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Cryptographic protection of TCP Streams (tcpcrypt)  
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Abstract

This document presents `tcpcrypt`, a TCP extension for cryptographically protecting TCP segments. `Tcpcrypt` maintains the confidentiality of data transmitted in TCP segments against a passive eavesdropper. It protects connections against denial-of-service attacks involving desynchronizing of sequence numbers, and when enabled, against forged RST segments. Finally, applications that perform authentication can obtain end-to-end confidentiality and integrity guarantees by tying authentication to `tcpcrypt` Session ID values.

The extension defines two new TCP options, `CRYPT` and `MAC`, which are designed to provide compatible interworking with TCPs that do not implement `tcpcrypt`. The `CRYPT` option allows hosts to negotiate the use of `tcpcrypt` and establish shared secret encryption keys. The `MAC` option carries a message authentication code with which hosts can verify the integrity of transmitted TCP segments. `Tcpcrypt` is designed to require relatively low overhead, particularly at servers, so as to be useful even in the case of servers accepting many TCP connections per second.

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## 1. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [RFC2119].

## 2. Introduction

This document describes tcpcrypt, an extension to TCP for cryptographic protection of session data. Tcpcrypt was designed to meet the following goals:

- o Maintain confidentiality of communications against a passive adversary. Ensure that an adversary must actively intercept and modify the traffic to eavesdrop, either by re-encrypting all traffic or by forcing a downgrade to an unencrypted session.
- o Minimize computational cost, particularly on servers.
- o Provide interfaces to higher-level software to facilitate end-to-end security, either in the application level protocol or after the fact. (E.g., client and server log session IDs and can compare them after the fact; if there was no tampering or eavesdropping, the IDs will match.)
- o Be compatible with further extensions that allow authenticated resumption of TCP connections when either end changes IP address.
- o Facilitate multipath TCP [RFC6824] by identifying a TCP stream with a session ID independent of IP addresses and port numbers.
- o Provide for incremental deployment and graceful fallback, even in the presence of NATs and other middleboxes that might remove unknown options, and traffic normalizers.

## 3. Idealized protocol

This section describes the tcpcrypt protocol at an abstract level, without reference to particular cryptographic algorithms or data encodings. Readers who simply wish to see the key exchange protocol should skip to Section 3.4.

### 3.1. Stages of the protocol

A tcpcrypt endpoint goes through multiple stages. It begins in a setup phase and ends up in one of two states, ENCRYPTING or DISABLED,

before applications may send or receive data. The ENCRYPTING and DISABLED states are definitive and mutually exclusive; an endpoint that has been in one of the two states MUST NOT ever enter the other, nor ever re-enter the setup phase.

#### 3.1.1. The setup phase

The setup phase negotiates use of the tcpcrypt extension. During this phase, two hosts agree on a suite of cryptographic algorithms and establish shared secret session keys.

The setup phase uses the Data portion of TCP segments to exchange cryptographic keys. Implementations MUST NOT include application data in TCP segments during setup and MUST NOT allow applications to read or write data. System calls MUST behave the same as for TCP connections that have not yet entered the ESTABLISHED state; calls to read and write SHOULD block or return temporary errors, while calls to poll or select SHOULD consider connections not ready.

When setup succeeds, tcpcrypt enters the ENCRYPTING state. Importantly, a successful setup also produces an important value called the `_Session ID_`. The Session ID is tied to the negotiated algorithms and cryptographic keys, and is unique over all time with overwhelming probability.

Operating systems MUST make the Session ID available to applications. To prevent man-in-the-middle attacks, applications MAY authenticate the session ID through any protocol that ensures both endpoints of a connection have the same value. Applications MAY alternatively just log Session IDs so as to enable attack detection after the fact through comparison of the values logged at both ends.

The setup phase can also fail for various reasons, in which case tcpcrypt enters the DISABLED state.

Applications MAY test whether setup succeeded by querying the operating system for the Session ID. Requests for the Session ID MUST return an error when tcpcrypt is not in the ENCRYPTING state. Applications SHOULD authenticate the returned Session ID. Applications relying on tcpcrypt for security SHOULD authenticate the Session ID and SHOULD treat unauthenticated Session IDs the same as connections in the DISABLED state.

#### 3.1.2. The ENCRYPTING state

When the setup phase succeeds, tcpcrypt enters the ENCRYPTING state. Once in this state, applications may read and write data with the expected semantics of TCP connections.

In the ENCRYPTING state, a host MUST encrypt the Data portion of all TCP segments transmitted and MUST include a Message Authentication Code (MAC) in all segments transmitted. A host MUST furthermore ignore any TCP segments received without the RST bit set, unless those segments also contain a valid MAC option.

A host SHOULD accept RST segments without valid MACs by default. However, the application SHOULD be allowed to force unMACed RST segments to be dropped by enabling the TCP\_CRYPT\_RSTCHK option on the connection.

Once in the ENCRYPTING state, an endpoint MUST NOT directly or indirectly transition to the DISABLED state under any circumstances.

### 3.1.3. The DISABLED state

When setup fails, tcpcrypt enters the DISABLED state. In this case, the host MUST continue just as TCP would without tcpcrypt, unless network conditions would cause a plain TCP connection to fail as well. Entering the DISABLED state prohibits the endpoint from ever entering the ENCRYPTING state.

An implementation MUST behave identically to ordinary TCP in the DISABLED state, except that the first segment transmitted after entering the DISABLED state MAY include a TCP CRYPT option with a DECLINE suboption (and optionally other suboptions such as UNKNOWN) to indicate that tcpcrypt is supported but not enabled. Section 4.3.2 describes how this is done.

Operating systems MUST allow applications to turn off tcpcrypt by setting the state to DISABLED before opening a connection. An active opener with tcpcrypt disabled MUST behave identically to an implementation of TCP without tcpcrypt. A passive opener with tcpcrypt disabled MUST also behave like normal TCP, except that it MAY optionally respond to SYN segments containing a CRYPT option with SYN-ACK segments containing a DECLINE suboption, so as to indicate that tcpcrypt is supported but not enabled.

## 3.2. Cryptographic algorithms

The setup phase employs three types of cryptographic algorithms:

- o A `_public key cipher_` is used with a short-lived public key to exchange (or agree upon) a random, shared secret.
- o An `_extract function_` is used to generate a pseudo-random key from some initial keying material, typically the output of the public key cipher. The notation `Extract (S, IKM)` denotes the output of

the extract function with salt *S* and initial keying material *IKM*.

- o A `_collision-resistant pseudo-random function (CPRF)_` is used to generate multiple cryptographic keys from a pseudo-random key, typically the output of the extract function. We use the notation `CPRF (K, TAG, L)` to designate the output of *L* bytes of the pseudo-random function identified by key *K* on *TAG*. A collision-resistant function is one on which, for sufficiently large *L*, an attacker cannot find two distinct inputs *K*<sub>1</sub>, *TAG*<sub>1</sub> and *K*<sub>2</sub>, *TAG*<sub>2</sub> such that `CPRF (K1, TAG1, L) = CPRF (K2, TAG2, L)`. Collision resistance is important to assure the uniqueness of Session IDs, which are generated using the CPRF.

The Extract and CPRF functions used by default are the Extract and Expand functions of HKDF [RFC5869]. These are defined as follows:

```

HKDF-Extract(salt, IKM) -> PRK
    PRK = HMAC-Hash(salt, IKM)

HKDF-Expand(PRK, TAG, L) -> OKM
    T(0) = empty string (zero length)
    T(1) = HMAC-Hash(PRK, T(0) | TAG | 0x01)
    T(2) = HMAC-Hash(PRK, T(1) | TAG | 0x02)
    T(3) = HMAC-Hash(PRK, T(2) | TAG | 0x03)
    ...

    OKM = first L octets of T(1) | T(2) | T(3) | ...

```

The symbol `|` denotes concatenation, and the counter concatenated with *TAG* is a single octet.

Because the public key cipher, the extract function, and the expand function all make use of cryptographic hashes in their constructions, the three algorithms are negotiated as a unit employing a single hash function. For example, the OAEP+-RSA [RFC2437] cipher, which uses a SHA-256-based mask-generation function, is coupled with HKDF [RFC5869] using HMAC-SHA256 [RFC2104].

The encrypting phase employs an `_authenticated encryption mode_` to encrypt all application data. This mode authenticates both application data and most of the TCP header (excepting header fields commonly modified by middleboxes).

Note that public key generation, public key encryption, and shared secret generation all require randomness. Other tcpcrypt functions may also require randomness depending on the algorithms and modes of operation selected. A weak pseudo-random generator at either host will defeat tcpcrypt's security. Thus, any host implementing



tcpcrypt MUST have a cryptographically secure source of randomness or pseudo-randomness.

### 3.3. "C" and "S" roles

Tcpcrypt transforms a single pseudo-random key (PRK) into cryptographic session keys for each direction. Doing so requires an asymmetry in the protocol, as the key derivation function must be perturbed differently to generate different keys in each direction. Tcpcrypt includes other asymmetries in the roles of the two hosts, such as the process of negotiating algorithms (e.g., proposing vs. selecting cipher suites).

We use the terms "C" and "S" to denote the distinct roles of the two hosts in tcpcrypt's setup phase. In the case of key transport, "C" is the host that supplies a public key, while "S" is the host that encrypts a pre-master secret with the key belonging to "C". Which role a host plays can have performance implications, because for some public key algorithms encryption is much faster than decryption. For instance, on a machine at the time of writing, encryption with a 2,048-bit RSA-3 key is over two orders of magnitude faster than decryption.

Because servers often need to establish connections at a faster rate than clients, and because servers are often passive openers, by default the passive opener plays the "S" role. However, operating systems MUST provide a mechanism for the passive opener to reverse roles and play the "C" role, as discussed in Section 4.2.

### 3.4. Key exchange protocol

Every machine C has a short-lived public encryption key or key agreement parameter, PK\_C, which gets refreshed periodically and SHOULD NOT ever be written to persistent storage.

When a host C connects to S, the two engage in the following protocol:

```
C -> S: HELLO
S -> C: PKCONF, pub-cipher-list
C -> S: INIT1, sym-cipher-list, N_C, pub-cipher, PK_C
S -> C: INIT2, sym-cipher, KX_S
```

The parameters are defined as follows:

- o pub-cipher-list: a list of public key ciphers and parameters acceptable to S. These are defined in Figure 3.

- o sym-cipher-list: a list of symmetric cipher suites acceptable to C. These are specified in Table 6 as parameters for ASM, discussed in Section 3.6.
- o N\_C: Nonce chosen at random by C.
- o pub-cipher: the type of PK\_C.
- o PK\_C: C's public key or key agreement parameter.
- o sym-cipher: the symmetric cipher selected by S.
- o KX\_S: key exchange information produced by S. KX\_S will depend on whether key transport is being done (e.g., RSA) or key agreement (e.g., Diffie-Hellman). KX\_S is defined in Table 1.

Cipher	KX_S	PMS
OAEP+-RSA exp3	ENC (PK_C, R_S)	R_S
ECDHE	N_S, PK_S	key-agreement-output

ENC (PK\_C, R\_S) denotes an encryption of R\_S with public key PK\_C. R\_S and N\_S are random values chosen by S. Their lengths are defined in Figure 3. PK\_S is S's key agreement parameter. PMS is the Pre Master Secret from which keys are ultimately derived.

Table 1

The two sides then compute a pseudo-random key (PRK) from which all session keys are derived as follows:

```
param := { num-pub-ciphers, pub-cipher-list, init1, init2 }
PRK   := Extract (N_C, { param, PMS })
```

Here num-pub-ciphers is a single octet specifying how many three-byte algorithm specifiers were provided by the "S" host in a PKCONF suboption (described in Section 4.3.4). pub-cipher-list is this many three-byte specifiers, taken from the body of the PKCONF suboption. init1 and init2 are the complete data payload from the TCP segments with the INIT1 and INIT2 suboptions (detailed in Section 4.3.9).

A series of "session secrets" and corresponding Session IDs are then computed as follows:

```

ss[0] := PRK
ss[i] := CPRF (ss[i-1], CONST_NEXTK, K_LEN)

SID[i] := CPRF (ss[i], CONST_SESSID, K_LEN)

```

The value `ss[0]` is used to generate all key material for the current connection. `SID[0]` is the session ID for the current connection, and will with overwhelming probability be unique for each individual TCP connection. The most computationally expensive part of the key exchange protocol is the public key cipher. The values of `ss[i]` for  $i > 0$  can be used to avoid public key cryptography when establishing subsequent connections between the same two hosts, as described in Section 3.8. The TAG values are constants defined in Table 7. The `K_LEN` values and nonce sizes are negotiated, and are specified in Figure 3.

Given a session secret, `ss`, the two sides compute a series of master keys as follows:

```

mk[0] := CPRF (ss, CONST_REKEY | flags, K_LEN)
mk[i] := CPRF (mk[i-1], CONST_REKEY, K_LEN)

```

Where `flags` is a single octet from 0x0 to 0x3 computed as follows:

```

bit  0 1 2 3 4 5 6 7
+---+---+---+---+
|0 0 0 0 0 0 s c|
+---+---+---+---+

```

Here bit "s" is set when the "S" mode host has indicated application-level support for tcpcrypt. The "c" bit is set when the "C" mode host has indicated application-level support for tcpcrypt. Both bits are 0 by default unless the application has enabled the `TCP_CRYPT_SUPPORT` option described in Section 6.

Finally, each master key `mk` is used to generate keys for authenticated encryption for the "S" and "C" roles. Key `k_cs` is used by "C" to encrypt and "S" to decrypt, while `k_sc` is used by "S" to encrypt and "C" to decrypt.

```

k_cs := CPRF (mk, CONST_KEY_C, ae_len)
k_sc := CPRF (mk, CONST_KEY_S, ae_len)

```

tcpcrypt does not use HKDF directly for key derivation because it requires multiple expand steps with different keys. This is needed for forward secrecy so that `ss[n]` can be forgotten once a session is established, and `mk[n]` can be forgotten once a session is rekeyed.

There is no key confirmation step in tcpcrypt. This is not required since in tcpcrypt's threat model, a connection to an adversary can be made and so keys need not be verified. If an erroneous key negotiation that yields two different keys occurs, all subsequent packets will be dropped due to an incorrect MAC, causing the TCP connection to hang. This is not a threat because in plain TCP, an active attacker could have modified sequence and ack numbers to hang the connection anyway.

### 3.5. Data encryption and authentication

tcpcrypt encrypts and authenticates all application data. It also authenticates some parts of the TCP header. There are several TCP-specific constraints with regards to authenticated encryption that tcpcrypt must meet for performance and compatibility with middleboxes:

- o The ciphertext for a particular byte position in tcpcrypt's sequence must never change, even if reencryption occurs after coalescing and retransmission. This is because a middlebox may discard a changed payload on retransmission.
- o Authentication must occur only on fields not modified by middleboxes. In particular, port numbers must not be authenticated, and sequence and ack numbers must be authenticated according to an offset from the initial sequence number, because these can be modulated by a middlebox.
- o An efficient mechanism is needed for recomputing the authentication tag when only the ack numbers change. For example, on retransmissions, the authenticated encryption authentication tag can be efficiently updated without having to recompute the tag on the entire packet payload.

Authenticated encryption modes such as GCM do not meet these criteria. For example, even with identical plaintext, ciphertext values depend on the byte position at which one starts encrypting a segment. Hence two small segments will appear to have different content from their coalesced counterpart; middleboxes might drop such coalesced retransmissions after falsely detecting subterfuge attacks. Furthermore, existing authenticated encryption modes do not allow efficient updating of the authentication tag when only small parts of the data have changed. A new mode is needed to meet all these constraints, and we introduce Authenticated Sequence Mode (ASM) in Section 3.6 as a solution.

ASM takes three parameters: a cipher, a MAC and an ACK MAC. At a high-level, the cipher is used to encrypt the TCP payload in counter

mode, using a counter derived from TCP's sequence number. The MAC covers the ciphertext and parts of the TCP header. The ACK MAC covers the ACK numbers and is XORed with the previously computed MAC to produce the authenticated encryption authentication tag. This tag can be quickly updated if only the ACK numbers have changed. This approach is principled because ACK messages are conceptually separate from data packets, so MACing them separately is appropriate. In TCP, ACKs are piggybacked to data segments merely as an optimization.

XORing two PRF-based MACs together was shown secure by Katz and Lindell [aggregate-macs].

### 3.6. Authenticated Sequence Mode (ASM)

ASM is parameterized by a cipher, MAC and ACK MAC. The operations supported by ASM are:

ASM-Encrypt (PRK, Seq, Message, Assoc-Data, Up-Data) ->  
(Ciphertext, Auth-Tag)

ASM-Decrypt (PRK, Seq, Cipher-Text, Assoc-Data, Up-Data, Auth-Tag) ->  
{ (Valid, Message) OR  
(Invalid, )  
}

ASM-Update (PRK, Up-Data-Prev, Up-Data-New, Auth-Tag-Prev) ->  
Auth-Tag

The arguments and return values are:

- o \_PRK\_ a pseudo-random key.
- o \_Seq\_ the byte position in the stream of Message or Cipher-Text. In tcpcrypt, this is an extended version of TCP's sequence number.
- o \_Message\_ the Message to encrypt. In tcpcrypt, this is TCP's payload.
- o \_Assoc-Data\_ the associated data to be MACed but not encrypted. In tcpcrypt, this contains parts of the TCP header.
- o \_Up-Data\_ the updatable data to be MACed but not encrypted, that can also be efficiently updated and reMACed. In tcpcrypt, this will cover an extended version of TCP's ACK numbers.

- o `_Ciphertext_` the encrypted version of Message.
- o `_Auth-Tag_` the authenticated encryption authentication tag. In `tcpcrypt`, this will be the MAC option.

ASM-Decrypt returns one of the constants Valid or Invalid, depending on whether the authentication tag can be verified successfully or not. For Valid inputs, the Message is returned as well.

The PRK supplied to ASM is expanded into keys used for individual operation as follows:

```
k_enc := CPRF (PRK, CONST_KEY_ENC, cipher-key-len)
k_mac := CPRF (PRK, CONST_KEY_MAC, mac-key-len)
k_ack := CPRF (PRK, CONST_KEY_ACK, ack-mac-key-len)
```

The next sections describe ASM operations in detail.

### 3.6.1. ASM-Encrypt

The interface to encrypt is as follows:

```
ASM-Encrypt (PRK, Seq, Message, Assoc-Data, Up-Data) ->
(Ciphertext, Auth-Tag)
```

Keys (denoted by `k_*`) are derived from PRK as explained in Section 3.6.

The following steps occur:

1. Message is encrypted to produce Ciphertext using the cipher in counter mode. Seq is the counter and `k_enc` is the key. When encrypting Seq, its value must always be a multiple of the cipher's block size. In the event that the message does not begin on an even block boundary, Seq must be rounded down, encrypted, and leading bytes of its encryption discarded.
2. The MAC is run over the concatenation of Ciphertext and Assoc-Data to produce MAC1, using `k_mac` as the key.
3. The ACK MAC is run over Up-Data to produce MAC2, using `k_ack` as the key.
4. MAC1 and MAC2 are XORed to produce Auth-Tag.

Using AES-128 as an example, encryption in counter mode using Seq as the counter happens as follows.

- o Compute  $B = \text{Seq} - (\text{Seq} \% 16)$ .
- o Let  $B^* = 0^{\{128-|B|\}} \parallel B$  be  $B$  in network (big-endian) byte order with enough 0 bits pre-pended to make  $B^*$  exactly 128 bits long.
- o Let  $C = \text{ENC-AES}(k_{\text{enc}}, B^*)$ .
- o Discard the first  $(\text{Seq}-B)$  bytes on  $C$  and begin byte-by-byte XORing the remaining portion with the message.
- o Continue computing  $\text{ENC-AES}(k_{\text{enc}}, B^* + 16)$ ,  $\text{ENC-AES}(k_{\text{enc}}, B^* + 32)$ , etc. to generate enough bytes to XOR with the whole message.

If AES-128 is used as the ACK MAC, the Ack number (64-bit extended, offset from ISN) is first padded on the left with enough zeros to produce a 128-bit big-endian value. The number is then encrypted using AES.

### 3.6.2. ASM-Decrypt

The interface to decrypt is as follows:

```
ASM-Decrypt (PRK, Seq, Cipher-Text, Assoc-Data, Up-Data, Auth-Tag) ->
    { (Valid, Message) OR
      (Invalid, )
```

Keys (denoted by  $k_*$ ) are derived from PRK as explained in Section 3.6.

The following steps occur:

1. The MAC is run over the concatenation of Ciphertext and Assoc-Data to produce MAC1, using  $k_{\text{mac}}$  as the key.
2. The ACK MAC is run over Up-Data to produce MAC2, using  $k_{\text{ack}}$  as the key.
3. MAC1 and MAC2 are XORed and compared to Auth-Tag. If different, the process stops and the constant Invalid is returned along with no message. Otherwise the process continues.
4. Ciphertext is decrypted to produce Message using the cipher in counter mode. Seq is the counter and  $k_{\text{enc}}$  is the key. The Valid constant is returned along with Message.

### 3.6.3. ASM-Update

The interface to update the authenticated encryption authentication tag is as follows:

```
ASM-Update (PRK, Up-Data-Prev, Up-Data-New, Auth-Tag-Prev) ->
Auth-Tag
```

Keys (denoted by  $k_*$ ) are derived from PRK as explained in Section 3.6.

The following steps occur:

1. The ACK MAC is run over Up-Data-Prev using  $k_{ack}$  to produce MAC2-Prev.
2. MAC2-Prev is XORed with Auth-Tag-Prev to produce MAC1.
3. The ACK MAC is run over Up-Data to produce MAC2, using  $k_{ack}$  as the key.
4. MAC1 and MAC2 are XORed to produce Auth-Tag.

### 3.7. Re-keying

We refer to the two encryption keys ( $k_{cs}$ ,  $k_{sc}$ ) as a key set. We refer to the key set generated by  $mk[i]$  as the key set with generation number  $i$  within a session. Initially, the two hosts use the key set with generation number 0.

Either host may decide to evolve the encryption key at one or more points within a session, by incrementing the generation number of its transmit keys. When switching keys to generation  $j$ , a host must label the segments it transmits with a REKEY option containing  $j$ , so that the recipient host knows to check the MAC and decrypt the segment using the new keyset:

```
A -> B: REKEY<j>, MAC<...>, Data<...>
```

Upon receiving a REKEY< $j$ > segment, a recipient using transmit keys from a generation less than  $j$  must also update its transmit keys and start including a REKEY< $j$ > option in all of its segments. A host must continue transmitting REKEY options until all segments with other generation numbers have been processed at both ends.

Implementations **MUST** always transmit and retransmit identical ciphertext Data bytes for the same TCP sequence numbers. Thus, a retransmitted segment **MUST** always use the same keyset as the original



segment. Hosts MUST NOT combine segments that were encrypted with different keysets.

Implementations SHOULD delete older-generation keys from memory once they have received all segments they will need to decrypt with the old keys and received acknowledgments for all segments that would need to be retransmitted encrypted under old keys.

### 3.8. Session caching

When two hosts have already negotiated session secret `ss[i-1]`, they can establish a new connection without public key operations using `ss[i]`. The four-message protocol of Section 3.4 is replaced by:

```
A -> B: NEXTK1, SID[i]
B -> A: NEXTK2
```

Which symmetric keys a host uses for transmitted segments is determined by its role in the original session `ss[0]`. It does not depend on which host is the passive opener in the current session. If A had the "C" role in the first session, then A uses `k_cs` for sending segments and `k_sc` for receiving. Otherwise, if A had the "S" role originally, it uses `k_sc` and `k_cs`, respectively. B similarly uses the transmit keys that correspond to its role in the original session.

After using `ss[i]` to compute `mk[0]`, implementations SHOULD compute and cache `ss[i+1]` for possible use by a later session, then erase `ss[i]` from memory. Hosts SHOULD keep `ss[i+1]` around for a period of time until it is used or the memory needs to be reclaimed. Hosts SHOULD NOT write a cached `ss[i+1]` value to non-volatile storage.

It is an implementation-specific issue as to how long `ss[i+1]` should be retained if it is unused. If the passive opener times it out before the active opener does, the only cost is the additional ten bytes to send NEXTK1 for the next connection. The behavior then falls back to a normal public-key handshake.

#### 3.8.1. Session caching control

Implementations MUST allow applications to control session caching by setting the following option:

`TCP_CRYPT_CACHE_FLUSH` When set on a TCP endpoint that is in the ENCRYPTING state, this option causes the operating system to flush from memory the cached `ss[i+1]` (or `ss[i+1+n]` if other connections have already been established). When set on an endpoint that is in the setup phase, causes any cached `ss[i]` that would have been

used to be flushed from memory. In either case, future connections will have to undertake another round of the public key protocol in Section 3.4. Applications SHOULD set TCP\_CRYPT\_CACHE\_FLUSH whenever authentication of the session ID fails.

#### 4. Extensions to TCP

The tcpcrypt extension adds two new kinds of option: CRYPT and MAC. Both are described in this section. During the setup phase, all TCP segments MUST have the CRYPT option. In the ENCRYPTING state, all segments MUST have the MAC option and may include the CRYPT option for various purposes such as re-keying or keep-alive probes.

