QUIC: A UDP-Based Multiplexed and Secure Transport
draft-ietf-quic-transport-13

Abstract

   This document defines the core of the QUIC transport protocol. This
   document describes connection establishment, packet format,
   multiplexing and reliability. Accompanying documents describe the
   cryptographic handshake and loss detection.

Note to Readers

   Discussion of this draft takes place on the QUIC working group
   mailing list (quic@ietf.org), which is archived at
   <https://mailarchive.ietf.org/arch/search/?email_list=quic>.

   Working Group information can be found at <https://github.com/
   quicwg>; source code and issues list for this draft can be found at
   <https://github.com/quicwg/base-drafts/labels/-transport>.

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1. Introduction

   QUIC is a multiplexed and secure transport protocol that runs on top
   of UDP. QUIC aims to provide a flexible set of features that allow
   it to be a general-purpose secure transport for multiple
   applications.

   o Version negotiation

   o Low-latency connection establishment

   o Authenticated and encrypted header and payload

   o Stream multiplexing

   o Stream and connection-level flow control

   o Connection migration and resilience to NAT rebinding

   QUIC implements techniques learned from experience with TCP, SCTP and
   other transport protocols. QUIC uses UDP as substrate so as to not
   require changes to legacy client operating systems and middleboxes to
   be deployable. QUIC authenticates all of its headers and encrypts

most of the data it exchanges, including its signaling. This allows
the protocol to evolve without incurring a dependency on upgrades to
middleboxes. This document describes the core QUIC protocol,
including the conceptual design, wire format, and mechanisms of the
QUIC protocol for connection establishment, stream multiplexing,
stream and connection-level flow control, connection migration, and
data reliability.

Accompanying documents describe QUIC's loss detection and congestion
control [QUIC-RECOVERY], and the use of TLS 1.3 for key negotiation
[QUIC-TLS].

QUIC version 1 conforms to the protocol invariants in
[QUIC-INVARIANTS].

2. Conventions and Definitions

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT",
"SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and
"OPTIONAL" in this document are to be interpreted as described in BCP
14 [RFC2119] [RFC8174] when, and only when, they appear in all
capitals, as shown here.

Definitions of terms that are used in this document:

Client: The endpoint initiating a QUIC connection.

Server: The endpoint accepting incoming QUIC connections.

Endpoint: The client or server end of a connection.

Stream: A logical, bi-directional channel of ordered bytes within a
   QUIC connection.

Connection: A conversation between two QUIC endpoints with a single
   encryption context that multiplexes streams within it.

Connection ID: An opaque identifier that is used to identify a QUIC
   connection at an endpoint. Each endpoint sets a value that its
   peer includes in packets.

QUIC packet: A well-formed UDP payload that can be parsed by a QUIC
   receiver.

QUIC is a name, not an acronym.

2.1. Notational Conventions

Packet and frame diagrams use the format described in Section 3.1 of [RFC2360], with the following additional conventions:

[x] Indicates that x is optional

x (A) Indicates that x is A bits long

x (A/B/C) ... Indicates that x is one of A, B, or C bits long

x (i) ... Indicates that x uses the variable-length encoding in
   Section 7.1

x (*) ... Indicates that x is variable-length

3. Versions

QUIC versions are identified using a 32-bit unsigned number.

The version 0x00000000 is reserved to represent version negotiation.
This version of the specification is identified by the number
0x00000001.

Other versions of QUIC might have different properties to this
version. The properties of QUIC that are guaranteed to be consistent
across all versions of the protocol are described in
[QUIC-INVARIANTS].

Version 0x00000001 of QUIC uses TLS as a cryptographic handshake
protocol, as described in [QUIC-TLS].

Versions with the most significant 16 bits of the version number
cleared are reserved for use in future IETF consensus documents.

Versions that follow the pattern 0x?a?a?a?a are reserved for use in
forcing version negotiation to be exercised. That is, any version
number where the low four bits of all octets is 1010 (in binary). A
client or server MAY advertise support for any of these reserved
versions.

Reserved version numbers will probably never represent a real
protocol; a client MAY use one of these version numbers with the
expectation that the server will initiate version negotiation; a
server MAY advertise support for one of these versions and can expect
that clients ignore the value.

[[RFC editor: please remove the remainder of this section before
publication.]]

The version number for the final version of this specification
(0x00000001), is reserved for the version of the protocol that is
published as an RFC.

Version numbers used to identify IETF drafts are created by adding
the draft number to 0xff000000. For example, draft-ietf-quic-
transport-13 would be identified as 0xff00000D.

Implementors are encouraged to register version numbers of QUIC that
they are using for private experimentation on the GitHub wiki at
<https://github.com/quicwg/base-drafts/wiki/QUIC-Versions>.

4. Packet Types and Formats

We first describe QUIC's packet types and their formats, since some
are referenced in subsequent mechanisms.

All numeric values are encoded in network byte order (that is, big-
endian) and all field sizes are in bits. When discussing individual
bits of fields, the least significant bit is referred to as bit 0.
Hexadecimal notation is used for describing the value of fields.

Any QUIC packet has either a long or a short header, as indicated by
the Header Form bit. Long headers are expected to be used early in
the connection before version negotiation and establishment of 1-RTT
keys. Short headers are minimal version-specific headers, which are
used after version negotiation and 1-RTT keys are established.

4.1. Long Header

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+
|1|  Type (7)  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Version (32)                           |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|DCIL(4)|SCIL(4)|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|               Destination Connection ID (0/32..144)       ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                 Source Connection ID (0/32..144)          ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         Length (i)                        ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Packet Number (8/16/32)                    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         Payload (*)                       ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
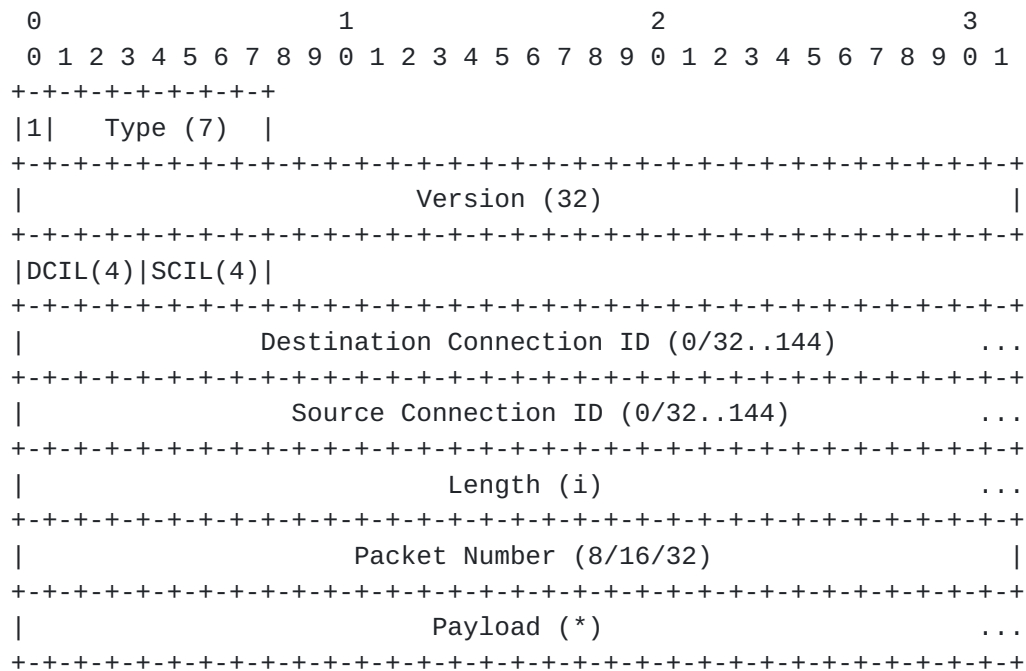
Figure 1: Long Header Format

Long headers are used for packets that are sent prior to the
completion of version negotiation and establishment of 1-RTT keys.
Once both conditions are met, a sender switches to sending packets
using the short header (Section 4.2). The long form allows for
special packets - such as the Version Negotiation packet - to be
represented in this uniform fixed-length packet format. A long
header contains the following fields:

Header Form: The most significant bit (0x80) of octet 0 (the first
   octet) is set to 1 for long headers.

Long Packet Type: The remaining seven bits of octet 0 contain the
   packet type. This field can indicate one of 128 packet types.
   The types specified for this version are listed in Table 1.

Version: The QUIC Version is a 32-bit field that follows the Type.
   This field indicates which version of QUIC is in use and
   determines how the rest of the protocol fields are interpreted.

DCIL and SCIL: The octet following the version contains the lengths
   of the two connection ID fields that follow it. These lengths are
   encoded as two 4-bit unsigned integers. The Destination
   Connection ID Length (DCIL) field occupies the 4 high bits of the
   octet and the Source Connection ID Length (SCIL) field occupies
   the 4 low bits of the octet. An encoded length of 0 indicates
   that the connection ID is also 0 octets in length. Non-zero

encoded lengths are increased by 3 to get the full length of the
connection ID, producing a length between 4 and 18 octets
inclusive. For example, an octet with the value 0x50 describes an
8-octet Destination Connection ID and a zero-length Source
Connection ID.

Destination Connection ID: The Destination Connection ID field
   follows the connection ID lengths and is either 0 octets in length
   or between 4 and 18 octets. Section 4.7 describes the use of this
   field in more detail.

Source Connection ID: The Source Connection ID field follows the
   Destination Connection ID and is either 0 octets in length or
   between 4 and 18 octets. Section 4.7 describes the use of this
   field in more detail.

Length: The length of the remainder of the packet (that is, the
   Packet Number and Payload fields) in octets, encoded as a
   variable-length integer (Section 7.1).

Packet Number: The packet number field is 1, 2, or 4 octets long.
   The packet number has confidentiality protection separate from
   packet protection, as described in Section 5.6 of [QUIC-TLS]. The
   length of the packet number field is encoded in the plaintext
   packet number. See Section 4.8 for details.

Payload: The payload of the packet.

The following packet types are defined:

```
        +------+----------------+---------------+
        | Type | Name           | Section       |
        +------+----------------+---------------+
        | 0x7F | Initial        | Section 4.4.1 |
        |      |                |               |
        | 0x7E | Retry          | Section 4.4.2 |
        |      |                |               |
        | 0x7D | Handshake      | Section 4.4.3 |
        |      |                |               |
        | 0x7C | 0-RTT Protected | Section 4.5   |
        +------+----------------+---------------+
```

Table 1: Long Header Packet Types

The header form, type, connection ID lengths octet, destination and
source connection IDs, and version fields of a long header packet are
version-independent. The packet number and values for packet types
defined in Table 1 are version-specific. See [QUIC-INVARIANTS] for

details on how packets from different versions of QUIC are
interpreted.

The interpretation of the fields and the payload are specific to a
version and packet type. Type-specific semantics for this version
are described in the following sections.

The end of the packet is determined by the Length field. The Length
field covers the both the Packet Number and Payload fields, both of
which are confidentiality protected and initially of unknown length.
The size of the Payload field is learned once the packet number
protection is removed.

Senders can sometimes coalesce multiple packets into one UDP
datagram. See Section 4.6 for more details.

4.2. Short Header

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+
|0|K|1|1|0|R R R|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|               Destination Connection ID (0..144)           ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                     Packet Number (8/16/32)                ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                     Protected Payload (*)                  ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
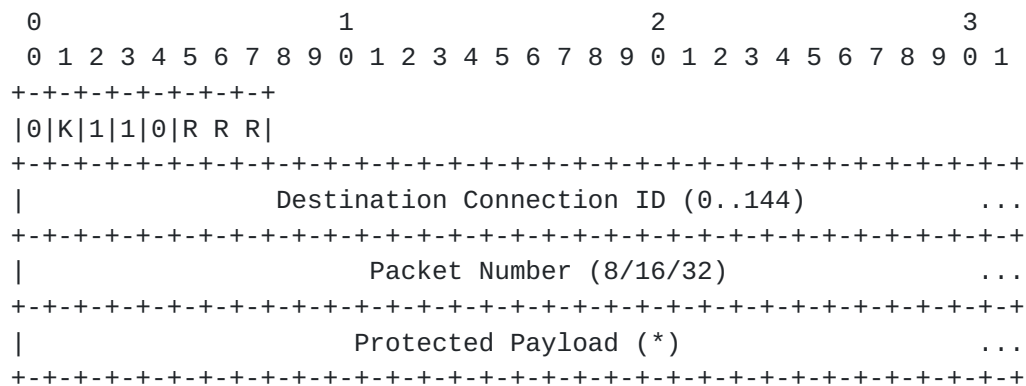
Figure 2: Short Header Format

The short header can be used after the version and 1-RTT keys are
negotiated. This header form has the following fields:

Header Form: The most significant bit (0x80) of octet 0 is set to 0
   for the short header.

