* The recommendation for TLS encapsulation (Appendix A) now includes TLS 1.3.

* Examples of TLS encapsulation are provided using TLS 1.3 (Appendix B).

* More security considerations are added.

1.2. Terminology and Notation

This document distinguishes between the IKE peer that initiates TCP connections to be used for TCP encapsulation and the roles of Initiator and Responder for particular IKE messages. During the course of IKE exchanges, the role of IKE Initiator and Responder may swap for a given SA (as with IKE SA rekeys), while the Initiator of the TCP connection is still responsible for tearing down the TCP connection and re-establishing it if necessary. For this reason, this document will use the term "TCP Originator" to indicate the IKE peer that initiates TCP connections. The peer that receives TCP connections will be referred to as the "TCP Responder". If an IKE SA is rekeyed one or more times, the TCP Originator MUST remain the peer that originally initiated the first IKE SA.

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.

2. Configuration

One of the main reasons to use TCP encapsulation is that UDP traffic may be entirely blocked on a network. Because of this, support for TCP encapsulation is not specifically negotiated in the IKE exchange. Instead, support for TCP encapsulation must be preconfigured on both the TCP Originator and the TCP Responder.

Compliant implementations MUST support TCP encapsulation on TCP port 4500, which is reserved for IPsec NAT traversal.

Beyond a flag indicating support for TCP encapsulation, the configuration for each peer can include the following optional parameters:

* Alternate TCP ports on which the specific TCP Responder listens for incoming connections. Note that the TCP Originator may initiate TCP connections to the TCP Responder from any local port.

* An extra framing protocol to use on top of TCP to further encapsulate the stream of IKE and IPsec packets. See Appendix A for a detailed discussion.

Since TCP encapsulation of IKE and IPsec packets adds overhead and has potential performance trade-offs compared to direct or UDP-encapsulated SAs (as described in Section 9), implementations SHOULD prefer ESP direct or UDP-encapsulated SAs over TCP-encapsulated SAs when possible.

3. TCP-Encapsulated Data Formats

Like UDP encapsulation, TCP encapsulation uses the first 4 bytes of a message to differentiate IKE and ESP messages. TCP encapsulation also adds a 16-bit Length field that precedes every message to define the boundaries of messages within a stream. The value in this field is equal to the length of the original message plus the length of the field itself, in octets. If the first 32 bits of the message are zeros (a non-ESP marker), then the contents comprise an IKE message. Otherwise, the contents comprise an ESP message. AH messages are not supported for TCP encapsulation.

Although a TCP stream may be able to send very long messages, implementations SHOULD limit message lengths to match the lengths used for UDP encapsulation of ESP messages. The maximum message length is used as the effective MTU for connections that are being encrypted using ESP, so the maximum message length will influence characteristics of these connections, such as the TCP Maximum Segment Size (MSS).

Due to the fact that the Length field is 16 bits and includes both the message length and the length of the field itself, it is impossible to encapsulate messages greater than 65533 octets in length. In most cases, this is not a problem. Note that a similar limitation exists for encapsulation ESP in UDP [RFC3948].

The minimum size of an encapsulated message is 1 octet (for NAT-keepalive packets, see Section 6.6). Empty messages (where the Length field equals 2) MUST be silently ignored by receiver.

Note that this method of encapsulation will also work for placing IKE and ESP messages within any protocol that presents a stream abstraction, beyond TCP.

3.1. TCP-Encapsulated IKE Message Format

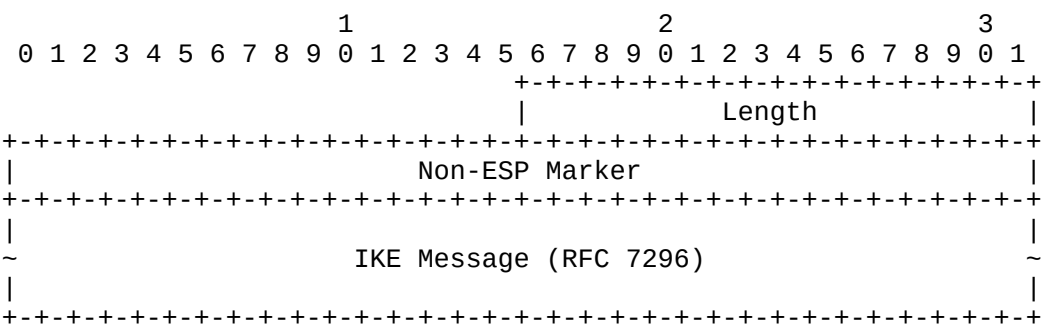


Figure 1: IKE Message Format for TCP Encapsulation

The IKE message is preceded by a 16-bit Length field in network byte order that specifies the length of the IKE message (including the

non-ESP marker) within the TCP stream. As with IKE over UDP port 4500, a zeroed 32-bit non-ESP marker is inserted before the start of the IKE header in order to differentiate the traffic from ESP traffic between the same addresses and ports.

Length (2 octets, unsigned integer): Length of the IKE message, including the Length field and non-ESP marker. The value in the Length field MUST NOT be 0 or 1. The receiver MUST treat these values as fatal errors and MUST close the TCP connection.

Non-ESP Marker (4 octets): Four zero-valued bytes.

3.2. TCP-Encapsulated ESP Packet Format

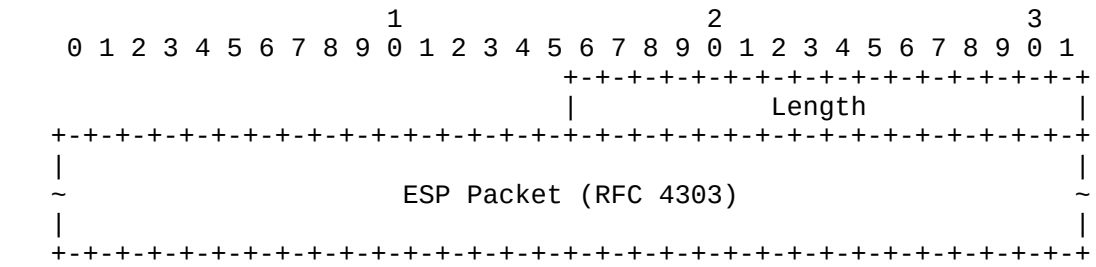


Figure 2: ESP Packet Format for TCP Encapsulation

The ESP packet is preceded by a 16-bit Length field in network byte order that specifies the length of the ESP packet within the TCP stream.

The Security Parameter Index (SPI) field [RFC7296] in the ESP header MUST NOT be a zero value.

Length (2 octets, unsigned integer): Length of the ESP packet, including the Length field. The value in the Length field MUST NOT be 0 or 1. The receiver MUST treat these values as fatal errors and MUST close TCP connection.

4. TCP-Encapsulated Stream Prefix

Each stream of bytes used for IKE and IPsec encapsulation MUST begin with a fixed sequence of 6 bytes as a magic value, containing the characters "IKETCP" as ASCII values.