The idealized protocol of the previous section is embedded in the TCP handshake. Unfortunately, since the maximum TCP header size is 60 bytes and the basic TCP header fields require 20 bytes, there are at most 40 option payload bytes available, which is not enough to hold the INIT1 and INIT2 messages. Tcpcrypt therefore uses the Data portion of TCP segments (after the SYN exchanges) to send the body of these messages.

Operating systems MUST keep track of which phase a data segment belongs to, and MUST only deliver data to applications from segments that are processed in the ENCRYPTING or DISABLED states.

##### 4.1. Protocol states

The setup phase is divided into six states: CLOSED, NEXTK-SENT, HELLO-SENT, C-MODE, LISTEN, and S-MODE. Together with the ENCRYPTING and DISABLED states already discussed, this means a tcpcrypt endpoint can be in one of eight states.

In addition to tcpcrypt's state, each endpoint will also be in one of the 11 TCP states described in the TCP protocol specification [RFC0793]. Not all pairs of states are valid. Table 2 shows which TCP states an endpoint can be in for each tcpcrypt state.

Tcpcrypt state	TCP states for an active opener	TCP states for a passive opener
CLOSED	CLOSED	CLOSED
NEXTK-SENT	SYN-SENT	n/a
HELLO-SENT	SYN-SENT	SYN-RCVD
C-MODE	ESTABLISHED, FIN-WAIT-1	ESTABLISHED, FIN-WAIT-1
LISTEN	n/a	LISTEN
S-MODE	(SYN-RCVD), ESTABLISHED	SYN-RCVD
ENCRYPTING	(SYN-RCVD), ESTABLISHED+	SYN-RCVD, ESTABLISHED+
DISABLED	any	any

Valid tcpcrypt and TCP state combinations. States in parentheses occur only with simultaneous open. ESTABLISHED+ means ESTABLISHED or any later state (FIN-WAIT-1, FIN-WAIT-2, CLOSING, TIME-WAIT, CLOSE-WAIT, or LAST-ACK).

Table 2

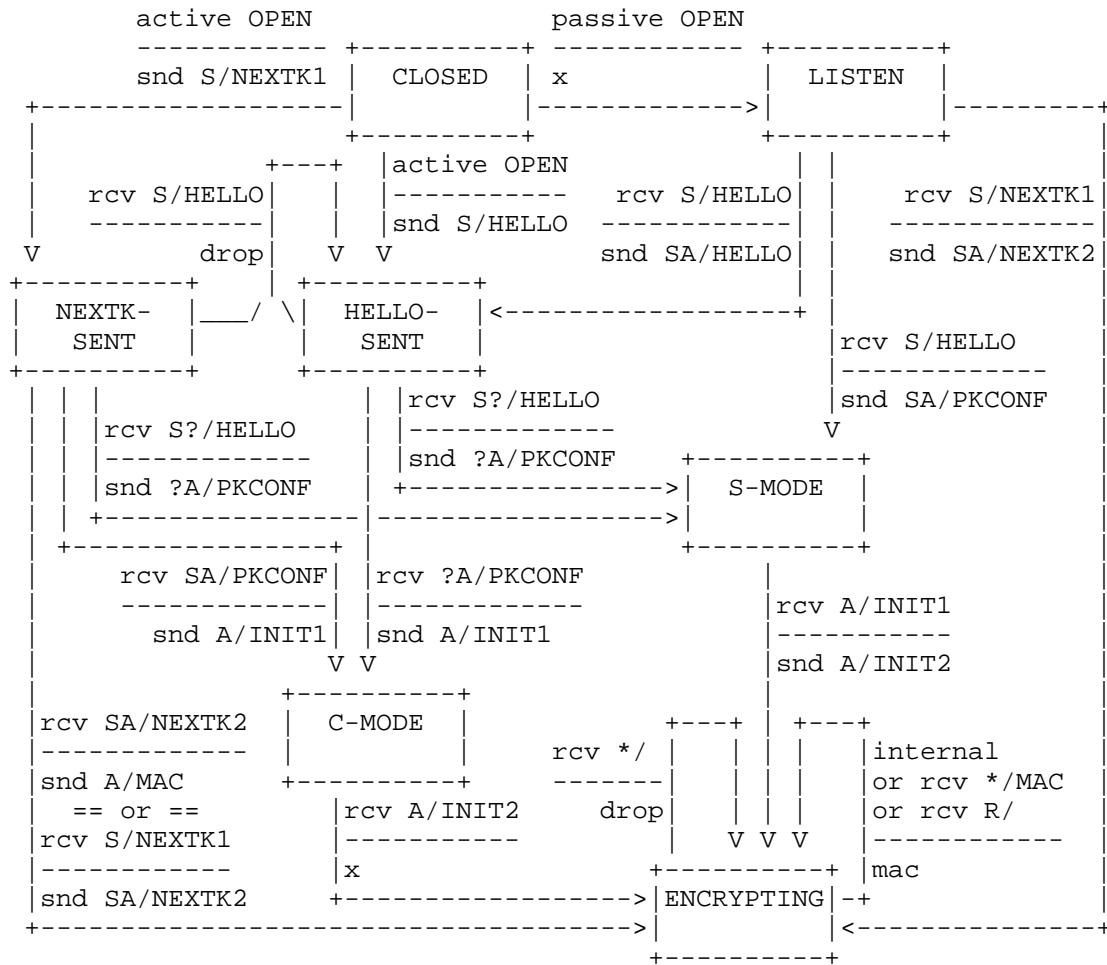
Figure 1 shows how tcpcrypt transitions between states. Each transition is labeled by events that may trigger the transition above the line, and an action the local host is permitted to take in response below the line. "snd" and "rcv" denote sending and receiving segments, respectively. "internal" means any possible event except for receiving a segment (i.e., timers and system calls). "drop" means discarding the last received segment and preventing it from having any effect on TCP's state. "mac" means any valid TCP action, including no action, except that any segments transmitted must be encrypted and contain a valid TCP MAC option. "x" indicates that a host sends no segments when taking a transition.

A segment is described as "F/Op". F specifies constraints on the control bits of the TCP header, as follows:

F	Meaning
S	SYN=1, ACK=0, FIN=0, RST=0
SA	SYN=1, ACK=1, FIN=0, RST=0
A	SYN=0, ACK=1, FIN=0, RST=0
S?	SYN=1, ACK=any, FIN=0, RST=0
?A	SYN=any, ACK=1, FIN=0, RST=0
R	RST=1
*	any

Op designates message types in the abstract protocol, which also correspond to particular suboptions of the TCP CRYPT option, described in Section 4.3, or "MAC" for a valid TCP MAC option, as described in Section 4.4. A segment with SYN=1 and ACK=0 that contains the NEXTK1 suboption will also explicitly or implicitly contain the HELLO suboption; such a segment matches event constraints on either option--e.g., it matches any of the "rcv S/HELLO", "rcv S?/HELLO", and "rcv S/NEXTK1" events. An empty Op matches any segment with the appropriate control bits. A segment MUST contain the TCP MAC option if and only if Op is "MAC".

The "drop" transitions from NEXTK-SENT and HELLO-SENT to HELLO-SENT change TCP slightly by ignoring a segment and preventing a TCP transition from SYN-SENT to SYN-RCVD that would otherwise occur during simultaneous open. Therefore, these transitions SHOULD be disabled by default. They MAY be enabled on one side by an application that wishes to enable tcpcrypt on simultaneous open, as discussed in Section 4.2.1.



State diagram for tcpcrypt. Transitions to DISABLED and CLOSED are not shown.

Figure 1

Any segment that would be discarded by TCP (e.g., for being out of window) MUST also be ignored by tcpcrypt. However, certain segments that might otherwise be accepted by TCP MUST be dropped by tcpcrypt and prevented from affecting TCP's state.

Except for these drop actions, tcpcrypt MUST abide by the TCP protocol specification [RFC0793]. Thus, any segment transmitted by a host MUST be permitted by the TCP specification in addition to matching either a transition in Figure 1 or one of the transitions to

DISABLED or CLOSED described below. In particular, a host MUST NOT acknowledge an INIT1 segment unless either the acknowledgment contains an INIT2 or the host transitions to DISABLED.

Various events cause transitions to DISABLED from states other than ENCRYPTING. In particular:

- o Operating systems MUST provide a mechanism for applications to transition to DISABLED from the CLOSED and LISTEN states.
- o A host in the setup phase MUST transition to DISABLED upon receiving any segment without a TCP CRYPT option.
- o A host in the setup phase MUST transition to DISABLED upon receiving any segment with the FIN or RST control bit set.
- o A host in the setup phase MUST transition to DISABLED upon sending a segment with the FIN bit set. (As discussed below, however, a host MUST NOT send a FIN segment from the C-MODE state.)

Other specific conditions cause a transition to DISABLED and are discussed in the sections that follow.

CLOSED is a pseudo-state representing a connection that does not exist. A tcpcrypt connection's lifetime is identical to that of its associated TCP connection. Thus, tcpcrypt transitions to CLOSED exactly when TCP transitions to CLOSED.

A host MUST NOT send a FIN segment from the C-MODE state. The reason is that the remote side can be in the ENCRYPTING state and would thus require the segment to contain a valid MAC, yet a host in C-MODE cannot compute the necessary encryption keys before receiving the INIT2 segment.

If a CLOSE happens in C-MODE, a host MUST delay sending a FIN segment until receiving an ACK for its INIT1 segment. If the remote host is in ENCRYPTING, the ACK segment will contain INIT2 and the local host can transition to ENCRYPTING before sending the FIN. If the remote host is not in ENCRYPTING, the ACK will not contain INIT2, and thus the local host can transition to DISABLED before sending the FIN.

If a CLOSE happens in C-MODE, an implementation MAY delay processing the CLOSE event and entering the TCP FIN-WAIT-1 state until sending the FIN. If it does not, the implementation MUST ensure all relevant timers correspond to the time of transmission of the FIN segment, not the time of entry into the FIN-WAIT-1 state.

The only valid tcpcrypt state transition from ENCRYPTING is to

CLOSED, which occurs only when TCP transitions to CLOSED. tcpcrypt per se cannot cause TCP to transition to CLOSED.

#### 4.2. Role negotiation

A passive opener receiving an S/HELLO segment may choose to play the "S" role (by transitioning to S-MODE) or the "C" role (by transitioning to HELLO-SENT). An active opener may accept the role not chosen by the passive opener, or may instead disable tcpcrypt. During simultaneous open, one endpoint must choose the "C" role while the other chooses the "S" role. Operating systems MUST allow applications to guide these choices on a per-connection basis.

Applications SHOULD be able to exert this control by setting a per-connection `_CMODE disposition_`, which can take on one of the following five values:

`TCP_CRYPT_CMODE_DEFAULT` This disposition SHOULD be the default. A passive opener will only play the "S" role, but an active opener can play either the "C" or the "S" role. Simultaneous open without session caching will cause tcpcrypt to be disabled unless the remote host has set the `TCP_CMODE_ALWAYS[_NK]` disposition.

`TCP_CRYPT_CMODE_ALWAYS`

`TCP_CRYPT_CMODE_ALWAYS_NK` With this disposition, a host will only play the "C" role. The `_NK` version additionally prevents the use of session caching if the session was originally established in the "S" role.

`TCP_CRYPT_CMODE_NEVER`

`TCP_CRYPT_CMODE_NEVER_NK` With this disposition, a host will only play the "S" role. The `_NK` version additionally prevents the use of session caching if the session was originally established in the "C" role.

The `CMODE` disposition prohibits certain state transitions, as summarized in Table 3. If an event occurs for which all valid transitions in Figure 1 are prohibited, a host MUST transition to `DISABLED`. Operating systems MAY add additional `CMODE` dispositions, for instance to force or prohibit session caching.

CMODE disposition	Prohibited transitions
TCP_CRYPT_CMODE_DEFAULT	LISTEN --> HELLO-SENT HELLO-SENT --> HELLO-SENT NEXTK-SENT --> HELLO-SENT
TCP_CRYPT_CMODE_ALWAYS[_NK]	any --> S-MODE
TCP_CRYPT_CMODE_NEVER[_NK]	LISTEN --> HELLO-SENT HELLO-SENT --> HELLO-SENT NEXTK-SENT --> HELLO-SENT any --> C-MODE

State transitions prohibited by each CMODE disposition

Table 3

#### 4.2.1. Simultaneous open

During simultaneous open, two ends of a TCP connection are both active openers. If both hosts attempt to use session caching by simultaneously transmitting S/NEXTK1 segments, and if both transmit the same session ID, then both may reply with SA/NEXTK2 segments and immediately enter the ENCRYPTING state. In this case, the host that played "C" when the session was initially negotiated MUST use the symmetric encryption keys for "C" (i.e., encrypt with k<sub>cs</sub>, decrypt with k<sub>sc</sub>), while the host that initially played "S" uses the "S" keys for the new connection.

If both hosts in a simultaneous open do not attempt to use session caching, or if the two hosts use incompatible Session IDs, then they MUST engage in public-key-based key negotiation to use tcpcrypt. Doing so requires one host to play the "C" role and the other to play the "S" role. With the TCP\_CRYPT\_CMODE\_DEFAULT disposition, these roles are usually determined by the passive opener choosing the "S" role. With no passive opener, both active openers will end up in S-MODE, then transition to DISABLED upon receiving an unexpected PKCONF.

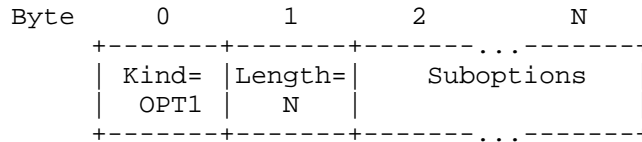
Simultaneous open can work with key negotiation if exactly one of the two hosts selects the TCP\_CRYPT\_CMODE\_ALWAYS disposition. This host will then drop S/HELLO segments and remain in C-MODE while the other host transitions to S-MODE. Applications SHOULD NOT set TCP\_CRYPT\_CMODE\_ALWAYS on both sides of a simultaneous open, as this will result in tcpcrypt being disabled. The reception of two simultaneous HELLO (or NEXTK) messages will disable tcpcrypt because



it is not explicit as to who is playing the "C" or "S" role.

4.3. The TCP CRYPT option

A CRYPT option has the following format:

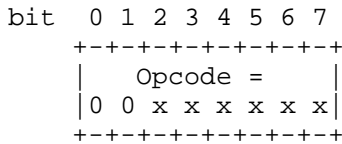


Format of TCP CRYPT option

Kind is always OPT1. Length is the total length of the option, including the two bytes used for Kind and Length. These first two bytes are then followed by zero or more suboptions. Suboptions determine the meaning of the TCP CRYPT option. When a TCP header contains more than one CRYPT option, a host MUST interpret them the same as if all the suboptions appeared in a single CRYPT option. This makes tcpcrypt options future-proof as new suboptions can be placed in a separate CRYPT option, which can be ignored if not understood, while other CRYPT options can still be processed.

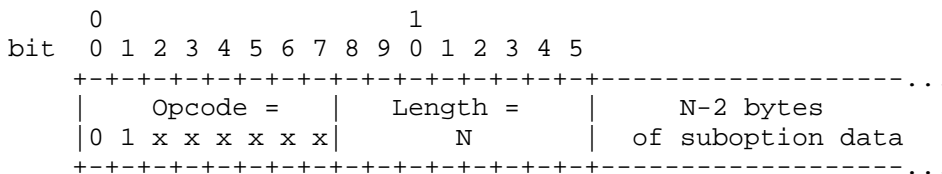
Each suboption begins with an Opcode byte. The specific format of the option depends on the two most significant bits of the Opcode.

Suboptions with opcodes from 0x00 to 0x3f contain no data other than the single opcode byte:



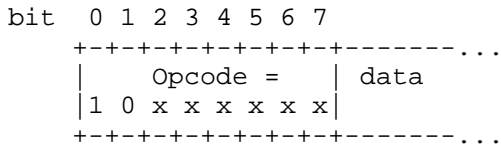
Hosts MUST ignore any opcodes of this format that they do not recognize.

Suboptions with opcodes from 0x40 to 0x7f contain an opcode, a length field, and data bytes.



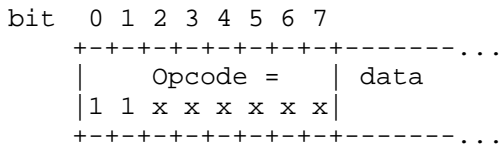
Hosts MUST ignore any opcodes of this format that they do not recognize.

Suboptions with opcodes from 0x80 to 0xbf contain zero or more bytes of data whose length depends on the opcode. These suboptions can be either fixed length or variable length; implementations that understand these opcodes will know which they are; if the suboption is fixed length the implementation will know the length; otherwise it will know where to look for the length field.



If a host sees an unknown opcode in this range, it MUST ignore the suboption and all subsequent suboptions in the same TCP CRYPT option. However, if more than one CRYPT option appears in the TCP header, the host MUST continue processing suboptions from the next TCP CRYPT option. Skipping suboptions in the TCP CRYPT option applies only to this option range since the length of the suboption cannot be determined by the receiver. In other cases, where the length is known, the receiver skips to the next suboption.

Suboptions with opcodes from 0xc0 to 0xff also contain an opcode-specific length of data. As before, these suboptions can be either fixed length or variable length. Suboptions in this range are classed as mandatory as far as the protocol is concerned. However, they are not MANDATORY to implement unless otherwise stated, as discussed below.



Should a host encounter an unknown opcode greater than or equal to 0xc0 during the setup phase of the protocol, the host MUST transition to the DISABLED state. It SHOULD respond with both a DECLINE suboption and an UNKNOWN suboption specifying the opcode of the unknown mandatory suboption, after which the host MUST NOT send any further CRYPT options.

Should a host encounter an unknown opcode greater than or equal to 0xc0 while in the ENCRYPTING state, the host MUST respond with an UNKNOWN suboption specifying the opcode of the unknown mandatory

suboption, and should ensure the session continues with the same encryption and authentication state as it had before the segment was received. This may require ignoring other suboptions within the same message, or reverting any half-negotiated state.

Table 4 summarizes the opcodes discussed in this document. It is MANDATORY that all implementations support every opcode in this table. Each opcode is listed with the length in bytes of the suboption (including the opcode byte), or \* for variable-length suboptions. The last column specifies in which of the (S)etup phase, (E)NCRYPTING state, and (D)ISABLED state an opcode may be used. A host MUST NOT send an option unless it is in one of the stages indicated by this column.

Value	Length	Name	Stages
0x01	1	HELLO	S
0x02	1	HELLO-app-support	S
0x03	1	HELLO-app-mandatory	S
0x04	1	DECLINE	SD
0x05	1	NEXTK2	S
0x06	1	NEXTK2-app-support	S
0x07	1	INIT1	S
0x08	1	INIT2	S
0x41	*	PKCONF	S
0x42	*	PKCONF-app-support	S
0x43	*	UNKNOWN	SED
0x44	*	SYNCOOKIE	S
0x45	*	ACKCOOKIE	SED
0x80	5	SYNC_REQ	E
0x81	5	SYNC_OK	E
0x82	2	REKEY	E
0x83	6	REKEYSTREAM	E
0x84	10	NEXTK1	S

Opcodes for suboptions of the TCP CRYPT option.

Table 4

If a TCP segment (sent by an active opener) has the SYN flag set, the ACK flag clear, and one or more TCP CRYPT options, there is an implicit HELLO suboption even if that suboption does not appear in the segment. In particular, when such a SYN segment contains a single, empty, two-byte TCP CRYPT option, the passive opener MUST interpret that option as equivalent to the three-byte TCP option composed of bytes OPT1, 3, 1 (Kind = OPT1, Length = 3, Suboption =

HELLO).

A host **MUST** enter the **DISABLED** state if, during the setup phase, it receives a segment containing neither a **TCP CRYPT** nor a **TCP MAC** option. This is for robustness against middleboxes that strip options. A host **MUST** also enter **DISABLED** if, during the setup phase, it receives a **DECLINE** suboption or any unrecognized suboption with opcode greater than or equal to 0xc0. The **DECLINE** option is the preferred way for a host to refuse **tcpcrypt**. A host **MAY** also choose reply without a **TCP CRYPT** option to disable **tcpcrypt**. Once a host has entered **DISABLED**, it **MUST NOT** include the **MAC** option in any transmitted segment. The host **MAY** include a **CRYPT** option in the next segment transmitted, but only if the segment also contains the **DECLINE** suboption. All subsequently transmitted packets **MUST NOT** contain the **CRYPT** option.

We now precisely specify the format of each suboption. In the sections that follow, all multi-byte values are encoded in big-endian format.

#### 4.3.1. The HELLO suboption

The **HELLO** dataless suboption **MUST** only appear in a segment with the **SYN** control bit set. It is used by an active opener to indicate interest in using **tcpcrypt** for a connection, and by a passive opener to indicate that the passive opener wishes to play the "C" role.

The initial **SYN** segment from an active opener wishing to use **tcpcrypt** **MUST** contain a **TCP CRYPT** option with either an explicit or an implicit **HELLO** suboption.

After receiving a **SYN** segment with the **HELLO** suboption, a passive opener **MUST** respond in one of three ways:

- o To continue setting up **tcpcrypt** and play the "S" role, the passive opener **MUST** respond with a **PKCONF** suboption in the **SYN-ACK** segment and transition to **S-MODE**.
- o To continue setting up **tcpcrypt** and play the "C" role, the passive opener **MUST** respond with a **HELLO** suboption in the **SYN-ACK** segment and transition to **HELLO-SENT**.
- o To continue without **tcpcrypt**, the passive opener **MUST** respond with either no **CRYPT** option or the **DECLINE** suboption in the **SYN-ACK** segment, then transition to the **DISABLED** state.

An active opener receiving **HELLO** in a **SYN-ACK** segment must either transition to **S-MODE** and respond with a **PKCONF** suboption, or

transition to DISABLED.

There are three variants of the HELLO option used for application-level authentication, each encoded differently as shown in Table 4. The variants are: a plain HELLO where the application is not tcpcrypt-aware (but the kernel is), an "application supported" HELLO where the application is tcpcrypt-aware and is advertising the fact, and a "application mandatory" HELLO where the application requires the remote application to support tcpcrypt otherwise the connection MUST revert to plain TCP. The application supported HELLO can be used, for example, when implementing HTTP digest authentication - an application can check whether the peer's application is tcpcrypt aware and proceed to authenticate tcpcrypt's session ID over HTTP, otherwise reverting to standard HTTP digest authentication. The application mandatory HELLO can be used, for example, when implementing an SSL library that attempts tcpcrypt but reverts to SSL if the peer's SSL library does not support tcpcrypt. The application mandatory HELLO avoids double encrypting (SSL-over-tcpcrypt) since the connection will revert to plain TCP if the remote SSL library is not tcpcrypt-aware.

#### 4.3.2. The DECLINE suboption

The DECLINE dataless suboption is sent by a host to indicate that the host will not enable tcpcrypt on a connection. If a host is in the DISABLED state or transitioning to the DISABLED state, and the host transmits a segment containing a CRYPT option, then the segment MUST contain the DECLINE suboption.

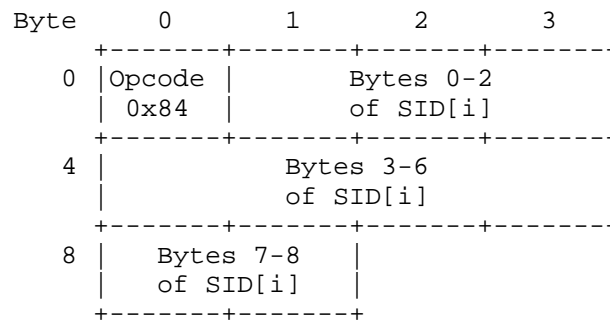
A passive opener SHOULD send a DECLINE suboption in response to a HELLO suboption or NEXTK1 suboption in a received SYN segment if it supports tcpcrypt but does not wish to engage in encryption for this particular session.

Implementations MUST NOT send segments containing the DECLINE suboption from the C-MODE or ENCRYPTING states.

#### 4.3.3. The NEXTK1 and NEXTK2 suboptions

The NEXTK1 suboption MUST only appear in a segment with the SYN control bit set and the ACK bit clear. It is used by the active opener to initiate a TCP session without the overhead of public key cryptography. The new session key is derived from a previously negotiated session secret, as described in Section 3.8.

The suboption is always 10 bytes in length; the data contains the first nine bytes of SID[i] and is used to start the session with session secret ss[i]. The format of the suboption is:



Format of the NEXTK1 suboption

The active opener MUST use the lowest value of *i* that has not already appeared in a NEXTK1 segment exchanged with the same host and for the same pre-session seed.

If the passive opener recognizes SID[*i*] and knows *ss*[*i*], it SHOULD respond with a segment containing the dataless NEXTK2 suboption. The NEXTK2 option MUST only appear in a segment with both the SYN and ACK bits set.

If the passive opener does not recognize SID[*i*], or SID[*i*] is not valid or has already been used, the passive opener SHOULD respond with a PKCONF or HELLO option and continue key negotiation as usual.

