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T. Pauly
Apple Inc.
C. Perkins
University of Glasgow
K. Rose
Akamai Technologies, Inc.
C. Wood
Apple Inc.
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A Survey of Transport Security Protocols
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Abstract

This document provides a survey of commonly used or notable network security protocols, with a focus on how they interact and integrate with applications and transport protocols. Its goal is to supplement efforts to define and catalog transport services [RFC8095] by describing the interfaces required to add security protocols. It examines Transport Layer Security (TLS), Datagram Transport Layer Security (DTLS), Quick UDP Internet Connections with TLS (QUIC + TLS), MinimalT, CurveCP, tcpcrypt, Internet Key Exchange with Encapsulating Security Protocol (IKEv2 + ESP), SRTP (with DTLS), and WireGuard. This survey is not limited to protocols developed within the scope or context of the IETF, and those included represent a superset of features a TAPS system may need to support.

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Table of Contents

- 1. Introduction 3
- 2. Terminology 4
- 3. Security Features 5
- 4. Transport Security Protocol Descriptions 7
 - 4.1. TLS 7
 - 4.1.1. Protocol Description 7
 - 4.1.2. Security Features 8
 - 4.1.3. Protocol Dependencies 9
 - 4.2. DTLS 9
 - 4.2.1. Protocol Description 9
 - 4.2.2. Security Features 10
 - 4.2.3. Protocol Dependencies 10
 - 4.3. (IETF) QUIC with TLS 10
 - 4.3.1. Protocol Description 11
 - 4.3.2. Security Features 11
 - 4.3.3. Protocol Dependencies 11
 - 4.3.4. Variant: Google QUIC 11
 - 4.4. IKEv2 with ESP 12
 - 4.4.1. Protocol descriptions 12
 - 4.4.2. Security Features 13
 - 4.4.3. Protocol Dependencies 14
 - 4.5. Secure RTP (with DTLS) 14
 - 4.5.1. Protocol description 14
 - 4.5.2. Security Features 15
 - 4.5.3. Protocol Dependencies 16
 - 4.5.4. Variant: ZRTP for Media Path Key Agreement 16
 - 4.6. tcpcrypt 16
 - 4.6.1. Protocol Description 16
 - 4.6.2. Security Features 17
 - 4.6.3. Protocol Dependencies 18
 - 4.7. WireGuard 18

4.7.1.	Protocol description	18
4.7.2.	Security Features	19
4.7.3.	Protocol Dependencies	19
4.8.	MinimalT	19
4.8.1.	Protocol Description	19
4.8.2.	Protocol Features	20
4.8.3.	Protocol Dependencies	20
4.9.	CurveCP	20
4.9.1.	Protocol Description	20
4.9.2.	Protocol Features	22
4.9.3.	Protocol Dependencies	22
5.	Security Features and Transport Dependencies	22
5.1.	Mandatory Features	22
5.2.	Optional Features	23
5.3.	Optional Feature Availability	24
6.	Transport Security Protocol Interfaces	26
6.1.	Pre-Connection Interfaces	26
6.2.	Connection Interfaces	27
6.3.	Post-Connection Interfaces	27
7.	IANA Considerations	28
8.	Security Considerations	28
9.	Privacy Considerations	28
10.	Acknowledgments	28
11.	Normative References	28
	Authors' Addresses	33

1. Introduction

This document provides a survey of commonly used or notable network security protocols, with a focus on how they interact and integrate with applications and transport protocols. Its goal is to supplement efforts to define and catalog transport services [RFC8095] by describing the interfaces required to add security protocols. It examines Transport Layer Security (TLS), Datagram Transport Layer Security (DTLS), Quick UDP Internet Connections with TLS (QUIC + TLS), MinimalT, CurveCP, tcpcrypt, Internet Key Exchange with Encapsulating Security Protocol (IKEv2 + ESP), SRTP (with DTLS), and WireGuard. For each protocol, this document provides a brief description, the security features it provides, and the dependencies it has on the underlying transport. This is followed by defining the set of transport security features shared by these protocols. Finally, we distill the application and transport interfaces provided by the transport security protocols.

Selected protocols represent a superset of functionality and features a TAPS system may need to support, both internally and externally - via an API - for applications [I-D.ietf-taps-arch]. Ubiquitous IETF protocols such as (D)TLS, as well as non-standard protocols such as

Google QUIC, are both included despite overlapping features. As such, this survey is not limited to protocols developed within the scope or context of the IETF. Outside of this candidate set, protocols that do not offer new features are omitted. For example, newer protocols such as WireGuard make unique design choices that have important implications on applications, such as how to best configure peer public keys and to delegate algorithm selection to the system. In contrast, protocols such as ALTS [ALTS] are omitted since they do not represent features deemed unique.

Also, authentication-only protocols such as TCP-AO [RFC5925] and IPsec AH [RFC4302] are excluded from this survey. TCP-AO adds authenticity protections to long-lived TCP connections, e.g., replay protection with per-packet Message Authentication Codes. (This protocol obsoletes TCP MD5 "signature" options specified in [RFC2385].) One prime use case of TCP-AO is for protecting BGP connections. Similarly, AH adds per-datagram authenticity and adds similar replay protection. Despite these improvements, neither protocol sees general use and both lack critical properties important for emergent transport security protocols: confidentiality, privacy protections, and agility. Thus, we omit these and related protocols from our survey.