Key Phase Bit: The second bit (0x40) of octet 0 indicates the key
   phase, which allows a recipient of a packet to identify the packet
   protection keys that are used to protect the packet. See
   [QUIC-TLS] for details.

[[Editor's Note: this section should be removed and the bit
definitions changed before this draft goes to the IESG.]]

Third Bit: The third bit (0x20) of octet 0 is set to 1.

[[Editor's Note: this section should be removed and the bit
definitions changed before this draft goes to the IESG.]]

Fourth Bit: The fourth bit (0x10) of octet 0 is set to 1.

[[Editor's Note: this section should be removed and the bit
definitions changed before this draft goes to the IESG.]]

Google QUIC Demultipexing Bit: The fifth bit (0x8) of octet 0 is set
   to 0. This allows implementations of Google QUIC to distinguish
   Google QUIC packets from short header packets sent by a client
   because Google QUIC servers expect the connection ID to always be
   present. The special interpretation of this bit SHOULD be removed
   from this specification when Google QUIC has finished
   transitioning to the new header format.

Reserved: The sixth, seventh, and eighth bits (0x7) of octet 0 are
   reserved for experimentation.

Destination Connection ID: The Destination Connection ID is a
   connection ID that is chosen by the intended recipient of the
   packet. See Section 6.1 for more details.

Packet Number: The packet number field is 1, 2, or 4 octets long.
   The packet number has confidentiality protection separate from
   packet protection, as described in Section 5.6 of [QUIC-TLS]. The
   length of the packet number field is encoded in the plaintext
   packet number. See Section 4.8 for details.

Protected Payload: Packets with a short header always include a
   1-RTT protected payload.

The header form and connection ID field of a short header packet are
version-independent. The remaining fields are specific to the
selected QUIC version. See [QUIC-INVARIANTS] for details on how
packets from different versions of QUIC are interpreted.

4.3. Version Negotiation Packet

A Version Negotiation packet is inherently not version-specific, and
does not use the long packet header (see Section 4.1. Upon receipt
by a client, it will appear to be a packet using the long header, but
will be identified as a Version Negotiation packet based on the
Version field having a value of 0.

The Version Negotiation packet is a response to a client packet that
contains a version that is not supported by the server, and is only
sent by servers.

The layout of a Version Negotiation packet is:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+
|1|  Unused (7) |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       Version (32)                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|DCIL(4)|SCIL(4)|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|               Destination Connection ID (0/32..144)      ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                 Source Connection ID (0/32..144)         ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Supported Version 1 (32)              ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                   [Supported Version 2 (32)]             ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
                                ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                   [Supported Version N (32)]             ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
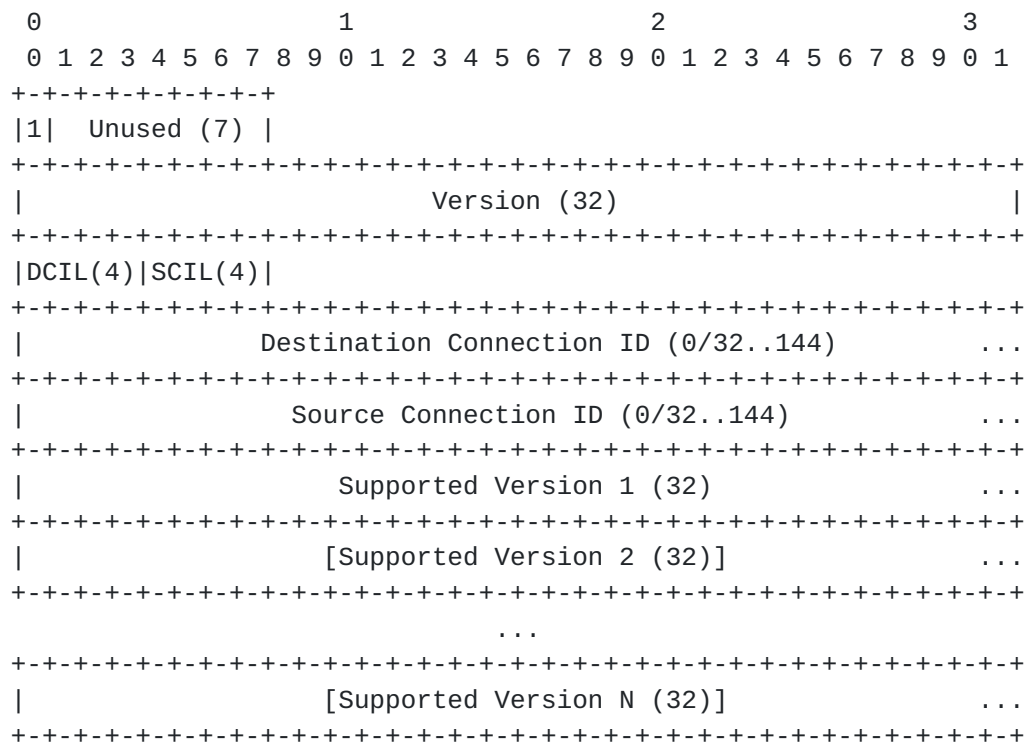
Figure 3: Version Negotiation Packet

The value in the Unused field is selected randomly by the server.

The Version field of a Version Negotiation packet MUST be set to 0x00000000.

The server MUST include the value from the Source Connection ID field of the packet it receives in the Destination Connection ID field. The value for Source Connection ID MUST be copied from the Destination Connection ID of the received packet, which is initially randomly selected by a client. Echoing both connection IDs gives clients some assurance that the server received the packet and that the Version Negotiation packet was not generated by an off-path attacker.

The remainder of the Version Negotiation packet is a list of 32-bit versions which the server supports.

A Version Negotiation packet cannot be explicitly acknowledged in an ACK frame by a client. Receiving another Initial packet implicitly acknowledges a Version Negotiation packet.

The Version Negotiation packet does not include the Packet Number and
Length fields present in other packets that use the long header form.
Consequently, a Version Negotiation packet consumes an entire UDP
datagram.

See Section 6.3 for a description of the version negotiation process.

4.4. Cryptographic Handshake Packets

Once version negotiation is complete, the cryptographic handshake is
used to agree on cryptographic keys. The cryptographic handshake is
carried in Initial (Section 4.4.1) and Handshake (Section 4.4.3)
packets.

All these packets use the long header and contain the current QUIC
version in the version field.

In order to prevent tampering by version-unaware middleboxes, Initial
packets are protected with connection- and version-specific keys
(Initial keys) as described in [QUIC-TLS]. This protection does not
provide confidentiality or integrity against on-path attackers, but
provides some level of protection against off-path attackers.

4.4.1. Initial Packet

The Initial packet uses long headers with a type value of 0x7F. It
carries the first CRYPTO frames sent by the client and server to
perform key exchange, and may carry ACKs in either direction. The
Initial packet is protected by Initial keys as described in
[QUIC-TLS].

The Initial packet has two additional header fields that follow the
normal Long Header.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       Token Length (i)  ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                          Token (*)                          ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Token Length: A variable-length integer specifying the length of the
   Token field, in bytes. It may be zero if no token is present.
   Initial packets sent by the server MUST include a zero-length
   token.

Token: An optional token blob previously received in either a Retry
   packet or NEW_TOKEN frame.

The client and server use the Initial packet type for any packet that
contains an initial cryptographic handshake message. In addition to
the first packet(s). This includes all cases where a new packet
containing the initial cryptographic message needs to be created,
such as the packets sent after receiving a Version Negotiation
(Section 4.3) or Retry packet (Section 4.4.2).

A server sends its first Initial packet in response to a client
Initial. A server may send multiple Initial packets. The
cryptographic key exchange could require multiple round trips or
retransmissions of this data.

The payload of an Initial packet includes a CRYPTO frame (or frames)
containing a cryptographic handshake message, ACK frames, or both.
The first CRYPTO frame sent always begins at an offset of 0 (see
Section 6.4). The client's complete first message MUST fit in a
single packet (see Section 6.4). Note that if the server sends a
HelloRetryRequest, the client will send a second Initial packet with
a CRYPTO frame with an offset starting at the end of the CRYPTO
stream in the first Initial.

4.4.1.1. Connection IDs

When an Initial packet is sent by a client which has not previously
received a Retry packet from the server, it populates the Destination
Connection ID field with an unpredictable value. This MUST be at
least 8 octets in length. Until a packet is received from the
server, the client MUST use the same value unless it abandons the
connection attempt and starts a new one. The initial Destination
Connection ID is used to determine packet protection keys for Initial
packets.

The client populates the Source Connection ID field with a value of
its choosing and sets the SCIL field to match.

The Destination Connection ID field in the server's Initial packet
contains a connection ID that is chosen by the recipient of the
packet (i.e., the client); the Source Connection ID includes the
connection ID that the sender of the packet wishes to use (see
Section 6.1). The server MUST use consistent Source Connection IDs
during the handshake.

On first receiving an Initial or Retry packet from the server, the
client uses the Source Connection ID supplied by the server as the
Destination Connection ID for subsequent packets. Once a client has

received an Initial packet from the server, it MUST discard any
packet it receives with a different Source Connection ID.

4.4.1.2. Tokens

If the client has a suitable token available from a previous
connection, it SHOULD populate the Token field.

If the client received a Retry packet from the server and sends an
Initial packet in response, then it sets the Destination Connection
ID to the value from the Source Connection ID in the Retry packet.
Changing Destination Connection ID also results in a change to the
keys used to protect the Initial packet. It also sets the Token
field to the token provided in the Retry. The client MUST NOT change
the Source Connection ID because the server could include the
connection ID as part of its token validation logic.

When a server receives an Initial packet with an address validation
token, it SHOULD attempt to validate it. If the token is invalid
then the server SHOULD proceed as if the client did not have a
validated address, including potentially sending a Retry. If the
validation succeeds, the server SHOULD then allow the handshake to
proceed (see Section 6.7).

Note: The rationale for treating the client as unvalidated rather
   than discarding the packet is that the client might have received
   the token in a previous connection using the NEW_TOKEN frame, and
   if the server has lost state, it might be unable to validate the
   token at all, leading to connection failure if the packet is
   discarded.

4.4.1.3. Starting Packet Numbers

The first Initial packet contains a packet number of 0. Each packet
sent after the Initial packet is associated with a packet number
space and its packet number increases monotonically in that space
(see Section 4.8).

4.4.1.4. Minimum Packet Size

The payload of a UDP datagram carrying the Initial packet MUST be
expanded to at least 1200 octets (see Section 8), by adding PADDING
frames to the Initial packet and/or by combining the Initial packet
with a 0-RTT packet (see Section 4.6).