When two hosts have previously negotiated a tcpcrypt session, either host may use the NEXTK1 option regardless of which host was the active opener or played the "C" role in the previous session. However, a given host must either encrypt with *k\_cs* for all sessions derived from the same pre-session seed, or *k\_sc*. Thus, which keys a host uses to send segments depends only whether the host played the "C" or "S" role in the initial session that used *ss*[0]; it is not affected by which host was the active opener transmitting the SYN segment containing a NEXTK1 suboption.

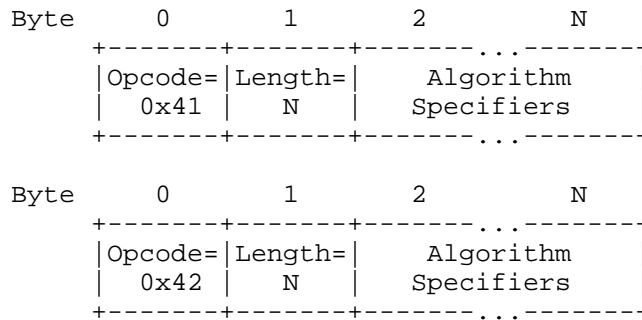
A host MUST reject a NEXTK1 message if it has previously sent or received one with the same SID[*i*]. In the event that two hosts simultaneously send SYN segments to each other with the same SID[*i*], but the two segments are not part of a simultaneous open, both connections will have to revert to public key cryptography. To avoid this limitation, implementations MAY chose to implement session caching such that a given pre-session key is only good for either passive or active opens at the same host, not both.

In the case of simultaneous open, two hosts that simultaneously send SYN packets with NEXTK1 and the same SID[*i*] may establish a

connection, as described in Section 4.2.1.

4.3.4. The PKCONF suboption

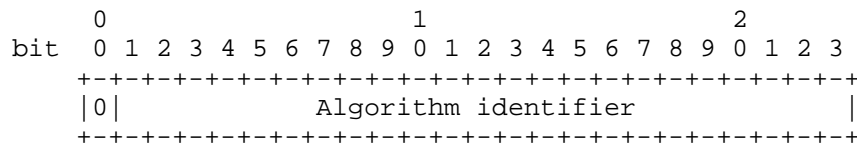
The PKCONF option has one of the following two formats:



Formats of the PKCONF suboption

The two are treated identically by tcpcrypt, except that opcode 0x42 (PKCONF-app-support) signals that the application on the sending host has set the TCP\_CRYPT\_SUPPORT option to non-zero, and hence the receiving host should return 1 for the TCP\_CRYPT\_PEER\_SUPPORT socket option, as discussed in Section 6.

The suboption data, whose length (N-2) must be divisible by 3, contains one or more 3-byte algorithm specifiers of the following form:



Format of algorithm specifier within PKCONF. Fields starting with 1 are reserved for future use by algorithm identifiers longer than three bytes.

The algorithm identifier specifies a number of parameters, defined in Figure 3.

Hosts MUST implement OAEP+RSA3 and ECDHE-P256 and ECDHE-P521, but MAY by default disable certain algorithms and key sizes. In particular, implementations SHOULD disable larger RSA keys (Algorithm identifiers 0x102-0x103) by default unless such larger keys and ciphertexts can fit into a single TCP segment.

Servers demanding utmost performance SHOULD use RSA because the RSA encrypt operation is much faster than Diffie-Hellman operations, resulting in a higher connection rate.

Depending on the encoding of the PKCONF suboption (see Table 4), it can indicate whether "S's" application is tcpcrypt-aware or not. For the "C" role, the encoding of the HELLO suboption does this. This mechanism can be used for bootstrapping application-level authentication without requiring probing in upper layer protocols to check for support (which may not be possible). The application controls these encodings via the TCP\_CRYPT\_SUPPORT socket option.

#### 4.3.5. The UNKNOWN suboption

The UNKNOWN option has the following format:

Byte	0	1	2	N
+-----+-----+-----+-----+-----+				
	Opcode=	Length=	N-2 unknown one-byte	
	0x42	N	opcodes received	
+-----+-----+-----+-----+-----+				

Format of the UNKNOWN suboption

This suboption is sent in response to an unknown suboption that has been received. The contents of the option are a complete list of the mandatory suboption opcodes from the received packet that were not understood. Note that this option is only sent once, in the next packet that the host sends. This means that it is reliable when sent in a SYN-ACK, but unreliable otherwise. Any mechanism sending new mandatory attributes must take this into account. If multiple packets, each containing unknown options, are received before an UNKNOWN suboption can be sent, the options list MUST contain the union of the two sets. The order of the opcode list is not significant.

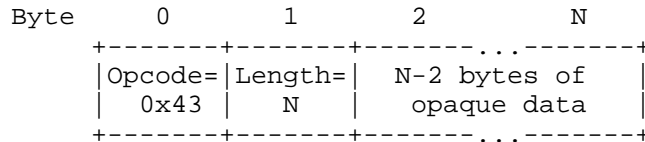
If a host receives an unknown option, it SHOULD reply with the UNKNOWN suboption to notify the other side. If the host transitions to DISABLED as a result of the unknown option, then the host MUST also include the DECLINE suboption if it sends an UNKNOWN suboption (or more generally if it includes a CRYPT option in the next packet).

As a special case, if PKCONF (0x41) or INIT1 (0x06) appears in the unknown opcode list, it does not mean the sender does not understand the option (since these options are MANDATORY). Instead, it means the sender does not implement any of the algorithms specified in the PKCONF or INIT1 message. In either case, the segment must also contain a DECLINE suboption.



## 4.3.6. The SYNCOOKIE and ACKCOOKIE suboptions

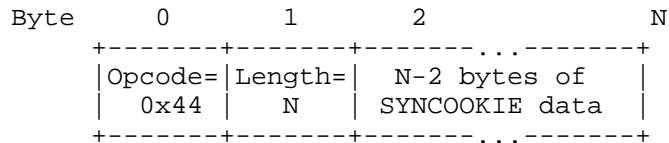
A passive opener MAY include the SYNCOOKIE suboption in a segment with both the SYN and ACK flags set. SYNCOOKIE allows a server to be stateless until the TCP handshake has completed. It has the following format:



Format of the SYNCOOKIE suboption

The data is opaque as far as the protocol is concerned; it is entirely up to implementations how to make use of this suboption to hold state. It is OPTIONAL to send a SYNCOOKIE, but MANDATORY to understand and respond to them.

The ACKCOOKIE suboption echoes the contents of a SYNCOOKIE; it MUST be sent in a packet acknowledging receipt of a packet containing a SYNCOOKIE, and MUST NOT be sent in any other packet. It has the following format:



Format of the ACKCOOKIE suboption

Servers that rely on suboption data from ACKCOOKIE to reconstruct session state SHOULD embed a cryptographically strong message authentication code within the SYNCOOKIE data so as to be able to reject forged ACKCOOKIE suboptions.

Though an implementation MUST NOT send a SYNCOOKIE in any context except the SYN-ACK packet returned by a passive opener, implementations SHOULD accept SYNCOOKIES in other contexts and reply with the appropriate ACKCOOKIE if possible.

## 4.3.7. The SYNC\_REQ and SYNC\_OK suboptions

Many hosts implement TCP Keep-Alives [RFC1122] as an option for applications to ensure that the other end of a TCP connection still exists even when there is no data to be sent. A TCP Keep-Alive

segment carries a sequence number one prior to the beginning of the send window, and may carry one byte of "garbage" data. Such a segment causes the remote side to send an acknowledgment.

Unfortunately, Keep-Alive acknowledgments might not contain unique data. Hence, an old but cryptographically valid acknowledgment could be replayed by an attacker to prolong the existence of a session at one host after the other end of the connection no longer exists. (Such an attack might prevent a process with sensitive data from exiting, giving an attacker more time to compromise a host and extract the sensitive data.)

The TCP Timestamps Option (TSopt) [RFC1323] could alternatively have been used to make Keep-Alives unique. However, because some middleboxes change the value of TSopt in packets, tcpcrypt does not protect the contents of the TCP TSopt option. Hence the SYNC\_REQ and SYNC\_OK suboptions allow the cryptographically protected TCP CRYPT option to contain unique data.

The SYNC\_REQ suboption is always 5 bytes, and has the following format:

Byte	0	1	2	3	4
	+-----+-----+-----+-----+-----+				
	Opcode=	Clock			
	0x80				
	+-----+-----+-----+-----+-----+				

Format of the SYNC\_REQ suboption

Clock is a 32-bit non-decreasing value. A host MUST increment Clock at least once for every interval in which it sends a Keep-Alive. Implementations that support TSopt MAY chose to use the same value for Clock that they would put in the TSval field of the TCP TSopt. However, implementations SHOULD "fuzz" any system clocks used to avoid disclosing either when a host was last rebooted or at what rate the hardware clock drifts.

A host that receives a SYNC\_REQ suboption MUST reply with a SYNC\_OK suboption, which is always five bytes and has the following format:

Byte	0	1	2	3	4
	+-----+-----+-----+-----+-----+				
	Opcode=	Received-Clock			
	0x81				
	+-----+-----+-----+-----+-----+				

Format of the SYNC\_OK suboption

The value of Received-Clock depends on the values of the Clock fields in SYNC\_REQ messages a host has received. A host must set Received-Clock to a value at least as high as the most recently received Clock, but no higher than the highest Clock value received this session. If a host delays acknowledgment of multiple packets with SYNC\_REQ suboptions, it SHOULD send a single SYNC\_OK with Received-Clock set to the highest Clock in the packets it is acknowledging.

Because middleboxes sometimes "correct" inconsistent retransmissions, Keep-Alive segments with one byte of garbage data MUST use the same ciphertext byte as previously transmitted for that sequence number. Otherwise, a middlebox might change the byte back to its value in the original transmission, causing the cryptographic MAC to fail.

#### 4.3.8. The REKEY and REKEYSTREAM suboptions

The REKEY and REKEYSTREAM suboptions are used to evolve encryption keys. Exactly one of the two options is valid for any given symmetric encryption algorithm. All algorithms in Table 6 use the REKEY option. REKEYSTREAM is reserved for future use should tcpcrypt evolve to support a stream cipher. We refer to a segment containing either option as a REKEY segment.

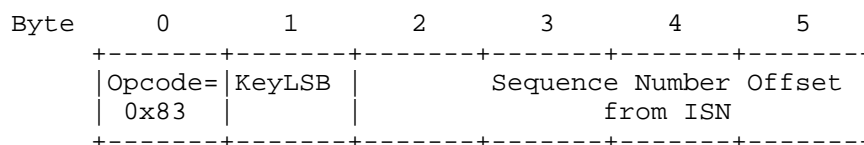
REKEY allows hosts to wipe from memory keys that could decrypt previously transmitted segments. It also allows the use of message authentication codes that are only secure up to a fixed number of messages. However, implementations MUST work in the presence of middleboxes that "correct" inconsistent data retransmissions. Hence, the value of ciphertext bytes must be the same in the original transmission and all retransmissions of a particular sequence number. This means a host MUST always use the same encryption key when transmitting or retransmitting the same range of sequence numbers. Re-keying only affects data transmitted in the future. Moreover, segments encrypted with different keysets MUST NOT be combined in retransmissions.

When switching keys, the REKEY suboption specifies which key set has been used to encrypt and integrity-protect the current segment. The suboption is always two bytes, and has the following format:

Byte	0	1
	+-----+	+-----+
	Opcode=	KeyLSB
	0x82	
	+-----+	+-----+

Format of the REKEY suboption

KeyLSB is the generation number of the keys used to encrypt and MAC the current segment, modulo 256. REKEYSTREAM is the same as REKEY but includes the TCP Sequence Number offset at which the key change took effect, for cases in which decryption requires knowing how many bytes have been encrypted thus far with a key. To interoperate with middleboxes that rewrite sequence numbers, offsets from the Initial Sequence Number (ISN) are used instead of TCP sequence numbers throughout tcpcrypt. The same occurs when dealing with acknowledgment numbers.



Format of the REKEYSTREAM suboption

A host MAY use REKEY to increment the session key generation number beyond the highest generation it knows the other side to be using. We call this process `_initiating_` re-keying. When one host initiates re-keying, the other host MUST increment its key generation number to match, as described below (unless the other host has also simultaneously initiated re-keying).

A host MAY initiate re-keying by including a REKEY suboption in a `_syncable_` segment. A syncable segment is one that either contains data, or is acknowledgment-only but contains a SYNC\_REQ suboption with a fresh Clock value--i.e., higher than any Clock value it has previously transmitted. We say a syncable segment is `_synced_` when the transmitter knows the remote side has received it and all previous sequence numbers. A data segment is synced when the transmitter receives a cumulative acknowledgment for its sequence number (a Selective Acknowledgment [RFC2018] is insufficient). An acknowledgment-only segment is synced when the sender receives an acknowledgment for its sequence number and a SYNC\_OK with a high enough Clock number.

A host MUST NOT initiate re-keying with an acknowledgment-only segment that has either no SYNC\_REQ suboption or a SYNC\_REQ with an old Clock value, because such a segment is not syncable. A host MUST NOT initiate re-keying with any KeyLSB other than its current key number plus one modulo 256.

When a host receives a segment containing a REKEY suboption, it MUST proceed as follows:

1. The receiver computes RECEIVE-KEY-NUMBER to be the closest integer to its own transmit key number that also equals KeyLSB modulo 256. If no number is closest (because KeyLSB is exactly 128 away from the transmit number modulo 256), the receiver MUST discard the segment. If RECEIVE-KEY-NUMBER is negative, the receiver MUST also discard the segment.
2. The receiver MUST authenticate and decrypt the segment using the receive keys with generation number RECEIVE-KEY-NUMBER. The receiver MUST discard the packet as usual if the MAC is invalid.
3. If RECEIVE-KEY-NUMBER is greater than the receiver's current transmit key number, the receiver must wait to receive all sequence numbers prior to the REKEY segment's. Once it receives segments covering all these missing sequence numbers (if any), it MUST increase its transmit number to RECEIVE-KEY-NUMBER and transmit a REKEY suboption. If the receiver has gotten multiple REKEY segments with different KeyLSB values, it MUST increase its transmit key number to the highest RECEIVE-KEY-NUMBER of any segment for which it is not missing prior sequence numbers.

After sending a REKEY (whether initiating re-keying or just responding), a host MUST continue to send REKEY in all subsequent segments until at least one of the following holds:

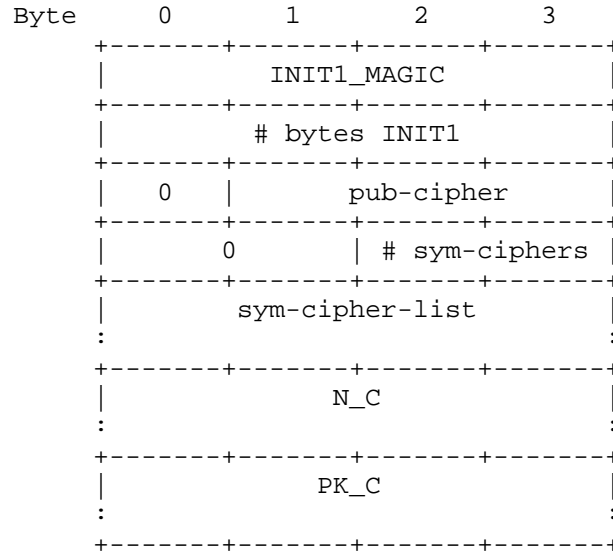
- o One of the REKEY segments the host transmitted for its current transmit key number was syncable, and it has been synced.
- o The host receives a cumulative acknowledgment for one of its REKEY segments with the current transmit key number, and the cumulative acknowledgment is in a segment encrypted with the new key but not containing a REKEY suboption.

A host SHOULD erase old keys from memory once the above requirements are met.

A host MUST NOT initiate re-keying if it initiated a re-keying less than 60 seconds ago and has not transmitted at least 1 Megabyte (increased its sequence number by 1,048,576) since the last re-keying. A host MUST NOT initiate re-keying if it has outstanding unacknowledged REKEY segments for key numbers that are 127 or more below the current key. A host SHOULD not initiate more than one concurrent re-key operation if it has no data to send.

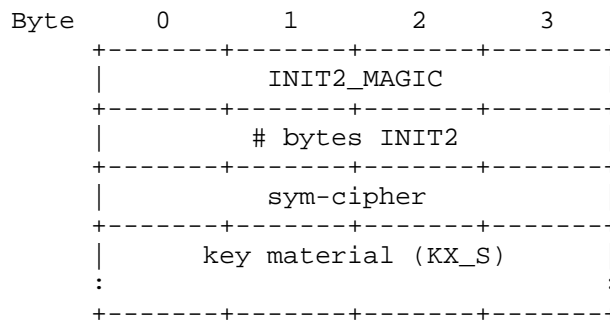
## 4.3.9. The INIT1 and INIT2 suboptions

The INIT1 dataless suboption indicates that the Data portion of the TCP segment contains the following data structure:



The constant INIT1\_MAGIC is specified in Table 7. # bytes INIT1 specifies the length of the entire INIT1 structure, including the four-byte INIT1\_MAGIC that precedes the length. pub-cipher is a three-byte public key suite as specified in Figure 3, which specifies both the length of N\_C and the type of PK\_C. sym-cipher-list is a list of four-byte symmetric algorithm specifiers from Table 6. Of those listed, 0x00000100 (AES-128 / HMAC-SHA-256-128 / AES-128) is MANDATORY to implement, and the others OPTIONAL. # sym-ciphers specifies the number of four-byte entries in this list.

The INIT2 dataless suboption indicates that the Data portion of the TCP segment contains the following data structure:

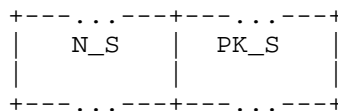


Format of the INIT2 suboption

Figure 2

The INIT2\_MAGIC constant is specified in Table 7. # bytes INIT2 is the total length of the INIT2 structure, including the 4-byte INIT2\_MAGIC constant preceding the length. sym-cipher specifies which entry of sym-cipher-list from the INIT1 message the host transmitting the INIT2 segment has selected.

The key material depends on the public key cipher selected, as described in Section 3.4. When ECDHE is used, key material is encoded as follows:



The length of N\_S depends on pub-cipher and is given in Figure 3. PK\_S uses the rest of the message. When OAEP+RSA exp3 is used, KX\_S is simply a ciphertext in big-endian format.

Hosts MUST set the TCP PSH control bits on INIT1 and INIT2 segments. Implementations MUST NOT set the TCP FIN control bit on INIT segments.

#### 4.4. The TCP MAC option

The MAC option is used to authenticate a TCP segment. Once a host has entered the encrypting phase for a session, the HOST must include a TCP MAC option in all segments it sends. Furthermore, once in the encrypting phase, a host MUST ignore any segments it receives that do not have a valid MAC option, except for segments with the RST bit set if the application has not requested cryptographic verification of RST segments.

The length of the MAC option is determined by the symmetric message authentication code selected. The format of the MAC option is:

Byte	0	1	2	N+1
	Kind	Len=	N-byte	
	OPT2	2+N	MAC	

Format of TCP MAC option

The MAC is the authentication tag as output from authenticated encryption. Apart from payload, two headers are included in the authenticated encryption process: a pseudo-header structure we call Assoc-Data, and an acknowledgment structure we call Up-Data. The format of Assoc-Data is as follows:

Byte	0	1	2	3
0	0x8000		length	
4	off	flags	window	
8	0x0000		urg	
12	seqno offset hi			
16	seqno offset			
20	options			
:	:			

Assoc-Data data structure

The fields of Assoc-Data are defined as follows:

length

Total size of the TCP segment from the start of the TCP header to the end of the IP datagram.

off

Byte 12 of the TCP header (Data Offset)

flags

Byte 13 of the TCP header (Control Bits)



window

Bytes 14-15 of the TCP header (Window)

urg

Bytes 18-19 of the TCP header (Urgent Pointer)

seqno offset hi

Number of times the seqno offset field has wrapped from 0xffffffff  
-> 0

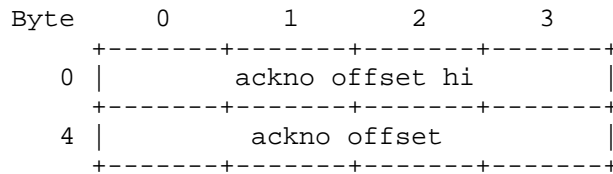
seqno offset

The low 32 bits of the sequence number offset (the Sequence Number  
in the TCP header - ISN)

options

These are bytes 20-off of the TCP header. However, where the  
TSOPT (8), Skeeter (16), Bubba (17), MD5 (19), TCP-AO (29), and  
MAC (OPT2) options appear, their contents (all but the kind and  
length bytes) are replaced with all zeroes.

The format of the Up-Data structure is as follows:



Up-Data data structure

The fields of Up-Data are defined as follows:

ackno offset hi The number of times ackno offset has wrapped from  
0xffffffff -> 0.

ackno offset The lower 32 bits of the acknowledgment number offset  
from the remote end's ISN (TCP's acknowledgment header - ISN  
received).

The two structures, Assoc-Data and Up-Data, are used in ASM to  
calculate the TCP MAC option. All multi-byte values are encoded in  
big-endian format.

5. Examples

To illustrate these suboptions, consider the following series of ways

in which a TCP connection may be established from host A to host B. We use notation S for SYN-only packet, SA for SYN-ACK packet, and A for packets with the ACK bit but not SYN bit. These examples are not normative.

#### 5.1. Example 1: Normal handshake

```
(1) A -> B: S  CRYPT<>
(2) B -> A: SA CRYPT<PKCONF<0x200,0x201>>
(3) A -> B: A  data<INIT1...>
(4) B -> A: A  data<INIT2...>
(5) A -> B: A  MAC<m> data<...>
```

(1) A indicates interest in using tcpcrypt. In (2), the server indicates willingness to use ECDHE with curves P256 and P521. Messages (3) and (4) complete the INIT1 and INIT2 key exchange messages described above, which are embedded in the data portion of the TCP segment. (5) From this point on, all messages are encrypted and their integrity protected by a MAC option.

#### 5.2. Example 2: Normal handshake with SYN cookie

```
(1) A -> B: S  CRYPT<>
(2) B -> A: SA CRYPT<PKCONF<0x200,0x201>, SYNCOOKIE<val>>
(3) A -> B: A  CRYPT<ACKCOOKIE<val>> data<INIT1...>
(4) B -> A: A  data<INIT2...>
(5) B -> A: A  MAC<m> data<...>
```

Same as previous example, except the server sends the client a SYN cookie value, which the client must echo in (3). Here also the application level protocol begins by B transmitting data, while in the previous example, A was the first to transmit application-level data.

#### 5.3. Example 3: tcpcrypt unsupported

```
(1) A -> B: S  CRYPT<>
(2) B -> A: SA
(3) A -> A: A
```

(1) A indicates interest in using tcpcrypt. (2) B does not support tcpcrypt, or a middle box strips out the CRYPT TCP option. (3) the client completes a normal three-way handshake, and tcpcrypt is not enabled for the connection.

## 5.4. Example 4: Reusing established state

```
(1) A -> B: S  CRYPT<NEXTK1<ID>>
(2) B -> A: SA CRYPT<NEXTK2>
(3) A -> A: A  MAC<m>
```

(1) A indicates interest in using tcpcrypt with a session key derived from an existing key, to avoid the use of public key cryptography for the new session. (2) B supports tcpcrypt, has ID in its session ID cache, and is willing to proceed with session caching. (3) the client completes tcpcrypt's handshake within TCP's three-way handshake and tcpcrypt is enabled for the connection.

## 5.5. Example 5: Decline of state reuse

```
(1) A -> B: S  CRYPT<NEXTK1<ID>>
(2) B -> A: SA CRYPT<PKCONF<0x200,0x201>>
(3) A -> B: A  data<INIT1...>
(4) B -> A: A  data<INIT2...>
(5) A -> B: A  MAC<m> data<...>
```

A wishes to use a key derived from a previous session key, but B does not recognize the session ID or has flushed it from its cache. Therefore, session establishment proceeds as in the first connection, using public key cryptography to negotiate a new series of session secrets (ss[i] values).

## 5.6. Example 6: Reversal of client and server roles

```
(1) A -> B: S  CRYPT<>
(2) B -> A: SA CRYPT<HELLO>
(3) A -> B: A  CRYPT<PKCONF<0x100>>
(4) B -> A: A  data<INIT1...>
(5) A -> B: A  data<INIT2...>
(6) B -> A: A  MAC<m> data<...>
```

Here the passive opener, B, wishes to play the role of the decryptor using RSA. By sending a HELLO suboption, B causes A to switch roles, so that now A is "S" and B plays the role of "C".

## 6. API extensions

The getsockopt call should have new options for IPPROTO\_TCP:

TCP\_CRYPT\_SESSID -> returns the session ID and MUST return an error if tcpcrypt is in not in the ENCRYPTING state (e.g., because it has transitioned to DISABLED).

TCP\_CRYPT\_CMODE -> returns 1 if the local host played the "C" role in session key negotiation, 0 otherwise.