2. Terminology

The following terms are used throughout this document to describe the roles and interactions of transport security protocols:

- o **Transport Feature:** a specific end-to-end feature that the transport layer provides to an application. Examples include confidentiality, reliable delivery, ordered delivery, message-versus-stream orientation, etc.
- o **Transport Service:** a set of Transport Features, without an association to any given framing protocol, which provides functionality to an application.
- o **Transport Protocol:** an implementation that provides one or more different transport services using a specific framing and header format on the wire. A Transport Protocol services an application.
- o **Application:** an entity that uses a transport protocol for end-to-end delivery of data across the network. This may also be an upper layer protocol or tunnel encapsulation.
- o **Security Feature:** a feature that a network security layer provides to applications. Examples include authentication, encryption, key generation, session resumption, and privacy. Features may be

Mandatory or Optional for an application's implementation. Security Features extend the set of Transport Features described in [RFC8095] and provided by Transport Services implementations.

- o Security Protocol: a defined network protocol that implements one or more security features. Security protocols may be used alongside transport protocols, and in combination with other security protocols when appropriate.
- o Handshake Protocol: a protocol that enables peers to validate each other and to securely establish shared cryptographic context.
- o Record: Framed protocol messages.
- o Record Protocol: a security protocol that allows data to be divided into manageable blocks and protected using shared cryptographic context.
- o Session: an ephemeral security association between applications.
- o Cryptographic context: a set of cryptographic parameters, including but not necessarily limited to keys for encryption, authentication, and session resumption, enabling authorized parties to a session to communicate securely.
- o Connection: the shared state of two or more endpoints that persists across messages that are transmitted between these endpoints. A connection is a transient participant of a session, and a session generally lasts between connection instances.
- o Peer: an endpoint application party to a session.
- o Client: the peer responsible for initiating a session.
- o Server: the peer responsible for responding to a session initiation.

3. Security Features

In this section, we enumerate Security Features exposed by protocols discussed in the remainder of this document. Protocol security (and privacy) properties that are unrelated to the API surface exposed by such protocols, such as client or server identity hiding, are not listed here as features.

- o Forward-secure key establishment: Cryptographic key establishment with forward secure properties.

- o Cryptographic algorithm negotiation: Negotiate support of protocol algorithms, including: encryption, hash, MAC (PRF), and digital signature algorithms.
- o Session caching and management: Manage session state cache used for subsequent connections aimed towards amortizing connection establishment costs.
- o Peer authentication (certificate, raw public key, pre-shared key, or EAP-based): Peer authentication using select or protocol-specific mechanisms.
- o Mutual authentication: Connection establishment wherein both endpoints are authenticated.
- o Application-layer authentication delegation: Out-of-band peer authentication performed by applications outside of the connection establishment.
- o Record (channel or datagram) confidentiality and integrity: Encryption and authentication of application plaintext bytes sent between peers over a channel or in individual datagrams.
- o Partial record confidentiality: Encryption of some portion of records.
- o Optional record integrity: Optional authentication of certain records.
- o Record replay prevention: Protocol detection and defense against record replays, e.g., due to in-network retransmissions.
- o Early data support (starting with TLS 1.3): Transmission of application data prior to connection (handshake) establishment.
- o Connection mobility: a property of a connection that allows it to be multihomed or resilient across network interface or address changes, e.g., NAT rebindings that occur without an endpoint's knowledge. Mobility allows cryptographic key material and other state information to be reused in the event of a connection change.
- o Application-layer feature negotiation: Securely negotiate application-specific functionality, including those necessary for connection handling and management, e.g., the TLS parent connection protocol type via ALPN [RFC7301] or desired application identity via SNI [RFC6066].

- o Configuration extensions: Add protocol features via extensions or configuration options. TLS extensions are a primary example of this feature.
- o Out-of-order record receipt: Processing of records received out-of-order.
- o Source validation (cookie or puzzle based): Peer source validation and DoS mitigation via explicit proof of origin (cookie) or work mechanisms (puzzles).
- o Length-hiding padding: Protocol-drive record padding aimed at hiding plaintext message length and mitigating amplification attack vectors.

4. Transport Security Protocol Descriptions

This section contains descriptions of security protocols currently used to protect data being sent over a network.

For each protocol, we describe its provided features and dependencies on other protocols.

4.1. TLS

TLS (Transport Layer Security) [RFC5246] is a common protocol used to establish a secure session between two endpoints. Communication over this session "prevents eavesdropping, tampering, and message forgery." TLS consists of a tightly coupled handshake and record protocol. The handshake protocol is used to authenticate peers, negotiate protocol options, such as cryptographic algorithms, and derive session-specific keying material. The record protocol is used to marshal (possibly encrypted) data from one peer to the other. This data may contain handshake messages or raw application data.

4.1.1. Protocol Description

TLS is the composition of a handshake and record protocol [I-D.ietf-tls-tls13]. The record protocol is designed to marshal an arbitrary, in-order stream of bytes from one endpoint to the other. It handles segmenting, compressing (when enabled), and encrypting data into discrete records. When configured to use an authenticated encryption with associated data (AEAD) algorithm, it also handles nonce generation and encoding for each record. The record protocol is hidden from the client behind a bytestream-oriented API.

The handshake protocol serves several purposes, including: peer authentication, protocol option (key exchange algorithm and

ciphersuite) negotiation, and key derivation. Peer authentication may be mutual; however, commonly, only the server is authenticated. X.509 certificates are commonly used in this authentication step, though other mechanisms, such as raw public keys [RFC7250], exist. The client is not authenticated unless explicitly requested by the server.