4.4.2. Retry Packet

   A Retry packet uses long headers with a type value of 0x7E. It
   carries an address validation token created by the server. It is
   used by a server that wishes to perform a stateless retry (see
   Section 6.7).

```
    0                   1                   2                   3
    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |     ODCIL(8   |      Original Destination Connection ID (*)   |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                         Retry Token (*) ...
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

   A Retry packet is not encrypted at all. Instead, the payload of a
   Retry packet contains two values in the clear.

   ODCIL: The length of the Original Destination Connection ID.

   Original Destination Connection ID: The Destination Connection ID
      from the Initial packet that this Retry is in response to. The
      length of this field is given in DCIL.

   Retry Token: An opaque token that the server can use to validate the
      client's address.

   The server populates the Destination Connection ID with the
   connection ID that the client included in the Source Connection ID of
   the Initial packet. This might be a zero-length value.

   The server includes a connection ID of its choice in the Source
   Connection ID field. The client MUST use this connection ID in the
   Destination Connection ID of subsequent packets that it sends.

   The Packet Number field of a Retry packet MUST be set to 0. This
   value is subsequently protected as normal. [[Editor's Note: This
   isn't ideal, because it creates a "cheat" where the client assumes a
   value. That's a problem, so I'm tempted to suggest that this include
   any value less than 2^30 so that normal processing works - and can be
   properly exercised.]]

   A Retry packet is never explicitly acknowledged in an ACK frame by a
   client.

   A server MUST only send a Retry in response to a client Initial
   packet.

If the Original Destination Connection ID field does not match the
Destination Connection ID from most recent the Initial packet it
sent, clients MUST discard the packet. This prevents an off-path
attacker from injecting a Retry packet with a bogus new Source
Connection ID.

Otherwise, the client SHOULD respond with a new Initial packet with
the Token field set to the token received in the Retry packet.

4.4.3. Handshake Packet

A Handshake packet uses long headers with a type value of 0x7D. It
is used to carry acknowledgments and cryptographic handshake messages
from the server and client.

A server sends its cryptographic handshake in one or more Handshake
packets in response to an Initial packet if it does not send a Retry
packet. Once a client has received a Handshake packet from a server,
it uses Handshake packets to send subsequent cryptographic handshake
messages and acknowledgments to the server.

The Destination Connection ID field in a Handshake packet contains a
connection ID that is chosen by the recipient of the packet; the
Source Connection ID includes the connection ID that the sender of
the packet wishes to use (see Section 4.7).

The first Handshake packet sent by a server contains a packet number
of 0. Handshake packets are their own packet number space. Packet
numbers are incremented normally for other Handshake packets.

Servers MUST NOT send more than three datagrams including Initial and
Handshake packets without receiving a packet from a verified source
address. Source addresses can be verified through an address
validation token (delivered via a Retry packet or a NEW_TOKEN frame)
or by receiving any message from the client encrypted using the
Handshake keys.

The payload of this packet contains CRYPTO frames and could contain
PADDING, or ACK frames. Handshake packets MAY contain
CONNECTION_CLOSE frames if the handshake is unsuccessful.

4.5. Protected Packets

All QUIC packets use packet protection. Packets that are protected
with the static handshake keys or the 0-RTT keys are sent with long
headers; all packets protected with 1-RTT keys are sent with short
headers. The different packet types explicitly indicate the
encryption level and therefore the keys that are used to remove

packet protection. 0-RTT and 1-RTT protected packets share a single
packet number space.

Packets protected with handshake keys only use packet protection to
ensure that the sender of the packet is on the network path. This
packet protection is not effective confidentiality protection; any
entity that receives the Initial packet from a client can recover the
keys necessary to remove packet protection or to generate packets
that will be successfully authenticated.

Packets protected with 0-RTT and 1-RTT keys are expected to have
confidentiality and data origin authentication; the cryptographic
handshake ensures that only the communicating endpoints receive the
corresponding keys.

Packets protected with 0-RTT keys use a type value of 0x7C. The
connection ID fields for a 0-RTT packet MUST match the values used in
the Initial packet (Section 4.4.1).

The client can send 0-RTT packets after receiving an Initial
Section 4.4.1 or Handshake (Section 4.4.3) packet, if that packet
does not complete the handshake. Even if the client receives a
different connection ID in the Handshake packet, it MUST continue to
use the same Destination Connection ID for 0-RTT packets, see
Section 4.7.

The version field for protected packets is the current QUIC version.

The packet number field contains a packet number, which has
additional confidentiality protection that is applied after packet
protection is applied (see [QUIC-TLS] for details). The underlying
packet number increases with each packet sent, see Section 4.8 for
details.

The payload is protected using authenticated encryption. [QUIC-TLS]
describes packet protection in detail. After decryption, the
plaintext consists of a sequence of frames, as described in
Section 5.

4.6. Coalescing Packets

A sender can coalesce multiple QUIC packets (typically a
Cryptographic Handshake packet and a Protected packet) into one UDP
datagram. This can reduce the number of UDP datagrams needed to send
application data during the handshake and immediately afterwards. It
is not necessary for senders to coalesce packets, though failing to
do so will require sending a significantly larger number of datagrams

during the handshake. Receivers MUST be able to process coalesced packets.

Senders SHOULD coalesce packets in order of increasing encryption levels (Initial, Handshake, 0-RTT, 1-RTT), as this makes it more likely the receiver will be able to process all the packets in a single pass. A packet with a short header does not include a length, so it will always be the last packet included in a UDP datagram.

Senders MUST NOT coalesce QUIC packets with different Destination Connection IDs into a single UDP datagram. Receivers SHOULD ignore any subsequent packets with a different Destination Connection ID than the first packet in the datagram.

Every QUIC packet that is coalesced into a single UDP datagram is separate and complete. Though the values of some fields in the packet header might be redundant, no fields are omitted. The receiver of coalesced QUIC packets MUST individually process each QUIC packet and separately acknowledge them, as if they were received as the payload of different UDP datagrams. If one or more packets in a datagram cannot be processed yet (because the keys are not yet available) or processing fails (decryption failure, unknown type, etc.), the receiver MUST still attempt to process the remaining packets. The skipped packets MAY either be discarded or buffered for later processing, just as if the packets were received out-of-order in separate datagrams.

4.7. Connection ID Encoding

A connection ID is used to ensure consistent routing of packets, as described in Section 6.1. The long header contains two connection IDs: the Destination Connection ID is chosen by the recipient of the packet and is used to provide consistent routing; the Source Connection ID is used to set the Destination Connection ID used by the peer.

During the handshake, packets with the long header are used to establish the connection ID that each endpoint uses. Each endpoint uses the Source Connection ID field to specify the connection ID that is used in the Destination Connection ID field of packets being sent to them. Upon receiving a packet, each endpoint sets the Destination Connection ID it sends to match the value of the Source Connection ID that they receive.

During the handshake, an endpoint might receive multiple packets with the long header, and thus be given multiple opportunities to update the Destination Connection ID it sends. A client MUST only change the value it sends in the Destination Connection ID in response to

the first packet of each type it receives from the server (Retry or
Initial); a server MUST set its value based on the Initial packet.
Any additional changes are not permitted; if subsequent packets of
those types include a different Source Connection ID, they MUST be
discarded. This avoids problems that might arise from stateless
processing of multiple Initial packets producing different connection
IDs.

Short headers only include the Destination Connection ID and omit the
explicit length. The length of the Destination Connection ID field
is expected to be known to endpoints.

Endpoints using a connection-ID based load balancer could agree with
the load balancer on a fixed or minimum length and on an encoding for
connection IDs. This fixed portion could encode an explicit length,
which allows the entire connection ID to vary in length and still be
used by the load balancer.

The very first packet sent by a client includes a random value for
Destination Connection ID. The same value MUST be used for all 0-RTT
packets sent on that connection (Section 4.5). This randomized value
is used to determine the handshake packet protection keys (see
Section 5.3.2 of [QUIC-TLS]).

A Version Negotiation (Section 4.3) packet MUST use both connection
IDs selected by the client, swapped to ensure correct routing toward
the client.

The connection ID can change over the lifetime of a connection,
especially in response to connection migration (Section 6.11).
NEW_CONNECTION_ID frames (Section 7.13) are used to provide new
connection ID values.

4.8. Packet Numbers

The packet number is an integer in the range 0 to $2^{62}-1$. The value
is used in determining the cryptographic nonce for packet encryption.
Each endpoint maintains a separate packet number for sending and
receiving.

Packet numbers are divided into 3 spaces in QUIC:

o Initial space: All Initial packets Section 4.4.1 are in this
   space.

o Handshake space: All Handshake packets Section 4.4.3 are in this
   space.

o Application data space: All 0-RTT and 1-RTT encrypted packets
   Section 4.5 are in this space.

As described in [QUIC-TLS], each packet type uses different
encryption keys.

Conceptually, a packet number space is the encryption context in
which a packet can be processed and ACKed. Initial packets can only
be sent with Initial encryption keys and ACKed in packets which are
also Initial packets. Similarly, Handshake packets can only be sent
and acknowledged in Handshake packets.

This enforces cryptographic separation between the data sent in the
different packet sequence number spaces. Each packet number space
starts at packet number 0. Subsequent packets sent in the same
packet number space MUST increase the packet number by at least one.

0-RTT and 1-RTT data exist in the same packet number space to make
loss recovery algorithms easier to implement between the two packet
types.

A QUIC endpoint MUST NOT reuse a packet number within the same packet
number space in one connection (that is, under the same cryptographic
keys). If the packet number for sending reaches $2^{62} - 1$, the sender
MUST close the connection without sending a CONNECTION_CLOSE frame or
any further packets; an endpoint MAY send a Stateless Reset
(Section 6.13.4) in response to further packets that it receives.

In the QUIC long and short packet headers, the number of bits
required to represent the packet number are reduced by including only
a variable number of the least significant bits of the packet number.
One or two of the most significant bits of the first octet determine
how many bits of the packet number are provided, as shown in Table 2.

First octet pattern	Encoded Length	Bits Present
0b0xxxxxxx	1 octet	7
0b10xxxxxx	2	14
0b11xxxxxx	4	30

Table 2: Packet Number Encodings for Packet Headers

Note that these encodings are similar to those in Section 7.1, but
use different values.

The encoded packet number is protected as described in Section 5.6
[QUIC-TLS]. Protection of the packet number is removed prior to
recovering the full packet number. The full packet number is
reconstructed at the receiver based on the number of significant bits
present, the content of those bits, and the largest packet number
received on a successfully authenticated packet. Recovering the full
packet number is necessary to successfully remove packet protection.

Once packet number protection is removed, the packet number is
decoded by finding the packet number value that is closest to the
next expected packet. The next expected packet is the highest
received packet number plus one. For example, if the highest
successfully authenticated packet had a packet number of 0xaa82f30e,
then a packet containing a 14-bit value of 0x9b3 will be decoded as
0xaa8309b3.

The sender MUST use a packet number size able to represent more than
twice as large a range than the difference between the largest
acknowledged packet and packet number being sent. A peer receiving
the packet will then correctly decode the packet number, unless the
packet is delayed in transit such that it arrives after many higher-
numbered packets have been received. An endpoint SHOULD use a large
enough packet number encoding to allow the packet number to be
recovered even if the packet arrives after packets that are sent
afterwards.

As a result, the size of the packet number encoding is at least one
more than the base 2 logarithm of the number of contiguous
unacknowledged packet numbers, including the new packet.

For example, if an endpoint has received an acknowledgment for packet
0x6afa2f, sending a packet with a number of 0x6b2d79 requires a
packet number encoding with 14 bits or more; whereas the 30-bit
packet number encoding is needed to send a packet with a number of
0x6bc107.

A Version Negotiation packet (Section 4.3) does not include a packet
number. The Retry packet (Section 4.4.2) has special rules for
populating the packet number field.

5. Frames and Frame Types

The payload of all packets, after removing packet protection,
consists of a sequence of frames, as shown in Figure 4. Version
Negotiation and Stateless Reset do not contain frames.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                          Frame 1 (*)                        ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                          Frame 2 (*)                        ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
                             ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                          Frame N (*)                        ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
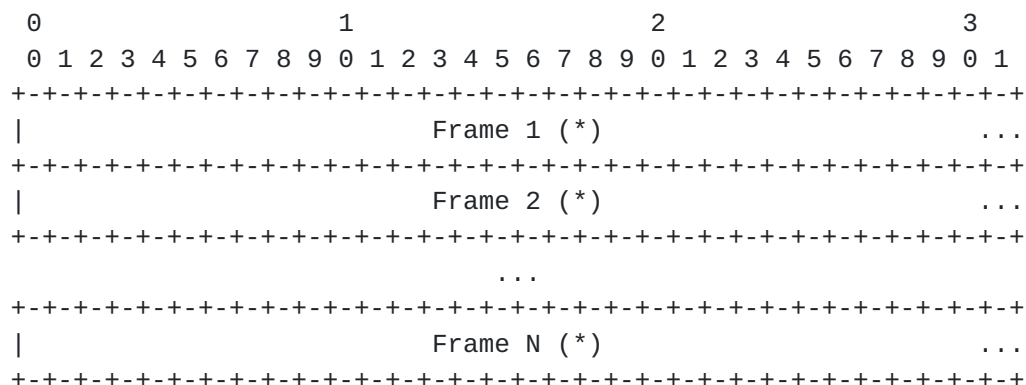
Figure 4: Contents of Protected Payload

Protected payloads MUST contain at least one frame, and MAY contain
multiple frames and multiple frame types.

Frames MUST fit within a single QUIC packet and MUST NOT span a QUIC
packet boundary. Each frame begins with a Frame Type, indicating its
type, followed by additional type-dependent fields:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                           Type (i)                          ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                   Type-Dependent Fields (*)                 ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
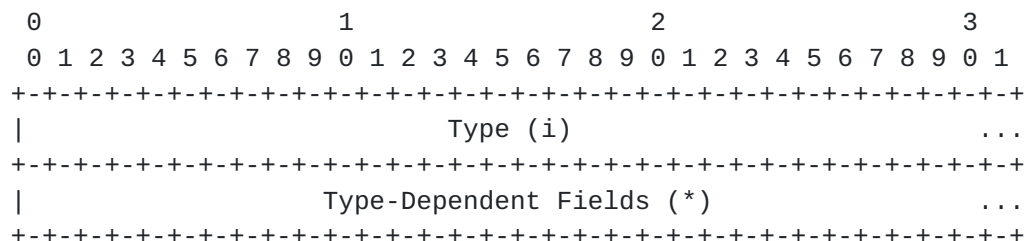
Figure 5: Generic Frame Layout

The frame types defined in this specification are listed in Table 3.
The Frame Type in STREAM frames is used to carry other frame-specific
flags. For all other frames, the Frame Type field simply identifies
the frame. These frames are explained in more detail as they are
referenced later in the document.