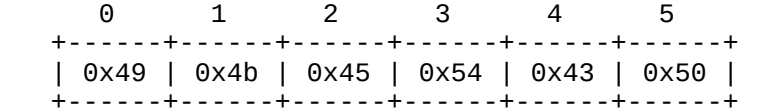
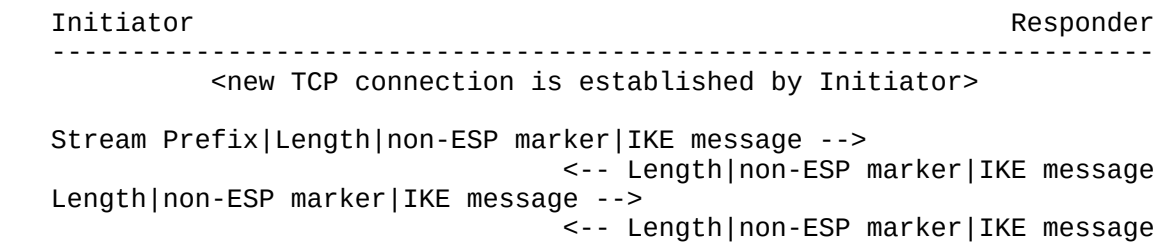


Figure 3: TCP-Encapsulated Stream Prefix

This value is intended to identify and validate that the TCP connection is being used for TCP encapsulation as defined in this document, to avoid conflicts with the prevalence of previous non-standard protocols that used TCP port 4500. This value is only sent once, by the TCP Originator only, at the beginning of the TCP stream of IKE and ESP messages.



[...]

```
Length|ESP packet ->
                                        <- Length|ESP packet
```

If other framing protocols are used within TCP to further encapsulate or encrypt the stream of IKE and ESP messages, the stream prefix must be at the start of the TCP Originator's IKE and ESP message stream within the added protocol layer (Appendix A). Although some framing protocols do support negotiating inner protocols, the stream prefix should always be used in order for implementations to be as generic as possible and not rely on other framing protocols on top of TCP.

5. Applicability

TCP encapsulation is applicable only when it has been configured to be used with specific IKE peers. If a Responder is configured to accept and is allowed to use TCP encapsulation, it MUST listen on the configured port(s) in case any peers will initiate new IKE sessions. Initiators MAY use TCP encapsulation for any IKE session to a peer that is configured to support TCP encapsulation, although it is recommended that Initiators only use TCP encapsulation when traffic over UDP is blocked.

Since the support of TCP encapsulation is a configured property, not a negotiated one, it is recommended that if there are multiple IKE endpoints representing a single peer (such as multiple machines with different IP addresses when connecting by Fully Qualified Domain Name (FQDN), or endpoints used with IKE redirection), all of the endpoints equally support TCP encapsulation.

If TCP encapsulation is being used for a specific IKE SA, all IKE messages for that IKE SA and ESP packets for its Child SAs MUST be sent over a TCP connection until the SA is deleted or IKEv2 Mobility and Multihoming (MOBIKE) is used to change the SA endpoints and/or the encapsulation protocol. See Section 7.1 for more details on using MOBIKE to transition between encapsulation modes.

5.1. Recommended Fallback from UDP

Since UDP is the preferred method of transport for IKE messages, implementations that use TCP encapsulation should have an algorithm for deciding when to use TCP after determining that UDP is unusable. If an Initiator implementation has no prior knowledge about the network it is on and the status of UDP on that network, it SHOULD always attempt to negotiate IKE over UDP first. IKEv2 defines how to use retransmission timers with IKE messages and, specifically, IKE_SA_INIT messages [RFC7296]. Generally, this means that the implementation will define a frequency of retransmission and the maximum number of retransmissions allowed before marking the IKE SA as failed. An implementation can attempt negotiation over TCP once it has hit the maximum retransmissions over UDP, or slightly before to reduce connection setup delays. It is recommended that the initial message over UDP be retransmitted at least once before falling back to TCP, unless the Initiator knows beforehand that the network is likely to block UDP.

When switching from UDP to TCP, a new IKE_SA_INIT exchange MUST be initiated with the Initiator's new SPI and with recalculated content of NAT_DETECTION_*_IP notifications.

6. Using TCP Encapsulation

6.1. Connection Establishment and Teardown

When the IKE Initiator uses TCP encapsulation, it will initiate a TCP

connection to the Responder using the Responder's preconfigured TCP port. The first bytes sent on the TCP stream MUST be the stream prefix value (Section 4). After this prefix, encapsulated IKE messages will negotiate the IKE SA and initial Child SA [RFC7296]. After this point, both encapsulated IKE (Figure 1) and ESP (Figure 2) messages will be sent over the TCP connection. The TCP Responder MUST wait for the entire stream prefix to be received on the stream before trying to parse out any IKE or ESP messages. The stream prefix is sent only once, and only by the TCP Originator.

In order to close an IKE session, either the Initiator or Responder SHOULD gracefully tear down IKE SAs with DELETE payloads. Once the SA has been deleted, the TCP Originator SHOULD close the TCP connection if it does not intend to use the connection for another IKE session to the TCP Responder. If the TCP connection is no longer associated with any active IKE SA, the TCP Responder MAY close the connection to clean up IKE resources if the TCP Originator didn't close it within some reasonable period of time (e.g., a few seconds).

An unexpected FIN or a TCP Reset on the TCP connection may indicate a loss of connectivity, an attack, or some other error. If a DELETE payload has not been sent, both sides SHOULD maintain the state for their SAs for the standard lifetime or timeout period. The TCP Originator is responsible for re-establishing the TCP connection if it is torn down for any unexpected reason. Since new TCP connections may use different IP addresses and/or ports due to NAT mappings or local address or port allocations changing, the TCP Responder MUST allow packets for existing SAs to be received from new source IP addresses and ports. Note that the IPv6 Flow-ID header MUST remain constant when a new TCP connection is created to avoid ECMP load balancing.

A peer MUST discard a partially received message due to a broken connection.

Whenever the TCP Originator opens a new TCP connection to be used for an existing IKE SA, it MUST send the stream prefix first, before any IKE or ESP messages. This follows the same behavior as the initial TCP connection.

Multiple IKE SAs MUST NOT share a single TCP connection, unless one is a rekey of an existing IKE SA, in which case there will temporarily be two IKE SAs on the same TCP connection.

If a TCP connection is being used to continue an existing IKE/ESP session, the TCP Responder can recognize the session using either the IKE SPI from an encapsulated IKE message or the ESP SPI from an encapsulated ESP packet. If the session had been fully established previously, it is suggested that the TCP Originator send an UPDATE_SA_ADDRESSES message if MOBIKE is supported and an empty informational message if it is not.

The TCP Responder MUST NOT accept any messages for the existing IKE session on a new incoming connection, unless that connection begins with the stream prefix. If either the TCP Originator or TCP Responder detects corruption on a connection that was started with a valid stream prefix, it SHOULD close the TCP connection. The connection can be corrupted if there are too many subsequent messages that cannot be parsed as valid IKE messages or ESP messages with known SPIs, or if the authentication check for an IKE message or ESP message with a known SPI fails. Implementations SHOULD NOT tear down a connection if only a few consecutive ESP packets have unknown SPIs since the SPI databases may be momentarily out of sync. If there is instead a syntax issue within an IKE message, an implementation MUST send the INVALID_SYNTAX notify payload and tear down the IKE SA as usual, rather than tearing down the TCP connection directly.

A TCP Originator SHOULD only open one TCP connection per IKE SA, over which it sends all of the corresponding IKE and ESP messages. This helps ensure that any firewall or NAT mappings allocated for the TCP connection apply to all of the traffic associated with the IKE SA equally.

As with TCP Originators, a TCP Responder SHOULD send packets for an IKE SA and its Child SAs over only one TCP connection at any given time. It SHOULD choose the TCP connection on which it last received a valid and decryptable IKE or ESP message. In order to be considered valid for choosing a TCP connection, an IKE message must be successfully decrypted and authenticated, not be a retransmission of a previously received message, and be within the expected window for IKE message IDs. Similarly, an ESP message must be successfully decrypted and authenticated, and must not be a replay of a previous message.

Since a connection may be broken and a new connection re-established by the TCP Originator without the TCP Responder being aware, a TCP Responder SHOULD accept receiving IKE and ESP messages on both old and new connections until the old connection is closed by the TCP Originator. A TCP Responder MAY close a TCP connection that it perceives as idle and extraneous (one previously used for IKE and ESP messages that has been replaced by a new connection).