The handshake protocol is also extensible. It allows for a variety of extensions to be included by either the client or server. These extensions are used to specify client preferences, e.g., the application-layer protocol to be driven with the TLS connection [RFC7301], or signals to the server to aid operation, e.g., Server Name Indication (SNI) [RFC6066]. Various extensions also exist to tune the parameters of the record protocol, e.g., the maximum fragment length [RFC6066] and record size limit [I-D.ietf-tls-record-limit].

Alerts are used to convey errors and other atypical events to the endpoints. There are two classes of alerts: closure and error alerts. A closure alert is used to signal to the other peer that the sender wishes to terminate the connection. The sender typically follows a close alert with a TCP FIN segment to close the connection. Error alerts are used to indicate problems with the handshake or individual records. Most errors are fatal and are followed by connection termination. However, warning alerts may be handled at the discretion of the implementation.

Once a session is disconnected all session keying material must be destroyed, with the exception of secrets previously established expressly for purposes of session resumption. TLS supports stateful and stateless resumption. (Here, "state" refers to bookkeeping on a per-session basis by the server. It is assumed that the client must always store some state information in order to resume a session.)

4.1.2. Security Features

- o Forward-secure key establishment.
- o Cryptographic algorithm negotiation.
- o Stateful and stateless cross-connection session resumption.
- o Session caching and management.
- o Peer authentication (Certificate, raw public key, and pre-shared key).
- o Mandatory server authentication, optional client authentication.

- o Application authentication delegation.
- o Record (channel) confidentiality and integrity.
- o Record replay prevention.
- o Application-layer feature negotiation.
- o Configuration extensions.
- o Early data support (starting with TLS 1.3).
- o Optional record-layer padding (starting with TLS 1.3).

4.1.3. Protocol Dependencies

- o TCP for in-order, reliable transport.
- o (Optionally) A PKI trust store for certificate validation.

4.2. DTLS

DTLS (Datagram Transport Layer Security) [RFC6347] is based on TLS, but differs in that it is designed to run over UDP instead of TCP. Since UDP does not guarantee datagram ordering or reliability, DTLS modifies the protocol to make sure it can still provide the same security guarantees as TLS. DTLS was designed to be as close to TLS as possible, so this document will assume that all properties from TLS are carried over except where specified.

4.2.1. Protocol Description

DTLS is modified from TLS to operate with the possibility of packet loss, reordering, and duplication that may occur when operating over UDP. To enable out-of-order delivery of application data, the DTLS record protocol itself has no inter-record dependencies. However, as the handshake requires reliability, each handshake message is assigned an explicit sequence number to enable retransmissions of lost packets and in-order processing by the receiver. Handshake message loss is remedied by sender retransmission after a configurable period in which the expected response has not yet been received.

As the DTLS handshake protocol runs atop the record protocol, to account for long handshake messages that cannot fit within a single record, DTLS supports fragmentation and subsequent reconstruction of handshake messages across records. The receiver must reassemble records before processing.

DTLS relies on unique UDP 4-tuples to identify connections. Since all application-layer data is encrypted, demultiplexing over the same 4-tuple requires the use of a connection identifier extension [I-D.ietf-tls-dtls-connection-id] to permit identification of the correct connection-specific cryptographic context without the use of trial decryption. (Note that this extension is only supported in DTLS 1.2 and 1.3 {{I-D.ietf-tls-dtls13}}.)

Since datagrams can be replayed, DTLS provides optional anti-replay detection based on a window of acceptable sequence numbers [RFC6347].

4.2.2. Security Features

- o Record replay protection.
- o Record (datagram) confidentiality and integrity.
- o Out-of-order record receipt.
- o DoS mitigation (cookie-based).

See also the features from TLS.

4.2.3. Protocol Dependencies

- o The DTLS record protocol explicitly encodes record lengths, so although it runs over a datagram transport, it does not rely on the transport protocol's framing beyond requiring transport-level reconstruction of datagrams fragmented over packets. (Note: DTLS 1.3 short header records omit the explicit length field.)
- o UDP 4-tuple uniqueness, or the connection identifier extension, for demultiplexing.
- o Path MTU discovery.

4.3. (IETF) QUIC with TLS

QUIC (Quick UDP Internet Connections) is a new standards-track transport protocol that runs over UDP, loosely based on Google's original proprietary gQUIC protocol [I-D.ietf-quic-transport]. (See Section 4.3.4 for more details.) The QUIC transport layer itself provides support for data confidentiality and integrity. This requires keys to be derived with a separate handshake protocol. A mapping for QUIC over TLS 1.3 [I-D.ietf-quic-tls] has been specified to provide this handshake.

4.3.1. Protocol Description

As QUIC relies on TLS to secure its transport functions, it creates specific integration points between its security and transport functions:

- o Starting the handshake to generate keys and provide authentication (and providing the transport for the handshake).
- o Client address validation.
- o Key ready events from TLS to notify the QUIC transport.
- o Exporting secrets from TLS to the QUIC transport.

The QUIC transport layer support multiple streams over a single connection. QUIC implements a record protocol for TLS handshake messages to establish a connection. These messages are sent in special INITIAL and CRYPTO frames [I-D.ietf-quic-transport], types of which are encrypted using different keys. INITIAL frames are encrypted using "fixed" keys derived from the QUIC version and public packet information (Connection ID). CRYPTO frames are encrypted using TLS handshake secrets. Once TLS completes, QUIC uses the resultant traffic secrets to for the QUIC connection to protect the rest of the streams. QUIC supports 0-RTT (early) data using previously negotiated connection secrets. Early data is sent in 0-RTT packets, which may be included in the same datagram as the Initial and Handshake packets.

4.3.2. Security Features

- o DoS mitigation (cookie-based).