```
+-------------+-------------------+-------------+
| Type Value  | Frame Type Name   | Definition  |
+-------------+-------------------+-------------+
| 0x00        | PADDING           | Section 7.2 |
|             |                   |             |
| 0x01        | RST_STREAM        | Section 7.3 |
|             |                   |             |
| 0x02        | CONNECTION_CLOSE  | Section 7.4 |
|             |                   |             |
| 0x03        | APPLICATION_CLOSE | Section 7.5 |
|             |                   |             |
| 0x04        | MAX_DATA          | Section 7.6 |
|             |                   |             |
| 0x05        | MAX_STREAM_DATA   | Section 7.7 |
|             |                   |             |
| 0x06        | MAX_STREAM_ID     | Section 7.8 |
|             |                   |             |
| 0x07        | PING              | Section 7.9 |
|             |                   |             |
| 0x08        | BLOCKED           | Section 7.10 |
|             |                   |             |
| 0x09        | STREAM_BLOCKED    | Section 7.11 |
|             |                   |             |
| 0x0a        | STREAM_ID_BLOCKED | Section 7.12 |
|             |                   |             |
| 0x0b        | NEW_CONNECTION_ID | Section 7.13 |
|             |                   |             |
| 0x0c        | STOP_SENDING      | Section 7.14 |
|             |                   |             |
| 0x0d        | ACK               | Section 7.15 |
|             |                   |             |
| 0x0e        | PATH_CHALLENGE    | Section 7.17 |
|             |                   |             |
| 0x0f        | PATH_RESPONSE     | Section 7.18 |
|             |                   |             |
| 0x10 - 0x17 | STREAM            | Section 7.20 |
|             |                   |             |
| 0x18        | CRYPTO            | Section 7.21 |
|             |                   |             |
| 0x19        | NEW_TOKEN         | Section 7.19 |
|             |                   |             |
| 0x20        | ACK_ECN           | Section 7.16 |
+-------------+-------------------+-------------+
```

Table 3: Frame Types

All QUIC frames are idempotent. That is, a valid frame does not
cause undesirable side effects or errors when received more than
once.

The Frame Type field uses a variable length integer encoding (see
Section 7.1) with one exception. To ensure simple and efficient
implementations of frame parsing, a frame type MUST use the shortest
possible encoding. Though a two-, four- or eight-octet encoding of
the frame types defined in this document is possible, the Frame Type
field for these frames are encoded on a single octet. For instance,
though 0x4007 is a legitimate two-octet encoding for a variable-
length integer with a value of 7, PING frames are always encoded as a
single octet with the value 0x07. An endpoint MUST treat the receipt
of a frame type that uses a longer encoding than necessary as a
connection error of type PROTOCOL_VIOLATION.

5.1. Extension Frames

QUIC frames do not use a self-describing encoding. An endpoint
therefore needs to understand the syntax of all frames before it can
successfully process a packet. This allows for efficient encoding of
frames, but it means that an endpoint cannot send a frame of a type
that is unknown to its peer.

An extension to QUIC that wishes to use a new type of frame MUST
first ensure that a peer is able to understand the frame. An
endpoint can use a transport parameter to signal its willingness to
receive one or more extension frame types with the one transport
parameter.

An IANA registry is used to manage the assignment of frame types, see
Section 13.2.

6. Life of a Connection

A QUIC connection is a single conversation between two QUIC
endpoints. QUIC's connection establishment intertwines version
negotiation with the cryptographic and transport handshakes to reduce
connection establishment latency, as described in Section 6.4. Once
established, a connection may migrate to a different IP or port at
either endpoint, due to NAT rebinding or mobility, as described in
Section 6.11. Finally a connection may be terminated by either
endpoint, as described in Section 6.13.

6.1. Connection ID

   Each connection is identified by a collection of identifiers assigned
   to it. A connection ID can be 0 octets in length (and thus unlikely
   to be unique), or between 4 and 18 octets (inclusive). Connection
   IDs are selected independently in each direction.

   The primary function of a connection ID is to ensure that changes in
   addressing at lower protocol layers (UDP, IP, and below) don't cause
   packets for a QUIC connection to be delivered to the wrong endpoint.
   Each endpoint selects connection IDs using an implementation-specific
   (and perhaps deployment-specific) method which will allow packets
   with that connection ID to be routed back to the endpoint and
   identified by the endpoint upon receipt.

   A zero-length connection ID MAY be used when the connection ID is not
   needed for routing and the address/port tuple of packets is
   sufficient to associate them to a connection. An endpoint whose peer
   has selected a zero-length connection ID MUST continue to use a zero-
   length connection ID for the lifetime of the connection and MUST NOT
   send packets from any other local address.

   When an endpoint has requested a non-zero-length connection ID, it
   will issue a series of connection IDs over the lifetime of a
   connection. The series of connection IDs issued by an endpoint is
   ordered, with the final connection ID selected during the handshake
   coming first. Additional connection IDs are provided using the
   NEW_CONNECTION_ID frame (Section 7.13), each with a specified
   sequence number. The series of connection IDs issued SHOULD be
   contiguous, but might not appear to be upon receipt due to reordering
   or loss.

   Each connection ID MUST be used on only one local address. When
   packets are sent for the first time on a new local address, a new
   connection ID MUST be used with a higher sequence number than any
   connection ID previously used on any local address. At any time, an
   endpoint MAY change to a new connection ID on a local address already
   in use.

   An endpoint MUST NOT send packets with a connection ID which has a
   lower sequence number than the highest sequence number of any
   connection ID ever sent or received on that local address. This
   ensures that when an endpoint migrates to a new path or changes
   connection ID on an existing path, the packets will use a new
   connection ID in both directions.

   Implementations SHOULD ensure that peers have a connection ID with a
   matching sequence number available when changing to a new connection

ID. An implementation could do this by always supplying a
corresponding connection ID to a peer for each connection ID received
from that peer.

While endpoints select connection IDs as appropriate for their
implementation, the connection ID MUST NOT include the unprotected
sequence number. Endpoints need to be able to recover the sequence
number associated with each connection ID they generate without
relying on information available to unaffiliate parties. A
connection ID that encodes an unencrypted sequence number could be
used to correlate connection IDs across network paths.

6.2. Matching Packets to Connections

Incoming packets are classified on receipt. Packets can either be
associated with an existing connection, or - for servers -
potentially create a new connection.

Hosts try to associate a packet with an existing connection. If the
packet has a Destination Connection ID corresponding to an existing
connection, QUIC processes that packet accordingly. Note that more
than one connection ID can be associated with a connection; see
Section 6.1.

If the Destination Connection ID is zero length and the packet
matches the address/port tuple of a connection where the host did not
require connection IDs, QUIC processes the packet as part of that
connection. Endpoints MUST drop packets with zero-length Destination
Connection ID fields if they do not correspond to a single
connection.

6.2.1. Client Packet Handling

Valid packets sent to clients always include a Destination Connection
ID that matches the value the client selects. Clients that choose to
receive zero-length connection IDs can use the address/port tuple to
identify a connection. Packets that don't match an existing
connection MAY be discarded.

Due to packet reordering or loss, clients might receive packets for a
connection that are encrypted with a key it has not yet computed.
Clients MAY drop these packets, or MAY buffer them in anticipation of
later packets that allow it to compute the key.

If a client receives a packet that has an unsupported version, it
MUST discard that packet.

6.2.2. Server Packet Handling

If a server receives a packet that has an unsupported version and
sufficient length to be an Initial packet for some version supported
by the server, it SHOULD send a Version Negotiation packet as
described in Section 6.3.1. Servers MAY rate control these packets
to avoid storms of Version Negotiation packets.

The first packet for an unsupported version can use different
semantics and encodings for any version-specific field. In
particular, different packet protection keys might be used for
different versions. Servers that do not support a particular version
are unlikely to be able to decrypt the content of the packet.
Servers SHOULD NOT attempt to decode or decrypt a packet from an
unknown version, but instead send a Version Negotiation packet,
provided that the packet is sufficiently long.

Servers MUST drop other packets that contain unsupported versions.

Packets with a supported version, or no version field, are matched to
a connection as described in Section 6.2. If not matched, the server
continues below.

If the packet is an Initial packet fully conforming with the
specification, the server proceeds with the handshake (Section 6.4).
This commits the server to the version that the client selected.

If a server isn't currently accepting any new connections, it SHOULD
send a Handshake packet containing a CONNECTION_CLOSE frame with
error code SERVER_BUSY.

If the packet is a 0-RTT packet, the server MAY buffer a limited
number of these packets in anticipation of a late-arriving Initial
Packet. Clients are forbidden from sending Handshake packets prior
to receiving a server response, so servers SHOULD ignore any such
packets.

Servers MUST drop incoming packets under all other circumstances.
They SHOULD send a Stateless Reset (Section 6.13.4) if a connection
ID is present in the header.

6.3. Version Negotiation

Version negotiation ensures that client and server agree to a QUIC
version that is mutually supported. A server sends a Version
Negotiation packet in response to each packet that might initiate a
new connection, see Section 6.2 for details.

The size of the first packet sent by a client will determine whether
a server sends a Version Negotiation packet. Clients that support
multiple QUIC versions SHOULD pad their Initial packets to reflect
the largest minimum Initial packet size of all their versions. This
ensures that the server responds if there are any mutually supported
versions.

6.3.1. Sending Version Negotiation Packets

If the version selected by the client is not acceptable to the
server, the server responds with a Version Negotiation packet (see
Section 4.3). This includes a list of versions that the server will
accept.

This system allows a server to process packets with unsupported
versions without retaining state. Though either the Initial packet
or the Version Negotiation packet that is sent in response could be
lost, the client will send new packets until it successfully receives
a response or it abandons the connection attempt.

6.3.2. Handling Version Negotiation Packets

When the client receives a Version Negotiation packet, it first
checks that the Destination and Source Connection ID fields match the
Source and Destination Connection ID fields in a packet that the
client sent. If this check fails, the packet MUST be discarded.

Once the Version Negotiation packet is determined to be valid, the
client then selects an acceptable protocol version from the list
provided by the server. The client then attempts to create a
connection using that version. Though the contents of the Initial
packet the client sends might not change in response to version
negotiation, a client MUST increase the packet number it uses on
every packet it sends. Packets MUST continue to use long headers and
MUST include the new negotiated protocol version.

The client MUST use the long header format and include its selected
version on all packets until it has 1-RTT keys and it has received a
packet from the server which is not a Version Negotiation packet.

A client MUST NOT change the version it uses unless it is in response
to a Version Negotiation packet from the server. Once a client
receives a packet from the server which is not a Version Negotiation
packet, it MUST discard other Version Negotiation packets on the same
connection. Similarly, a client MUST ignore a Version Negotiation
packet if it has already received and acted on a Version Negotiation
packet.

A client MUST ignore a Version Negotiation packet that lists the
client's chosen version.

Version negotiation packets have no cryptographic protection. The
result of the negotiation MUST be revalidated as part of the
cryptographic handshake (see Section 6.6.4).

6.3.3. Using Reserved Versions

For a server to use a new version in the future, clients must
correctly handle unsupported versions. To help ensure this, a server
SHOULD include a reserved version (see Section 3) while generating a
Version Negotiation packet.

The design of version negotiation permits a server to avoid
maintaining state for packets that it rejects in this fashion. The
validation of version negotiation (see Section 6.6.4) only validates
the result of version negotiation, which is the same no matter which
reserved version was sent. A server MAY therefore send different
reserved version numbers in the Version Negotiation Packet and in its
transport parameters.

A client MAY send a packet using a reserved version number. This can
be used to solicit a list of supported versions from a server.

6.4. Cryptographic and Transport Handshake

QUIC relies on a combined cryptographic and transport handshake to
minimize connection establishment latency. QUIC uses the CRYPTO
frame Section 7.21 to transmit the cryptographic handshake. Version
0x00000001 of QUIC uses TLS 1.3 as described in [QUIC-TLS]; a
different QUIC version number could indicate that a different
cryptographic handshake protocol is in use.

QUIC provides reliable, ordered delivery of the cryptographic
handshake data. QUIC packet protection ensures confidentiality and
integrity protection that meets the requirements of the cryptographic
handshake protocol:

o authenticated key exchange, where

   * a server is always authenticated,

   * a client is optionally authenticated,

   * every connection produces distinct and unrelated keys,

* keying material is usable for packet protection for both 0-RTT
  and 1-RTT packets, and

* 1-RTT keys have forward secrecy

o authenticated values for the transport parameters of the peer (see
   Section 6.6)

o authenticated confirmation of version negotiation (see
   Section 6.6.4)

o authenticated negotiation of an application protocol (TLS uses
   ALPN [RFC7301] for this purpose)

o for the server, the ability to carry data that provides assurance
   that the client can receive packets that are addressed with the
   transport address that is claimed by the client (see Section 6.9)

The initial CRYPTO frame MUST be sent in a single packet. Any second
attempt that is triggered by address validation MUST also be sent
within a single packet. This avoids having to reassemble a message
from multiple packets.

The first client packet of the cryptographic handshake protocol MUST
fit within a 1232 octet QUIC packet payload. This includes overheads
that reduce the space available to the cryptographic handshake
protocol.

The CRYPTO frame can be sent in different packet number spaces.
CRYPTO frames in each packet number space carry a separate sequence
of handshake data starting from an offset of 0.

6.5. Example Handshake Flows

Details of how TLS is integrated with QUIC are provided in
[QUIC-TLS], but some examples are provided here.

Figure 6 provides an overview of the 1-RTT handshake. Each line
shows a QUIC packet with the packet type and packet number shown
first, followed by the contents. So, for instance the first packet
is of type Initial, with packet number 0, and contains a CRYPTO frame
carrying the ClientHello.

Note that multiple QUIC packets - even of different encryption levels
- may be coalesced into a single UDP datagram (see Section 4.6, and
so this handshake may consist of as few as 4 UDP datagrams, or any
number more. For instance, the server's first flight contains
packets from the Initial encryption level (obfuscation), the

Handshake level, and "0.5-RTT data" from the server at the 1-RTT
encryption level.