6.2. Retransmissions

Section 2.1 of [RFC7296] describes how IKEv2 deals with the unreliability of the UDP protocol. In brief, the exchange Initiator is responsible for retransmissions and must retransmit request messages until a response message is received. If no reply is received after several retransmissions, the SA is deleted. The Responder never initiates retransmission, but it must send a response message again in case it receives a retransmitted request.

When IKEv2 uses a reliable transport protocol, like TCP, the retransmission rules are as follows:

* The exchange Initiator SHOULD NOT retransmit request message (*); if no response is received within some reasonable period of time, the IKE SA is deleted.

* If a new TCP connection for the IKE SA is established while the exchange Initiator is waiting for a response, the Initiator MUST retransmit its request over this connection and continue to wait for a response.

* The exchange Responder does not change its behavior, but acts as described in Section 2.1 of [RFC7296].

(*) This is an optimization; implementations may continue to use the retransmission logic from Section 2.1 of [RFC7296] for simplicity.

6.3. Cookies and Puzzles

IKEv2 provides a DoS attack protection mechanism through Cookies, which is described in Section 2.6 of [RFC7296]. [RFC8019] extends this mechanism for protection against DDoS attacks by means of Client Puzzles. Both mechanisms allow the Responder to avoid keeping state until the Initiator proves its IP address is legitimate (and after solving a puzzle if required).

The connection-oriented nature of TCP transport brings additional considerations for using these mechanisms. In general, Cookies provide less value in the case of TCP encapsulation; by the time a

Responder receives the IKE_SA_INIT request, the TCP session has already been established and the Initiator's IP address has been verified. Moreover, a TCP/IP stack creates state once a TCP SYN packet is received (unless SYN Cookies described in [RFC4987] are employed), which contradicts the statelessness of IKEv2 Cookies. In particular, with TCP, an attacker is able to mount a SYN flooding DoS attack that an IKEv2 Responder cannot prevent using stateless IKEv2 Cookies. Thus, when using TCP encapsulation, it makes little sense to send Cookie requests without Puzzles unless the Responder is concerned with a possibility of TCP sequence number attacks (see [RFC6528] and [RFC9293] for details). Puzzles, on the other hand, still remain useful (and their use requires using Cookies).

The following considerations are applicable for using Cookie and Puzzle mechanisms in the case of TCP encapsulation:

* The exchange Responder SHOULD NOT send an IKEv2 Cookie request without an accompanied Puzzle; implementations might choose to have exceptions to this for cases like mitigating TCP sequence number attacks.

* If the Responder chooses to send a Cookie request (possibly along with Puzzle request), then the TCP connection that the IKE_SA_INIT request message was received over SHOULD be closed after the Responder sends its reply and no repeated requests are received within some short period of time to keep the Responder stateless (see Section 6.3.1). Note that the Responder MUST NOT include the Initiator's TCP port into the Cookie calculation (*) since the Cookie can be returned over a new TCP connection with a different port.

* The exchange Initiator acts as described in Section 2.6 of [RFC7296] and Section 7 of [RFC8019], i.e., using TCP encapsulation doesn't change the Initiator's behavior.

(*) Examples of Cookie calculation methods are given in Section 2.6 of [RFC7296] and in Section 7.1.1.3 of [RFC8019], and they don't include transport protocol ports. However, these examples are given for illustrative purposes since the Cookie generation algorithm is a local matter and some implementations might include port numbers that won't work with TCP encapsulation. Note also that these examples include the Initiator's IP address in Cookie calculation. In general, this address may change between two initial requests (with and without Cookies). This may happen due to NATs, which have more freedom to change source IP addresses for new TCP connections than for UDP. In such cases, cookie verification might fail.

6.3.1. Statelessness versus Delay of SA Establishment

There is a trade-off in choosing the period of time after which the TCP connection is closed. If it is too short, then the proper Initiator that repeats its request would need to re-establish the TCP connection, introducing additional delay. On the other hand, if it is too long, then the Responder's resources would be wasted in case the Initiator never comes back. This document doesn't mandate the duration of time because it doesn't affect interoperability, but it is believed that 5-10 seconds is a good compromise. Also, note that if the Responder requests that the Initiator solve a puzzle, then the Responder can estimate how long it would take the Initiator to find a solution and adjust the time interval accordingly.

6.4. Error Handling in IKE_SA_INIT

Section 2.21.1 of [RFC7296] describes how error notifications are handled in the IKE_SA_INIT exchange. In particular, it is advised that the Initiator should not act immediately after receiving an

error notification; instead, it should wait some time for a valid response since the IKE_SA_INIT messages are completely unauthenticated. This advice does not apply equally in the case of TCP encapsulation. If the Initiator receives a response message over TCP, then either this message is genuine and was sent by the peer or the TCP session was hijacked and the message is forged. In the latter case, no genuine messages from the Responder will be received.

Thus, in the case of TCP encapsulation, an Initiator SHOULD NOT wait for additional messages in case it receives an error notification from the Responder in the IKE_SA_INIT exchange.

In the IKE_SA_INIT exchange, if the Responder returns an error notification that implies a recovery action from the Initiator (such as INVALID_KE_PAYLOAD or INVALID_MAJOR_VERSION, see Section 2.21.1 of [RFC7296]), then the Responder SHOULD NOT close the TCP connection immediately in anticipation of the fact that the Initiator will repeat the request with corrected parameters. See also Section 6.3.

6.5. NAT-Detection Payloads

When negotiating over UDP, IKE_SA_INIT packets include NAT_DETECTION_SOURCE_IP and NAT_DETECTION_DESTINATION_IP payloads to determine if UDP encapsulation of IPsec packets should be used. These payloads contain SHA-1 digests of the SPIs, IP addresses, and ports as defined in [RFC7296]. IKE_SA_INIT packets sent on a TCP connection SHOULD include these payloads with the same content as when sending over UDP and SHOULD use the applicable TCP ports when creating and checking the SHA-1 digests.

If a NAT is detected due to the SHA-1 digests not matching the expected values, no change should be made for encapsulation of subsequent IKE or ESP packets since TCP encapsulation inherently supports NAT traversal. However, for the transport mode IPsec SAs, implementations need to handle TCP and UDP packet checksum fixup during decapsulation, as defined for UDP encapsulation in [RFC3948].

Implementations MAY use the information that a NAT is present to influence keepalive timer values.

6.6. NAT-Keepalive Packets

Encapsulating IKE and IPsec inside of a TCP connection can impact the strategy that implementations use to maintain middlebox port mappings.

In general, TCP port mappings are maintained by NATs longer than UDP port mappings, so IPsec ESP NAT-keepalive packets [RFC3948] SHOULD NOT be sent when using TCP encapsulation. Any implementation using TCP encapsulation MUST silently drop incoming NAT-keepalive packets and not treat them as errors. NAT-keepalive packets over a TCP-encapsulated IPsec connection will be sent as a 1-octet-long payload with the value 0xFF, preceded by the 2-octet Length specifying a length of 3 (since it includes the length of the Length field).

6.7. Dead Peer Detection and Transport Keepalives

Peer liveness should be checked using IKE informational packets [RFC7296].

Note that, depending on the configuration of TCP and TLS on the connection, TCP keep-alives [RFC1122] and TLS keep-alives [RFC6520] MAY be used. These MUST NOT be used as indications of IKE peer liveness, for which purpose the standard IKEv2 mechanism of exchanging (usually empty) INFORMATIONAL messages is used (see Section 1.4 of [RFC7296]).

6.8. Implications of TCP Encapsulation on IPsec SA Processing

Using TCP encapsulation affects some aspects of IPsec SA processing.