TCP\_CRYPT\_CONF -> returns the four-byte authenticated encryption algorithm in use by the connection (as specified in Table 6). In addition, implementations SHOULD provide the three-byte public key cipher (Figure 3) initially used to negotiate the session keys, as well as the public key length for algorithms with variable key sizes (e.g., OAEP+-RSA3).

TCP\_CRYPT\_PEER\_SUPPORT -> returns 1 if the remote application is tcpcrypt-aware, as indicated by the remote host's use of a HELLO-app-support, HELLO-app-mandatory, or PKCONF-app-support CRYPT suboption (see Table 4).

The setsockopt call should have:

TCP\_CRYPT\_CACHE\_FLUSH -> setting this option to non-zero wipes cached session keys. Useful if application-level authentication discovers a man in the middle attack, to prevent the next connection from using NEXTK.

The following options should be readable and writable with getsockopt and setsockopt:

TCP\_CRYPT\_ENABLE -> one bit, enables or disables tcpcrypt extension on an unconnected (listening or new) socket.

TCP\_CRYPT\_RSTCHK -> one bit, means ignore unauthenticated RST packets for this connection when set to 1.

TCP\_CRYPT\_CMODE\_{DEFAULT,NEVER,ALWAYS}[\_NK] -> As described in Section 4.2.

TCP\_CRYPT\_PKCONF -> set of allowed public key algorithms and CPRFs this host advertises in CRYPT PKCONF suboptions.

TCP\_CRYPT\_CCONF -> set of allowed symmetric ciphers and message authentication codes this host advertises in CRYPT INIT1 segments.

TCP\_CRYPT\_SCONF -> order of preference of symmetric ciphers.

TCP\_CRYPT\_SUPPORT -> set to 1 if the application is tcpcrypt-aware. set to 2 if the application is tcpcrypt-aware and wishes to enter the DISABLED state if the remote application is not tcpcrypt-aware. An active opener SHOULD set the default value of 0 for each new connection. A passive opener SHOULD use a default value of 0 for each port, but SHOULD inherit the value of the

listening socket for accepted connections. The behavior for each value is as follows:

When set to 0 The host MUST transition to the DISABLED state upon receiving a HELLO-app-mandatory option. The host MUST NOT send the HELLO-app-support, HELLO-app-mandatory, NEXTK2-app-support, or PKCONF-app-support options.

When set to 1 The "C" role host MUST use HELLO-app-support in place of the HELLO option, while the "S" role host MUST use the "PKCONF-app-support" in place of the "PKCONF" option. Either role must use NEXTK2-app-support in place of NEXTK2.

When set to 2 The "C" role host MUST use HELLO-app-mandatory option in place of the HELLO option, while the "S" role host MUST use "PKCONF-app-support" in place of the "PKCONF" option. Either role must use NEXTK2-app-support in place of NEXTK2. Either host MUST transition to DISABLED upon receipt of a HELLO or PKCONF option, but MUST proceed as usual in response to HELLO-app-support, HELLO-app-mandatory, and PKCONF-app-support.

Finally, system administrators must be able to set the following system-wide parameters:

- o Default TCP\_CRYPT\_ENABLE value
- o Default TCP\_CRYPT\_PKCONF value
- o Default TCP\_CRYPT\_CCONF value
- o Default TCP\_CRYPT\_SCONF value
- o Types, key lengths, and regeneration intervals of local host's short-lived public keys

The session ID can be used for end-to-end security. For instance, applications might sign the session ID with public keys to authenticate their ends of a connection. Because session IDs are not secret, servers can sign them in batches to amortize the cost of the signature over multiple connections. Alternatively, DSA signatures are cheaper to compute than to verify, so might be a good way for servers to authenticate themselves. A voice application could display the session ID on both parties' screens, and if they confirm by voice that they have the same ID, then the conversation is secure.

7. Acknowledgments

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8. IANA Considerations

The following numbers need assignment by IANA:

- o New TCP option kind number for CRYPT
- o New TCP option kind number for MAC

A new registry entitled "tcpcrypt CRYPT suboptions" needs to be maintained by IANA as per the following table.

Symbol	Value
HELLO	0x01
HELLO-app-support	0x02
HELLO-app-mandatory	0x03
DECLINE	0x04
NEXTK2	0x05
NEXTK2-app-support	0x06
INIT1	0x07
INIT2	0x08
PKCONF	0x41
PKCONF-app-support	0x42
UNKNOWN	0x43
SYNCOOKIE	0x44
ACKCOOKIE	0x45
SYNC_REQ	0x80
SYNC_OK	0x81
REKEY	0x82
REKEYSTREAM	0x83
NEXTK1	0x84
IV	0x85

TCP CRYPT suboptions.

Table 5

A "tcpcrypt Algorithm Identifiers" registry needs to be maintained by

IANA as per the following table.

Algorithm Identifier	Value
Cipher: OAEP+-RSA with exponent 3 min/max key size 2048/4096 bits ... min/max key size 4096/8192 bits ... min/max key size 8192/16384 bits .. min key size 16384 bits ..... Extract: HKDF-Extract-SHA256 CPRF: HKDF-Expand-SHA256 N_C len: 32 bytes R_S len: 48 bytes K_LEN: 32 bytes	0x000100 0x000101 0x000102 0x000103
Cipher: ECDHE-P256 Extract: HKDF-Extract-SHA256 CPRF: HKDF-Expand-SHA256 N_C len: 32 bytes N_S len: 32 bytes K_LEN: 32 bytes	0x000200
Cipher: ECDHE-P521 Extract: HKDF-Extract-SHA256 CPRF: HKDF-Expand-SHA256 N_C len: 32 bytes N_S len: 32 bytes K_LEN: 32 bytes	0x000201

TCP CRYPT algorithm identifiers.

Figure 3

A "tcpcrypt ASM parameter" registry needs to be maintained by IANA as per the following table.

Cipher	MAC	ACK MAC	Sym-cipher
AES-128	HMAC-SHA-256-128	AES-128	0x00000100
AES-128	Poly1305-AES-128	AES-128	0x00000200
AES-128	CMAC-AES-128	AES-128	0x00000300

ASM parameters corresponding to 4-byte sym-cipher specifiers in INIT1 and INIT2 messages. ASM itself is specified in Section 3.6. HMAC-SHA-256-128 is HMAC-SHA-256 with a 128-bit key and output truncated to 128 bits.

Table 6

## 9. Security Considerations

Tcpcrypt guarantees that no man-in-the-middle attacks occurred if Session IDs match on both ends of a connection, unless the attacker has broken the underlying cryptographic primitives (e.g., RSA). A proof has been published [tcpcrypt].

If the application performs no authentication, then there are no guarantees against active attackers. Session IDs can be logged on both ends and man-in-the-middle attacks can be detected after the fact by comparing Session IDs offline.

Session IDs are not confidential.

Tcpcrypt can be downgraded to regular TCP during the connection setup phase by removing any of the CRYPT options. The downgrade, and absence of protection, can of course be detected by the application as no Session ID will be returned.

By default tcpcrypt does not protect against RST packet injection. The connection must be configured with TCP\_CRYPT\_RSTCHK enabled to protect against malicious (unMACed) RSTs.

tcpcrypt uses short-lived keys to provide some forward secrecy. If a key is compromised all connections (new and cached) derived from that key will be compromised. The life of these keys should be kept to a minimum for stronger protection. A life of less than two minutes is recommended. Keys can be generated as frequently as practical, for example when servers have idle CPU time. For ECDHE-based key agreement, a new key can be chosen for each connection.

In the 4-way handshake, tcpcrypt does not have a key confirmation



step. Hence, an active attacker can cause a connection to hang, though this is possible even without tcpcrypt by altering sequence and ack numbers.

Attackers cannot force passive openers to move forward in their session caching chain without guessing the content of the NEXTK1 option, which will be hard without key knowledge.

## 10. References

### 10.1. Normative References

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#### Appendix A. Protocol constant values

Value	Name
0x01	CONST_NEXTK
0x02	CONST_SESSID
0x03	CONST_REKEY
0x04	CONST_KEY_C
0x05	CONST_KEY_S
0x06	CONST_KEY_ENC
0x07	CONST_KEY_MAC
0x08	CONST_KEY_ACK
0x15101a0e	INIT1_MAGIC
0x097105e0	INIT2_MAGIC

Protocol constants.

Table 7

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Abstract

This document describes an experimental method to extend the limited space for control options in every segment of a TCP connection. It can use a dual handshake so that, from the very first SYN segment, extra option space can immediately start to be used optimistically. At the same time a dual handshake prevents a legacy server from getting confused and sending the control options to the application as user-data. The dual handshake is only one strategy - a single handshake will usually suffice once deployment has got started. The protocol is designed to traverse most known middleboxes including connection splitters, because it sits wholly within the TCP Data. It also provides reliable ordered delivery for control options. Therefore, it should allow new TCP options to be introduced i) with minimal middlebox traversal problems; ii) with incremental deployment from legacy servers; iii) without an extra round of handshaking delay iv) without having to provide its own loss recovery and ordering mechanism and v) without arbitrary limits on available space.

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1. Introduction

TCP has become hard to extend, partly because the option space was limited to 40B when TCP was first defined [RFC0793] and partly because many middleboxes only forward TCP headers that conform to the stereotype they expect.

This specification ensures new TCP capabilities can traverse most middleboxes by tunnelling TCP options within the TCP Data as 'Inner Options' (Figure 1). Then the TCP receiver can reconstruct the Inner Options sent by the sender, even if the middlebox resegments the data stream and even if it strips 'Outer' options from the TCP header that it does not recognise. The two words 'Inner Space' are appropriate as a name for the scheme; 'Inner' because it encapsulates options within the TCP Data and 'Space' because the space within the TCP Data is virtually unlimited--constrained only by the maximum segment size.



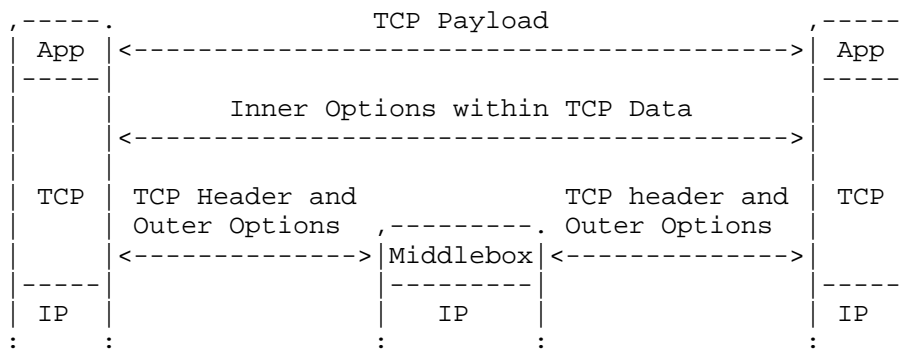


Figure 1: Encapsulation Approach

TCP options fall into three main categories:

- a. Those that have to remain as Outer Options--typically those concerned with transmission of each TCP segment, e.g. Timestamps and Selective ACKnowledgements (SACK);
- b. Those that are best as Inner Options--typically those concerned with transmission of the data as a stream, e.g. the TCP Authentication Option [RFC5925] or tcpcrypt [I-D.bittau-tcpinc];
- c. Those that can be either Inner or Outer Options--typically those used at the start of a connection which is also inherently the start of the first segment so segmentation is not a concern.

Pressure of space is most acute in the initial segments of each half-connection, i.e. the SYN and SYN/ACK, and particularly the SYN. Even though Inner Space is not suitable for category (a) options, moving all of categories (b) and (c) into Inner Space frees up plenty of outer space in the header for category (a).

The following list of options that might be required on a SYN illustrates how acute the problem is:

- o 4B: Maximum Segment Size (MSS) [RFC0793];
- o 2B: SACK-ok [RFC2018];
- o 3B: Window Scale [RFC7323];
- o 10B: Timestamp [RFC7323];
- o 12B: Multipath TCP [RFC6824];

- o 6-18B: TCP Fast Open on a resumed connection [I-D.ietf-tcpm-fastopen];

- o 16B: TCP-AO [RFC5925];

There is probably potential for compressing together multiple options in order to mitigate the option space problem. However, the option space problem has to be faced, because complex special placement is already being contemplated for options that can be larger than 40B on their own (e.g. the key agreement options of tcpcrypt [I-D.bittau-tcpinc]).

Given the Inner Space protocol places control options within TCP Data, it is critical that a legacy TCP receiver is never confused into passing this mix to an application as if it were pure data. Naively, both ends could handshake to check they understand the protocol, but this would introduce a round of delay and it would not solve the shortage of space in a SYN. Instead, the client uses dual handshakes; one suitable for an upgraded server, and the other for an ordinary server. Then, if the client discovers that the server does not understand the new protocol, it can abort the upgraded handshake before the server passes corrupt data to the application. Otherwise, if the server does understand the new protocol, the client can abort the ordinary handshake. Either way, it has added zero extra delay. Interworking of the dual handshake with TCP Fast Open [I-D.ietf-tcpm-fastopen] is carefully defined so that either server can pass data to the application as soon as the initial SYN arrives.

When control options are placed within the TCP Data they inherently get delivered reliably and in order. Although this was not originally recognised as part of the design brief, it offers the significant benefit of simplifying the design of new TCP options. Reliable ordered delivery no longer has to be individually crafted into the design of each new TCP option.

Solving the five problems of i) option-space exhaustion; ii) middlebox traversal; iii) legacy server confusion; iv) reliable ordered control message delivery; and v) handshake latency; does not come without cost:

- o So that the Inner Space protocol is immune to option stripping, it flags its presence using a magic number within the TCP Data of the initial segment in each direction, not a conventional TCP option in the header. This introduces a risk that payload in an ordinary SYN or SYN/ACK might be mistaken for the Inner Space protocol (an initial worst-case estimate of the probability is one connection globally every 40 years). Nonetheless, the risk is zero in the (currently common) case of an ordinary connection without payload

during the handshake. There is also no risk of a mistake the other way round--an upgraded connection cannot be mistaken for an ordinary connection.

- o Although the dual handshake introduces no extra latency, it introduces extra connection processing & state, extra traffic and extra header processing. Initial estimates put the percentage overhead in single digits for connection processing and state, and traffic overhead at only a few hundredths of a percent. Nonetheless, once the most popular TCP servers have upgraded, only a single handshake will be necessary most of the time and overhead should drop to vanishingly small proportions.

Finally, it should be noted that the ambition of this work is more than just an incrementally deployable, low latency way to extend TCP option space. The aim is to move towards a more structured way for middleboxes to interact transparently with, rather than arbitrarily interfere with, end-system TCP stacks. This has been achieved for connection and stream control options, but it will still be hard to introduce new per-segment control options, which will still have to be located within the traditional Outer TCP Options.

#### 1.1. Motivation for Adoption Now (to be removed before publication)

It seems inevitable that ultimately more option space will be needed, particularly given that many of the TCP options introduced recently consume large numbers of bits in order to provide sufficient information entropy, which is not amenable to compression.

Extension of TCP option space requires support from both ends. This means it will take many years before the facility is functional for most pairs of end-points. Therefore, given the problem is already becoming pressing, a solution needs to start being deployed now.

#### 1.2. Scope

This experimental specification extends the TCP wire protocol. It is independent of the dynamic rate control behaviour of TCP and it is independent of (and thus compatible with) any protocol that encapsulates TCP, including IPv4 and IPv6.

#### 1.3. Experiment Goals

TCP is critical to the robust functioning of the Internet, therefore any proposed modifications to TCP need to be thoroughly tested.

Success criteria: The experimental protocol will be considered successful if it satisfies the following requirements in the

consensus opinion of the IETF tcpm working group. The protocol needs to be sufficiently well specified so that more than one implementation can be built in order to test its function, robustness, overhead and interoperability (with itself, with previous version of TCP, and with various commonly deployed middleboxes). Non-functional issues such as recommendations on message timing also need to be tested. Various optional extensions to the protocol are proposed in Appendix A so experiments are also needed to determine whether these extensions ought to remain optional, or perhaps be removed or become mandatory.

Duration: To be credible, the experiment will need to last at least 12 months from publication of the present specification. If successful, it would then be appropriate to progress to a standards track specification, complemented by a report on the experiments.

#### 1.4. Document Roadmap

The body of the document starts with a full specification of the Inner Space extension to TCP (Section 2). It is rather terse, answering 'What?' and 'How?' questions, but deferring 'Why?' to Section 3. The careful design choices made are not necessarily apparent from a superficial read of the specification, so the Design Rationale section is fairly extensive. The body of the document ends with Section 4 that checks possible interactions between the new scheme and pre-existing variants of TCP, including interaction with partial implementations of TCP in known middleboxes.

Appendix A specifies optional extensions to the protocol that will need to be implemented experimentally to determine whether they are useful. And Appendix B discusses the merits of the chosen design against alternative schemes.

#### 1.5. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119]. In this document, these words will appear with that interpretation only when in ALL CAPS. Lower case uses of these words are not to be interpreted as carrying RFC-2119 significance.

TCP Header: As defined in [RFC0793]. Even though the present specification places TCP options beyond the Data Offset, the term 'TCP Header' is still used to mean only those fields at the head of the segment, delimited by the TCP Data Offset.

Inner TCP Options (or just Inner Options): TCP options placed in the space that the present specification makes available beyond the Data Offset.

Outer TCP Options (or just Outer Options): The TCP options in the traditional location directly after the base TCP Header and before the TCP Data Offset.

Prefix TCP Options: Inner Options to be processed before the Outer Options.

Suffix TCP Options: Inner Options to be processed after the Outer Options.

TCP options: Any TCP options, whether inner, outer or both. This specification makes this term on its own ambiguous so it should be qualified if it is intended to mean TCP options in a certain location.

TCP Payload: Data to be passed to the layer above TCP. The present specification redefines the TCP Payload so that it does not include the Inner TCP Options, the Inner Space Option and any Magic Number, even though they are located beyond the Data Offset.

TCP Data: The information in a TCP segment after the Data Offset, including the TCP Payload, Inner TCP Options, the Inner Space Option and the Magic Number defined in the present specification.

client: The process taking the role of actively opening a TCP connection.

server: The process taking the role of TCP listener.

Upgraded Segment: A segment that will only be fully understood by a host complying with the present specification (even though it might appear valid to a pre-existing TCP receiver). Similarly, Upgraded SYN, Upgraded SYN/ACK etc.

Ordinary Segment: A segment complying with pre-existing TCP specifications but not the present specification. Similarly, Ordinary SYN, Ordinary SYN/ACK etc.

Upgraded Connection: A connection starting with an Upgraded SYN.

Ordinary Connection: A connection starting with an Ordinary SYN.

Upgraded Host: A host complying with the present document as well as with pre-existing TCP specifications. Similarly Upgraded TCP Client, Upgraded TCP Server, etc.

Legacy Host: A host complying with pre-existing TCP specifications, but not with the present document. Similarly Legacy TCP Client, Legacy TCP Server, etc.

Note that the term 'Ordinary' is used for segments and connections, but the term 'Legacy' is used for hosts. This is because, if the Inner Space protocol were widely used in future, a host that could not open an Upgraded Connection would be considered deficient and therefore 'Legacy', whereas an Ordinary Connection would not be considered deficient in the future; because it will always be legitimate to open an Ordinary Connection if extra option space is not needed.

## 2. Protocol Specification

### 2.1. Protocol Interaction Model

#### 2.1.1. Dual 3-Way Handshake

During initial deployment, an Upgraded TCP Client sends two alternative SYNs: an Ordinary SYN in case the server is legacy and a SYN-U in case the server is upgraded. The two SYNs MUST have the same network addresses and the same destination port, but different source ports. Once the client establishes which type of server has responded, it continues the connection appropriate to that server type and aborts the other without completing the 3-way handshake.

The format of the SYN-U will be described later (Section 2.2.2). At this stage it is only necessary to know that the client can put either TCP options or payload (or both) in a SYN-U, in the space traditionally intended only for payload. So if the server's response shows that it does not recognise the Upgraded SYN-U, the client is responsible for aborting the Upgraded Connection. This ensures that a Legacy TCP Server will never erroneously confuse the application by passing it TCP options as if they were user-data.

Section 3.1 explains various strategies the client can use to send the SYN-U first and defer or avoid sending the Ordinary SYN. However, such strategies are local optimizations that do not need to be standardized. The rules below cover the most aggressive case, in which the client sends the SYN-U then the Ordinary SYN back-to-back to avoid any extra delay. Nonetheless, the rules are just as applicable if the client defers or avoids sending the Ordinary SYN.

Table 1 summarises the TCP 3-way handshake exchange for each of the two SYNs in the two right-hand columns, between an Upgraded TCP Client (the active opener) and either:

1. a Legacy Server, in the top half of the table (steps 2-4), or
2. an Upgraded Server, in the bottom half of the table (steps 2-4)

Because the two SYNs come from different source ports, the server will treat them as separate connections, probably using separate threads (assuming a threaded server). A load balancer might forward each SYN to separate replicas of the same logical server. Each replica will deal with each incoming SYN independently - it does not need to co-ordinate with the other replica.

		Ordinary Connection	Upgraded Connection
1	Upgraded Client	>SYN	>SYN-U
/\/\	/\/\/\/\/\/\/\/\	/\/\/\/\/\/\/\/\	/\/\/\/\/\/\/\/\
2	Legacy Server	<SYN/ACK	<SYN/ACK
3a	Upgraded Client	Waits for response to both SYNs	
3b	"	>ACK	>RST
4		Cont...	
/\/\	/\/\/\/\/\/\/\/\	/\/\/\/\/\/\/\/\	/\/\/\/\/\/\/\/\
2	Upgraded Server	<SYN/ACK	<SYN/ACK-U
3a	Upgraded Client	Waits for response to SYN-U	
3b	"	>RST	>ACK
4			Cont...

Table 1: Dual 3-Way Handshake in Two Server Scenarios

Each column of the table shows the required 3-way handshake exchange within each connection, using the following symbols:

> means client to server;

< means server to client;

Cont... means the TCP connection continues.

The connection that starts with an Ordinary SYN is called the 'Ordinary Connection' and the one that starts with a SYN-U is called the 'Upgraded Connection'. An Upgraded Server MUST respond to a SYN-U with an Upgraded SYN/ACK (termed a SYN/ACK-U and defined in Section 2.2.2). Then the client recognises that it is talking to an Upgraded Server. The client's behaviour depends on which response it receives first, as follows:

- o If the client first receives a SYN/ACK response on the Ordinary Connection, it MUST wait for the response on the Upgraded Connection. It then proceeds as follows:
  - \* If the response on the Upgraded Connection is an Ordinary SYN/ACK, the client MUST reset (RST) the Upgraded Connection and it can continue with the Ordinary Connection.
  - \* If the response on the Upgraded Connection is an Upgraded SYN/ACK-U, the client MUST reset (RST) the Ordinary Connection and it can continue with the Upgraded Connection.
- o If the client first receives an Ordinary SYN/ACK response on the Upgraded Connection, it MUST reset (RST) the Upgraded Connection immediately. It can then wait for the response on the Ordinary Connection and, once it arrives, continue as normal.
- o If the client first receives an Upgraded SYN/ACK-U response on the Upgraded Connection, it MUST reset (RST) the Ordinary Connection immediately and continue with the Upgraded Connection.

#### 2.1.2. Dual Handshake Retransmission Behaviour

If the client receives a response to the SYN, but a short while after that {ToDo: duration TBA} the response to the SYN-U has not arrived, it SHOULD retransmit the SYN-U. If latency is more important than the extra TCP option space, in parallel to any retransmission, or instead of any retransmission, the client MAY give up on the Upgraded (SYN-U) Connection by sending a reset (RST) and completing the 3-way handshake of the Ordinary Connection.

If the client receives no response at all to either the SYN or the SYN-U, it SHOULD solely retransmit one or the other, not both. If latency is more important than the extra TCP option space, it will retransmit the SYN. Otherwise it will retransmit the SYN-U. It MUST



NOT retransmit both segments, because the lack of response could be due to severe congestion.

### 2.1.3. Continuing the Upgraded Connection

Once an Upgraded Connection has been successfully negotiated in the SYN, SYN/ACK exchange, either host can allocate any amount of the TCP Data space in any subsequent segment for extra TCP options. In fact, the sender has to use the upgraded segment structure in every subsequent segment of the connection that contains non-zero TCP Payload. The sender can use the upgraded structure in a segment carrying no user-data (e.g. a pure ACK), but it does not have to.