```
Client                                                      Server

Initial[0]: CRYPTO[CH] ->

                                    Initial[0]: CRYPTO[SH] ACK[0]
                         Handshake[0]: CRYPTO[EE, CERT, CV, FIN]
                                  <- 1-RTT[0]: STREAM[1, "..."]

Initial[1]: ACK[0]
Handshake[0]: CRYPTO[FIN], ACK[0]
1-RTT[0]: STREAM[0, "..."], ACK[0] ->

                            1-RTT[1]: STREAM[55, "..."], ACK[0]
                                      <- Handshake[1]: ACK[0]
```

                    Figure 6: Example 1-RTT Handshake

Figure 7 shows an example of a connection with a 0-RTT handshake and
a single packet of 0-RTT data. Note that as described in
Section 4.8, the server ACKs the 0-RTT data at the 1-RTT encryption
level, and the client's sequence numbers at the 1-RTT encryption
level continue to increment from its 0-RTT packets.

```
Client                                                      Server

Initial[0]: CRYPTO[CH]
0-RTT[0]: STREAM[0, "..."] ->

                                    Initial[0]: CRYPTO[SH] ACK[0]
                          Handshake[0] CRYPTO[EE, CERT, CV, FIN]
                            <- 1-RTT[0]: STREAM[1, "..."] ACK[0]

Initial[1]: ACK[0]
0-RTT[1]: CRYPTO[EOED]
Handshake[0]: CRYPTO[FIN], ACK[0]
1-RTT[2]: STREAM[0, "..."] ACK[0] ->

                          1-RTT[1]: STREAM[55, "..."], ACK[1,2]
                                      <- Handshake[1]: ACK[0]
```

                    Figure 7: Example 1-RTT Handshake

6.6. Transport Parameters

   During connection establishment, both endpoints make authenticated
   declarations of their transport parameters. These declarations are
   made unilaterally by each endpoint. Endpoints are required to comply
   with the restrictions implied by these parameters; the description of
   each parameter includes rules for its handling.

   The format of the transport parameters is the TransportParameters
   struct from Figure 8. This is described using the presentation
   language from Section 3 of [I-D.ietf-tls-tls13].

```
uint32 QuicVersion;

enum {
   initial_max_stream_data(0),
   initial_max_data(1),
   initial_max_bidi_streams(2),
   idle_timeout(3),
   preferred_address(4),
   max_packet_size(5),
   stateless_reset_token(6),
   ack_delay_exponent(7),
   initial_max_uni_streams(8),
   disable_migration(9),
   (65535)
} TransportParameterId;

struct {
   TransportParameterId parameter;
   opaque value<0..2^16-1>;
} TransportParameter;

struct {
   select (Handshake.msg_type) {
      case client_hello:
         QuicVersion initial_version;

      case encrypted_extensions:
         QuicVersion negotiated_version;
         QuicVersion supported_versions<4..2^8-4>;
   };
   TransportParameter parameters<22..2^16-1>;
} TransportParameters;