1. Section 8.1 of [RFC4301] requires all tunnel mode IPsec SAs to be able to copy the Don't Fragment (DF) bit from inner IPv4 header to the outer (tunnel) one. With TCP encapsulation, this is generally not possible because the TCP/IP stack manages the DF bit in the outer IPv4 header, and usually the stack ensures that the DF bit is set for TCP packets to avoid IP fragmentation. Note, that this behavior is compliant with generic tunneling considerations since the outer TCP header acts as a link-layer protocol and its fragmentation and reassembly have no correlation with the inner payload.

2. The other feature that is less applicable with TCP encapsulation is an ability to split traffic of different QoS classes into different IPsec SAs, created by a single IKE SA. In this case, the Differentiated Services Code Point (DSCP) field is usually copied from the inner IP header to the outer (tunnel) one, ensuring that IPsec traffic of each SA receives the corresponding level of service. With TCP encapsulation, all IPsec SAs created by a single IKE SA will share a single TCP connection; thus, they will receive the same level of service (see Section 9.3). If this functionality is needed, implementations should create several IKE SAs each over separate TCP connections and assign a corresponding DSCP value to each of them.

TCP encapsulation of IPsec packets may have implications on performance of the encapsulated traffic. Performance considerations are discussed in Section 9.

7. Interaction with IKEv2 Extensions

7.1. MOBIKE Protocol

The MOBIKE protocol, which allows SAs to migrate between IP addresses, is defined in [RFC4555]; [RFC4621] further clarifies the details of the protocol. When an IKE session that has negotiated MOBIKE is transitioning between networks, the Initiator of the transition may switch between using TCP encapsulation, UDP encapsulation, or no encapsulation. Implementations that implement both MOBIKE and TCP encapsulation within the same connection configuration MUST support dynamically enabling and disabling TCP encapsulation as interfaces change.

When a MOBIKE-enabled Initiator changes networks, the INFORMATIONAL exchange with the UPDATE_SA_ADDRESSES notification SHOULD be initiated first over UDP before attempting over TCP. If there is a response to the request sent over UDP, then the ESP packets should be sent directly over IP or over UDP port 4500 (depending on if a NAT was detected), regardless of if a connection on a previous network was using TCP encapsulation. If no response is received within a certain period of time after several retransmissions, the Initiator ought to change its transport for this exchange from UDP to TCP and resend the request message. A new INFORMATIONAL exchange MUST NOT be started in this situation. If the Responder only responds to the request sent over TCP, then the ESP packets should be sent over the TCP connection, regardless of if a connection on a previous network did not use TCP encapsulation.

The value of the timeout and the specific number of retransmissions before switching to TCP can vary depending on the Initiator's configuration. Implementations ought to provide reasonable defaults to ensure that UDP attempts have a chance to succeed, but can shorten

the timeout based on historical data or metrics.

If the TCP transport was used for the previous network connection, the old TCP connection SHOULD be closed by the Initiator once MOBIKE finishes migration to a new connection (either TCP or UDP).

Since switching from UDP to TCP can happen during a single INFORMATIONAL message exchange, the content of the NAT_DETECTION_*_IP notifications will in most cases be incorrect (since UDP and TCP ports will most likely be different), and the peer may incorrectly detect the presence of a NAT. Section 3.5 of [RFC4555] states that a new INFORMATIONAL exchange with the UPDATE_SA_ADDRESSES notify is initiated in case the address (or transport) is changed while waiting for a response.

Section 3.5 of [RFC4555] also states that once an IKE SA is switched to a new IP address, all outstanding requests in this SA are immediately retransmitted using this address. See also Section 6.2.

The MOBIKE protocol defines the NO_NATS_ALLOWED notification that can be used to detect the presence of NAT between peer and to refuse to communicate in this situation. In the case of TCP, the NO_NATS_ALLOWED notification SHOULD be ignored because TCP generally has no problems with NAT boxes.

Section 3.7 of [RFC4555] describes an additional optional step in the process of changing IP addresses called "Return Routability Check". It is performed by Responders in order to be sure that the new Initiator’s address is, in fact, routable. In the case of TCP encapsulation, this check has little value since a TCP handshake proves the routability of the TCP Originator’s address; thus, the Return Routability Check SHOULD NOT be performed.

7.2. IKE Redirect

A redirect mechanism for IKEv2 is defined in [RFC5685]. This mechanism allows security gateways to redirect clients to another gateway either during IKE SA establishment or after session setup. If a client is connecting to a security gateway using TCP and then is redirected to another security gateway, the client needs to reset its transport selection. In other words, with the next security gateway, the client MUST first try UDP and then fall back to TCP while establishing a new IKE SA, regardless of the transport of the SA the redirect notification was received over (unless the client’s configuration instructs it to instantly use TCP for the gateway it is redirected to).

7.3. IKEv2 Session Resumption

Session resumption for IKEv2 is defined in [RFC5723]. Once an IKE SA is established, the server creates a resumption ticket where information about this SA is stored and transfers this ticket to the client. The ticket may be later used to resume the IKE SA after it is deleted. In the event of resumption, the client presents the ticket in a new exchange, called IKE_SESSION_RESUME. Some parameters in the new SA are retrieved from the ticket and others are renegotiated (more details are given in Section 5 of [RFC5723]).

Since network conditions may change while the client is inactive, the fact that TCP encapsulation was used in an old SA SHOULD NOT affect which transport is used during session resumption. In other words, the transport should be selected as if the IKE SA is being created from scratch.

7.4. IKEv2 Protocol Support for High Availability

[RFC6311] defines a support for High Availability in IKEv2. In case of cluster failover, a new active node must immediately initiate a special INFORMATION exchange containing the IKEV2_MESSAGE_ID_SYNC notification, which instructs the client to skip some number of Message IDs that might not be synchronized yet between nodes at the time of failover.

Synchronizing states when using TCP encapsulation is much harder than when using UDP; doing so requires access to TCP/IP stack internals, which is not always available from an IKE/IPsec implementation. If a cluster implementation doesn't synchronize TCP states between nodes, then after failover event the new active node will not have any TCP connection with the client, so the node cannot initiate the INFORMATIONAL exchange as required by [RFC6311]. Since the cluster usually acts as TCP Responder, the new active node cannot re-establish TCP connection because only the TCP Originator can do it. For the client, the cluster failover event may remain undetected for long time if it has no IKE or ESP traffic to send. Once the client sends an ESP or IKEv2 packet, the cluster node will reply with TCP RST and the client (as TCP Originator) will reestablish the TCP connection so that the node will be able to initiate the INFORMATIONAL exchange informing the client about the cluster failover.

This document makes the following recommendation: if support for High Availability in IKEv2 is negotiated and TCP transport is used, a client that is a TCP Originator SHOULD periodically send IKEv2 messages (e.g., by initiating liveness check exchange) whenever there is no IKEv2 or ESP traffic. This differs from the recommendations given in Section 2.4 of [RFC7296] in the following: the liveness check should be periodically performed even if the client has nothing to send over ESP. The frequency of sending such messages should be high enough to allow quick detection and restoration of broken TCP connections.

7.5. IKEv2 Fragmentation

IKE message fragmentation [RFC7383] is not required when using TCP encapsulation since a TCP stream already handles the fragmentation of its contents across packets. Since fragmentation is redundant in this case, implementations might choose to not negotiate IKE fragmentation. Even if fragmentation is negotiated, an implementation SHOULD NOT send fragments when going over a TCP connection, although it MUST support receiving fragments.

If an implementation supports both MOBIKE and IKE fragmentation, it SHOULD negotiate IKE fragmentation over a TCP-encapsulated session in case the session switches to UDP encapsulation on another network.

8. Middlebox Considerations

Many security networking devices, such as firewalls or intrusion prevention systems, network optimization/acceleration devices, and NAT devices, keep the state of sessions that traverse through them.