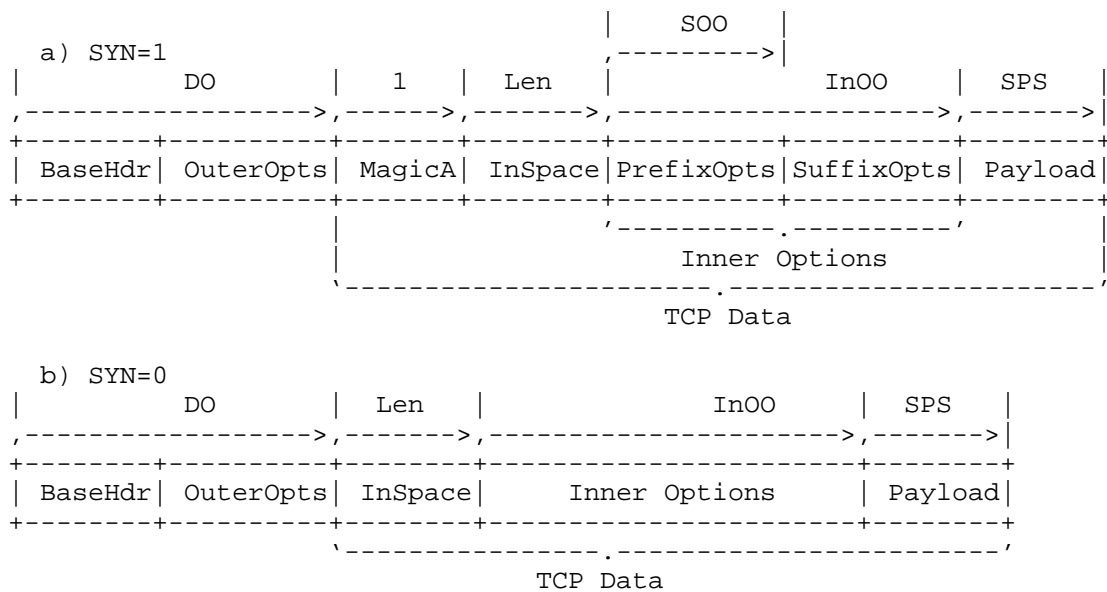
As well as extra option space, the facility offers other advantages, such as reliable ordered delivery of Inner TCP Options on empty segments and more robust middlebox traversal. If none of these features is needed, at any point the facility can be disabled for the rest of the connection, using the ModeSwitch TCP option in Appendix A.1. Interestingly, the ModeSwitch options itself can be very simple because it uses the reliable ordered delivery property of Inner Options, rather than having to cater for the possibility that a message to switch to disabled mode might be lost or reordered.

## 2.2. Upgraded Segment Structure and Format

### 2.2.1. Structure of an Upgraded Segment

An Upgraded Segment is structured as shown in Figure 2. Up to the TCP Data Offset, the structure is identical to an Ordinary TCP Segment, with a base TCP Header (BaseHdr) and the usual facility to set the Data Offset (DO) to allow space for TCP options. These regular TCP options are renamed by this specification to Outer TCP Options or just Outer Options, and labelled as OuterOpts in the figure.

The first segment in each direction (i.e. the SYN or the SYN/ACK) is identifiable as upgraded by the presence of the 4-octet Magic Number A (MagicA) at the start of the TCP Data. The probability that an Upgraded Server will mistake arbitrary data at the beginning of the payload of an Ordinary Segment for the Magic Number has to be allowed for, but it is vanishingly small (see Section 3.2.1). Once an Upgraded Connection has been negotiated during the SYN - SYN/ACK exchange, a magic number is not needed to identify Upgraded Segments, because both ends know that the protocol requires the sender to use the upgraded format on all subsequent segments with non-zero TCP Data. Aside from the magic number, the structure of the rest of an Upgraded Segment is effectively the same whether a) SYN=1 or b) SYN=0.



All offsets are specified in 4-octet (32-bit) words, except SPS, which is in octets.

Figure 2: The Structure of an Upgraded Segment (not to scale)

Unlike an Ordinary TCP Segment, the Payload of an Upgraded Segment does not start straight after the TCP Data Offset. Instead, Figure 2 shows that space is provided for additional Inner TCP Options before the TCP Payload. The size of this space is termed the Inner Options Offset (InOO). The TCP receiver reads the InOO field from the Inner Option Space (InSpace) option defined in Section 2.2.2.

The InSpace Option is located in a standardized location so that the receiver can find it:

- o On a segment with SYN=1, an Upgraded TCP Sender MUST locate the InSpace Option straight after the magic number, specifically 4 \* (DO + 1) octets from the start of the segment.
- o On a segment with SYN=0, an Upgraded TCP Sender MUST locate the InSpace Option at the beginning of the TCP Data, specifically 4 \* DO octets from the start of the segment.

Because the InSpace Option is only ever located in a standardized location it does not need to follow the RFC 793 format of a TCP option. Therefore, although we call InSpace an 'option', we do not describe it as a 'TCP option'.

The Sent Payload Size (SPS) is also read from within the InSpace Option. If the byte-stream has been resegmented, it allows the receiver to step from one InSpace Option to the next even if the InSpace Options are no longer at the start of each segment (see Section 2.3).

On a segment with SYN=1 (i.e. a SYN or SYN/ACK) the Suffix Options Offset (SOO) is also read from within the InSpace Option. It delineates the end of the Prefix TCP Options (PrefixOpts in the figure) and the start of the Suffix TCP Options (SuffixOpts). When SYN=1, the receiver processes PrefixOpts before OuterOpts, then SuffixOpts afterwards. When SYN=0, the receiver processes the Outer Options before the Inner Options. Full details of option processing are given in Section 2.3.

2.2.2. Format of the InSpace Option

The internal structure of the InSpace Option for an Upgraded SYN or SYN/ACK segment (SYN=1) is defined in Figure 3a) and for a segment with SYN=0 in Figure 3b).

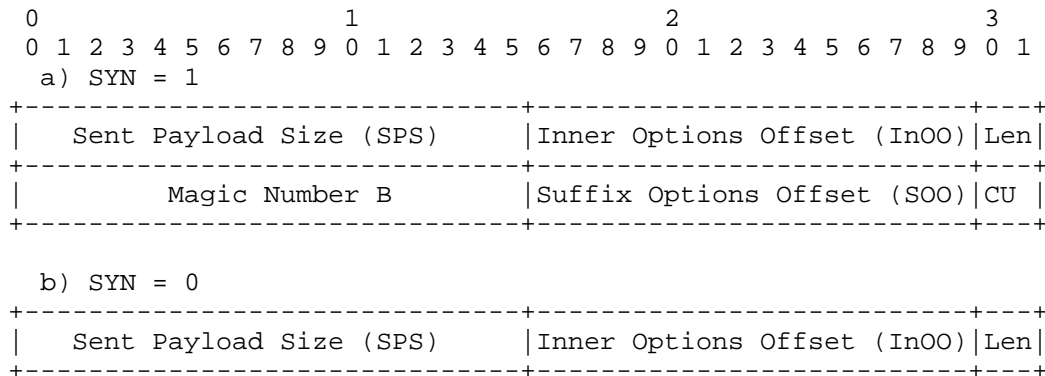


Figure 3: InSpace Option Format

The fields are defined as follows (see Section 3.3 for the rationale behind these format choices):

Option Length (Len): The 2-bit Len field specifies the length of the InSpace Option in 4-octets words (see Section 3.3 for rationale). For this experimental specification:

When SYN=1: the sender MUST use Len=2;

When SYN=0: the sender MUST use Len=1.

Sent Payload Size (SPS): In this 16-bit field the sender MUST record the size in octets of the TCP Payload when it was sent. This specification defines the TCP Payload as solely the user-data to be passed to the application. This excludes Inner TCP options, the InSpace Option and any magic number.

Inner Options Offset (InOO): This 14-bit field defines the total size of the Inner TCP Options in 4-octet words.

The following fields are only defined on a segment with SYN=1 (i.e. a SYN or SYN/ACK):

Magic Number B: The sender MUST fill this 16-bit field with Magic Number B {ToDo: Value TBA} to further reduce the chance that a receiver will mistake the end of an arbitrary Ordinary Payload for the InSpace Option.

Suffix Options Offset (SOO): The 14-bit SOO field defines an additional offset in 4-octet words from the start of the Inner Options that identifies the extent of the Prefix Options (see Section 2.3.2).

Currently Unused (CU): The sender MUST fill the CU field with zeros and they MUST be ignored and forwarded unchanged by other nodes, even if their value is different.

## 2.3. Inner TCP Option Processing

### 2.3.1. Writing Inner TCP Options

#### 2.3.1.1. Constraints on TCP Fast Open

If an Upgraded TCP Client uses a TCP Fast Open (TFO) cookie [I-D.ietf-tcpm-fastopen] in an Upgraded SYN-U, it MUST place the TFO option within the Inner TCP Options, beyond the Data Offset.

This rule is specific to TFO, but it can be generalised to any capability similar to TFO as follows: An Upgraded TCP Client MUST NOT place any TCP option in the Outer TCP Options of a SYN if it might cause a TCP server to pass user-data directly to the application before its own 3-way handshake completes.

If a client uses TCP Fast Open cookies on both the parallel connection attempts of a dual handshake, an Upgraded Server will deliver the TCP Payload to the application twice before the client aborts the Ordinary Connection. This is not a problem, because [I-D.ietf-tcpm-fastopen] requires that TFO is only used for applications that are robust to duplicate requests.

#### 2.3.1.2. Option Alignment

If the end of the last Inner TCP Option does not align on a 4-octet boundary, the sender MUST append sufficient no-op TCP options. On a SYN=1 segment, the end of the Prefix TCP Options MUST be similarly aligned.

If a block-mode transformation (e.g. compression or encryption) is being used, the sender might have to add some padding options to align the end of the Inner Options with the end of a block. Any future encryption specification will need to carefully define this padding in order not to weaken the cipher.

#### 2.3.1.3. Sequence Space Coverage

TCP's sequence number and acknowledgement number space MUST include all the TCP Data, i.e. the InSpace Option, any Inner Options, and any magic number as well as the TCP Payload. Similarly, the sender MUST NOT transmit any form of TCP Data unless the advertised receive window is sufficient. These rules have significant implications, which are discussed in Section 3.2.4.

#### 2.3.1.4. Presence or Absence of Payload

Whenever the sender includes non-zero user-data payload in a segment, it MUST also include an InSpace Option, whether or not there are any Inner Options.

If the sender includes no user-data in a segment (e.g. pure ACKs, RSTs) it MAY include an InSpace Option but it does not have to. {ToDo: Consider whether there is any reason to preclude Inner Options on a RST, FIN or FIN-ACK.}

Once a sender has included the InSpace Option and possibly other Inner Options on a segment with no TCP Payload, while it has no further user-data to send it SHOULD NOT repeat the same set of control options on subsequent segments. Thus, in a sequence of pure ACKs, any particular set of Inner Options will only appear once, and other pure ACKs will be empty. The only envisaged exception to this rule would be infrequent repetition (i.e. tens of minutes to hours) of the same control options, which might be necessary to provide a heartbeat or keep-alive capability.

#### 2.3.2. Reading Inner TCP Options

The rules for reading Inner TCP Options are divided between the following two subsections, depending on whether SYN=1 or SYN=0.

### 2.3.2.1. Reading Inner TCP Options (SYN=1)

This subsection applies when TCP receives a segment with SYN=1, i.e. when the server receives a SYN or the client receives a SYN/ACK.

Before processing any TCP options, unless the size of the TCP Data is less than 8 octets, an Upgraded Receiver MUST determine whether the segment is an Upgraded Segment by checking that all the following conditions apply:

- o The first 4 octets of the segment match Magic Number A;
- o The value of the Length field of the InSpace Option is 2;
- o The value of Magic Number B in the InSpace Option is correct;
- o The value of the Sent Payload Size matches the size of the TCP Payload.

If all these conditions pass, the receiver MAY walk the sequence of Inner TCP Options, using the length of each to check that the sum of their lengths equals InOO. The receiver then concludes that the received segment is an Upgraded Segment.

The receiver then processes the TCP Options in the following order:

1. Any Prefix TCP options (PrefixOpts in Figure 2)
2. Any Outer TCP options (OuterOpts in Figure 2);
3. Any Suffix TCP options (SuffixOpts in Figure 2)

The receiver removes the magic number, the InSpace Option and each TCP Option from the TCP Data as it processes each. This frees up receive buffer, so the receiver increases its local value of the receive window accordingly. Once only the TCP Payload remains, the receiver holds it ready to pass to the application. It then returns the appropriate Upgraded Acknowledgement to progress the dual handshake (see Section 2.1.1).

If any of the above tests to find the InSpace Option fails:

1. the receiver concludes that the received segment is an Ordinary Segment. It MUST then proceed by processing any Outer TCP options in the TCP Header in the normal order (OuterOpts in Figure 2).

2. If some previous control message causes the TCP receiver to alter the TCP Data (e.g. decompression, decryption), it reruns the above tests to check if the altered TCP Data now looks like an Upgraded Segment.
3. If it finds an InSpace Option, it suspends processing the Outer TCP Options and instead processes and removes TCP Options in the following order:
  1. Any Prefix Inner Options;
  2. Any remaining Outer TCP Options;
  3. Any Suffix Inner Options.
4. If it does not find an InSpace Option, it continues processing the remaining Outer TCP Options as normal.

For the avoidance of doubt the above rules imply that, as long as an InSpace Option has not been found in the segment, the receiver might rerun the tests for it multiple times if multiple Outer TCP Options alter the TCP Data. However, once the receiver has found an InSpace Option, it MUST NOT rerun the tests for an Upgraded Segment in the same segment.

If the receiver has not found an InSpace Option after processing all the Outer Options, it returns the appropriate Ordinary Acknowledgement to progress the dual handshake (see Section 2.1.1). As normal, it holds any TCP Payload ready to pass to the application.

#### 2.3.2.2. Reading Inner TCP Options (SYN=0)

This subsection applies once the TCP connection has successfully negotiated to use the upgraded InSpace structure.

As each segment with SYN=0 arrives, the receiver immediately processes any Outer TCP options.

As the receiver buffers TCP Data, it uses TCP's regular mechanisms to fill any gaps due to reordering or loss so that it can work its way along the ordered byte-stream. As the receiver encounters each set of Inner Options, it MUST process them in the order they were sent, as illustrated in Figure 4a) in Section 3.2.4. The receiver MUST remove the InSpace Option and Inner TCP Options from the TCP Data as it processes them, adding to the receive window accordingly. Once only the TCP Payload remains the receiver passes it to the application.

It uses each InSpace Option to calculate the extent of the associated Inner Options (using InOO), and the amount of payload data before the next InSpace Option (using Sent Payload Size). The receiver MUST NOT locate InSpace Options by assuming there is one at the start of the TCP Data in every segment, because resegmentation might invalidate this assumption.

Therefore, the receiver processes the Inner Options in the order they were sent, which is not necessarily the order in which they are received. And if an Inner Option applies to the data stream, the receiver applies it at the point in the data stream where the sender inserted it. As a consequence, the receiver always processes the Inner Options after the Outer Options.

The Inner Options are deliberately placed within the byte-stream so that the sender can transform them along with the payload data, e.g. to compress or encrypt them. A previous control message might have required the TCP receiver to alter the byte-stream before passing it to the application, e.g. decompression or decryption. If so, the TCP receiver applies transformations progressively, to one sent segment at a time, in the following order:

1. The receiver MUST apply any transformations to the byte-stream up to the end of the next set of Inner Options, i.e. over the extent of the next Sent Payload Size, InSpace Option and any Inner Options.
2. The receiver MUST then process and remove the InSpace Option and any Inner Options (which might change the way it transforms the next segment, e.g. a rekey option).
3. Having established the extent of the next sent segment, The receiver returns to step 1.

#### 2.3.3. Forwarding Inner TCP Options

Middleboxes exist that process some aspects of the TCP Header. Although the present specification defines a new location for Inner TCP Options beyond the Data Offset, this is intended for the exclusive use of the destination TCP implementation. Therefore:

- o A middlebox MUST treat any octets beyond the Data Offset as immutable user-data. Legacy Middleboxes already do not expect to find options beyond the Data Offset anyway.
- o A middlebox MUST NOT defer data in a segment with SYN=1 to a subsequent segment.



A TCP implementation is not necessarily aware whether it is deployed in a middlebox or in a destination, e.g. a split TCP connection might use a regular off-the-shelf TCP implementation. Therefore, a general-purpose TCP that implements the present specification will need a configuration switch to disable any search for options beyond the Data Offset and to enable immediate forwarding of data in a SYN.

#### 2.4. Exceptions

{ToDo: Define behaviour of forwarding or receiving nodes if the structure or format of an Upgraded Segment is not as specified.}

If an Upgraded TCP Receiver receives an InSpace Option with a Length it does not recognise as valid, it MUST drop the packet and acknowledge the octets up to the start of the unrecognised option.

Values of Sent Payload Size greater than  $2^{16} - 25$  (=65,511) octets in a regular (non-jumbo) InSpace Option MUST be treated as the distance to the next InSpace option, but they MUST NOT be taken as indicative of the size of the TCP Payload when it was sent. This is because the TCP Payload in a regular IPv6 packet cannot be greater than  $(2^{16} - 1 - 20 - 4)$  octets (given the minimum TCP header is 20 octets and the minimum InSpace Option is 4 octets). A Sent Payload Size of 0xFFFF octets MAY be used to minimise the occurrence of empty InSpace options without permanently disabling the Inner Space protocol for the rest of the connection.

If the size of the payload is greater than 65,511 octets, the sender MUST use a Jumbo InSpace Option (Appendix A.3).

#### 2.5. SYN Flood Protection

An implementation of the Inner Space protocol MUST support the EchoCookie TCP option [I-D.briscoe-tcpm-echo-cookie]. To indicate its support for EchoCookie, an Ordinary Client would send an empty EchoCookie TCP option on the SYN. Support for the Inner Space protocol makes this redundant. Therefore an Inner Space client MUST NOT send an empty EchoCookie TCP option on a SYN-U.

The EchoCookie TCP option replaces the SYN Cookie mechanism [RFC4987], which only has sufficient space to hold the result of one TCP option negotiation (the MSS), and then only a subset of the possible values (see the discussion under Security Considerations Section 6).

### 3. Design Rationale

This section is informative, not normative.

#### 3.1. Dual Handshake and Migration to Single Handshake

In traditional [RFC0793] TCP, the space for options is limited to 40B by the maximum possible Data Offset. Before a TCP sender places options beyond that, it has to be sure that the receiver will understand the upgraded protocol, otherwise it will confuse and potentially crash the application by passing it TCP options as if they were payload data.

The Dual Handshake (Section 2.1.1) ensures that a Legacy TCP Server will never pass on TCP options as if they were user-data. If a SYN carries TCP Data, a TCP server typically holds it back from the application until the 3-way handshake completes. This gives the client the opportunity to abort the Upgraded Connection if the response from the server shows it does not recognise an Upgraded SYN.

The strategy of sending two SYNs in parallel is not essential to the Alternative SYN approach. It is merely an initial strategy that minimises latency when the client does not know whether the server has been upgraded. Evolution to a single SYN with greater option space could proceed as follows:

- o Clients could maintain a white-list of upgraded servers discovered by experience and send just the Upgraded SYN-U in these cases.
- o Then, for white-listed servers, the client could send an Ordinary SYN only in the rare cases when an attempt to use an Upgraded Connection had previously failed (perhaps a mobile client encountering a new blockage on a new path to a server that it had previously accessed over a good path).
- o In the longer term, once it can be assumed that most servers are upgraded and the risk of having to fall back to legacy has dropped to near-zero, clients could send just the Upgraded SYN first, without maintaining a white-list, but still be prepared to send an Ordinary SYN in the rare cases when that might fail.

There is concern that, although dual handshake approaches might well eventually migrate to a single handshake, they do not scale when there are numerous choices to be made simultaneously. For instance:

- o trying IPv6 then IPv4 [RFC6555];

- o and trying SCTP and TCP in parallel  
[I-D.wing-tsvwg-happy-eyeballs-sctp];
- o and trying ECN and non-ECN in parallel;
- o and so on.

Nonetheless, it is not necessary to try every possible combination of  $N$  choices, which would otherwise require  $2^N$  handshakes (assuming each choice is between two options). Instead, a selection of the choices could be attempted together. At the extreme, two handshakes could be attempted, one with all the new features, and one without all the new features.

### 3.2. In-Band Inner Option Space

#### 3.2.1. Non-Deterministic Magic Number Approach

This section justifies the magic number approach by contrasting it with a more 'conventional' approach. A conventional approach would use a regular (Outer) TCP option to point to the dividing line within the TCP Data between the extra Inner Options and the TCP Payload.

This 'conventional' approach cannot provide extra option space over a path on which a middlebox strips TCP options that it does not recognise. [Hondall] quantifies the prevalence of such paths. It reports on experiments conducted in 2010-2011 that found unknown options were stripped from the SYN-SYN/ACK exchange on 14% of paths to port 80 (HTTP), 6% of paths to port 443 (HTTPS) and 4% of paths to port 34343 (unassigned). Further analysis found that the option-stripping middleboxes fell into two main categories:

- o about a quarter appeared to actively remove options that they did not recognise (perhaps assuming they might be indicative of an attack?);
- o the rest were some type of higher layer proxy that split the TCP connection, unwittingly failing to pass unknown options between the two connections.

In contrast, the magic number approach ensures that not only are the Inner Options tucked away beyond the Data Offset, but the option that gives the extent of the Inner Options is also beyond the Data Offset (see Section 2.2.1). This ensures that all the TCP Headers and options up to the Data Offset are completely indistinguishable from an Ordinary Segment. It is very unusual for a middlebox not to forward TCP Data unchanged, so it will be highly likely (but not certain--see Appendix A.2.4) to forward the extra Inner Options.

The downside of the magic number approach is that it is slightly non-deterministic, quantified as follows:

- o The probability that an Upgraded SYN=1 segment will be mistaken for an Ordinary Segment is precisely zero.
- o In the currently common case of a SYN with zero payload, the probability that it will be mistaken for an Upgraded Segment is also precisely zero.
- o However, there will be a very small probability (roughly  $2^{-66}$  or 1 in 74 billion billion ( $74 * 10^{18}$ )) that payload data in an Ordinary SYN=1 segment could be mistaken for an Upgraded SYN or SYN/ACK, if it happens to contain a pattern in exactly the right place that matches the correct Sent Payload Size, Length and Magic Numbers of an InSpace Option. {ToDo: Estimate how often a collision will occur globally. Rough estimate: 1 connection collision globally every 40 years.}

The above probability is based on the assumptions that:

- o the magic numbers will be chosen randomly (in reality they will not--for instance, a magic number that looked just like the start of an HTTP connection would be rejected)
- o data at the start of Ordinary SYN=1 segments is random (in reality it is not--the first few bytes of most payloads are very predictable).

Therefore even though  $2^{-66}$  is a vanishingly small probability, the actual probability of a collision will be much lower.

If a collision does occur, it will result in TCP removing a number of 32-bit words of data from the start of a byte-stream before passing it to the application.

### 3.2.2. Non-Goal: Security Middlebox Evasion

The purpose of locating control options within the TCP Data is not to evade security. Security middleboxes can be expected to evolve to examine control options in the new inner location. Instead, the purpose is to traverse middleboxes that block new TCP options unintentionally--as a side effect of their main purpose--merely because their designers were too careless to consider that TCP might evolve. This category of middleboxes tends to forward the TCP Payload unaltered.

By sitting within the TCP Data, the Inner Space protocol should traverse enough existing middleboxes to reach critical mass and prove itself useful. In turn, this will open an opportunity to introduce integrity protection for the TCP Data (which includes Inner Options). Whereas today, no operating system would introduce integrity protection of Outer TCP options, because in too many cases it would fail and abort the connection. Once the integrity of Inner Options is protected, it will raise the stakes. Any attempt to meddle with control options within the TCP Data will not just close off the theoretical potential benefit of a protocol advance that no-one knows they want yet; it will fail integrity checks and therefore completely break any communication. It is unlikely that a network operator will buy a middlebox that does that.

Then middlebox designers will be on the back foot. To completely block communications they will need a sound justification. If they block an attack, that will be fine. But if they want to block everything abnormal, they will have to block the whole communication, or nothing. So the operator will want to choose middlebox vendors who take much more care to ensure their policies track the latest protocol advances--to avoid costly support calls.

### 3.2.3. Avoiding the Start of the First Two Segments

Some middleboxes discard a segment sent to a well-known port (particularly port 80) if the TCP Data does not conform to the expected app-layer protocol (particularly HTTP). Often such middleboxes only parse the start of the app-layer header (e.g. Web filters only continue until they find the URL being accessed, or DPI boxes only continue until they have identified the application-layer protocol).

The segment structure defined in Section 2.2.1 would not traverse such middleboxes. An alternative segment structure that avoids the start of the first two segments in each direction is defined in Appendix A.4. It is not mandatory to implement in the present specification. However, it is hoped that it will be included in some experimental implementations so that it can be decided whether it is worth making mandatory.

### 3.2.4. Control Options Within Data Sequence Space

Including Inner Options within TCP's sequence space gives the sender a simple way to ensure that control options will be delivered reliably and in order to the remote TCP, even if the control options are on segments without user-data. By using TCP's existing stream delivery mechanisms, it adds no extra protocol processing, no extra packets and no extra bits.

The sender can even choose to place control options on a segment without user-data, e.g. to reliably re-key TCP-level encryption on a connection currently sending no data in one direction. The sender can even add an InSpace Option without further Inner Options. Then it can ensure that the segment will automatically be delivered reliably and in order to the remote TCP, even though it carries no user-data or other TCP control options, e.g. for a test probe, a tail-loss probe or a keep-alive.

Figure 4a) illustrates control options arriving reliably and in order at the receiving TCP stack in comparison with the traditional approach shown in Figure 4b), in which control options are outside the sequence space. In the traditional approach, during a period when the remote TCP is sending no user-data, the local TCP may receive control options E, B and D without ever knowing that they are out of order, and without ever knowing that C is missing.