struct {
  enum { IPv4(4), IPv6(6), (15) } ipVersion;
  opaque ipAddress<4..2^8-1>;
  uint16 port;
  opaque connectionId<0..18>;
  opaque statelessResetToken[16];
} PreferredAddress;
```

                 Figure 8: Definition of TransportParameters

   The "extension_data" field of the quic_transport_parameters extension
   defined in [QUIC-TLS] contains a TransportParameters value. TLS
   encoding rules are therefore used to encode the transport parameters.

QUIC encodes transport parameters into a sequence of octets, which
are then included in the cryptographic handshake. Once the handshake
completes, the transport parameters declared by the peer are
available. Each endpoint validates the value provided by its peer.
In particular, version negotiation MUST be validated (see
Section 6.6.4) before the connection establishment is considered
properly complete.

Definitions for each of the defined transport parameters are included
in Section 6.6.1. Any given parameter MUST appear at most once in a
given transport parameters extension. An endpoint MUST treat receipt
of duplicate transport parameters as a connection error of type
TRANSPORT_PARAMETER_ERROR.

6.6.1. Transport Parameter Definitions

An endpoint MUST include the following parameters in its encoded
TransportParameters:

initial_max_stream_data (0x0000): The initial stream maximum data
   parameter contains the initial value for the maximum data that can
   be sent on any newly created stream. This parameter is encoded as
   an unsigned 32-bit integer in units of octets. This is equivalent
   to an implicit MAX_STREAM_DATA frame (Section 7.7) being sent on
   all streams immediately after opening.

initial_max_data (0x0001): The initial maximum data parameter
   contains the initial value for the maximum amount of data that can
   be sent on the connection. This parameter is encoded as an
   unsigned 32-bit integer in units of octets. This is equivalent to
   sending a MAX_DATA (Section 7.6) for the connection immediately
   after completing the handshake.

idle_timeout (0x0003): The idle timeout is a value in seconds that
   is encoded as an unsigned 16-bit integer. The maximum value is
   600 seconds (10 minutes).

An endpoint MAY use the following transport parameters:

initial_max_bidi_streams (0x0002): The initial maximum bidirectional
   streams parameter contains the initial maximum number of
   application-owned bidirectional streams the peer may initiate,
   encoded as an unsigned 16-bit integer. If this parameter is
   absent or zero, application-owned bidirectional streams cannot be
   created until a MAX_STREAM_ID frame is sent. Setting this
   parameter is equivalent to sending a MAX_STREAM_ID (Section 7.8)
   immediately after completing the handshake containing the
   corresponding Stream ID. For example, a value of 0x05 would be

equivalent to receiving a MAX_STREAM_ID containing 16 when
received by a client or 17 when received by a server.

initial_max_uni_streams (0x0008): The initial maximum unidirectional
   streams parameter contains the initial maximum number of
   application-owned unidirectional streams the peer may initiate,
   encoded as an unsigned 16-bit integer. If this parameter is
   absent or zero, unidirectional streams cannot be created until a
   MAX_STREAM_ID frame is sent. Setting this parameter is equivalent
   to sending a MAX_STREAM_ID ([Section 7.8](#)) immediately after
   completing the handshake containing the corresponding Stream ID.
   For example, a value of 0x05 would be equivalent to receiving a
   MAX_STREAM_ID containing 18 when received by a client or 19 when
   received by a server.

max_packet_size (0x0005): The maximum packet size parameter places a
   limit on the size of packets that the endpoint is willing to
   receive, encoded as an unsigned 16-bit integer. This indicates
   that packets larger than this limit will be dropped. The default
   for this parameter is the maximum permitted UDP payload of 65527.
   Values below 1200 are invalid. This limit only applies to
   protected packets ([Section 4.5](#)).

ack_delay_exponent (0x0007): An 8-bit unsigned integer value
   indicating an exponent used to decode the ACK Delay field in the
   ACK frame, see [Section 7.15](#). If this value is absent, a default
   value of 3 is assumed (indicating a multiplier of 8). The default
   value is also used for ACK frames that are sent in Initial and
   Handshake packets. Values above 20 are invalid.

disable_migration (0x0009): The endpoint does not support connection
   migration ([Section 6.11](#)). Peers MUST NOT send any packets,
   including probing packets ([Section 6.11.1](#)), from a local address
   other than that used to perform the handshake. This parameter is
   a zero-length value.

A server MAY include the following transport parameters:

stateless_reset_token (0x0006): The Stateless Reset Token is used in
   verifying a stateless reset, see [Section 6.13.4](#). This parameter
   is a sequence of 16 octets.

preferred_address (0x0004): The server's Preferred Address is used
   to effect a change in server address at the end of the handshake,
   as described in [Section 6.12](#).

A client MUST NOT include a stateless reset token or a preferred
address. A server MUST treat receipt of either transport parameter
as a connection error of type TRANSPORT_PARAMETER_ERROR.

6.6.2. Values of Transport Parameters for 0-RTT

A client that attempts to send 0-RTT data MUST remember the transport
parameters used by the server. The transport parameters that the
server advertises during connection establishment apply to all
connections that are resumed using the keying material established
during that handshake. Remembered transport parameters apply to the
new connection until the handshake completes and new transport
parameters from the server can be provided.

A server can remember the transport parameters that it advertised, or
store an integrity-protected copy of the values in the ticket and
recover the information when accepting 0-RTT data. A server uses the
transport parameters in determining whether to accept 0-RTT data.

A server MAY accept 0-RTT and subsequently provide different values
for transport parameters for use in the new connection. If 0-RTT
data is accepted by the server, the server MUST NOT reduce any limits
or alter any values that might be violated by the client with its
0-RTT data. In particular, a server that accepts 0-RTT data MUST NOT
set values for initial_max_data or initial_max_stream_data that are
smaller than the remembered value of those parameters. Similarly, a
server MUST NOT reduce the value of initial_max_bidi_streams or
initial_max_uni_streams.

Omitting or setting a zero value for certain transport parameters can
result in 0-RTT data being enabled, but not usable. The following
transport parameters SHOULD be set to non-zero values for 0-RTT:
initial_max_bidi_streams, initial_max_uni_streams, initial_max_data,
initial_max_stream_data.

The value of the server's previous preferred_address MUST NOT be used
when establishing a new connection; rather, the client should wait to
observe the server's new preferred_address value in the handshake.

A server MUST reject 0-RTT data or even abort a handshake if the
implied values for transport parameters cannot be supported.

6.6.3. New Transport Parameters

New transport parameters can be used to negotiate new protocol
behavior. An endpoint MUST ignore transport parameters that it does
not support. Absence of a transport parameter therefore disables any
optional protocol feature that is negotiated using the parameter.

New transport parameters can be registered according to the rules in
Section 13.1.

6.6.4. Version Negotiation Validation

Though the cryptographic handshake has integrity protection, two
forms of QUIC version downgrade are possible. In the first, an
attacker replaces the QUIC version in the Initial packet. In the
second, a fake Version Negotiation packet is sent by an attacker. To
protect against these attacks, the transport parameters include three
fields that encode version information. These parameters are used to
retroactively authenticate the choice of version (see Section 6.3).

The cryptographic handshake provides integrity protection for the
negotiated version as part of the transport parameters (see
Section 6.6). As a result, attacks on version negotiation by an
attacker can be detected.

The client includes the initial_version field in its transport
parameters. The initial_version is the version that the client
initially attempted to use. If the server did not send a Version
Negotiation packet Section 4.3, this will be identical to the
negotiated_version field in the server transport parameters.

A server that processes all packets in a stateful fashion can
remember how version negotiation was performed and validate the
initial_version value.

A server that does not maintain state for every packet it receives
(i.e., a stateless server) uses a different process. If the
initial_version matches the version of QUIC that is in use, a
stateless server can accept the value.

If the initial_version is different from the version of QUIC that is
in use, a stateless server MUST check that it would have sent a
Version Negotiation packet if it had received a packet with the
indicated initial_version. If a server would have accepted the
version included in the initial_version and the value differs from
the QUIC version that is in use, the server MUST terminate the
connection with a VERSION_NEGOTIATION_ERROR error.

The server includes both the version of QUIC that is in use and a
list of the QUIC versions that the server supports.

The negotiated_version field is the version that is in use. This
MUST be set by the server to the value that is on the Initial packet
that it accepts (not an Initial packet that triggers a Retry or
Version Negotiation packet). A client that receives a

negotiated_version that does not match the version of QUIC that is in use MUST terminate the connection with a VERSION_NEGOTIATION_ERROR error code.

The server includes a list of versions that it would send in any version negotiation packet (Section 4.3) in the supported_versions field. The server populates this field even if it did not send a version negotiation packet.

The client validates that the negotiated_version is included in the supported_versions list and - if version negotiation was performed - that it would have selected the negotiated version. A client MUST terminate the connection with a VERSION_NEGOTIATION_ERROR error code if the current QUIC version is not listed in the supported_versions list. A client MUST terminate with a VERSION_NEGOTIATION_ERROR error code if version negotiation occurred but it would have selected a different version based on the value of the supported_versions list.

When an endpoint accepts multiple QUIC versions, it can potentially interpret transport parameters as they are defined by any of the QUIC versions it supports. The version field in the QUIC packet header is authenticated using transport parameters. The position and the format of the version fields in transport parameters MUST either be identical across different QUIC versions, or be unambiguously different to ensure no confusion about their interpretation. One way that a new format could be introduced is to define a TLS extension with a different codepoint.

6.7. Stateless Retries

A server can process an initial cryptographic handshake messages from a client without committing any state. This allows a server to perform address validation (Section 6.9), or to defer connection establishment costs.

A server that generates a response to an Initial packet without retaining connection state MUST use the Retry packet (Section 4.4.2). This packet causes a client to restart the connection attempt and includes the token in the new Initial packet (Section 4.4.1) to prove source address ownership.

6.8. Using Explicit Congestion Notification

QUIC endpoints use Explicit Congestion Notification (ECN) [RFC3168] to detect and respond to network congestion. ECN allows a network node to indicate congestion in the network by setting a codepoint in the IP header of a packet instead of dropping it. Endpoints react to

congestion by reducing their sending rate in response, as described
in [QUIC-RECOVERY].

To use ECN, QUIC endpoints first determine whether a path and peer
support ECN marking. Verifying the path occurs at the beginning of a
connection and when the connection migrates to a new path (see
Section 6.11).

Each endpoint independently verifies and enables ECN for the path
from it to the peer.

To verify that both a path and the peer support ECN, an endpoint MUST
set one of the ECN Capable Transport (ECT) codepoints - ECT(0) or
ECT(1) - in the IP header [RFC8311] of all outgoing packets.

If an ECT codepoint set in the IP header is not corrupted by a
network device, then a received packet contains either the codepoint
sent by the peer or the Congestion Experienced (CE) codepoint set by
a network device that is experiencing congestion.

On receiving a packet with an ECT or CE codepoint, an endpoint that
supports ECN increases the corresponding ECT(0), ECT(1), or CE count,
and includes these counters in subsequent (see Section 8.1) ACK_ECN
frames (see Section 7.16).

A packet detected by a receiver as a duplicate does not affect the
receiver's local ECN codepoint counts to mitigate security concerns
(Section 12.7).

If an endpoint receives a packet without an ECT or CE codepoint, it
responds per Section 8.1 with an ACK frame.

If an endpoint does not support ECN or does not have access to
received ECN codepoints, it acknowledges received packets per
Section 8.1 with an ACK frame.

If a packet sent with an ECT codepoint is newly acknowledged by the
peer in an ACK frame, the endpoint stops setting ECT codepoints in
subsequent packets, with the expectation that either the network or
the peer no longer supports ECN.

To protect the connection from arbitrary corruption of ECN codepoints
by the network, an endpoint verifies the following when an ACK_ECN
frame is received:

o The total increase in ECT(0), ECT(1), and CE counters reported in
   the ACK_ECN frame MUST be equal to the total number of packets
   newly acknowledged in this ACK_ECN frame.

o The increase in ECT(0) and ECT(1) counters MUST be no greater than
   the number of packets newly acknowledged that were sent with the
   corresponding codepoint.

Upon successful verification, an endpoint continues to set ECT
codepoints in subsequent packets with the expectation that the path
is ECN-capable.

If verification fails, then the endpoint ceases setting ECT
codepoints in subsequent packets with the expectation that either the
network or the peer does not support ECN.

If an endpoint sets ECT codepoints on outgoing packets and encounters
a retransmission timeout due to the absence of acknowledgments from
the peer (see [QUIC-RECOVERY]), the endpoint MAY cease setting ECT
codepoints in subsequent packets. Doing so allows the connection to
traverse network elements that drop packets carrying ECT or CE
codepoints in the IP header.

6.9. Proof of Source Address Ownership

Transport protocols commonly spend a round trip checking that a
client owns the transport address (IP and port) that it claims.
Verifying that a client can receive packets sent to its claimed
transport address protects against spoofing of this information by
malicious clients.

This technique is used primarily to avoid QUIC from being used for
traffic amplification attack. In such an attack, a packet is sent to
a server with spoofed source address information that identifies a
victim. If a server generates more or larger packets in response to
that packet, the attacker can use the server to send more data toward
the victim than it would be able to send on its own.

Several methods are used in QUIC to mitigate this attack. Firstly,
the initial handshake packet is padded to at least 1200 octets. This
allows a server to send a similar amount of data without risking
causing an amplification attack toward an unproven remote address.

A server eventually confirms that a client has received its messages
when the first Handshake-level message is received. This might be
insufficient, either because the server wishes to avoid the
computational cost of completing the handshake, or it might be that
the size of the packets that are sent during the handshake is too
large. This is especially important for 0-RTT, where the server
might wish to provide application data traffic - such as a response
to a request - in response to the data carried in the early data from
the client.

To send additional data prior to completing the cryptographic
handshake, the server then needs to validate that the client owns the
address that it claims.

Source address validation is therefore performed by the core
transport protocol during the establishment of a connection.

A different type of source address validation is performed after a
connection migration, see Section 6.10.

6.9.1. Client Address Validation Procedure

QUIC uses token-based address validation. Any time the server wishes
to validate a client address, it provides the client with a token.
As long as the token's authenticity can be checked (see
Section 6.9.3) and the client is able to return that token, it proves
to the server that it received the token.

Upon receiving the client's Initial packet, the server can request
address validation by sending a Retry packet containing a token.