See also the properties of TLS.

4.3.3. Protocol Dependencies

- o QUIC transport relies on UDP.
- o QUIC transport relies on TLS 1.3 for key exchange, peer authentication, and shared secret derivation.

4.3.4. Variant: Google QUIC

Google QUIC (gQUIC) is a UDP-based multiplexed streaming protocol designed and deployed by Google following experience from deploying SPDY, the proprietary predecessor to HTTP/2. gQUIC was originally known as "QUIC": this document uses gQUIC to unambiguously

distinguish it from the standards-track IETF QUIC. The proprietary technical forebear of IETF QUIC, gQUIC was originally designed with tightly-integrated security and application data transport protocols.

4.4. IKEv2 with ESP

IKEv2 [RFC7296] and ESP [RFC4303] together form the modern IPsec protocol suite that encrypts and authenticates IP packets, either for creating tunnels (tunnel-mode) or for direct transport connections (transport-mode). This suite of protocols separates out the key generation protocol (IKEv2) from the transport encryption protocol (ESP). Each protocol can be used independently, but this document considers them together, since that is the most common pattern.

4.4.1. Protocol descriptions

4.4.1.1. IKEv2

IKEv2 is a control protocol that runs on UDP port 500. Its primary goal is to generate keys for Security Associations (SAs). An SA contains shared (cryptographic) information used for establishing other SAs or keying ESP; See Section 4.4.1.2. IKEv2 first uses a Diffie-Hellman key exchange to generate keys for the "IKE SA", which is a set of keys used to encrypt further IKEv2 messages. It then goes through a phase of authentication in which both peers present blobs signed by a shared secret or private key, after which another set of keys is derived, referred to as the "Child SA". These Child SA keys are used by ESP.

IKEv2 negotiates which protocols are acceptable to each peer for both the IKE and Child SAs using "Proposals". Each proposal may contain an encryption algorithm, an authentication algorithm, a Diffie-Hellman group, and (for IKE SAs only) a pseudorandom function algorithm. Each peer may support multiple proposals, and the most preferred mutually supported proposal is chosen during the handshake.

The authentication phase of IKEv2 may use Shared Secrets, Certificates, Digital Signatures, or an EAP (Extensible Authentication Protocol) method. At a minimum, IKEv2 takes two round trips to set up both an IKE SA and a Child SA. If EAP is used, this exchange may be expanded.

Any SA used by IKEv2 can be rekeyed upon expiration, which is usually based either on time or number of bytes encrypted.

There is an extension to IKEv2 that allows session resumption [RFC5723].

MOBIKE is a Mobility and Multihoming extension to IKEv2 that allows a set of Security Associations to migrate over different addresses and interfaces [RFC4555].

When UDP is not available or well-supported on a network, IKEv2 may be encapsulated in TCP [RFC8229].

4.4.1.2. ESP

ESP is a protocol that encrypts and authenticates IPv4 and IPv6 packets. The keys used for both encryption and authentication can be derived from an IKEv2 exchange. ESP Security Associations come as pairs, one for each direction between two peers. Each SA is identified by a Security Parameter Index (SPI), which is marked on each encrypted ESP packet.

ESP packets include the SPI, a sequence number, an optional Initialization Vector (IV), payload data, padding, a length and next header field, and an Integrity Check Value.

From [RFC4303], "ESP is used to provide confidentiality, data origin authentication, connectionless integrity, an anti-replay service (a form of partial sequence integrity), and limited traffic flow confidentiality."

Since ESP operates on IP packets, it is not directly tied to the transport protocols it encrypts. This means it requires little or no change from transports in order to provide security.

ESP packets may be sent directly over IP, but where network conditions warrant (e.g., when a NAT is present or when a firewall blocks such packets) they may be encapsulated in UDP [RFC3948] or TCP [RFC8229].

4.4.2. Security Features

4.4.2.1. IKEv2

- o Forward-secure key establishment.
- o Cryptographic algorithm negotiation.
- o Peer authentication (Certificate, raw public key, pre-shared key, and EAP).
- o Mutual authentication.
- o Record (datagram) confidentiality and integrity.

- o Session resumption.
- o Connection mobility.
- o DoS mitigation (cookie-based).

4.4.2.2. ESP

- o Record confidentiality and integrity.
- o Record replay protection.

4.4.3. Protocol Dependencies

4.4.3.1. IKEv2

- o Availability of UDP to negotiate, or implementation support for TCP-encapsulation.
- o Some EAP authentication types require accessing a hardware device, such as a SIM card; or interacting with a user, such as password prompting.

4.4.3.2. ESP

- o Since ESP is below transport protocols, it does not have any dependencies on the transports themselves, other than on UDP or TCP where encapsulation is employed.

4.5. Secure RTP (with DTLS)

Secure RTP (SRTP) is a profile for RTP that provides confidentiality, message authentication, and replay protection for RTP data packets and RTP control protocol (RTCP) packets [RFC3711].

4.5.1. Protocol description

SRTP adds confidentiality and optional integrity protection to RTP data packets, and adds confidentiality and mandatory integrity protection to RTCP packets. For RTP data packets, this is done by encrypting the payload section of the packet and optionally appending an authentication tag (MAC) as a packet trailer, with the RTP header authenticated but not encrypted (the RTP header was left unencrypted to enable RTP header compression [RFC2508] [RFC3545]). For RTCP packets, the first packet in the compound RTCP packet is partially encrypted, leaving the first eight octets of the header as clear-text to allow identification of the packet as RTCP, while the remainder of

the compound packet is fully encrypted. The entire RTCP packet is then authenticated by appending a MAC as packet trailer.