These devices commonly track the transport-layer and/or application-layer data to drop traffic that is anomalous or malicious in nature. While many of these devices will be more likely to pass TCP-encapsulated traffic as opposed to UDP-encapsulated traffic, some may still block or interfere with TCP-encapsulated IKE and IPsec traffic.

A network device that monitors the transport layer will track the state of TCP sessions, such as TCP sequence numbers. If the IKE implementation has its own minimal implementation of TCP, it SHOULD still use common TCP behaviors to avoid being dropped by middleboxes.

Operators that intentionally block IPsec because of security implications might want to also block TCP port 4500 or use other methods to reject TCP encapsulated IPsec traffic (e.g., filter out TCP connections that begin with the "IKETCP" stream prefix).

9. Performance Considerations

Several aspects of TCP encapsulation for IKE and IPsec packets may negatively impact the performance of connections within a tunnel-mode IPsec SA. Implementations should be aware of these performance impacts and take these into consideration when determining when to use TCP encapsulation. Implementations MUST favor using direct ESP or UDP encapsulation over TCP encapsulation whenever possible.

9.1. TCP-in-TCP

If the outer connection between IKE peers is over TCP, inner TCP connections may suffer negative effects from using TCP within TCP. Running TCP within TCP is discouraged since the TCP algorithms generally assume that they are running over an unreliable datagram layer.

If the outer (tunnel) TCP connection experiences packet loss, this loss will be hidden from any inner TCP connections since the outer connection will retransmit to account for the losses. Since the outer TCP connection will deliver the inner messages in order, any messages after a lost packet may have to wait until the loss is recovered. This means that loss on the outer connection will be interpreted only as delay by inner connections. The burstiness of inner traffic can increase since a large number of inner packets may be delivered across the tunnel at once. The inner TCP connection may interpret a long period of delay as a transmission problem, triggering a retransmission timeout, which will cause spurious retransmissions. The sending rate of the inner connection may be unnecessarily reduced if the retransmissions are not detected as spurious in time.

The inner TCP connection’s round-trip-time estimation will be affected by the burstiness of the outer TCP connection if there are long delays when packets are retransmitted by the outer TCP connection. This will make the congestion control loop of the inner TCP traffic less reactive, potentially permanently leading to a lower sending rate than the outer TCP would allow for.

TCP-in-TCP can also lead to "TCP meltdown", where stacked instances of TCP can result in significant impacts to performance [TCP-MELTDOWN]. This can occur when losses in the lower TCP (closer to the link) increase delays seen by the higher TCP (closer to the application) that create timeouts, which, in turn, cause retransmissions that can then cause losses in the lower TCP by overrunning its buffer. The very mechanism intended to avoid loss (retransmission) interacts between the two layers to increase loss. To limit this effect, the timeouts of the two TCP layers need to be carefully managed, e.g., such that the higher layer has a much longer timeout than the lower layer.

Note that any negative effects will be shared among all flows going through the outer TCP connection. This is of particular concern for any latency-sensitive or real-time applications using the tunnel. If such traffic is using a TCP-encapsulated IPsec connection, it is recommended that the number of inner connections sharing the tunnel be limited as much as possible.

9.2. Added Reliability for Unreliable Protocols

Since ESP is an unreliable protocol, transmitting ESP packets over a

TCP connection will change the fundamental behavior of the packets. Some application-level protocols that prefer packet loss to delay (such as Voice over IP or other real-time protocols) may be negatively impacted if their packets are retransmitted by the TCP connection due to packet loss.

9.3. Quality-of-Service Markings

Quality-of-Service (QoS) markings, such as the Differentiated Services Code Point (DSCP) and Traffic Class, should be used with care on TCP connections used for encapsulation. Individual packets SHOULD NOT use different markings than the rest of the connection since packets with different priorities may be routed differently and cause unnecessary delays in the connection.

9.4. Maximum Segment Size

A TCP connection used for IKE encapsulation SHOULD negotiate its MSS in order to avoid unnecessary fragmentation of packets.

9.5. Tunneling ECN in TCP

Since there is not a one-to-one relationship between outer IP packets and inner ESP/IP messages when using TCP encapsulation, the markings for Explicit Congestion Notification (ECN) [RFC3168] cannot easily be mapped. However, any ECN Congestion Experienced (CE) marking on inner headers should be preserved through the tunnel.

Implementations SHOULD follow the ECN compatibility mode for tunnel ingress as described in [RFC6040]. In compatibility mode, the outer tunnel TCP connection marks its packet headers as not ECN-capable.

Upon egress, if the arriving outer header is marked with CE, the implementation will drop the inner packet since there is not a distinct inner packet header onto which to translate the ECN markings.

10. Security Considerations

IKE Responders that support TCP encapsulation may become vulnerable to new Denial-of-Service (DoS) attacks that are specific to TCP, such as SYN-flooding attacks. TCP Responders should be aware of this additional attack surface.

TCP connections are also susceptible to RST and other spoofing attacks [RFC4953]. This specification makes IPsec tolerant of sudden TCP connection drops, but if an attacker is able to tear down TCP connections, IPsec connection’s performance can suffer, effectively making this a DoS attack.

TCP data injection attacks have no effect on application data since IPsec provides data integrity. However, they can have some effect, mostly by creating DoS attacks:

* If an attacker alters the content of the Length field that separates packets, then the Receiver will incorrectly identify the boundaries of the following packets and will drop all of them or even tear down the TCP connection if the content of the Length field happens to be 0 or 1 (see Section 3).

* If the content of an IKE message is altered, then it will be dropped by the receiver; if the dropped message is the IKE request message, then the Initiator will tear down the IKE SA after some timeout since, in most cases, the request message will not be retransmitted (as advised in Section 6.2); thus, the response will never be received.

* If an attacker alters the non-ESP marker, then IKE packets will be dispatched to ESP (and sometimes visa versa) and those packets will be dropped.

* If an attacker modifies TCP-Encapsulated stream prefix or unencrypted IKE messages before IKE SA is established, then in most cases this will result in failure to establish IKE SA, often with false "authentication failed" diagnostics.

[RFC5961] discusses how TCP injection attacks can be mitigated.

Note that data injection attacks are also possible on IP level (e.g., when IP fragmentation is used), resulting in DoS attacks even if TCP encapsulation is not used. On the other hand, TCP injection attacks are easier to mount than the IP fragmentation injection attacks because TCP keeps a long receive window open that’s a sitting target for such attacks.

If an attacker successfully mounts an injection attack on a TCP connection used for encapsulating IPsec traffic and modifies a Length field, the receiver might not be able to correctly identify the boundaries of the following packets in the stream since it will try to parse arbitrary data as an ESP or IKE header. After such a parsing failure, all following packets will be dropped. Communication will eventually recover, but this might take several minutes and can result in IKE SA deletion and re-creation.

To speed up the recovery from such attacks, implementations are advised to follow recommendations in Section 6.1 and close the TCP connection if incoming packets contain SPIs that don’t match any known SAs. Once the TCP connection is closed, it will be re-created by the TCP Originator as described in Section 6.1.

To avoid performance degradation caused by closing and re-creating TCP connections, implementations MAY alternatively try to resync after they receive unknown SPIs by searching the TCP stream for a 64-bit binary vector consisting of a known SPI in the first 32 bits and a valid Sequence Number for this SPI in the second 32 bits. Then, they can validate the Integrity Check Value (ICV) of this packet candidate by taking the preceding 16 bits as the Length field. They can also search for 4 bytes of zero (non-ESP marker) followed by 128 bits of IKE SPIs of the IKE SA(s) associated with this TCP connection and then validate the ICV of this IKE message candidate by taking the 16 bits preceding the non-ESP marker as the Length field. Implementations SHOULD limit the attempts to resync, because if the injection attack is ongoing, then there is a high probability that the resync process will not succeed or will quickly come under attack again.