This token is repeated in the client's next Initial packet. Because
the token is consumed by the server that generates it, there is no
need for a single well-defined format. A token could include
information about the claimed client address (IP and port), a
timestamp, and any other supplementary information the server will
need to validate the token in the future.

The Retry packet is sent to the client and a legitimate client will
respond with an Initial packet containing the token from the Retry
packet when it continues the handshake. In response to receiving the
token, a server can either abort the connection or permit it to
proceed.

A connection MAY be accepted without address validation - or with
only limited validation - but a server SHOULD limit the data it sends
toward an unvalidated address. Successful completion of the
cryptographic handshake implicitly provides proof that the client has
received packets from the server.

The client should allow for additional Retry packets being sent in
response to Initial packets sent containing a token. There are
several situations in which the server might not be able to use the
previously generated token to validate the client's address and must
send a new Retry. A reasonable limit to the number of tries the
client allows for, before giving up, is 3. That is, the client MUST
echo the address validation token from a new Retry packet up to 3
times. After that, it MAY give up on the connection attempt.

6.9.2. Address Validation for Future Connections

A server MAY provide clients with an address validation token during
one connection that can be used on a subsequent connection. Address
validation is especially important with 0-RTT because a server
potentially sends a significant amount of data to a client in
response to 0-RTT data.

The server uses the NEW_TOKEN frame Section 7.19 to provide the
client with an address validation token that can be used to validate
future connections. The client may then use this token to validate
future connections by including it in the Initial packet's header.
The client MUST NOT use the token provided in a Retry for future
connections.

Unlike the token that is created for a Retry packet, there might be
some time between when the token is created and when the token is
subsequently used. Thus, a resumption token SHOULD include an
expiration time. The server MAY include either an explicit
expiration time or an issued timestamp and dynamically calculate the
expiration time. It is also unlikely that the client port number is
the same on two different connections; validating the port is
therefore unlikely to be successful.

6.9.3. Address Validation Token Integrity

An address validation token MUST be difficult to guess. Including a
large enough random value in the token would be sufficient, but this
depends on the server remembering the value it sends to clients.

A token-based scheme allows the server to offload any state
associated with validation to the client. For this design to work,
the token MUST be covered by integrity protection against
modification or falsification by clients. Without integrity
protection, malicious clients could generate or guess values for
tokens that would be accepted by the server. Only the server
requires access to the integrity protection key for tokens.

6.10. Path Validation

Path validation is used by an endpoint to verify reachability of a
peer over a specific path. That is, it tests reachability between a
specific local address and a specific peer address, where an address
is the two-tuple of IP address and port. Path validation tests that
packets can be both sent to and received from a peer.

Path validation is used during connection migration (see Section 6.11
and Section 6.12) by the migrating endpoint to verify reachability of

a peer from a new local address. Path validation is also used by the
peer to verify that the migrating endpoint is able to receive packets
sent to the its new address. That is, that the packets received from
the migrating endpoint do not carry a spoofed source address.

Path validation can be used at any time by either endpoint. For
instance, an endpoint might check that a peer is still in possession
of its address after a period of quiescence.

Path validation is not designed as a NAT traversal mechanism. Though
the mechanism described here might be effective for the creation of
NAT bindings that support NAT traversal, the expectation is that one
or other peer is able to receive packets without first having sent a
packet on that path. Effective NAT traversal needs additional
synchronization mechanisms that are not provided here.

An endpoint MAY bundle PATH_CHALLENGE and PATH_RESPONSE frames that
are used for path validation with other frames. For instance, an
endpoint may pad a packet carrying a PATH_CHALLENGE for PMTU
discovery, or an endpoint may bundle a PATH_RESPONSE with its own
PATH_CHALLENGE.

6.10.1. Initiation

To initiate path validation, an endpoint sends a PATH_CHALLENGE frame
containing a random payload on the path to be validated.

An endpoint MAY send additional PATH_CHALLENGE frames to handle
packet loss. An endpoint SHOULD NOT send a PATH_CHALLENGE more
frequently than it would an Initial packet, ensuring that connection
migration is no more load on a new path than establishing a new
connection.

The endpoint MUST use fresh random data in every PATH_CHALLENGE frame
so that it can associate the peer's response with the causative
PATH_CHALLENGE.

6.10.2. Response

On receiving a PATH_CHALLENGE frame, an endpoint MUST respond
immediately by echoing the data contained in the PATH_CHALLENGE frame
in a PATH_RESPONSE frame, with the following stipulation. Since a
PATH_CHALLENGE might be sent from a spoofed address, an endpoint MAY
limit the rate at which it sends PATH_RESPONSE frames and MAY
silently discard PATH_CHALLENGE frames that would cause it to respond
at a higher rate.

To ensure that packets can be both sent to and received from the
peer, the PATH_RESPONSE MUST be sent on the same path as the
triggering PATH_CHALLENGE: from the same local address on which the
PATH_CHALLENGE was received, to the same remote address from which
the PATH_CHALLENGE was received.

6.10.3. Completion

A new address is considered valid when a PATH_RESPONSE frame is
received containing data that was sent in a previous PATH_CHALLENGE.
Receipt of an acknowledgment for a packet containing a PATH_CHALLENGE
frame is not adequate validation, since the acknowledgment can be
spoofed by a malicious peer.

For path validation to be successful, a PATH_RESPONSE frame MUST be
received from the same remote address to which the corresponding
PATH_CHALLENGE was sent. If a PATH_RESPONSE frame is received from a
different remote address than the one to which the PATH_CHALLENGE was
sent, path validation is considered to have failed, even if the data
matches that sent in the PATH_CHALLENGE.

Additionally, the PATH_RESPONSE frame MUST be received on the same
local address from which the corresponding PATH_CHALLENGE was sent.
If a PATH_RESPONSE frame is received on a different local address
than the one from which the PATH_CHALLENGE was sent, path validation
is considered to have failed, even if the data matches that sent in
the PATH_CHALLENGE. Thus, the endpoint considers the path to be
valid when a PATH_RESPONSE frame is received on the same path with
the same payload as the PATH_CHALLENGE frame.

6.10.4. Abandonment

An endpoint SHOULD abandon path validation after sending some number
of PATH_CHALLENGE frames or after some time has passed. When setting
this timer, implementations are cautioned that the new path could
have a longer round-trip time than the original.

Note that the endpoint might receive packets containing other frames
on the new path, but a PATH_RESPONSE frame with appropriate data is
required for path validation to succeed.

If path validation fails, the path is deemed unusable. This does not
necessarily imply a failure of the connection - endpoints can
continue sending packets over other paths as appropriate. If no
paths are available, an endpoint can wait for a new path to become
available or close the connection.

A path validation might be abandoned for other reasons besides
failure. Primarily, this happens if a connection migration to a new
path is initiated while a path validation on the old path is in
progress.

6.11. Connection Migration

QUIC allows connections to survive changes to endpoint addresses
(that is, IP address and/or port), such as those caused by a endpoint
migrating to a new network. This section describes the process by
which an endpoint migrates to a new address.

An endpoint MUST NOT initiate connection migration before the
handshake is finished and the endpoint has 1-RTT keys. An endpoint
also MUST NOT initiate connection migration if the peer sent the
"disable_migration" transport parameter during the handshake. An
endpoint which has sent this transport parameter, but detects that a
peer has nonetheless migrated to a different network MAY treat this
as a connection error of type INVALID_MIGRATION. However, note that
not all changes of peer address are intentional migrations. The peer
could experience an unintended change of address due to NAT
rebinding; endpoints SHOULD perform path validation (Section 6.10) if
the rebinding does not cause the connection to fail.

This document limits migration of connections to new client
addresses, except as described in Section 6.12. Clients are
responsible for initiating all migrations. Servers do not send non-
probing packets (see Section 6.11.1) toward a client address until it
sees a non-probing packet from that address. If a client receives
packets from an unknown server address, the client MAY discard these
packets.

6.11.1. Probing a New Path

An endpoint MAY probe for peer reachability from a new local address
using path validation Section 6.10 prior to migrating the connection
to the new local address. Failure of path validation simply means
that the new path is not usable for this connection. Failure to
validate a path does not cause the connection to end unless there are
no valid alternative paths available.

An endpoint uses a new connection ID for probes sent from a new local
address, see Section 6.11.5 for further discussion.

Receiving a PATH_CHALLENGE frame from a peer indicates that the peer
is probing for reachability on a path. An endpoint sends a
PATH_RESPONSE in response as per Section 6.10.

PATH_CHALLENGE, PATH_RESPONSE, and PADDING frames are "probing frames", and all other frames are "non-probing frames". A packet containing only probing frames is a "probing packet", and a packet containing any other frame is a "non-probing packet".

6.11.2. Initiating Connection Migration

A endpoint can migrate a connection to a new local address by sending packets containing frames other than probing frames from that address.

Each endpoint validates its peer's address during connection establishment. Therefore, a migrating endpoint can send to its peer knowing that the peer is willing to receive at the peer's current address. Thus an endpoint can migrate to a new local address without first validating the peer's address.

When migrating, the new path might not support the endpoint's current sending rate. Therefore, the endpoint resets its congestion controller, as described in Section 6.11.4.

The new path might not have the same ECN capability. Therefore, the endpoint verifies ECN capability as described in Section 6.8.

Receiving acknowledgments for data sent on the new path serves as proof of the peer's reachability from the new address. Note that since acknowledgments may be received on any path, return reachability on the new path is not established. To establish return reachability on the new path, an endpoint MAY concurrently initiate path validation Section 6.10 on the new path.

6.11.3. Responding to Connection Migration

Receiving a packet from a new peer address containing a non-probing frame indicates that the peer has migrated to that address.

In response to such a packet, an endpoint MUST start sending subsequent packets to the new peer address and MUST initiate path validation (Section 6.10) to verify the peer's ownership of the unvalidated address.

An endpoint MAY send data to an unvalidated peer address, but it MUST protect against potential attacks as described in Section 6.11.3.1 and Section 6.11.3.2. An endpoint MAY skip validation of a peer address if that address has been seen recently.

An endpoint only changes the address that it sends packets to in response to the highest-numbered non-probing packet. This ensures

that an endpoint does not send packets to an old peer address in the
case that it receives reordered packets.

After changing the address to which it sends non-probing packets, an
endpoint could abandon any path validation for other addresses.

Receiving a packet from a new peer address might be the result of a
NAT rebinding at the peer.

After verifying a new client address, the server SHOULD send new
address validation tokens (Section 6.9) to the client.

6.11.3.1. Handling Address Spoofing by a Peer

It is possible that a peer is spoofing its source address to cause an
endpoint to send excessive amounts of data to an unwilling host. If
the endpoint sends significantly more data than the spoofing peer,
connection migration might be used to amplify the volume of data that
an attacker can generate toward a victim.

As described in Section 6.11.3, an endpoint is required to validate a
peer's new address to confirm the peer's possession of the new
address. Until a peer's address is deemed valid, an endpoint MUST
limit the rate at which it sends data to this address. The endpoint
MUST NOT send more than a minimum congestion window's worth of data
per estimated round-trip time (kMinimumWindow, as defined in
[QUIC-RECOVERY]). In the absence of this limit, an endpoint risks
being used for a denial of service attack against an unsuspecting
victim. Note that since the endpoint will not have any round-trip
time measurements to this address, the estimate SHOULD be the default
initial value (see [QUIC-RECOVERY]).

If an endpoint skips validation of a peer address as described in
Section 6.11.3, it does not need to limit its sending rate.

6.11.3.2. Handling Address Spoofing by an On-path Attacker

An on-path attacker could cause a spurious connection migration by
copying and forwarding a packet with a spoofed address such that it
arrives before the original packet. The packet with the spoofed
address will be seen to come from a migrating connection, and the
original packet will be seen as a duplicate and dropped. After a
spurious migration, validation of the source address will fail
because the entity at the source address does not have the necessary
cryptographic keys to read or respond to the PATH_CHALLENGE frame
that is sent to it even if it wanted to.

To protect the connection from failing due to such a spurious
migration, an endpoint MUST revert to using the last validated peer
address when validation of a new peer address fails.

If an endpoint has no state about the last validated peer address, it
MUST close the connection silently by discarding all connection
state. This results in new packets on the connection being handled
generically. For instance, an endpoint MAY send a stateless reset in
response to any further incoming packets.

Note that receipt of packets with higher packet numbers from the
legitimate peer address will trigger another connection migration.
This will cause the validation of the address of the spurious
migration to be abandoned.

6.11.4. Loss Detection and Congestion Control

The capacity available on the new path might not be the same as the
old path. Packets sent on the old path SHOULD NOT contribute to
congestion control or RTT estimation for the new path.

On confirming a peer's ownership of its new address, an endpoint
SHOULD immediately reset the congestion controller and round-trip
time estimator for the new path.

An endpoint MUST NOT return to the send rate used for the previous
path unless it is reasonably sure that the previous send rate is
valid for the new path. For instance, a change in the client's port
number is likely indicative of a rebinding in a middlebox and not a
complete change in path. This determination likely depends on
heuristics, which could be imperfect; if the new path capacity is
significantly reduced, ultimately this relies on the congestion
controller responding to congestion signals and reducing send rates
appropriately.

There may be apparent reordering at the receiver when an endpoint
sends data and probes from/to multiple addresses during the migration
period, since the two resulting paths may have different round-trip
times. A receiver of packets on multiple paths will still send ACK
frames covering all received packets.

While multiple paths might be used during connection migration, a
single congestion control context and a single loss recovery context
(as described in [QUIC-RECOVERY]) may be adequate. A sender can make
exceptions for probe packets so that their loss detection is
independent and does not unduly cause the congestion controller to
reduce its sending rate. An endpoint might arm a separate alarm when
a PATH_CHALLENGE is sent, which is disarmed when the corresponding

PATH_RESPONSE is received. If the alarm fires before the
PATH_RESPONSE is received, the endpoint might send a new
PATH_CHALLENGE, and restart the alarm for a longer period of time.

6.11.5. Privacy Implications of Connection Migration