Packets are encrypted using session keys, which are ultimately derived from a master key and an additional master salt and session salt. SRTP packets carry a 2-byte sequence number to partially identify the unique packet index. SRTP peers maintain a separate roll-over counter (ROC) for RTP data packets that is incremented whenever the sequence number wraps. The sequence number and ROC together determine the packet index. RTCP packets have a similar, yet differently named, field called the RTCP index which serves the same purpose.

Numerous encryption modes are supported. For popular modes of operation, e.g., AES-CTR, the (unique) initialization vector (IV) used for each encryption mode is a function of the RTP SSRC (synchronization source), packet index, and session "salting key".

SRTP offers replay detection by keeping a replay list of already seen and processed packet indices. If a packet arrives with an index that matches one in the replay list, it is silently discarded.

DTLS [RFC5764] is commonly used to perform mutual authentication and key agreement for SRTP [RFC5763]. Peers use DTLS to perform mutual certificate-based authentication on the media path, and to generate the SRTP master key. Peer certificates can be issued and signed by a certificate authority. Alternatively, certificates used in the DTLS exchange can be self-signed. If they are self-signed, certificate fingerprints are included in the signalling exchange (e.g., in SIP or WebRTC), and used to bind the DTLS key exchange in the media plane to the signalling plane. The combination of a mutually authenticated DTLS key exchange on the media path and a fingerprint sent in the signalling channel protects against active attacks on the media, provided the signalling can be trusted. Signalling needs to be protected as described in, for example, SIP [RFC3261] Authenticated Identity Management [RFC4474] or the WebRTC security architecture [I-D.ietf-rtcweb-security-arch], to provide complete system security.

4.5.2. Security Features

- o Forward-secure key establishment.
- o Cryptographic algorithm negotiation.
- o Mutual authentication.
- o Partial datagram confidentiality. (Packet headers are not encrypted.)

- o Optional authentication of data packets.
- o Mandatory authentication of control packets.
- o Out-of-order record receipt.

4.5.3. Protocol Dependencies

- o External key derivation and management protocol, e.g., DTLS [RFC5763].
- o External identity management protocol, e.g., SIP Authenticated Identity Management [RFC4474], WebRTC Security Architecture [I-D.ietf-rtcweb-security-arch].

4.5.4. Variant: ZRTP for Media Path Key Agreement

ZRTP [RFC6189] is an alternative key agreement protocol for SRTP. It uses standard SRTP to protect RTP data packets and RTCP packets, but provides alternative key agreement and identity management protocols.

Key agreement is performed using a Diffie-Hellman key exchange that runs on the media path. This generates a shared secret that is then used to generate the master key and salt for SRTP.

ZRTP does not rely on a PKI or external identity management system. Rather, it uses an ephemeral Diffie-Hellman key exchange with hash commitment to allow detection of man-in-the-middle attacks. This requires endpoints to display a short authentication string that the users must read and verbally compare to validate the hashes and ensure security. Endpoints cache some key material after the first call to use in subsequent calls; this is mixed in with the Diffie-Hellman shared secret, so the short authentication string need only be checked once for a given user. This gives key continuity properties analogous to the secure shell (ssh) [RFC4253].

4.6. tcpcrypt

Tcpcrypt is a lightweight extension to the TCP protocol to enable opportunistic encryption with hooks available to the application layer for implementation of endpoint authentication.

4.6.1. Protocol Description

Tcpcrypt extends TCP to enable opportunistic encryption between the two ends of a TCP connection [I-D.ietf-tcpinc-tcpencrypt]. It is a family of TCP encryption protocols (TEP), distinguished by key exchange algorithm. The use of a TEP is negotiated with a TCP option

during the initial TCP handshake via the mechanism described by TCP Encryption Negotiation Option (ENO) [I-D.ietf-tcpinc-tcpeno]. In the case of initial session establishment, once a tcpcrypt TEP has been negotiated the key exchange occurs within the data segments of the first few packets exchanged after the handshake completes. The initiator of a connection sends a list of supported AEAD algorithms, a random nonce, and an ephemeral public key share. The responder typically chooses a mutually-supported AEAD algorithm and replies with this choice, its own nonce, and ephemeral key share. An initial shared secret is derived from the ENO handshake, the tcpcrypt handshake, and the initial keying material resulting from the key exchange. The traffic encryption keys on the initial connection are derived from the shared secret. Connections can be re-keyed before the natural AEAD limit for a single set of traffic encryption keys is reached.

Each tcpcrypt session is associated with a ladder of resumption IDs, each derived from the respective entry in a ladder of shared secrets. These resumption IDs can be used to negotiate a stateful resumption of the session in a subsequent connection, resulting in use of a new shared secret and traffic encryption keys without requiring a new key exchange. Willingness to resume a session is signaled via the ENO option during the TCP handshake. Given the length constraints imposed by TCP options, unlike stateless resumption mechanisms (such as that provided by session tickets in TLS) resumption in tcpcrypt requires the maintenance of state on the server, and so successful resumption across a pool of servers implies shared state.

Owing to middlebox ossification issues, tcpcrypt only protects the payload portion of a TCP packet. It does not encrypt any header information, such as the TCP sequence number.

Tcpcrypt exposes a universally-unique connection-specific session ID to the application, suitable for application-level endpoint authentication either in-band or out-of-band.

4.6.2. Security Features

- o Forward-secure key establishment.
- o Record (channel) confidentiality and integrity.
- o Stateful cross-connection session resumption.
- o Session caching and management.
- o Application authentication delegation.