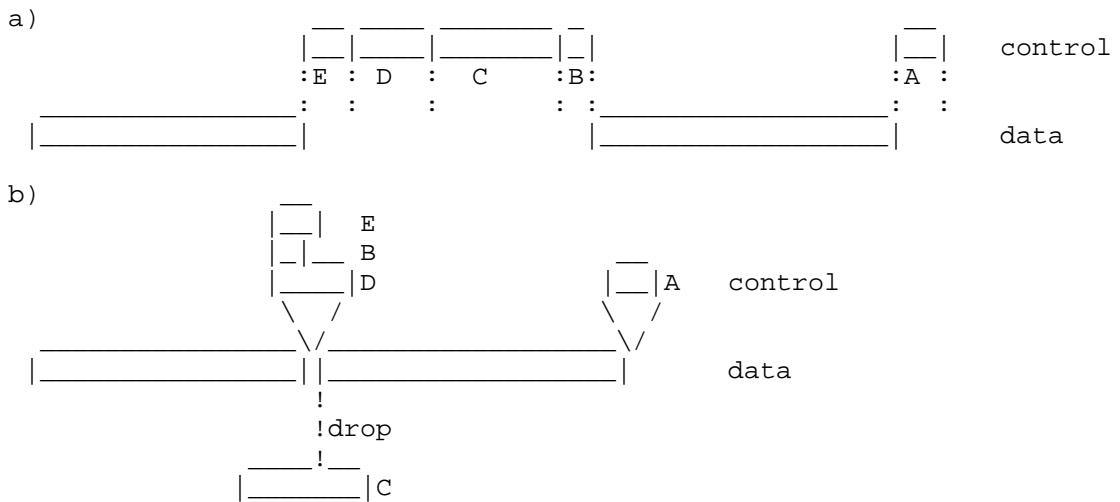


Figure 4: Control options a) inside vs. b) outside TCP sequence space`

By including Inner Options within the sequence space, each control option is automatically bound to the start of a particular byte in the data stream, which makes it easy to switch behaviour at a specific point mid-stream (e.g. re-keying or switching to a different control mode). With traditional TCP options, a bespoke reliable and ordered binding to the data stream would have to be developed for each TCP option that needs this capability (e.g. co-ordinating use of new keys in TCP-AO [RFC5925] or tcpcrypt [I-D.bittau-tcpinc]).

Including Inner Options in sequence also allows the receiver to tell the sender the exact point at which it encountered an unrecognised TCP option using only TCP's pre-existing byte-granularity acknowledgement scheme.

Middleboxes exist that rewrite TCP sequence and acknowledgement numbers, and they also rewrite options that refer to sequence numbers (at least those known when the middlebox was produced, such as SACK, but not any introduced afterwards). If Inner Options were not included in sequence, the number of bytes beyond the TCP Data Offset in each segment would not match the sequence number increment between segments. Then, such middleboxes could unintentionally corrupt the user-data and options by 'normalising' sequence or acknowledgement numbering. Fortunately, including Inner Options in sequence improves robustness against such middleboxes.

### 3.2.5. Rationale for the Sent Payload Size Field

A middlebox that splits a TCP connection can coalesce and/or divide the original segments. Segmentation offload hardware introduces similar resegmentation. Inclusion of the Sent Payload Size field in the InSpace Option makes the scheme robust against such resegmentation.

The Sent Payload Size is not strictly necessary on a SYN (SYN=1, ACK=0) because a SYN is never resegmented. However, for simplicity, the layout for a SYN is made the same as for a SYN/ACK. This future-proofs the protocol against the possibility that SYNs might be resegmented in future. And it makes it easy to introduce the alternative segment structure of Appendix A.4 if it is needed.

### 3.3. Rationale for the InSpace Option Format

The format of the InSpace Option (Figure 3) does not necessarily have to comply with the RFC 793 format for TCP options, because it is not intended to ever appear in a sequence of TCP options. In particular, it does not need an Option Kind, because the option is always in a known location. In effect the magic number serves as a multi-octet Option Kind for the first InSpace Option, and the location of each subsequent options is always known as an offset from the previous one, using InOO and Sent Payload Size fields.

Other aspects of the layout are justified as follows:

Length: Whatever the size of the InSpace Option, the right-hand edge of the Length field is always located 4 octets from the start of the option, so that the receiver can find it to determine the layout of the rest of the option. The option is always a multiple

of 4 octets long, so that any subsequent Inner TCP Options comply with TCP's option alignment requirements.

**Sent Payload Size:** This field is 16 bits wide, which is reasonable given segment size cannot exceed the limits set by the Total Length field in the IPv4 header and the Payload Length field in the IPv6 header, both of which are 16 bits wide.

If the sender were to use a jumbogram [RFC2675], it could use the Jumbo InSpace Option defined in Appendix A.3, which offers a 32-bit Sent Payload Size field. The Jumbo InSpace Option is not mandatory to implement for the present experimental specification. Even if it is implemented, it is only defined when SYN=0, given use of a jumbogram for a SYN or SYN/ACK would significantly exceed other limits that TCP sets for these segments.

**InSpace Options Offset** The 14-bit field is in units of 4-octet words, in order to restrict Inner Options to no less than the size of a maximum sized segment (given  $4 * 2^{14} = 2^{16}$  octets).

When SYN=1 the layout of the InSpace Option is extended to include:

**Suffix Options Offset:** The SOO field is the same 14-bit width as the InOO field, and for the same reason. Both the SOO and InOO fields are aligned 2 bits to the left of a word boundary so that they can be used directly in units of octets by masking out the 2-bit field to the right.

**Magic Number B:** The 32-bit size of Magic Number A is not enough to reduce the probability of mistaking the start of an Ordinary SYN Payload for the start of the Inner Space protocol. A 64-bit magic number could have been provided by using the next 4-octet word, but this would be unnecessarily large. Therefore, when SYN=1, 16 more bits of magic number are provided within the InSpace Option. Otherwise, these 16-bits would only have to be used for padding to align with the next 4-octet word boundary anyway.

### 3.4. Protocol Overhead

The overhead of the Inner Space protocol is quantified as follows:

Dual Handshake:

Latency:

Upgraded Server : zero;

Legacy Server: worst latency of the dual handshakes.



Connection Rate: The typical connection rate will inflate by  $P*D$ , where:

P [0-100%] is the proportion of connections that use extra option space;

D [0-100%] is the proportion of these that use a dual handshake (the remainder use a single handshake, e.g. by caching knowledge of upgraded servers).

For example, if  $P=80%$  and  $D=10%$ , the connection rate will inflate by 8%. P is difficult to predict. D is likely to be small, and in the longer term it should reduce to the proportion of connections to remaining legacy servers, which are likely to be the less frequently accessed ones. In the worst case if both P & D are 100%, the maximum that the connection rate can inflate by is 100% (i.e. to twice present levels).

Connection State: Connection state on servers and middleboxes will inflate by  $P*D/R$ , where

R is the average hold time of connection state measured in round trip times

This is because a server or middlebox only holds dual connection state for one round trip, until the RST on one of the two connections. For example, keeping P & D as they were in the above example, if  $R = 3$  round trips {ToDo: TBA}, connection state would inflate by 2.7%. In the longer term, any extra connection state would be focused on legacy servers, with none on upgraded servers. Therefore, if memory for dual handshake flow state was a problem, upgrading the server to support the Inner Space protocol would solve the problem.

Network Traffic: The network traffic overhead is  $2*H*P*D/J$  counting in bytes or  $2*P*D/K$  counting in packets, where

H is 88B for IPv4 or 108B for IPv6 (assuming the Ordinary SYN and SYN/ACK have a TCP header packed to the maximum of 60B with TCP options, they have no TCP payload, their IP headers have no extensions and the InSpace Option in the SYN-U and SYN/ACK-U is 8B);

J is the average number of bytes per TCP connection (in both directions)

K is the average number of packets per TCP connection (in both directions);

For example, keeping and P & D as they were in the above example, if J = 50KiB for IPv4 and K = 70 packets (ToDo: TBA), traffic overhead would be 0.03% counting in bytes or 0.2% counting in packets.

Processing: {ToDo: Implementation tests}

InSpace Option on every non-empty SYN=0 segment:

Network Traffic: The traffic overhead is  $P*Q*4/F$ , where

Q is the proportion of Inner Space connections that leave the protocol enabled after the initial handshake;

F is the average frame size in bytes (assuming one segment per frame).

This is because the InSpace option adds 4B per segment. For example, keeping P as it was in the above example and taking Q=10% and F=750B, the traffic overhead is 0.04%. It is as difficult to predict Q as it is to predict P.

Processing: {ToDo: Implementation tests}

#### 4. Interaction with Pre-Existing TCP Implementations

##### 4.1. Compatibility with Pre-Existing TCP Variants

A TCP option MUST by default only be used as an Outer Option, unless it is explicitly specified that it can (or must) be used as an Inner Option. The following list of pre-existing TCP options can be located as Inner Options:

- o Maximum Segment Size (MSS) [RFC0793];
- o SACK-ok [RFC2018];
- o Window Scale [RFC7323];
- o Multipath TCP [RFC6824], except the Data ACK part of the Data Sequence Signal (DSS) option;
- o TCP Fast Open [I-D.ietf-tcpm-fastopen];
- o The tcpcrypt CRYPT option [I-D.bittau-tcpinc].

The following MUST NOT be located as Inner Options:

- o Timestamp [RFC7323];
- o SACK [RFC2018];
- o The Data ACK part of the DSS option of Multipath TCP [RFC6824];
- o TCP-AO [RFC5925];
- o The tcpcrypt MAC option [I-D.bittau-tcpinc] as long as it covers the TCP header.

{ToDo: The above list is not authoritative. Many of the above schemes involve multiple different types of TCP option, and all the types need to be separately assessed.}

The Inner Space protocol supports TCP Fast Open, by constraining the client to obey the rules in Section 2.3.1.1).

All the sub-types of the MPTCP option [RFC6824] except one could be located as Inner Options. That is, MP\_CAPABLE, MP\_JOIN, ADD\_ADDR(2), REMOVE\_ADDR, MP\_PRIO, MP\_FAIL, MP\_FASTCLOSE. The Data Sequence Signal (DSS) of MPTCP consists of four separable parts: i) the Data ACK; ii) the mapping between the Data Sequence Number and the Subflow Sequence Number over a Data-Level Length; iii) the Checksum; and iv) the DATA\_FIN flag. If MPTCP were re-factored to take advantage of the Inner Space protocol, all these parts except the Data ACK could be located as Inner Options (the Checksum would not be necessary).

The MPTCP Data ACK has to remain as an Outer Option otherwise there would be a risk of flow control deadlock, as pointed out in [Raiciul2]. For instance, a Web client might pipeline multiple requests that fill a Web server's receive buffer, while the Web server might be busy sending a large response to the first request before it reads the second request. If the Data ACK were an Inner Option, the Web client would have to stop acknowledging the first response from the server (due to lack of receive window). Then the server would not be able to move on to the next request--a classic deadlock.

The TCP-AO has to be located as an Outer Option to prevent the possibility of flow-control deadlock (because it would consume receive window on pure ACKs).

All sub-options of the tcpcrypt CRYPT option could be located as Inner Options. However, as long as the tcpcrypt MAC option covers

the TCP header and Outer Options, it has to be located as an Outer Option for the same deadlock reason as TCP-AO.

An Upgraded Server can support SYN Cookies [RFC4987] for Ordinary Connections. For Upgraded Connections Section 2.5 defines a new EchoCookie TCP option that is a prerequisite for InSpace implementations, and provides sufficient space for the more extensive connection state requirements of an InSpace server.

{ToDo: TCP States and Transitions, Connectionless Resets, ICMP Handling, Forward-Compatibility.}

#### 4.2. Interaction with Middleboxes

The interaction with the assumptions about TCP made by middleboxes is covered extensively elsewhere:

- o Section 2.3.3 specifies forwarding behaviour for Inner Options;
- o The following sections explain the Inner Space protocol approach to middlebox traversal:
  - \* Section 3.2.1 justifies the magic number approach;
  - \* Section 3.2.2 explains why the protocol will remain robust as middleboxes evolve;
  - \* Section 3.2.4 justifies including Inner Options in sequence;
  - \* Section 3.2.5) explains how the protocol will remain robust to resegmentation.

#### 4.3. Interaction with the Pre-Existing TCP API

An aim of the Inner Space protocol is for legacy applications to continue to just work without modification. Therefore it is expected that the dual handshaking logic and any maintenance of a cached white-list of servers that support the Inner Space protocol will be implemented beneath the well-known socket interface.

Inner Space implementations will need to comply with the following behaviours to ensure that legacy applications continue to receive predictable behaviour from the socket interface:

Querying local port (TCP client): If an application calls "getsockname()" while the TCP client behind the socket is engaged in a dual TCP handshake, the call SHOULD block until the local TCP

has aborted one of the connections so it knows which of the two ports will continue to be used.

**Binding to an explicit port:** If an application specifies that it wants the TCP client to use a specific port, the Inner Space capability **MUST** be disabled, because the dual handshake has to try two ports. Use of a specific port might be necessary, for example in a port-testing application or if the application wants to explicitly control all the handshaking logic of the Inner Space protocol itself.

**Logging:** The dual handshake will show up as a specific signature in logs of network activity. Log formats might not be able to record two local ports against one socket, so logs might contain unexpected or erroneous data. Even if logs correctly track both connection attempts, log analysis software might not expect to see one socket attempt to use two different ports. {ToDo: All this needs to be turned into a predictability requirement.}

Note that Inner Space has no impact on queries for the remote port from a TCP server. If an application calls "getpeername()" while the TCP server behind the socket is (unwittingly) engaged in a dual handshake, it will return the port of the remote client, even though this connection might subsequently be aborted. This is because a TCP server is not aware of whether it is part of a dual handshake.

It would be appropriate to enable the Inner Space protocol on a per-host or per-user basis. The necessary configuration switch does not need to be standardised, but it might allow the following three states:

**Enabled:** The stack will enable Inner Space on any TCP connection that that needs Inner Space for its TCP options. The stack might still disable the Inner Space protocol autonomously after the initial handshake if it is not needed.

**Forwarding:** The Forwarding mode is for TCP implementations on middleboxes that implement split TCP connections, as discussed in Section 2.3.3. Forwarding mode is similar to Disabled, except it forwards data in SYN without deferring it until the incoming connection is established.

**Disabled:** Inner Space is not enabled by default on any connections, except those that specifically request it.

The socket API might also need to be extended for future applications that want to control the Inner Space protocol explicitly. Experience

will determine the best API, so these ideas are merely informational suggestions at this stage:

**Enabling/disabling Inner Space:** As well as the above per-host or per-user switches, the extended API might need to allow an application to disable Inner Options on a per-socket basis (e.g. for testing). A socket might need to be opened in one of three possible Inner Space modes: i) Enabled; ii) Enabled initially but can be disabled autonomously by the stack if redundant; iii) Enabled initially, then disables itself after the SYN/ACK; and iv) Disabled. It also ought to be possible for an application to disable Inner Options on-demand mid-connection.

**Querying support for Inner Space:** An application might need to be able to determine whether the host supports Inner Space and in which mode it is enabled on a particular socket. For instance, an application might need to choose different socket options depending on whether Inner Space is enabled to make the necessary space available.

**Latency vs Efficiency:** A socket that prefers efficient use of connection state over latency might use the optional explicit variant of the dual handshake (Appendix B). It is unlikely that a new option specific to Inner Space would be needed to express this preference, as many operating systems already offer a similar socket option.

**Logging:** Log formats and log analysis software might need to be extended to distinguish between the deliberate RST within the dual handshake and an unexpected connection RST.

## 5. IANA Considerations

This specification requires IANA to allocate values from the TCP Option Kind name-space against the following names:

- o "Inner Option Space Upgraded (InSpaceU)"
- o "Inner Option Space Ordinary (InSpaceO)"
- o "ModeSwitch"

Early implementation before the IANA allocation MUST follow [RFC6994] and use experimental option 254 and respective Experiment IDs:

- o 0xUUUU (16 bits);
- o 0xO000 (16 bits);

- o 0xMMMM (16 bits);

{ToDo: Values TBA and register them with IANA} then migrate to the assigned option after allocation.

## 6. Security Considerations

Certain cryptographic functions have different coverage rules for the TCP Header and TCP Payload. Placing some TCP options beyond the Data Offset could mean that they are treated differently from regular TCP options. This is a deliberate feature of the protocol, but application developers will need to be aware that this is the case.

A malicious host can send bogus SYN segments with a spoofed source IP address (a SYN flood attack). The Inner Space protocol does not alter the feasibility of this attack. However, the extra space for TCP options on a SYN allows the attacker to include more TCP options on a SYN than before, so it can make a server do more option processing before replying with a SYN/ACK. To mitigate this problem, a server under stress could deprioritise SYNs with longer option fields to focus its resources on SYNs that require less processing.

Each SYN in a SYN flood attack causes a TCP server to consume memory. The Inner Space protocol allows a potentially large amount of TCP option state to be negotiated during the SYN exchange, which could exhaust the TCP server's memory. The EchoCookie TCP option (see Section 2.5) allows the server to place this state in a cookie and send it on the SYN/ACK to the purported address of the client--rather than hold it in memory.

Then, as long as the client returns the cookie on the acknowledgement and the server verifies it, the server can recover its full record of all the TCP options it negotiated and continue the connection without delay. On the other hand, the server's responses to SYNs from spoofed addresses will scatter to those spoofed addresses and the server will not have consumed any memory while waiting in vain for them to reply. See the Security Considerations in [I-D.briscoe-tcpm-echo-cookie] for how the EchoCookie facility protects against reflection and amplification attacks.

## 7. Acknowledgements

The idea of this approach grew out of discussions with Joe Touch while developing draft-touch-tcpm-syn-ext-opt, and with Jana Iyengar and Olivier Bonaventure. The idea that it is architecturally preferable to place a protocol extension within a higher layer, and code its location into upgraded implementations of the lower layer, was originally articulated by Rob Hancock. {ToDo: Ref?} The following

people provided useful review comments: Joe Touch, Yuchung Cheng, John Leslie, Mirja Kuehlewind, Andrew Yourtchenko, Costin Raiciu, Marcelo Bagnulo Braun, Julian Chesterfield and Jaime Garcia.

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#### Appendix A. Protocol Extension Specifications

This appendix specifies protocol extensions that are OPTIONAL while the specification is experimental. If an implementation includes an extension, this section gives normative specification requirements.

However, if the extension is not implemented, the normative requirements can be ignored.

{Temporary note: The IETF may wish to consider making some of these extensions mandatory to implement if early testing shows they are useful or even necessary. Or it may wish to make at least the receiving side mandatory to implement to ensure that two-ended experiments are more feasible.}

A.1. Disabling InSpace and Generic Connection Mode Switching

This appendix is normative. It is separated from the body of the specification because it is OPTIONAL to implement while the Inner Space protocol is experimental. It defines the new ModeSwitch TCP option illustrated in Figure 5. This option provides a facility to disable the Inner Space protocol for the remainder of a connection. It also provides a general-purpose facility for a TCP connection to co-ordinate between the endpoints before switching into a yet-to-be-defined mode.

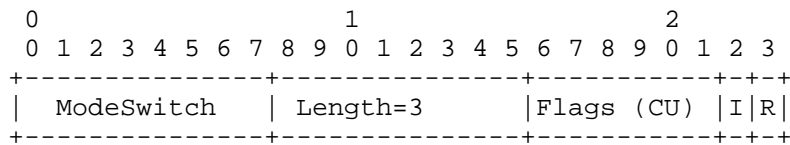


Figure 5: The ModeSwitch TCP Option

The Option Kind is ModeSwitch, the value of which is to be allocated by IANA {ToDo: Value TBA}. ModeSwitch MUST be used only as an Inner Option, because it uses the reliable ordered delivery property of Inner Options. Therefore implementation of the Inner Space protocol is REQUIRED for an implementation of ModeSwitch. Nonetheless, ModeSwitch is a generic facility for switching a connection between yet-to-be-defined modes that do not have to relate to extra option space.

The sender MUST set the option Length to 3 (octets). The Length field MUST be forwarded unchanged by other nodes, even if its value is different.

The Flags field is available for defining modes of the connection. Only two connection modes are currently defined. The first 6 bits of the Flags field are Currently Unused (CU) and the sender MUST set them to zero. The CU flags MUST be ignored and forwarded unchanged by other nodes, even if their value is non-zero.

The two 1-bit connection mode flags that are currently defined have the following meanings:

- o R: Request flag if 1. Request mode is a special mode that allows the hosts to co-ordinate a change to any other mode(s);
- o I: Inner Space mode: Enabled if 1, Disabled if 0.

The default Inner Space mode at the start of a connection is I=1, meaning Inner Space is in enabled mode.

The procedure for changing a mode or modes is as follows:

- o The host that wants to change modes (the requester) sends a ModeSwitch message as an Inner Option with R=1 and with the other flag(s) set to the mode(s) it wants to change to. The requester does not change modes yet.
- o The responder echoes the mode flag(s) it is willing to change to, with the request flag R=0.
- o The half-connection from the responder changes to the mode(s) it confirms directly after the end of the segment that echoes its confirmation, i.e. after the last octet of the TCP Payload following the ModeSwitch option that echoes its confirmation. Therefore it sends the segment carrying the confirmation in the prior mode(s) of the connection.
- o Once the requester receives the responder's confirmation message, it re-echoes its confirmation of the responder's confirmation, with the mode(s) set to those that both hosts agree on and R=0.
- o The half-connection from the requester changes to the mode(s) it confirms directly after the end of the segment that re-echoes its confirmation. Therefore it sends the segment carrying the confirmation in the prior mode(s) of the connection.
- o The responder can refuse a request to change into a mode in any one of three ways:
  - \* either implicitly by never confirming it;
  - \* or explicitly by sending a message with R=0 and the opposite mode;
  - \* or explicitly by sending a counter-request to switch to the opposite mode (that the connection is already in) with R=1.

The regular TCP sequence numbers and acknowledgement numbers of requests or confirmations can be used to disambiguate overlapping requests or responses.

Once a host switches to Disabled mode, it MUST NOT send any further InSpace Options. Therefore it can send no further Inner Options and it cannot switch back to Enabled mode for the rest of the connection.

To temporarily reduce InSpace overhead without permanently disabling the protocol, the sender can use a value of 0xFFFF in the Sent Payload Size (see Section 2.4).

#### A.2. Dual Handshake: The Explicit Variant

This appendix is normative. It is separated from the body of the specification because it is OPTIONAL to implement while the Inner Space protocol is experimental. It is not mandatory to implement because it will be more useful once the Inner Space protocol has become accepted widely enough that fewer middleboxes will discard SYN segments carrying this option (see Appendix B for when best to deploy it). It only works if both ends support it, but it can be deployed one end at a time, so there is no need for support in early experimental implementations.

{Temporary note: The choice between the explicit handshake in the present section or the handshake in Section 2.1.1 is a tradeoff between robustness against middlebox interference and minimal server state. During the IETF review process, one might be chosen as the only variant to go forward, at which point the other will be deleted. Alternatively, the IETF could require a server to understand both variants and a client could be implemented with either, or both. If both, the application could choose which to use at run-time. Then we will need a section describing the necessary API.}

This explicit dual handshake is similar to that in Section 2.1.1, except the SYN that the Upgraded Client sends on the Ordinary Connection is explicitly distinguishable from the SYN that would be sent by a Legacy Client. Then, if the server actually is an Upgraded Server, it can reset the Ordinary Connection itself, rather than creating connection state for at least a round trip until the client resets the connection.

For an explicit dual handshake, the TCP client still sends two alternative SYNs: a SYN-O intended for Legacy Servers and a SYN-U intended for Upgraded Servers. The two SYNs MUST have the same network addresses and the same destination port, but different source ports. Once the client establishes which type of server has responded, it continues the connection appropriate to that server

type and aborts the other. The SYN intended for Upgraded Servers includes additional options within the TCP Data (the SYN-U defined as before in Section 2.2.1).

Table 2 summarises the TCP 3-way handshake exchange for each of the two SYNs in the two right-hand columns, between an Upgraded TCP Client (the active opener) and either:

1. a Legacy Server, in the top half of the table (steps 2-4), or
2. an Upgraded Server, in the bottom half of the table (steps 2-4)

The table uses the same layout and symbols as Table 1, which has already been explained in Section 2.1.1.

		Ordinary Connection	Upgraded Connection
1	Upgraded Client	>SYN-0	>SYN-U
/\/\	/\/\/\/\/\/\/\/\	/\/\/\/\/\/\/\/\	/\/\/\/\/\/\/\/\
2	Legacy Server	<SYN/ACK	<SYN/ACK
3a	Upgraded Client	Waits for response to both SYNs	
3b	"	>ACK	>RST
4		Cont...	
/\/\	/\/\/\/\/\/\/\/\	/\/\/\/\/\/\/\/\	/\/\/\/\/\/\/\/\
2	Upgraded Server	<RST	<SYN/ACK-U
3	Upgraded Client		>ACK
4			Cont...