An attacker capable of blocking UDP traffic can force peers to use TCP encapsulation, thus, degrading the performance and making the connection more vulnerable to DoS attacks. Note that an attacker that is able to modify packets on the wire or to block them can prevent peers from communicating regardless of the transport being used.

TCP Responders should be careful to ensure that the stream prefix "IKETCP" uniquely identifies incoming streams as streams that use the TCP encapsulation protocol.

Attackers may be able to disrupt the TCP connection by sending spurious TCP Reset packets. Therefore, implementations SHOULD make sure that IKE session state persists even if the underlying TCP connection is torn down.

If MOBIKE is being used, all of the security considerations outlined for MOBIKE apply [RFC4555].

Similar to MOBIKE, TCP encapsulation requires a TCP Responder to handle changes to source address and port due to network or connection disruption. The successful delivery of valid new IKE or ESP messages over a new TCP connection is used by the TCP Responder to determine where to send subsequent responses. If an attacker is able to send packets on a new TCP connection that pass the validation checks of the TCP Responder, it can influence which path future packets will take. For this reason, the validation of messages on the TCP Responder must include decryption, authentication, and replay checks.

11. IANA Considerations

TCP port 4500 is already allocated to IPsec for NAT traversal in the "Service Name and Transport Protocol Port Number Registry". This port SHOULD be used for TCP-encapsulated IKE and ESP as described in this document.

This document updates the reference for TCP port 4500 from RFC 8229 to itself:

Service Name: ipsec-nat-t
Port Number / Transport Protocol: 4500/tcp
Description: IPsec NAT-Traversal
Reference: RFC 9329

12. References

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Appendix A. Using TCP Encapsulation with TLS

This section provides recommendations on how to use TLS in addition to TCP encapsulation.

When using TCP encapsulation, implementations may choose to use TLS 1.2 [RFC5246] or TLS 1.3 [RFC8446] on the TCP connection to be able to traverse middleboxes, which may otherwise block the traffic.

If a web proxy is applied to the ports used for the TCP connection and TLS is being used, the TCP Originator can send an HTTP CONNECT message to establish an SA through the proxy [RFC2817].

The use of TLS should be configurable on the peers and may be used as the default when using TCP encapsulation or may be used as a fallback when basic TCP encapsulation fails. The TCP Responder may expect to read encapsulated IKE and ESP packets directly from the TCP connection, or it may expect to read them from a stream of TLS data packets. The TCP Originator should be preconfigured regarding whether or not to use TLS when communicating with a given port on the TCP Responder.

When new TCP connections are re-established due to a broken connection, TLS must be renegotiated. TLS session resumption is

recommended to improve efficiency in this case.

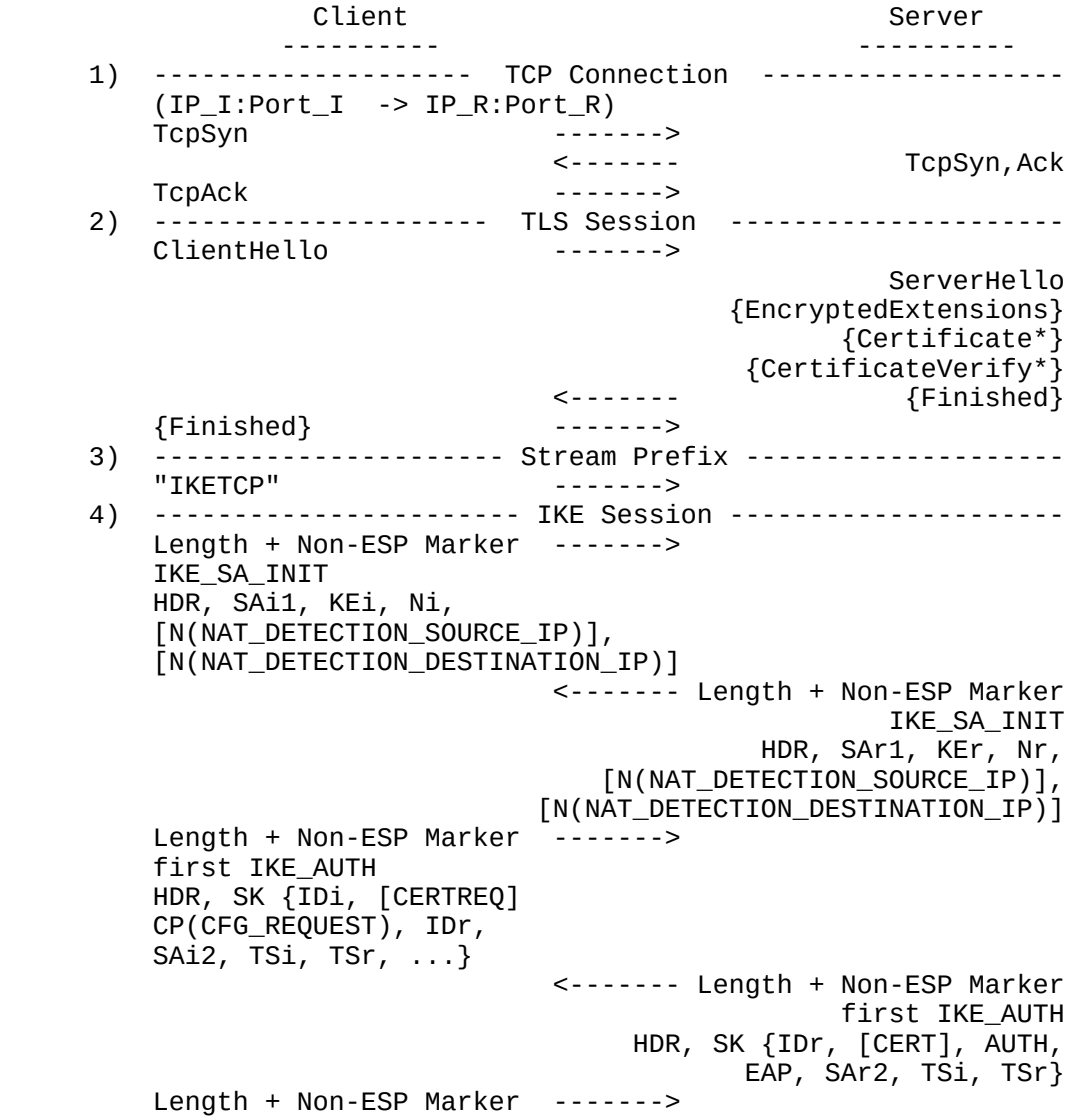
The security of the IKE session is entirely derived from the IKE negotiation and key establishment and not from the TLS session (which, in this context, is only used for encapsulation purposes); therefore, when TLS is used on the TCP connection, both the TCP Originator and the TCP Responder SHOULD allow the NULL cipher to be selected for performance reasons. Note that TLS 1.3 only supports AEAD algorithms and at the time of writing this document there was no recommended cipher suite for TLS 1.3 with the NULL cipher. It is RECOMMENDED to follow [RFC9325] when selecting parameters for TLS.