4.6.3. Protocol Dependencies

- o TCP.
- o TCP Encryption Negotiation Option (ENO).

4.7. WireGuard

WireGuard is a layer 3 protocol designed to complement or replace IPsec [WireGuard] for certain use cases. It uses UDP to encapsulate IP datagrams between peers. Unlike most transport security protocols, which rely on PKI for peer authentication, WireGuard authenticates peers using pre-shared public keys delivered out-of-band, each of which is bound to one or more IP addresses. Moreover, as a protocol suited for VPNs, WireGuard offers no extensibility, negotiation, or cryptographic agility.

4.7.1. Protocol description

WireGuard is a simple VPN protocol that binds a pre-shared public key to one or more IP addresses. Users configure WireGuard by associating peer public keys with IP addresses. These mappings are stored in a CryptoKey Routing Table. (See Section 2 of [WireGuard] for more details and sample configurations.) These keys are used upon WireGuard packet transmission and reception. For example, upon receipt of a Handshake Initiation message, receivers use the static public key in their CryptoKey routing table to perform necessary cryptographic computations.

WireGuard builds on Noise [Noise] for 1-RTT key exchange with identity hiding. The handshake hides peer identities as per the SIGMA construction [SIGMA]. As a consequence of using Noise, WireGuard comes with a fixed set of cryptographic algorithms:

- o x25519 [Curve25519] and HKDF [RFC5869] for ECDH and key derivation.
- o ChaCha20+Poly1305 [RFC7539] for packet authenticated encryption.
- o BLAKE2s [BLAKE2] for hashing.

There is no cryptographic agility. If weaknesses are found in any of these algorithms, new message types using new algorithms must be introduced.

WireGuard is designed to be entirely stateless, modulo the CryptoKey routing table, which has size linear with the number of trusted peers. If a WireGuard receiver is under heavy load and cannot

process a packet, e.g., cannot spare CPU cycles for point multiplication, it can reply with a cookie similar to DTLS and IKEv2. This cookie only proves IP address ownership. Any rate limiting scheme can be applied to packets coming from non-spoofed addresses.

4.7.2. Security Features

- o Forward-secure key establishment.
- o Peer authentication (Public-key and PSK).
- o Mutual authentication.
- o Record replay prevention (Stateful, timestamp-based).
- o DoS mitigation (cookie-based).

4.7.3. Protocol Dependencies

- o Datagram transport.
- o Out-of-band key distribution and management.

4.8. MinimalT

MinimalT is a UDP-based transport security protocol designed to offer confidentiality, mutual authentication, DoS prevention, and connection mobility [MinimalT]. One major goal of the protocol is to leverage existing protocols to obtain server-side configuration information used to more quickly bootstrap a connection. MinimalT uses a variant of TCP's congestion control algorithm.

4.8.1. Protocol Description

MinimalT is a secure transport protocol built on top of a widespread directory service. Clients and servers interact with local directory services to (a) resolve server information and (b) public ephemeral state information, respectively. Clients connect to a local resolver once at boot time. Through this resolver they recover the IP address(es) and public key(s) of each server to which they want to connect.

Connections are instances of user-authenticated, mobile sessions between two endpoints. Connections run within tunnels between hosts. A tunnel is a server-authenticated container that multiplexes multiple connections between the same hosts. All connections in a tunnel share the same transport state machine and encryption. Each tunnel has a dedicated control connection used to configure and

manage the tunnel over time. Moreover, since tunnels are independent of the network address information, they may be reused as both ends of the tunnel move about the network. This does however imply that connection establishment and packet encryption mechanisms are coupled.

Before a client connects to a remote service, it must first establish a tunnel to the host providing or offering the service. Tunnels are established in 1-RTT using an ephemeral key obtained from the directory service. Tunnel initiators provide their own ephemeral key and, optionally, a DoS puzzle solution such that the recipient (server) can verify the authenticity of the request and derive a shared secret. Within a tunnel, new connections to services may be established.

4.8.2. Protocol Features

- o Forward-secure key establishment.
- o DoS mitigation (puzzle-based).
- o Connection mobility (based on tunnel identifiers).

Additional (orthogonal) transport features include: connection multiplexing between hosts across shared tunnels, and congestion control state is shared across connections between the same host pairs.

4.8.3. Protocol Dependencies

- o A DNS-like resolution service to obtain location information (an IP address) and ephemeral keys.
- o A PKI trust store for certificate validation.

4.9. CurveCP

CurveCP [CurveCP] is a UDP-based transport security protocol from Daniel J. Bernstein. Unlike other transport security protocols, it is based entirely upon highly efficient public key algorithms. This removes many pitfalls associated with nonce reuse and key synchronization.

4.9.1. Protocol Description

CurveCP is a UDP-based transport security protocol. It is built on three principal features: exclusive use of public key authenticated encryption of packets, server-chosen cookies to prohibit memory and

computation DoS at the server, and connection mobility with a client-chosen ephemeral identifier.

There are two rounds in CurveCP. In the first round, the client sends its first initialization packet to the server, carrying its (possibly fresh) ephemeral public key C' , with zero-padding encrypted under the server's long-term public key. The server replies with a cookie and its own ephemeral key S' and a cookie that is to be used by the client. Upon receipt, the client then generates its second initialization packet carrying: the ephemeral key C' , cookie, and an encryption of C' , the server's domain name, and, optionally, some message data. The server verifies the cookie and the encrypted payload and, if valid, proceeds to send data in return. At this point, the connection is established and the two parties can communicate.