Table 2: Explicit Variant of Dual 3-Way Handshake in Two Server Scenarios

As before, an Upgraded Server MUST respond to a SYN-U with a SYN/ACK-U. Then, the client recognises that it is talking to an Upgraded Server.

Unlike before, an Upgraded Server MUST respond to a SYN-0 with a RST. However, the client cannot rely on this behaviour, because a

middlebox might be stripping Outer TCP Options which would turn the SYN-O into a regular SYN before it reached the server. Then the handshake would effectively revert to the implicit variant. Therefore the client's behaviour still depends on which SYN-ACK arrives first, so its response to SYN-ACKs has to follow the rules specified for the implicit handshake variant in Section 2.1.1.

The rules for processing TCP options are also unchanged from those in Section 2.3.

#### A.2.1. SYN-O Structure

The SYN-O is merely a SYN with an extra InSpaceO Outer TCP Option as shown in Figure 6. It merely identifies that the SYN is opening an Ordinary Connection, but explicitly identifies that the client supports the Inner Space protocol.

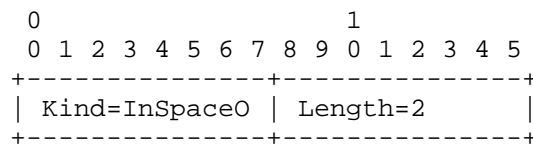


Figure 6: An InSpaceO TCP Option Flag

An InSpaceO TCP Option has Option Kind InSpaceO with value {ToDo: Value TBA} and MUST have Length = 2 octets.

To use this option, the client MUST place it with the Outer TCP Options. A Legacy Server will just ignore this TCP option, which is the normal behaviour for an option that TCP does not recognise [RFC0793].

#### A.2.2. Retransmission Behaviour - Explicit Variant

If the client receives a RST on one connection, but a short while after that {ToDo: duration TBA} the response to the SYN-U has not arrived, it SHOULD retransmit the SYN-U. If latency is more important than the extra TCP option space, in parallel to any retransmission, or instead of any retransmission, the client MAY send a SYN without any InSpace TCP Option, in case this is the cause of the black-hole. However, the presence of the RST implies that the SYN with the InSpaceO TCP Option (the SYN-O) probably reached the server, therefore it is more likely (but not certain) that the lack of response on the other connection is due to transmission loss or congestion loss.

If the client receives no response at all to either the SYN-O or the SYN-U, it SHOULD solely retransmit one or the other, not both. If latency is more important than the extra TCP option space, it SHOULD send a SYN without an InSpaceO TCP Option. Otherwise it SHOULD retransmit the SYN-U. It MUST NOT retransmit both segments, because the lack of response could be due to severe congestion.

### A.2.3. Corner Cases

There is a small but finite possibility that the Explicit Dual Handshake might encounter the cases below. The Implicit Handshake (Section 2.1.1) is robust to these possibilities, but the Explicit Handshake is not, unless the following additional rules are followed:

Both successful: This could occur if one load-sharing replica of a server is upgraded, while another is not. This could happen in either order but, in both cases, the client aborts the last connection to respond:

- \* The client completes the Ordinary Handshake (because it receives a SYN/ACK), but then, before it has aborted the Upgraded Connection, it receives a SYN/ACK-U on it. In this case, the client MUST abort the Upgraded Connection even though it would work. Otherwise the client will have opened both connections, one with Inner TCP Options and one without. This could confuse the application.
- \* The client completes the Upgraded Connection after receiving a SYN/ACK-U, but then it receives a SYN/ACK in response to the SYN-O. In this case, the client MUST abort the connection it initiated with the SYN-O.

Both aborted: The client might receive a RST in response to its SYN-O, then an Ordinary SYN/ACK on its Upgraded Connection in response to its SYN-U. This could occur i) if a split connection middlebox actively forwards unknown options but holds back or discards data in a SYN; or ii) if one load-sharing replica of a server is upgraded, while another is not.

Whatever the likely cause, the client MUST still respond with a RST on its Upgraded Connection. Otherwise, its Inner TCP Options will be passed as user-data to the application by a Legacy Server.

If confronted with this scenario where both connections are aborted, the client will not be able to include extra options on a SYN, but it might still be able to set up a connection with extra option space on all the other segments in both directions using the approach in Appendix A.2.4. If that doesn't work either, the

client's only recourse is to retry a new dual handshake on different source ports, or ultimately to fall-back to sending an Ordinary SYN.

#### A.2.4. Workaround if Data in SYN is Blocked

If a path either holds back or discards data in a SYN-U, but there is evidence that the server is upgraded from a RST response to the SYN-O, the strategy below might at least allow a connection to use extra option space on all the segments except the SYN.

It is assumed that the symptoms described in the 'both aborted' case (Appendix A.2.3) have occurred, i.e. the server has responded to the SYN-O with a RST, but it has responded to the SYN-U with an Ordinary SYN/ACK not a SYN/ACK-U, so the client has had to RST the Upgraded Connection as well. In this case, the client SHOULD attempt the following (alternatively it MAY give up and fall back to opening an Ordinary TCP connection).

The client sends an 'Alternative SYN-U' by including an InSpaceU Outer TCP Option (Figure 7). This Alternative SYN-U merely flags that the client is attempting to open an Upgraded Connection. The client MUST NOT include any Inner Options or InSpace Option or Magic Number. If the previous aborted SYN/ACK-U acknowledged the data that the client sent within the original SYN-U, the client SHOULD resend the TCP Payload data in the Alternative SYN-U, otherwise it might as well defer it to the first data segment.

```

0                               1
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5
+-----+-----+
| Kind=InSpaceU | Length=2      |
+-----+-----+

```

Figure 7: An InSpaceU Flag TCP option

An InSpaceU Flag TCP Option has Option Kind InSpaceU with value {ToDo: Value TBA} and MUST have Length = 2 octets.

To use this option, the client MUST place it with the Outer TCP Options. A Legacy Server will just ignore this TCP option, which is the normal behaviour for an option that TCP does not recognise [RFC0793]. Because the client has received a RST from the server in response to the SYN-O it can assume that the server is upgraded. So the client probably only needs to send a single Alternative SYN-U in this repeat attempt. Nonetheless, the RST might have been spurious.



Therefore the client MAY also send an Ordinary SYN in parallel, i.e. using the Implicit Dual Handshake (Section 2.1.1).

If an Upgraded Server receives a SYN carrying the InSpaceU option, it MUST continue the rest of the connection as if it had received a full SYN-U (Section 2.2), i.e. by processing any Outer Options in the SYN-U and responding with a SYN/ACK-U.

A.3. Jumbo InSpace TCP Option (only if SYN=0)

This appendix is normative. It is separated from the body of the specification because it is OPTIONAL to implement while the Inner Space protocol is experimental. In experimental implementations, it will be sufficient to implement the required behaviour for when the Length of a received InSpace Option is not recognised (Section 2.4).

If the IPv6 Jumbo extension header is used, the SentPayloadSize field will need to be 4 octets wide, not 2 octets. This section defines the format of the InSpace Option necessary to support jumbograms.

If sending a jumbogram, a sender MUST use the InSpace Option format defined in Figure 8. All the fields have the same meanings as defined in Section 2.2.2, except InOO and SentPayloadSize use more bits.

When reading a segment, the Jumbo InSpace Option could be present in a packet that is not a jumbogram (e.g. due to resegmentation). Therefore a receiver MUST use the Jumbo InSpace Option to work along the stream irrespective of whether arriving packets are jumbo sized or not.

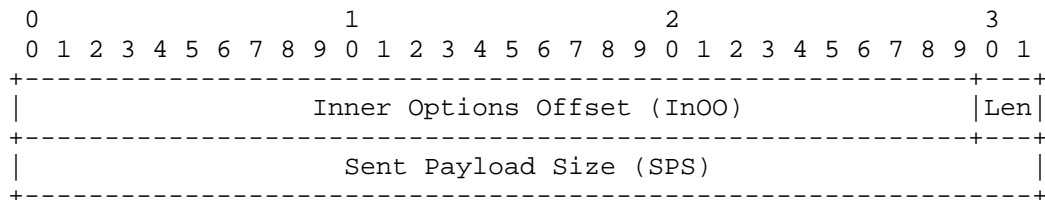


Figure 8: InSpace Option for a Jumbo Data-UNJH

A.4. Upgraded Segment Structure to Traverse DPI boxes

This appendix is normative. It is separated from the body of the specification because it is OPTIONAL to implement while the Inner Space protocol is experimental. If a receiver has implemented the Inner Space protocol but not this extension, no mechanism is provided for it to ask the sender to fall-back to the base Inner Space

protocol if it is sent a segment formatted according to this extension. However, it will at least fall-back naturally to regular TCP behaviour because of the dual handshake.

In experiments conducted between 2010 and 2011, [Hondall] reported that 7 of 142 paths (about 5%) blocked access to port 80 if the payload was not parsable as valid HTTP. This variant of the specification has been defined in case experiments prove that it significantly improves traversal of such deep packet inspection (DPI) boxes.

This variant starts the TCP Data with the expected app-layer headers on the first two segments in each direction:

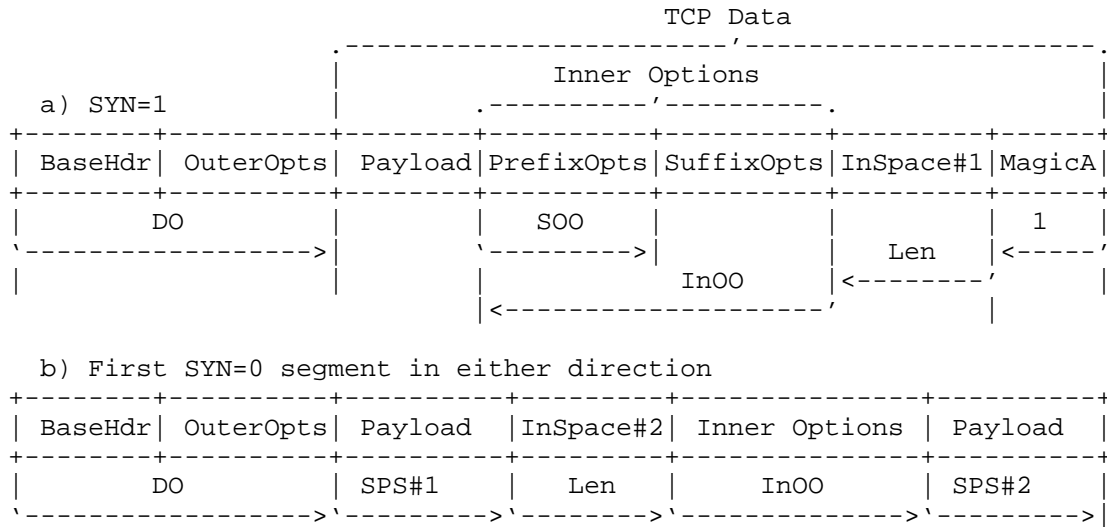
SYN=1: The structure in Figure 9a) is used on a SYN or SYN/ACK. The sender locates the 4-octet Magic Number A at the end of the segment. The sender right-aligns the 8-octet InSpace Option just before Magic Number A. Then it right-aligns the Inner Options against the InSpace Option, all after the end of the TCP Payload. The start of the Inner Options is therefore  $4 * (InOO + 3)$  octets before the end of the segment, where InOO is read from within the InSpace Option.

A receiver implementation will check whether Magic Number A is present at the end of the segment if it does not first find it at the start of the segment. Although the InnerOptions are located at the end of the TCP Payload, they are considered to be applied before the first octet of the TCP Payload.

SYN=0: The structure of the first non-SYN segment that contains any TCP Data is shown in Figure 9b).

The receiver will find the second InSpace Option (InSpace#2) located SPS#1 octets from the start of the segment, where SPS#1 is the value of Sent Payload Size that was read from the InSpace Option in the previous (SYN=1) segment that started the half-connection. Although the Inner Options are shifted, as for the first segment, they are still considered to be applied at the start of the TCP Data in this second segment.

From the second InSpace Option onwards, the structure of the stream reverts to that already defined in Section 2.2.1. So the value of Sent Payload Size (SPS#2) in the second InSpace Option (InSpace #2) defines the length of any remaining TCP Payload before the end of the first data segment, as shown.



All offsets are specified in 4-octet (32-bit) words, except SPS, which is in octets.

Figure 9: Segment Structures to Traverse DPI boxes (not to scale)

It is recognised that having to work from the end of the first segment makes processing more involved. Experimental implementation of this approach will determine whether the extra complexity improves DPI box traversal sufficiently to make it worthwhile.

Appendix B. Comparison of Alternatives

B.1. Implicit vs Explicit Dual Handshake

In the body of this specification, two variants of the dual handshake are defined:

1. The implicit dual handshake (Section 2.1.1) starting with just an Ordinary SYN (no InSpace0 flag option) on the Ordinary Connection;
2. The explicit dual handshake (Appendix A.2) starting with a SYN-0 (InSpace0 flag option) on the Ordinary Connection.

Both schemes double up connection state (for a round trip) on the Legacy Server. But only the implicit scheme doubles up connection state (for a round trip) on the Upgraded Server as well. On the other hand, the explicit scheme risks delay accessing a Legacy Server

if a middlebox discards the SYN-0 (it is possible that some firewalls will discard packets with unrecognised TCP options {ToDo: ref?}). Table 3 summarises these points.

	SYN (Implicit)	SYN-L (Explicit)
Minimum state on Upgraded Server	-	+
Minimum risk of delay to Legacy Server	+	-

Table 3: Comparison of Implicit vs. Explicit Dual Handshake on the Ordinary Connection

There is no need for the IETF to choose between these. If the specification allows either or both, the tradeoff can be left to implementers at build-time, or to the application at run-time.

Initially clients might choose the Implicit Dual Handshake to minimise delays due to middlebox interference. But later, perhaps once more middleboxes support the scheme, clients might choose the Explicit scheme, to minimise state on Upgraded Servers.

#### Appendix C. Protocol Design Issues (to be Deleted before Publication)

This appendix is informative, not normative. It records outstanding issues with the protocol design that will need to be resolved before publication.

Option alignment following re-segmentation: If the byte-stream is resegmented (e.g. by a connection splitter), the TCP options within the stream will not necessarily align on 4-octet word boundaries within the new segments.

Ossifies reliable ordered delivery into TCP design: At present it is theoretically possible to implement a variant of TCP that provides partial reliability. Inner Space as it stands would prevent a future partial reliable TCP, but not if out-of-order delivery were added, as discussed below.

Ideally Outer Options in Inner: Ideally enable Outer Options to be located beyond the Data Offset: i) without consuming receive window ii) either without consuming sequence space or, if otherwise, must be robust to middlebox correction; iii) delivered immediately on reception, not in sent order. Could use the Minion

[Iyengar10] variant (or a similar variant) of the consistent overhead byte-stuffing (COBS) encoding.

#### Appendix D. Change Log (to be Deleted before Publication)

A detailed version history can be accessed at  
<<http://datatracker.ietf.org/doc/draft-briscoe-tcpm-inner-space/history/>>

From briscoe-...-inner-space-00 to briscoe-...-inner-space-01:

Technical changes:

- \* Corrected DO to 4 \* DO (twice)
- \* Confirmed that receive window applies to Inner Options
- \* Generalised the cause of decryption/decompression from a previous TCP option to any previous control message
- \* Added requirement for a middlebox not to defer data on SYN
- \* Latency of dual handshake is worst of two
- \* Completed "Interaction with Pre-Existing TCP Implementations" section, covering other TCP variants, TCP in middleboxes and the TCP API. Shifted some TCP options to Outer only, because of RWND deadlock problem
- \* Added two outstanding issues: i) ossifies reliable ordered delivery; ii) Ideally Outer in Inner.

Editorial changes:

- \* Removed section on Echo TCP option to a separate I-D that is mandatory to implement for inner-space, and shifted some SYN flood discussion in Security Considerations
- \* Clarifications throughout
- \* Acknowledged more review comments

From draft-briscoe-tcpm-syn-op-sis-02 to draft-briscoe-tcpm-inner-space-00:

The Inner Space protocol is a development of a proposal called the SynOpSis (Sister SYN options) protocol. Most of the elements of Inner Space were in SynOpSis, such as the implicit and explicit dual handshakes; the use of a magic number to flag the existence

of the option; the various header offsets; and the option processing rules.

The main technical differences are: Inner Space extends option space on any segment, not just the SYN; this advance requires the introduction of the Sent Payload Size field and a general rearrangement and simplification of the protocol format; the option processing rules have been extended to assure compatibility with TFO and one degree of recursion has been introduced to cater for encryption or compression of Inner Options; The Echo option has been added to provide a SYN-cookie-like capability. Also, the default protocol has been pared down to the bare bones and optional extensions relegated to appendices.

The main editorial differences are: The emphasis of the Abstract and Introduction has expanded from a focus on just extra space using the dual handshake to include much more comprehensive middlebox traversal. A comprehensive Design Rationale section has been added.

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E. Rescorla  
Mozilla  
October 27, 2014

TCP Use TLS Option  
draft-rescorla-tcpinc-tls-option-01

Abstract

This document defines a TCP option (TCP-TLS) to indicate that TLS should be negotiated on a given TCP connection.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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This Internet-Draft will expire on April 30, 2015.

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## 1. Introduction

RFC EDITOR: PLEASE REMOVE THE FOLLOWING PARAGRAPH The source for this draft is maintained in GitHub. Suggested changes should be submitted as pull requests at <https://github.com/ekr/tcpinc-tls>. Instructions are on that page as well.

The TCPINC WG is chartered to define protocols to provide ubiquitous, transparent security for TCP connections.

While TLS [RFC5246] is by far the most popular mechanism for securing TCP data, adding it to a given protocol requires some sort of coordination; if a client just tries to initiate TLS with a non-TLS server, the server will most likely reject the protocol messages because they do not conform to its expectations for the application layer protocol. This coordination can take a number of forms, including:

- o An external signal in the URL that the client should do TLS (e.g., "https:")
- o Using a separate port for the secure and non-secure versions of the protocol.
- o An extension to the application protocol to negotiate use or non-use of TLS ("STARTTLS")

While mechanisms of this type are in wide use, they all require modifications to the application layer and thus do not meet the goals of TCPINC. This document describes a TCP option which allows a pair of communicating TCP endpoints to negotiate TLS use automatically



without modifying the application layer protocols, thus allowing for transparent deployment.

2. Overview

The basic idea behind the TCP-TLS option is simple. The SYN and SYN/ACK messages carry TCP options indicating the willingness to do TLS and some basic information about the expected TLS modes. If both sides want to do TLS and have compatible modes, then the application data is automatically TLS protected prior to being sent over TCP. Otherwise, the application data is sent as usual.

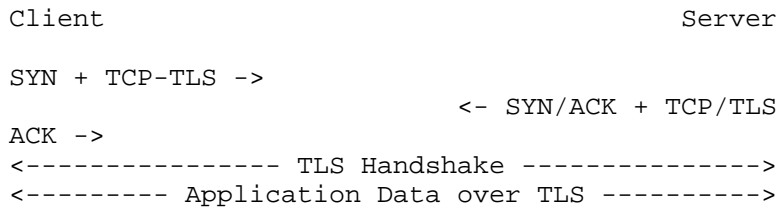


Figure 1: Negotiating TLS with TCP-TLS

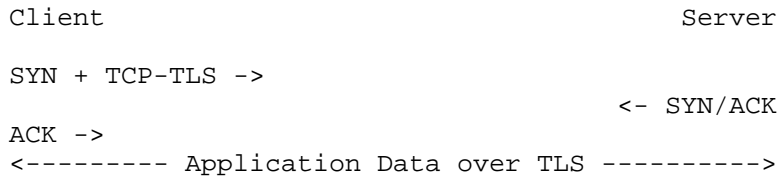
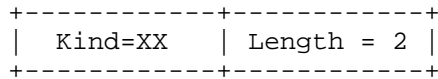


Figure 2: Fall back to TCP

If use of TLS is negotiated, the data sent over TCP simply is TLS data in compliance with {RFC5246}.

3. Extension Definition

The TCP-TLS option is very simple. For the normal case where each side knows who is the passive and who is the active opener, the option is empty. I.e.



In this case, the active opener MUST take on the role of TLS Client.

In the abnormal case of simultaneous open, the option includes a tiebreaker value.

```

+-----+-----+-----+-----+
| Kind=XX | Length = 8 | Tiebreaker |
+-----+-----+-----+-----+
|                                     |
|                                     |
+-----+-----+-----+-----+

```

The tiebreaker field is a 48-bit value which is used to determine the TLS roles, with the highest value being the TLS client and the lowest value being the TLS server. Applications MUST generate the tiebreaker randomly. If both sides generate the same tiebreaker value, then TCP-TLS MUST NOT be used (this has a vanishing probability of happening by accident.)

The default mode of operation MUST be the ordinary client/server mode and implementations MUST only use the simultaneous open mode if instructed by an application. If an implementation in simultaneous open mode receives an option without a tiebreaker, it MUST treat that tiebreaker as 0. If simultaneous open mode is not in use, and implementations detect a simultaneous open, then they MUST NOT try to negotiate TLS, regardless of the presence of this option.

If an endpoint sends the TCP-TLS option and correctly receives it from the other side it SHALL immediately negotiate TLS, taking on the role described above.

Once the TLS handshake has completed, all application data SHALL be sent over that negotiated TLS channel. Application data MUST NOT be sent prior to the TLS handshake.

If the TLS handshake fails for non-cryptographic reasons such as failure to negotiate a compatible cipher or the like, endpoints SHOULD behave as if the the TCP-TLS option was not present. This is obviously not the conventional behavior for TLS failure, but as the entire idea here is to be opportunistic and the attacker can simply suppress the TCP-TLS option entirely, this provides the maximum robustness against broken intermediaries. If the TLS handshake fails for cryptographic reasons that indicate damage to the datastream (e.g., a decryption failure or a Finished failure) then the endpoints SHOULD signal a connection failure, as this suggests that there is a middlebox modifying the data and there is a reasonable chance that the state is now corrupted.

#### 4. Transport Integrity

The basic operational mode defined by TCP-TLS protects only the application layer content, but not the TCP segment metadata. Upon receiving a packet, implementations MUST first check the TCP checksum and discard corrupt packets without presenting them to TLS. If the TCP checksum passes but TLS integrity fails, the connection MUST be torn down.

Thus, TCP-TLS provides automatic security for the content, but not protection against DoS-style attacks. For instance, attackers will be able to inject RST packets, bogus application segments, etc., regardless of whether TLS authentication is used. Because the application data is TLS protected, this will not result in the application receiving bogus data, but it will constitute a DoS on the connection.

This attack can be countered by using TCP-TLS in combination with TCP-AO [RFC5925], as follows:

1. The TLS connection is negotiated using the "tcpao" ALPN [I-D.ietf-tls-applayerprotoneg] indicator.
2. Upon TLS handshake completion, a TLS Exporter [RFC5705] is used to generate keying material of appropriate length using exporter label TBD.
3. Further packets are protected using TCP-AO with the generated keys.

The Finished messages MUST NOT be protected with AO. The first application data afterwards MUST be protected with AO. Note that because of retransmission, non-AO packets may be received after AO has been engaged; they MUST be ignored.

[[OPEN ISSUE: How do we negotiate the parameters? Do we need a use\_ao option like with RFC 5764? Is ALPN really what we want here?]]

[[TODO: verify that the state machine matches up here.]]

#### 5. Implementation Options

There are two primary implementation options for TCP-TLS:

- o Implement all of TCP-TLS in the operating system kernel.

- o Implement just the TCP-TLS negotiation option in the operating system kernel with an interface to tell the application that TCP-TLS has been negotiated and therefore that the application must negotiate TLS.

The former option obviously achieves easier deployment for applications, which don't have to do anything, but is more effort for kernel developers and requires a wider interface to the kernel to configure the TLS stack. The latter option is inherently more flexible but does not provide as immediate transparent deployment. It is also possible for systems to offer both options.

## 6. TLS Profile

Implementations of this specification MUST at minimum support TLS 1.2 [RFC5246] and MUST support cipher suite XXX. Implementations MUST NOT negotiate versions of TLS prior to TLS 1.2. [[OPEN ISSUE: What cipher suites? Presumably we require one authenticated and one anonymous cipher suite, all with GCM.]] [[OPEN ISSUE: If TLS 1.3 is ready, we may want to require that.]]

## 7. Channel Bindings

This specification is compatible with external authentication via TLS Channel Bindings [RFC5929]. If Channel Bindings are to be used, the TLS Extended Master Secret Extension [I-D.ietf-tls-session-hash]

## 8. NAT/Firewall considerations

If use of TLS is negotiated, the data sent over TCP simply is TLS data in compliance with [RFC5246]. Thus it is extremely likely to pass through NATs, firewalls, etc. The only kind of middlebox that is likely to cause a problem is one which does protocol enforcement that blocks TLS on arbitrary (non-443) ports but also passes unknown TCP options. Although no doubt such devices do exist, because this is a common scenario, a client machine should be able to probe to determine if it is behind such a device relatively readily.

## 9. IANA Considerations

IANA [shall register/has registered] the TCP option XX for TCP-TLS.

IANA [shall register/has registered] the ALPN code point "tcpao" to indicate the use of TCP-TLS with TCP-AO.