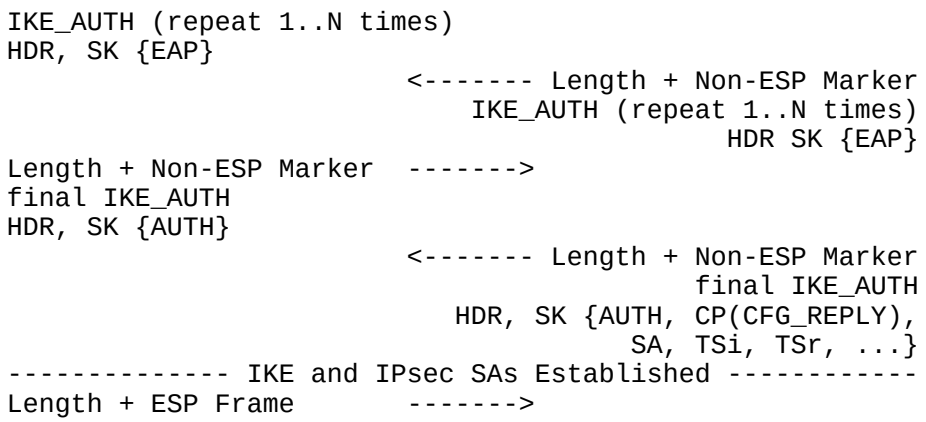
Implementations should be aware that the use of TLS introduces another layer of overhead requiring more bytes to transmit a given IKE and IPsec packet. For this reason, direct ESP, UDP encapsulation, or TCP encapsulation without TLS should be preferred in situations in which TLS is not required in order to traverse middleboxes.

Appendix B. Example Exchanges of TCP Encapsulation with TLS 1.3

This appendix contains examples of data flows in cases where TCP encapsulation of IKE and IPsec packets is used with TLS 1.3. The examples below are provided for illustrative purpose only; readers should refer to the main body of the document for details.

B.1. Establishing an IKE Session





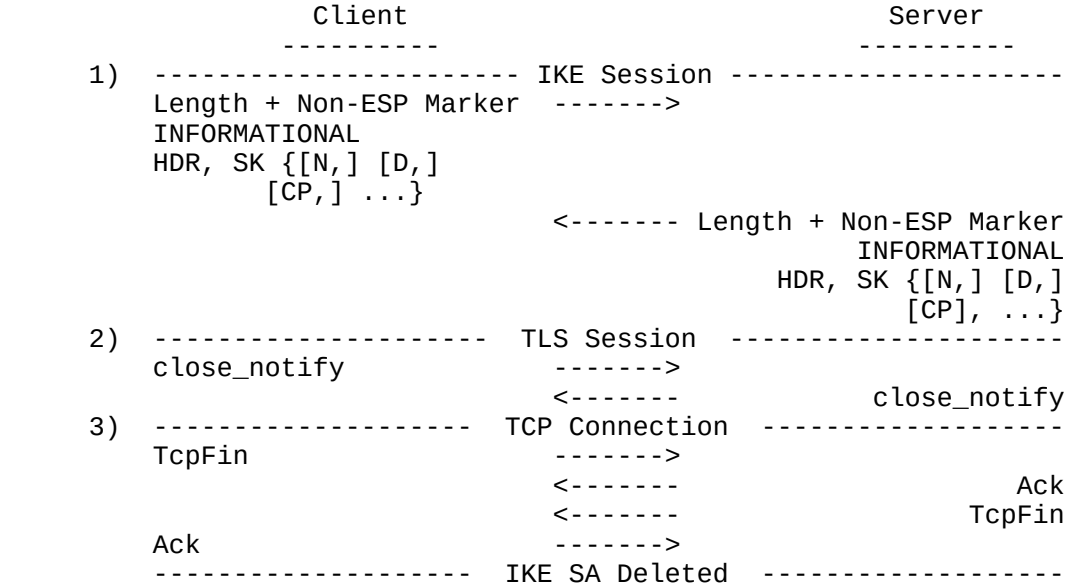
1. The client establishes a TCP connection with the server on port 4500 or on an alternate preconfigured port that the server is listening on.

2. If configured to use TLS, the client initiates a TLS handshake. During the TLS handshake, the server SHOULD NOT request the client's certificate since authentication is handled as part of IKE negotiation.

3. The client sends the stream prefix for TCP-encapsulated IKE (Section 4) traffic to signal the beginning of IKE negotiation.

4. The client and server establish an IKE connection. This example shows EAP-based authentication, although any authentication type may be used.

B.2. Deleting an IKE Session



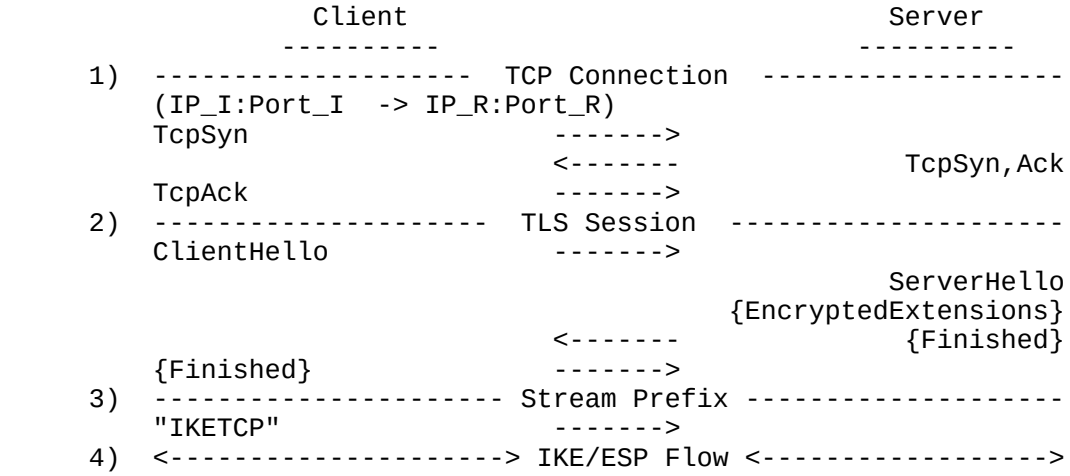
1. The client and server exchange informational messages to notify IKE SA deletion.

2. The client and server negotiate TLS session deletion using TLS CLOSE_NOTIFY.

3. The TCP connection is torn down.

The deletion of the IKE SA should lead to the disposal of the underlying TLS and TCP state.

B.3. Re-establishing an IKE Session



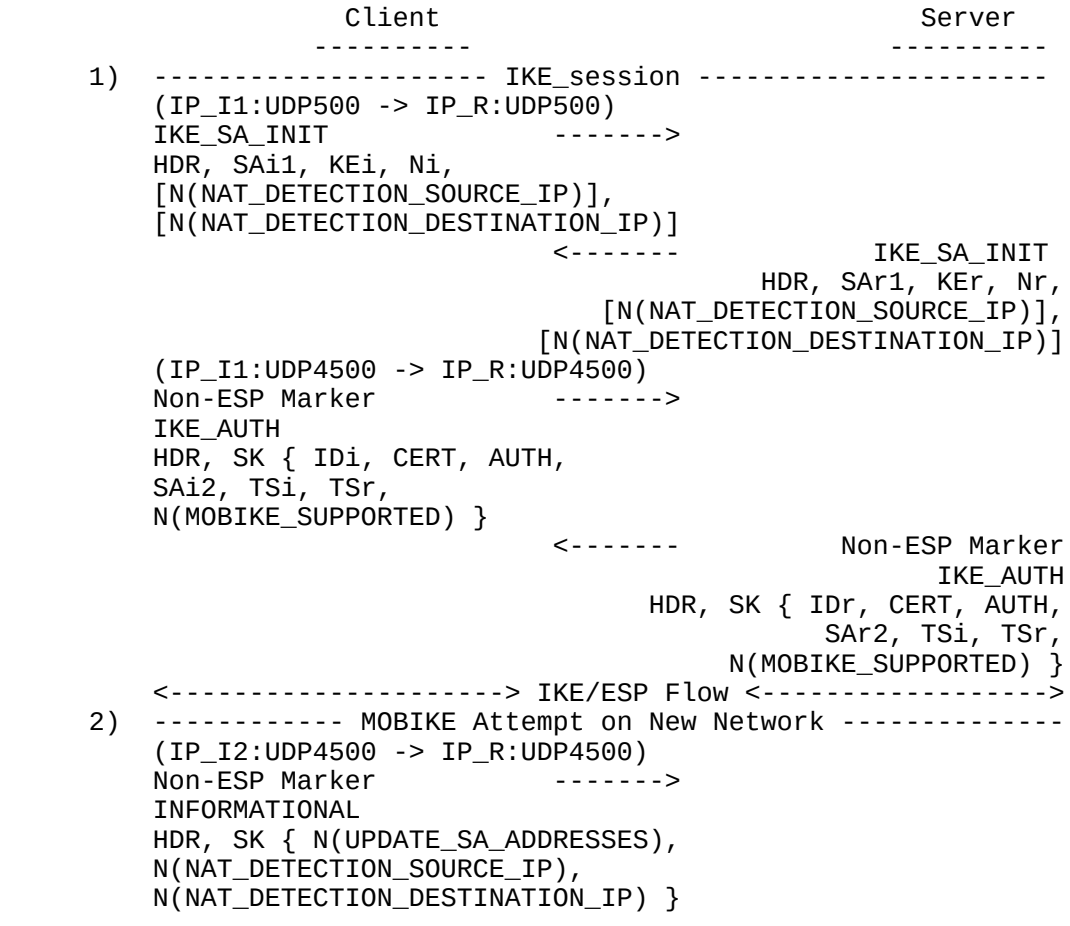
1. If a previous TCP connection was broken (for example, due to a TCP Reset), the client is responsible for re-initiating the TCP connection. The TCP Originator's address and port (IP_I and Port_I) may be different from the previous connection's address and port.