The use of public-key encryption and authentication, or "boxing", is done to simplify problems that come with symmetric key management and synchronization. For example, it allows the sender of a message to be in complete control of each message's nonce. It does not require either end to share secret keying material. Furthermore, it allows connections (or sessions) to be associated with unique ephemeral public keys as a mechanism for enabling forward secrecy given the risk of long-term private key compromise.

The client and server do not perform a standard key exchange. Instead, in the initial exchange of packets, each party provides its own ephemeral key to the other end. The client can choose a new ephemeral key for every new connection. However, the server must rotate these keys on a slower basis. Otherwise, it would be trivial for an attacker to force the server to create and store ephemeral keys with a fake client initialization packet.

Servers use cookies for source validation. After receiving a client's initial packet, encrypted under the server's long-term public key, a server generates and returns a stateless cookie that must be echoed back in the client's following message. This cookie is encrypted under the client's ephemeral public key. This stateless technique prevents attackers from hijacking client initialization packets to obtain cookie values to flood clients. (A client would detect the duplicate cookies and reject the flooded packets.) Similarly, replaying the client's second packet, carrying the cookie, will be detected by the server.

CurveCP supports a weak form of client authentication. Clients are permitted to send their long-term public keys in the second initialization packet. A server can verify this public key and, if untrusted, drop the connection and subsequent data.

Unlike some other protocols, CurveCP data packets leave only the ephemeral public key, the connection ID, and the per-message nonce in the clear. Everything else is encrypted.

4.9.2. Protocol Features

- o Datagram confidentiality and integrity (via public key encryption).
- o Connection mobility (based on a client-chosen ephemeral identifier).
- o Optional length-hiding and anti-amplification padding.

4.9.3. Protocol Dependencies

- o An unreliable transport protocol such as UDP.

5. Security Features and Transport Dependencies

There exists a common set of features shared across the transport protocols surveyed in this document. Mandatory features constitute a baseline of functionality that an application may assume for any TAPS implementation. They were selected on the basis that they are either (a) required for any secure transport protocol or (b) nearly ubiquitous amongst common secure transport protocols.

Optional features by contrast may vary from implementation to implementation, and so an application cannot simply assume they are available. Applications learn of and use optional features by querying for their presence and support. Optional features may not be implemented, or may be disabled if their presence impacts transport services or if a necessary transport service or application dependency is unavailable. In this context, an application dependency is one required from an application in order to function.

5.1. Mandatory Features

Mandatory features must be supported regardless of transport and application services available.

- o Record or datagram confidentiality and integrity.
- o Forward-secure key establishment.
- o Public-key certificate based authentication.
- o Unilateral responder authentication.

Note that most systems provide default trust stores used to authenticate peers based on certificates. In such systems, applications need not provide any trust information. Applications running on systems without such a feature must necessarily depend on applications for this information so as to authenticate peers.

5.2. Optional Features

In this section we list optional features along with their necessary application dependencies, if any.

- o Pre-shared key support (PSK):
 - * Application dependency: Application provisioning and distribution of pre-shared keys.
- o Cryptographic algorithm negotiation (AN):
 - * Application dependency: Application awareness of supported or desired algorithms.
- o Application authentication delegation (AD):
 - * Application dependency: Application opt-in and policy for endpoint authentication.
- o Mutual authentication (MA):
 - * Application dependency: Mutual authentication credentials required for application support.
- o DoS mitigation (DM):
 - * Application dependency: None.
- o Connection mobility (CM):
 - * Application dependency: None.
- o Source validation (SV):
 - * Application dependency: None.
- o Application-layer feature negotiation (AFN):
 - * Application dependency: Specification of application-layer features or functionality.

- o Configuration extensions (CX):
 - * Application dependency: Specification of application-specific extensions.
- o Session caching and management (SC):
 - * Application dependency: None.
- o Length-hiding padding (LHP):
 - * Application dependency: Knowledge of desired padding policies.
- o Early data support (ED):
 - * Application dependency: Anti-replay protections or hints of data idempotency.
- o Record replay prevention (RP):
 - * Application dependency: None.
- o Out-of-order receipt record (OO):
 - * Application dependency: None.

5.3. Optional Feature Availability

The following table lists the availability of the above-listed optional features in each of the analyzed protocols. "Mandatory" indicates that the feature is intrinsic to the protocol and cannot be disabled. "Supported" indicates that the feature is optionally provided natively or through a (standardized, where applicable) extension.

Pro toc ol	P S K	A N	A D	M A	D M	C M	S V	A F N	CX	SC	LH P	ED	RP	OO
TLS	S	S	S	S	S	U *	M	S	S	S	S	S	U	U
DTL S	S	S	S	S	S	S	M	S	S	S	S	U	M	M
IET F Q UIC	S	S	S	S	S	S	M	S	S	S	S	S	M	M
IKE v2+ ESP	S	S	S	M	S	S	M	S	S	S	S	U	M	M
SRT P+D TLS	S	S	S	S	S	U	M	S	S	S	U	U	M	M
tcp cry pt	U	S	M	U	U * *	U *	M	U	U	S	U	U	U	U
Wir eGu ard	S	U	S	M	S	U	M	U	U	U	S+	U	M	M
Min ima lT	U	U	U	M	S	M	M	U	U	U	S	U	U	U
Cur veC P	U	U	U	S	S	M	M	U	U	U	S	U	M	M

M=Mandatory S=Supported but not required U=Unsupported *=On TCP; MPTCP would provide this ability **=TCP provides SYN cookies natively, but these are not cryptographically strong +=For transport packets only

6. Transport Security Protocol Interfaces

This section describes the interface surface exposed by the security protocols described above. Note that not all protocols support each interface. We partition these interfaces into pre-connection (configuration), connection, and post-connection interfaces, following conventions in [I-D.ietf-taps-interface] and [I-D.ietf-taps-arch].