## 10. Security Considerations

The mechanisms in this document are inherently vulnerable to active attack because an attacker can remove the TCP-TLS option, thus downgrading you to ordinary TCP. Even when TCP-AO is used, all that is being provided is continuity of authentication from the initial handshake. If some sort of external authentication mechanism was provided or certificates are used, then you might get some protection against active attack.

Once the TCP-TLS option has been negotiated, then the connection is resistant to active data injection attacks. If TCP-AO is not used, then injected packets appear as bogus data at the TLS layer and will result in MAC errors followed by a fatal alert. The result is that while data integrity is provided, the connection is not resistant to DoS attacks intended to terminate it.

If TCP-AO is used, then any bogus packets injected by an attacker will be rejected by the TCP-AO integrity check and therefore will never reach the TLS layer. Thus, in this case, the connection is also resistant to DoS attacks, provided that endpoints require integrity protection for RST packets. If endpoints accept unauthenticated RST, then no DoS protection is provided.

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July 3, 2014

A DTLS Extension for TCP  
draft-thomson-tcpinc-dtls-00

Abstract

Opportunistic security is provided for TCP using a modified DTLS.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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## 1. Introduction

TCP [RFC0793] is a widely used protocol.

As part of a general "secure all the things" effort, the IETF is defining opportunistic security options for all the protocols it maintains. Opportunistic security ensures that we accelerate the eventual heat death of the universe, and discourages certain classes of attack [RFC7258].

Opportunistic approaches are the most practical way to ensure wider deployment of security because they don't immediately depend on solving hard problems like authentication.



In that spirit, reusing existing security protocols reduces the cost to implement, deploy and analyse new protocol modifications. TLS [RFC5246] and DTLS [RFC6347] represent the current best in class security protocols.

This specification defines how DTLS can be used to protect TCP. This addresses the requirements outlined in [I-D.bellovin-tcpsec]. A small modification to the TCP record layer allows for the protection of the TCP pseudo header, with an allowance for NAPT (editor: why does Bellovin even suggest that protection of IP/port is even feasible?) and per-option opt-out.

In addition, all the features of DTLS are made available:

- o Cipher suite negotiation and agility
- o Years of security analysis
- o Downgrade protection in the handshake
- o Session bindings
- o Optional peer authentication
- o A range of available extensions

In addition to this, new upgrades to DTLS can be trivially added. Thus, improvements to algorithms or the DTLS handshake are entirely portable.

### 1.1. Terminology

The usual. [RFC2119] explains what those are.

## 2. DTLS Layering

This extension to TCP places a continuous sequence of DTLS records as the payload of TCP. These records provide confidentiality and integrity protection for their content, plus integrity protection for the TCP header and pseudoheader.

An option negotiates the use of this extension. This option is added to the SYN message to indicate support, and to the ACK message to indicate acceptance.

Once enabled, all DTLS records, including handshake messages, are carried as TCP data. The data for the protected TCP stream is the concatenated content of DTLS messages.

TCP clients are automatically entered into the DTLS client role; and TCP servers automatically enter the DTLS server role. Where TCP simultaneous open is used, a lottery determines the roles Section 5.

### 3. DTLS Record Protection Option

This option is used to negotiate the use of DTLS. It is assigned a TCP option kind of 0xTBD Section 8.

The format of the DTLS record protection option is a single octet flags field, followed by a list of protected option kinds.

#### 3.1. DTLS Record Protection Flags

The content of the flags field is a bit pattern of features. The following features are defined in this document:

- o FORBID\_NAPT: Bit 0 (the first and most significant bit of the first octet) being set indicates that DTLS protection is to be extended to addressing elements, see Section 4.3.

A client can set these bits to request the defined alterations to the protocol. A server can accept these alterations by including these in its ACK message, or it can reject the alterations by clearing the bit.

All bits in this option MUST be set to zero unless they are explicitly understood. A sender MUST remove trailing octets that have all zero values from the option.

An IANA registry is established to maintain these bits Section 8.2.

#### 3.2. Protection Option Kinds

The DTLS record protection option includes a list of the TCP options that are covered by DTLS integrity protection, each occupying a single octet. Just as TCP options are terminated by a zero octet, this list is terminated by a zero value.

Any data following this list is reserved for extension and MUST be ignored.

### 4. Modified DTLS AEAD Operation

This mechanism MUST be used with an Authenticated Encryption with Additional Data (AEAD) mode. The DTLS record layer is modified to provide integrity protection for the TCP pseudoheader and header by including this as part of the additional data.

An important characteristic of this is that records are protected as though each individual DTLS record is part of a unique TCP segment. This ensures that repacketization by middleboxes does not result in records being marked as invalid.

TCP middleboxes can, and sometimes do, split or coalesce TCP segments. This affects the calculation of the authenticated data that is input to the AEAD protection.

To prevent this from invalidating integrity checks unnecessarily, the associated data passed to the AEAD algorithm contains a modified value of the TCP header and pseudoheader.

For a sender that transmits a single DTLS record in each TCP segment with only protected TCP options, this demands no additional calculation. However, a receiver needs to construct the TCP header and pseudoheader. The length of this packet is based on the length of the DTLS record, with the value of protected TCP options being extracted from the TCP header of the segment that carries the first byte of the DTLS record.

In TLS and DTLS, the additional data that is protected by the AEAD function is [RFC5246]:

```
additional_data = seq_num + TLSCompressed.type +
                  TLSCompressed.version + TLSCompressed.length;
```

where "+" denotes concatenation.

This specification expands the fields that are protected to include a constructed TCP pseudoheader and header as follows:

```
tcp_additional_data = pseudoheader + tcp_header +
                      additional_data;
```

Construction of the "pseudoheader" and "tcp\_header" portions of the authenticated data are described in the following sections.

#### 4.1. TCP Pseudoheader Construction

The pseudoheader that is used for AEAD input depends on the IP version in use, for IPv4 [RFC0793], with length of fields in bits shown in parentheses:

```
pseudoheader_v4 = source_address(32) + destination_address(32) +
                  zero(8) + protocol(8) + tcp_length(16)
```

Or for IPv6 [RFC2460]:

```
pseudoheader_v6 = source_address(128) + destination_address(128) +  
                  tcp_length(32) + zero(24) + protocol(8)
```

In both cases, the value for "tcp\_length" is derived by constructing a TCP header as described in Section 4.2.

The values for "source\_address" and "destination\_address" are replaced with zero bits, unless the FORBID\_NAPT flag is enabled. Setting these values to zero permits the use of NAPT devices.

#### 4.2. TCP Header Construction

In order to ensure that the protocol is robust in the presence of middleboxes, unprotected TCP options are removed from the TCP header before applying protection.

```
tcp_header = source_port(16) + destination_port(16) +  
             sequence_number(32) + acknowledgement_number(32) +  
             data_offset(4) + flags(12) + window(16) +  
             checksum(16) + urgent_pointer(16) + options(?)
```

The following construction rules apply:

**source\_port and destination\_port:** These fields MUST be replaced with zero bits unless the FORBID\_NAPT flag is enabled for the session. Setting these values to zero permits the use of port translation.

**sequence\_number:** This field MUST be set to the sequence number corresponding to the first octet of the DTLS record. If multiple segments are combined into a single packet, this will be different to the sequence number that appears in the TCP header.

**acknowledgement\_number and window:** These fields MUST be replaced with zero bits. Removing the acknowledgement and congestion window from integrity protection does provide some opportunities to an on-path attacker Section 7.2.

**data\_offset:** The data offset MUST be set to the size of the modified TCP header.

**flags:** The reserved and flags part of the TCP header is protected.

**checksum:** This field MUST be replaced with zero bits, just as it is when the TCP checksum is calculated.

**urgent\_pointer:** The urgent pointer is protected.

options: The set of options that are included under protection are included. Options that are not protected are removed. Section 3.2 described how options are selected for protection. The list of options is terminated with an option of kind 0x0 and padding to a multiple of 32 bits with zero octets.

This construction permits the addition and removal of options by middleboxes, as long as they are not in the list of options that are protected. It also permits repacketization and acknowledgment.

#### 4.3. Forbid NAPT

The DTLS record protection option Section 3 contains a FORBID\_NAPT bit that can be used to signal that network address and port translation (NAPT) is forbidden.

If the FORBID\_NAPT option is not set, addressing information is replaced with zero values. This is the IP (v4 or v6) address fields in the pseudoheader, and the source and destination port numbers.

Why anyone in their right mind would do this is beyond me, but it's in the requirements and this would seem to be sufficient to address those, albeit by making the whole mechanism more complex.

#### 5. DTLS Role Selection

Ordinarily, the role of DTLS client is assumed by the peer that sends the first TCP SYN packet (the TCP client), and the role of DTLS server is assumed by the peer that responds (the TCP server).

Peers that perform a TCP simultaneous open - that is, where both peers simultaneously send SYN packets to open a connection, often to work around middlebox limitations - are assigned client and server roles in DTLS based on the following rules.

If only one peer provides a DTLS handshake in TCP fast open data [I-D.ietf-tcpm-fastopen], then that peer becomes the client. Note that including the DTLS handshake message in the initial SYN packet is only safe if there is a previous confirmation from a server that it supports this protocol (see Section 6.1).

If neither or both peers provide the DTLS handshake option, then the peer that selects the numerically highest value for their ClientRandom assumes the client role. In the absence of the DTLS handshake option, role allocations are not determined until a ClientHello message is exchanged.

## 6. Design Characteristics

This section outlines a number of considerations that allow this protocol to actually be implemented.

### 6.1. Interaction with TCP Fast Open

TCP fast open [I-D.ietf-tcpm-fastopen] can be used to mitigate the additional latency cost imposed by the DTLS handshake. However, this represents a risk, since the payload of the initial packet is directly passed to an application if the opportunistic security option is not negotiated.

Adding data to an initial SYN is therefore only possible if there is a previous indication that a server supports the combination of TCP fast open and opportunistic security in combination.

A server that provides a TCP fast open cookie for an encrypted connection **MUST** accept encryption on future connections with that cookie, or reject the connection. This ensures that clients are able to send a DTLS handshake message in the initial SYN packet.

### 6.2. Zero Length DTLS Data

[RFC5246], Section 6.2 notes that the TLS record layer protects non-zero length blocks. This use of DTLS requires that frames be permitted to be empty, relying solely on integrity protection of the associated data.

This does not mean that the TCP segment contains no data, since it will contain the DTLS record header (including the explicit nonce, if any, and any bits produced by the AEAD cipher to ensure integrity).

### 6.3. Unauthenticated Acknowledgments

TCP segments that only acknowledge receipt of data, or update the receive window do not require authentication, since the corresponding fields are not protected. These frames can be accepted and processed, as long as only the receive window is updated.

By the same logic, protection of the TCP window scaling option [RFC1323] and the selective acknowledgment (SACK) option [RFC2018] are not made mandatory. These **SHOULD NOT** be added to the list of protected options Section 3.2.

#### 6.4. Interaction with DTLS Replay Protection

TCP segment retransmission and reassembly requires that a sender be able to retransmit. These frames will be retransmitted with the same data, including the DTLS serial number. To avoid having retransmissions erroneously discarded, any DTLS replay protection needs to allow for replay of records that appear in unacknowledged segments.

#### 6.5. TCP Keep-Alive

This protocol does not protect TCP keep-alive segments [RFC1122]; that is, segments that are sent purely to ensure that the connection is maintained through middleboxes. These can contain a single junk byte from just prior to the start of the congestion window. These segments are discarded without being validated.

This differs from [I-D.bittau-tcp-crypt], which protects keep-alive segments. Protection ensures that an attacker is unable to prolong the lifetime of a connection that is otherwise unwanted.

Since an unwanted connection can be terminated with an authenticated segment that bears a FIN or RST bit, this concern is unwarranted.

#### 6.6. Unprotected RST Segments

Existing TCP implementations, particularly middleboxes, rely TCP RST to terminate connections. If RST authentication is required, then it becomes impossible for a node which is not part of the association (either because it is a middlebox or because it is a legitimate endpoint which has lost state) to terminate the connection. An implementation MAY choose to respect an unauthenticated RST to permit these uses.

(Note: we may want to provide an option that the middlebox can include in a RST to prove that it is on-path to make this a little easier to accept.)

#### 6.7. Cipher Suite Selection

Implementations MUST support the TLS\_BLAH\_WITH\_BLAH\_BLAH cipher suite.

Implementations MUST NOT offer non-AEAD modes and MUST terminate the connection if a non-AEAD mode is erroneously offered.

## 7. Security Considerations

None of this document mandates any level of authentication for peers, which opens up all sorts of active attacks.

### 7.1. NAT

The choice to protect a TCP connection from addressing modification prevents network address and port translation from altering the addressing information on a connection. Unfortunately, this is a procedure that much of the Internet relies on. Enabling this feature is likely to break a lot of uses, but failure to use it exposes the connection to trivial re-routing attacks.

In the absence of peer authentication, and where there is a high level of assurance that no NAT is being used for a communications path, this protection might be used. Of course, any protection this provides is trivially circumvented by an on-path attacker.

### 7.2. Acknowledgments and Congestion Window Protection

This design permits a middlebox to generate acknowledgments and to perform repacketization. This opens a number of denial of service avenues for malicious middleboxes. Falsifying window advertisements can cause a sender to send more packets than might otherwise be sent. Similarly, sending a reduced acknowledgment sequence number can cause excessive retransmission. In a similar fashion, retransmissions can be suppressed by sending inflated acknowledgment sequence numbers.

These are options that are already available to an on-path attacker.

### 7.3. Traffic Redirection

Without the `FORBID_NAPT` flag enabled, it's possible for a middlebox to rewrite addressing information so that this flow. If only authenticated RST and FIN segments are accepted by the TCP stack, the target of this flow - who doesn't have access to the traffic keys - is unable to do anything to end the flow of data.

This isn't particularly interesting as an attack, since we have to assume that any middlebox capable of this is also capable of just generating the same volume of packets toward the victim.

### 7.4. Peer Authentication

In order to have this deployed, peers will have to avoid relying on authentication. That means that this is open to active attacks.



Implementations might consider using some form of key continuity. Clients SHOULD avoid key continuity for different servers to avoid tracking by correlating keying material. Full continuity might be more applicable for servers, where key continuity does not create any special tracking ability.

(This probably needs work.)

## 8. IANA Considerations

This document registers a new TCP option kind, and establishes a registry to maintain its contents.

### 8.1. Registration of DTLS Record Protection Option Kind

This document registers the DTLS record protection option with a TCP option kind of 0xTBD.

The format of this option is described in Section 3

### 8.2. Registry for DTLS Record Protection Flags

IANA will maintain a registry of "TCP DTLS Record Protection Flags" under the "Service Names and Transport Protocol Port Numbers" group of registries.

This registry controls a contiguous space starting from bit 0 to 2023 (inclusive). New registrations in this registry require IETF review [RFC5226], with the following information:

Bit Number: The bit number being assigned

Purpose: A brief description of the feature.

Specification: A reference to the specification that defines the feature.

The initial contents of this registry are:

Bit Number: 0

Purpose: Enables protection of addressing information.

Specification: This document.

## 9. References

### 9.1. Normative References

- [RFC0793] Postel, J., "Transmission Control Protocol", STD 7, RFC 793, September 1981.
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A TCP Authentication Option Extension for Payload Encryption  
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## Abstract

This document describes an extension to the TCP Authentication Option (TCP-AO) to encrypt the TCP segment payload in addition to providing TCP-AO's authentication of the payload, TCP header, and IP pseudoheader. This extension augments how the packet contents and headers are processed and which keys are derived, and adds a capability for in-band coordination of unauthenticated Diffie-Hellman key exchange at connection establishment. The extension preserves key rollover coordination and protection of long-lived connections.

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## 1. Introduction

This document describes an extension to the TCP Authentication Option (TCP-AO) [RFC5925] called TCP-AO-ENC to support its use to encrypt TCP segment payload contents in addition to authenticating the segment. TCP-AO-ENC is intended for use where TCP user data privacy is required and where TCP control protocol protection is also needed.

TCP-AO-ENC supports two different modes: authenticated encryption and unauthenticated (BTNS-style) encryption [RFC5387]. Authenticated mode (ENC-AUTH) relies on out-of-band coordination of master key tuples in the same way as TCP-AO, and protects all segments of a connection. Unauthenticated (ENC-BTNS) mode supports in-band unsigned Diffie-Hellman key exchange during the initial SYN, and protects connections from all except man-in-the-middle attacks during connection establishment.

This document assumes detailed familiarity with TCP-AO [RFC5925]. TCP-AO-ENC extends how TCP-AO generates traffic keys and how those keys are used to process TCP segment headers and payloads, but does not otherwise alter other aspects of the TCP-AO mechanism [RFC5926].

## 2. Conventions used in this document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC-2119 [RFC2119]. When used in lower case, these words have their conventional meaning and do not convey the interpretations in RFC-2119.

## 3. Background

The premise of TCP-AO-ENC is that it might be useful to allow TCP-AO to encrypt TCP segment payloads, in addition to authenticating the entire segment.

This is accomplished by the following additions, as a preview:

- o An encryption flag to indicate when segment payload encryption is used.
- o Traffic encryption key, in addition to the TCP-AO traffic (authentication) key. TCP-AO-ENC can be used with only symmetric ciphers that avoiding the need for padding (stream ciphers).
- o Augment input and output processing to include encryption/decryption.

TCP-AO-ENC does not change any other aspects of TCP-AO [RFC5925], and is compatible with TCP-AO-NAT [RFC6978]. TCP-AO-NAT is intended for use only where coordinated between endpoints for connections that match the shared Master Key Tuple (MKT) parameters, as with all other MKT parameters.

#### 4. Authenticated and Unauthenticated Modes

TCP-AO-ENC includes two modes: authenticated (ENC-AUTH) and unauthenticated (ENC-BTNS). The latter is consistent with the "Better Than Nothing Security" approach to protect communication in the absence of public key infrastructure (PKI) or pre-shared keys [RFC5387].

ENC-AUTH mode operates in the same way as original TCP-AO authentication, by relying on out-of-band Master Key Tuples (MKTs) that are deployed in advance of new connections. All segments of connections covered by ENC-AUTH are encrypted and authenticated using keying material derived from those MKTs.

ENC-BTNS mode can be used without an out-of-band key exchange protocol. It exchanges unauthenticated, unsigned Diffie-Hellman nonces during connection establishment in-band, and uses that information to derive keys used to protect the remainder of the connection. ENC-BTNS mode is susceptible to man-in-the-middle attacks in which the adversary both participates in the initial nonce exchange and processes subsequent segments; this protection increases the effort of the attacker and can help avoid low-effort DDOS attacks that disrupt established connections [RFC4953].

Because ENC-BTNS uses in-band nonce exchange only during the initial SYN, TCP-AO key rollover is not used in that mode. The KeyIDs used during the nonce exchange are recorded and used throughout the connection.

#### 5. Extension for Payload Encryption

The following describe the additions to TCP-AO needed to support TCP-AO-ENC.

##### 5.1. Additional Master Key Tuple components

TCP-AO-ENC augments the MKT as follows; as with other MKT components, these MUST NOT change during a connection:

- o TCP encryption mode. This indicates the use and mode (ENC-AUTH or ENC-BTNS) of segment payload encryption, or is clear when encryption is not used (e.g., for conventional TCP-AO).
- o Encryption Key Derivation Function (E-KDF). Indicates the key derivation function and its parameters, as used to generate traffic encryption keys from master keys in the same way that the TCP-AO KDG generates traffic (authentication) keys.

- o Encryption algorithm. Indicates the encryption algorithm and its parameters as used for encrypted connections.

PTCP-AO-ENC processes TCP packets in the same way as TCP-AO, except that it replaces the authentication input and output processing as follows:

## 5.2. Additional traffic keys

TCP-AO-ENC uses the E-KDF to derive four additional keys used for traffic encryption:

- o Send\_SYN\_traffic\_encryption\_key
- o Receive\_SYN\_traffic\_encryption\_key
- o Send\_other\_traffic\_encryption\_key
- o Receive\_other\_traffic\_encryption\_key

## 5.3. Per-Connection TCP-AO Parameters

The per-connection TCP-AO parameters are not affected by the use of TCP-AO-ENC-AUTH, except that MKTs indicated by Current\_key and Rnext\_key would indicate the use of payload encryption.

The per-connection TCP-AO parameters for TCP-AO-ENC-BTNS are augmented by the addition of the following Diffie-Hellman nonces:

- o Send\_nonce. The locally-generated Diffie-Hellman nonce.
- o Receive\_nonce. The Diffie-Hellman nonce generated by the remote end of the connection.

These nonces are exchanged during the initial SYN exchange in ENC-BTNS mode; for ENC-AUTH mode, similar information is exchanged out-of-band and is used to derive the encryption keys. KeyIDs used with these nonces are recorded during nonce exchange and used for the remainder of the connection.

The use of payload encryption as specified in these MKTs SHOULD NOT change during a TCP connection.



#### 5.4. Traffic Encryption Key Derivation Functions

Traffic encryption keys are derived from the MKTs using the E-KDF, in the same way and used on the same segments as their corresponding authentication keys, e.g.:

- o Send\_SYN\_traffic\_encryption\_key / Send\_SYN\_traffic\_key
- o Receive\_SYN\_traffic\_encryption\_key / Receive\_SYN\_traffic\_key
- o Send\_other\_traffic\_encryption\_key / Send\_other\_traffic\_key
- o Receive\_other\_traffic\_encryption\_key / Receive\_other\_traffic\_key

#### 6. TCP-AO-ENC Interaction with TCP

TCP-AO-ENC augments TCP segment send and receive processing to include encryption/decryption. Note that the encryption initialization vector MAY depend on TCP header state, but MUST NOT depend on the processing of previous segments because segments may arrive (and need to be decrypted) out of order.

##### 6.1. Sending TCP Segments

For ENC-BTNS, initial SYN and SYN-ACK are used to establish the Diffie-Hellman nonces as follows:

- o Initial SYN and SYN-ACK. The initial SYN (SYN and not ACK) and SYN-ACK segments are not encrypted or authenticated. Instead, their HMAC field contains the 128-bit Diffie-Hellman nonce in network-standard byte order.

Because these segments are not authenticated or encrypted, they SHOULD NOT contain user data. In a typical client-server system, user data usually commences in other segments anyway.

All other TCP segments are processed as follows:

1. The segment payload is encrypted in-place using the traffic encryption key.
2. The segment is authenticated using TCP-AO as per [RFC5925].

##### 6.2. Receiving TCP Segments

For ENC-BTNS, initial SYN and SYN-ACK are used to establish the Diffie-Hellman nonces as follows:

- o Initial SYN and SYN-ACK. The 128-bit unauthenticated Diffie-Hellman nonce is extracted from the HMAC field, and used to construct the encryption and traffic keys for the connection. Because these segments are not encrypted or authenticated, no further processing is required.

All other incoming TCP segments are processed as follows:

1. TCP-AO authenticates the segment, including discarding it if authentication fails, as per [RFC5925].
2. The segment payload is decrypted in-place using the traffic encryption key.

### 6.3. Other TCP Impact

TCP-AO-ENC has no impact on TCP beyond that of TCP-AO, including impact on TCP header size, connectionless resets, and ICMP handling.

TCP-AO-ENC is compatible with the use of TCP-AO-NAT if traversal of NAT boxes is desired.

## 7. Security Considerations

TCP-AO-ENC augments TCP-AO to provide segment payload privacy.

TCP-AO-ENC relies on TCP-AO's authentication to avoid replay attacks and to ensure that the segments originate from the intended source.

TCP-AO-ENC supports only stream ciphers because the TCP segment must be encrypted and decrypted in-situ. Support for padding would require additional option space to indicate the original message length, and this complication does not seem necessary.

The design of TCP-AO-ENC can support either symmetric or asymmetric keys. However, because TCP-AO derives traffic (authentication) keys from MKTs using KDFs, it was deemed sufficient that TCP-AO-ENC derive traffic encryption keys from MKTs using E-KDFs in a similar manner, and both endpoints would thus derive the same traffic encryption keys just as they derive the same traffic (authentication) keys. Extensions of TCP-AO-ENC to support asymmetric keying are possible if traffic keys are managed using an out-of-band mechanism, but not if they are derived from MKTs.

ENC-AUTH has no additional security considerations. ENC-BTNS cannot authenticate or encrypt the segments used for nonce exchange, i.e., the initial SYN and SYN-ACK. As a result, ENC-BTNS is susceptible to

man-in-the-middle attacks during connection establishment, but remains useful to ensure that established connections are protected.

#### 8. To be completed...

Where are required algorithms specified? This doc or a separate one?

- o E-KDF - also, can a MKT use the same alg for KDF and E-KDF?
- o Encryption algorithm - possibilities include AES CTR (CTR initial value can be the ESN) or AES CBC and Camellia CBC as per TLS 1.2.

#### 9. IANA Considerations

(TO BE CONFIRMED, BUT FOR NOW:)

There are no IANA considerations for this document. This section can be removed upon publication as an RFC.

#### 10. References

##### 10.1. Normative References

- [RFC2119] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", BCP 14, RFC 2119, March 1997.
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##### 10.2. Informative References

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## 11. Acknowledgments

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