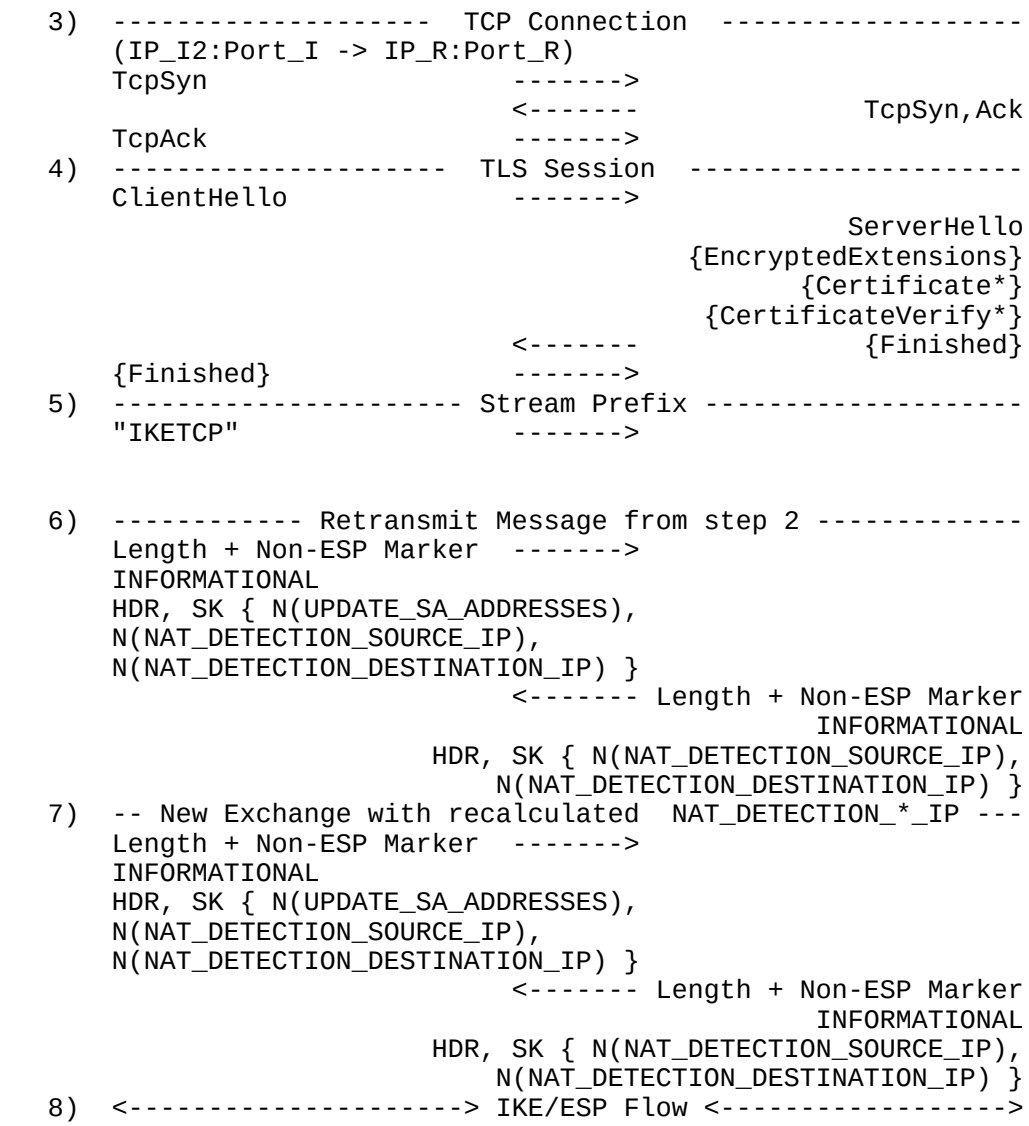
2. The client SHOULD attempt TLS session resumption if it has previously established a session with the server.

3. After TCP and TLS are complete, the client sends the stream prefix for TCP-encapsulated IKE traffic (Section 4).

4. The IKE and ESP packet flow can resume. If MOBIKE is being used, the Initiator SHOULD send an UPDATE_SA_ADDRESSES message.

B.4. Using MOBIKE between UDP and TCP Encapsulation





1. During the IKE_AUTH exchange, the client and server exchange MOBIKE_SUPPORTED notify payloads to indicate support for MOBIKE.

2. The client changes its point of attachment to the network and receives a new IP address. The client attempts to re-establish the IKE session using the UPDATE_SA_ADDRESSES notify payload, but the server does not respond because the network blocks UDP traffic.

3. The client brings up a TCP connection to the server in order to use TCP encapsulation.

4. The client initiates a TLS handshake with the server.

5. The client sends the stream prefix for TCP-encapsulated IKE traffic (Section 4).

6. The client sends the UPDATE_SA_ADDRESSES notify payload in the INFORMATIONAL exchange on the TCP-encapsulated connection. Note that this IKE message is the same as the one sent over UDP in step 2; it should have the same message ID and contents.

7. Once the client receives a response on the TCP-encapsulated connection, it immediately starts a new INFORMATIONAL exchange with an UPDATE_SA_ADDRESSES notify payload and recalculated NAT_DETECTION_*_IP notify payloads in order to get correct information about the presence of NATs.

8. The IKE and ESP packet flow can resume.

Acknowledgments

Thanks to the authors of RFC 8229 (Tommy Pauly, Samy Touati, and Ravi Mantha). Since this document clarifies and obsoletes RFC 8229, most of its text was borrowed from the original document.

The following people provided valuable feedback and advice while preparing RFC 8229: Stuart Cheshire, Delziel Fernandes, Yoav Nir, Christoph Paasch, Yaron Sheffer, David Schinazi, Graham Bartlett, Byju Pularikkal, March Wu, Kingwel Xie, Valery Smyslov, Jun Hu, and Tero Kivinen. Special thanks to Eric Kinnear for his implementation work.

The authors would like to thank Tero Kivinen, Paul Wouters, Joseph Touch, and Christian Huitema for their valuable comments while preparing this document.

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