6.1. Pre-Connection Interfaces

Configuration interfaces are used to configure the security protocols before a handshake begins or the keys are negotiated.

- o Identities and Private Keys The application can provide its identities (certificates) and private keys, or mechanisms to access these, to the security protocol to use during handshakes. Protocols: TLS, DTLS, QUIC + TLS, MinimalT, CurveCP, IKEv2, WireGuard, SRTP
- o Supported Algorithms (Key Exchange, Signatures, and Ciphersuites) The application can choose the algorithms that are supported for key exchange, signatures, and ciphersuites. Protocols: TLS, DTLS, QUIC + TLS, MinimalT, tcpcrypt, IKEv2, SRTP
- o Extensions (Application-Layer Protocol Negotiation): The application enables or configures extensions that are to be negotiated by the security protocol, such as ALPN [RFC7301]. Protocols: TLS, DTLS, QUIC + TLS
- o Session Cache Management The application provides the ability to save and retrieve session state (such as tickets, keying material, and server parameters) that may be used to resume the security session. Protocols: TLS, DTLS, QUIC + TLS, MinimalT
- o Authentication Delegation The application provides access to a separate module that will provide authentication, using EAP for example. Protocols: IKEv2, SRTP
- o Pre-Shared Key Import Either the handshake protocol or the application directly can supply pre-shared keys for the record protocol use for encryption/decryption and authentication. If the application can supply keys directly, this is considered explicit import; if the handshake protocol traditionally provides the keys directly, it is considered direct import; if the keys can only be shared by the handshake, they are considered non-importable.

* Explicit import: QUIC, ESP

- * Direct import: TLS, DTLS, MinimalT, tcpcrypt, WireGuard

- * Non-importable: CurveCP

6.2. Connection Interfaces

- o Identity Validation During a handshake, the security protocol will conduct identity validation of the peer. This can call into the application to offload validation. Protocols: All (TLS, DTLS, QUIC + TLS, MinimalT, CurveCP, IKEv2, WireGuard, SRTP (DTLS))
- o Source Address Validation The handshake protocol may delegate validation of the remote peer that has sent data to the transport protocol or application. This involves sending a cookie exchange to avoid DoS attacks. Protocols: QUIC + TLS, DTLS, WireGuard

6.3. Post-Connection Interfaces

- o Connection Termination The security protocol may be instructed to tear down its connection and session information. This is needed by some protocols to prevent application data truncation attacks. Protocols: TLS, DTLS, QUIC, MinimalT, tcpcrypt, IKEv2
- o Key Update The handshake protocol may be instructed to update its keying material, either by the application directly or by the record protocol sending a key expiration event. Protocols: TLS, DTLS, QUIC, MinimalT, tcpcrypt, IKEv2
- o Pre-Shared Key Export The handshake protocol will generate one or more keys to be used for record encryption/decryption and authentication. These may be explicitly exportable to the application, traditionally limited to direct export to the record protocol, or inherently non-exportable because the keys must be used directly in conjunction with the record protocol.
 - * Explicit export: TLS (for QUIC), tcpcrypt, IKEv2, DTLS (for SRTP)
 - * Direct export: TLS, DTLS, MinimalT
 - * Non-exportable: CurveCP
- o Key Expiration The record protocol can signal that its keys are expiring due to reaching a time-based deadline, or a use-based deadline (number of bytes that have been encrypted with the key). This interaction is often limited to signaling between the record layer and the handshake layer. Protocols: ESP ((Editor's note: One may consider TLS/DTLS to also have this interface))

- o Mobility Events The record protocol can be signaled that it is being migrated to another transport or interface due to connection mobility, which may reset address and state validation and induce state changes such as use of a new Connection Identifier (CID).
Protocols: QUIC, MinimalT, CurveCP, ESP, WireGuard (roaming)

7. IANA Considerations

This document has no request to IANA.

8. Security Considerations

This document summarizes existing transport security protocols and their interfaces. It does not propose changes to or recommend usage of reference protocols. Moreover, no claims of security and privacy properties beyond those guaranteed by the protocols discussed are made. For example, metadata leakage via timing side channels and traffic analysis may compromise any protocol discussed in this survey. Applications using Security Interfaces SHOULD take such limitations into consideration when using a particular protocol implementation.

9. Privacy Considerations

Analysis of how features improve or degrade privacy is intentionally omitted from this survey. All security protocols surveyed generally improve privacy by reducing information leakage via encryption. However, varying amounts of metadata remain in the clear across each protocol. For example, client and server certificates are sent in cleartext in TLS 1.2 [RFC5246], whereas they are encrypted in TLS 1.3 [RFC8446]. A survey of privacy features, or lack thereof, for various security protocols could be addressed in a separate document.

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Authors' Addresses

Tommy Pauly
Apple Inc.
One Apple Park Way
Cupertino, California 95014
United States of America

Email: tpauly@apple.com

Colin Perkins
University of Glasgow
School of Computing Science
Glasgow G12 8QQ
United Kingdom

Email: csp@csperkins.org

Kyle Rose
Akamai Technologies, Inc.
150 Broadway
Cambridge, MA 02144
United States of America

Email: krose@krose.org

Christopher A. Wood
Apple Inc.
One Apple Park Way
Cupertino, California 95014
United States of America

Email: cawood@apple.com