Using a stable connection ID on multiple network paths allows a
passive observer to correlate activity between those paths. An
endpoint that moves between networks might not wish to have their
activity correlated by any entity other than their peer, so different
connection IDs are used when sending from different local addresses,
as discussed in Section 6.1.

This eliminates the use of the connection ID for linking activity
from the same connection on different networks. Protection of packet
numbers ensures that packet numbers cannot be used to correlate
activity. This does not prevent other properties of packets, such as
timing and size, from being used to correlate activity.

Clients MAY move to a new connection ID at any time based on
implementation-specific concerns. For example, after a period of
network inactivity NAT rebinding might occur when the client begins
sending data again.

A client might wish to reduce linkability by employing a new
connection ID and source UDP port when sending traffic after a period
of inactivity. Changing the UDP port from which it sends packets at
the same time might cause the packet to appear as a connection
migration. This ensures that the mechanisms that support migration
are exercised even for clients that don't experience NAT rebindings
or genuine migrations. Changing port number can cause a peer to
reset its congestion state (see Section 6.11.4), so the port SHOULD
only be changed infrequently.

6.12. Server's Preferred Address

QUIC allows servers to accept connections on one IP address and
attempt to transfer these connections to a more preferred address
shortly after the handshake. This is particularly useful when
clients initially connect to an address shared by multiple servers
but would prefer to use a unicast address to ensure connection
stability. This section describes the protocol for migrating a
connection to a preferred server address.

Migrating a connection to a new server address mid-connection is left
for future work. If a client receives packets from a new server
address not indicated by the preferred_address transport parameter,
the client SHOULD discard these packets.

6.12.1. Communicating A Preferred Address

   A server conveys a preferred address by including the
   preferred_address transport parameter in the TLS handshake.

   Once the handshake is finished, the client SHOULD initiate path
   validation (see Section 6.10) of the server's preferred address using
   the connection ID provided in the preferred_address transport
   parameter.

   If path validation succeeds, the client SHOULD immediately begin
   sending all future packets to the new server address using the new
   connection ID and discontinue use of the old server address. If path
   validation fails, the client MUST continue sending all future packets
   to the server's original IP address.

6.12.2. Responding to Connection Migration

   A server might receive a packet addressed to its preferred IP address
   at any time after the handshake is completed. If this packet
   contains a PATH_CHALLENGE frame, the server sends a PATH_RESPONSE
   frame as per Section 6.10, but the server MUST continue sending all
   other packets from its original IP address.

   The server SHOULD also initiate path validation of the client using
   its preferred address and the address from which it received the
   client probe. This helps to guard against spurious migration
   initiated by an attacker.

   Once the server has completed its path validation and has received a
   non-probing packet with a new largest packet number on its preferred
   address, the server begins sending to the client exclusively from its
   preferred IP address. It SHOULD drop packets for this connection
   received on the old IP address, but MAY continue to process delayed
   packets.

6.12.3. Interaction of Client Migration and Preferred Address

   A client might need to perform a connection migration before it has
   migrated to the server's preferred address. In this case, the client
   SHOULD perform path validation to both the original and preferred
   server address from the client's new address concurrently.

   If path validation of the server's preferred address succeeds, the
   client MUST abandon validation of the original address and migrate to
   using the server's preferred address. If path validation of the
   server's preferred address fails, but validation of the server's

original address succeeds, the client MAY migrate to using the
original address from the client's new address.

If the connection to the server's preferred address is not from the
same client address, the server MUST protect against potential
attacks as described in Section 6.11.3.1 and Section 6.11.3.2. In
addition to intentional simultaneous migration, this might also occur
because the client's access network used a different NAT binding for
the server's preferred address.

Servers SHOULD initiate path validation to the client's new address
upon receiving a probe packet from a different address. Servers MUST
NOT send more than a minimum congestion window's worth of non-probing
packets to the new address before path validation is complete.

6.13. Connection Termination

Connections should remain open until they become idle for a pre-
negotiated period of time. A QUIC connection, once established, can
be terminated in one of three ways:

o idle timeout (Section 6.13.2)

o immediate close (Section 6.13.3)

o stateless reset (Section 6.13.4)

6.13.1. Closing and Draining Connection States

The closing and draining connection states exist to ensure that
connections close cleanly and that delayed or reordered packets are
properly discarded. These states SHOULD persist for three times the
current Retransmission Timeout (RTO) interval as defined in
[QUIC-RECOVERY].

An endpoint enters a closing period after initiating an immediate
close (Section 6.13.3). While closing, an endpoint MUST NOT send
packets unless they contain a CONNECTION_CLOSE or APPLICATION_CLOSE
frame (see Section 6.13.3 for details).

In the closing state, only a packet containing a closing frame can be
sent. An endpoint retains only enough information to generate a
packet containing a closing frame and to identify packets as
belonging to the connection. The connection ID and QUIC version is
sufficient information to identify packets for a closing connection;
an endpoint can discard all other connection state. An endpoint MAY
retain packet protection keys for incoming packets to allow it to
read and process a closing frame.

The draining state is entered once an endpoint receives a signal that
its peer is closing or draining. While otherwise identical to the
closing state, an endpoint in the draining state MUST NOT send any
packets. Retaining packet protection keys is unnecessary once a
connection is in the draining state.

An endpoint MAY transition from the closing period to the draining
period if it can confirm that its peer is also closing or draining.
Receiving a closing frame is sufficient confirmation, as is receiving
a stateless reset. The draining period SHOULD end when the closing
period would have ended. In other words, the endpoint can use the
same end time, but cease retransmission of the closing packet.

Disposing of connection state prior to the end of the closing or
draining period could cause delayed or reordered packets to be
handled poorly. Endpoints that have some alternative means to ensure
that late-arriving packets on the connection do not create QUIC
state, such as those that are able to close the UDP socket, MAY use
an abbreviated draining period which can allow for faster resource
recovery. Servers that retain an open socket for accepting new
connections SHOULD NOT exit the closing or draining period early.

Once the closing or draining period has ended, an endpoint SHOULD
discard all connection state. This results in new packets on the
connection being handled generically. For instance, an endpoint MAY
send a stateless reset in response to any further incoming packets.

The draining and closing periods do not apply when a stateless reset
(Section 6.13.4) is sent.

An endpoint is not expected to handle key updates when it is closing
or draining. A key update might prevent the endpoint from moving
from the closing state to draining, but it otherwise has no impact.

An endpoint could receive packets from a new source address,
indicating a client connection migration (Section 6.11), while in the
closing period. An endpoint in the closing state MUST strictly limit
the number of packets it sends to this new address until the address
is validated (see Section 6.10). A server in the closing state MAY
instead choose to discard packets received from a new source address.

6.13.2. Idle Timeout

A connection that remains idle for longer than the idle timeout (see
Section 6.6.1) is closed. A connection enters the draining state
when the idle timeout expires.

   The time at which an idle timeout takes effect won't be perfectly
   synchronized on both endpoints. An endpoint that sends packets near
   the end of an idle period could have those packets discarded if its
   peer enters the draining state before the packet is received.

6.13.3. Immediate Close

   An endpoint sends a closing frame (CONNECTION_CLOSE or
   APPLICATION_CLOSE) to terminate the connection immediately. Any
   closing frame causes all streams to immediately become closed; open
   streams can be assumed to be implicitly reset.

   After sending a closing frame, endpoints immediately enter the
   closing state. During the closing period, an endpoint that sends a
   closing frame SHOULD respond to any packet that it receives with
   another packet containing a closing frame. To minimize the state
   that an endpoint maintains for a closing connection, endpoints MAY
   send the exact same packet. However, endpoints SHOULD limit the
   number of packets they generate containing a closing frame. For
   instance, an endpoint could progressively increase the number of
   packets that it receives before sending additional packets or
   increase the time between packets.

   Note: Allowing retransmission of a packet contradicts other advice
      in this document that recommends the creation of new packet
      numbers for every packet. Sending new packet numbers is primarily
      of advantage to loss recovery and congestion control, which are
      not expected to be relevant for a closed connection.
      Retransmitting the final packet requires less state.

   After receiving a closing frame, endpoints enter the draining state.
   An endpoint that receives a closing frame MAY send a single packet
   containing a closing frame before entering the draining state, using
   a CONNECTION_CLOSE frame and a NO_ERROR code if appropriate. An
   endpoint MUST NOT send further packets, which could result in a
   constant exchange of closing frames until the closing period on
   either peer ended.

   An immediate close can be used after an application protocol has
   arranged to close a connection. This might be after the application
   protocols negotiates a graceful shutdown. The application protocol
   exchanges whatever messages that are needed to cause both endpoints
   to agree to close the connection, after which the application
   requests that the connection be closed. The application protocol can
   use an APPLICATION_CLOSE message with an appropriate error code to
   signal closure.

6.13.4. **Stateless Reset**

   A stateless reset is provided as an option of last resort for an
   endpoint that does not have access to the state of a connection. A
   crash or outage might result in peers continuing to send data to an
   endpoint that is unable to properly continue the connection. An
   endpoint that wishes to communicate a fatal connection error MUST use
   a closing frame if it has sufficient state to do so.

   To support this process, a token is sent by endpoints. The token is
   carried in the NEW_CONNECTION_ID frame sent by either peer, and
   servers can specify the stateless_reset_token transport parameter
   during the handshake (clients cannot because their transport
   parameters don't have confidentiality protection). This value is
   protected by encryption, so only client and server know this value.

   An endpoint that receives packets that it cannot process sends a
   packet in the following layout:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+
|0|K|1|1|0|0|0|0|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Random Octets (160..)                    ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                                                               +
|                                                               |
+                  Stateless Reset Token (128)                  +
|                                                               |
+                                                               +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

   This design ensures that a stateless reset packet is - to the extent
   possible - indistinguishable from a regular packet with a short
   header.

   The message consists of a header octet, followed by random octets of
   arbitrary length, followed by a Stateless Reset Token.

   A stateless reset will be interpreted by a recipient as a packet with
   a short header. For the packet to appear as valid, the Random Octets
   field needs to include at least 20 octets of random or unpredictable
   values. This is intended to allow for a destination connection ID of
   the maximum length permitted, a packet number, and minimal payload.
   The Stateless Reset Token corresponds to the minimum expansion of the

packet protection AEAD. More random octets might be necessary if the
endpoint could have negotiated a packet protection scheme with a
larger minimum AEAD expansion.

An endpoint SHOULD NOT send a stateless reset that is significantly
larger than the packet it receives. Endpoints MUST discard packets
that are too small to be valid QUIC packets. With the set of AEAD
functions defined in [QUIC-TLS], packets less than 19 octets long are
never valid.

An endpoint cannot determine the Source Connection ID from a packet
with a short header, therefore it cannot set the Destination
Connection ID in the stateless reset packet. The destination
connection ID will therefore differ from the value used in previous
packets. A random Destination Connection ID makes the connection ID
appear to be the result of moving to a new connection ID that was
provided using a NEW_CONNECTION_ID frame (Section 7.13).

Using a randomized connection ID results in two problems:

o The packet might not reach the peer. If the Destination
   Connection ID is critical for routing toward the peer, then this
   packet could be incorrectly routed. This causes the stateless
   reset to be ineffective in causing errors to be quickly detected
   and recovered. In this case, endpoints will need to rely on other
   methods - such as timers - to detect that the connection has
   failed.

o The randomly generated connection ID can be used by entities other
   than the peer to identify this as a potential stateless reset. An
   endpoint that occasionally uses different connection IDs might
   introduce some uncertainty about this.

Finally, the last 16 octets of the packet are set to the value of the
Stateless Reset Token.

A stateless reset is not appropriate for signaling error conditions.
An endpoint that wishes to communicate a fatal connection error MUST
use a CONNECTION_CLOSE or APPLICATION_CLOSE frame if it has
sufficient state to do so.

This stateless reset design is specific to QUIC version 1. An
endpoint that supports multiple versions of QUIC needs to generate a
stateless reset that will be accepted by peers that support any
version that the endpoint might support (or might have supported
prior to losing state). Designers of new versions of QUIC need to be
aware of this and either reuse this design, or use a portion of the
packet other than the last 16 octets for carrying data.

6.13.4.1. Detecting a Stateless Reset

An endpoint detects a potential stateless reset when a packet with a
short header either cannot be decrypted or is marked as a duplicate
packet. The endpoint then compares the last 16 octets of the packet
with the Stateless Reset Token provided by its peer, either in a
NEW_CONNECTION_ID frame or the server's transport parameters. If
these values are identical, the endpoint MUST enter the draining
period and not send any further packets on this connection. If the
comparison fails, the packet can be discarded.

6.13.4.2. Calculating a Stateless Reset Token

The stateless reset token MUST be difficult to guess. In order to
create a Stateless Reset Token, an endpoint could randomly generate
[RFC4086] a secret for every connection that it creates. However,
this presents a coordination problem when there are multiple
instances in a cluster or a storage problem for a endpoint that might
lose state. Stateless reset specifically exists to handle the case
where state is lost, so this approach is suboptimal.

A single static key can be used across all connections to the same
endpoint by generating the proof using a second iteration of a
preimage-resistant function that takes three inputs: the static key,
the connection ID chosen by the endpoint (see Section 6.1), and an
instance identifier. An endpoint could use HMAC [RFC2104] (for
example, HMAC(static_key, instance_id || connection_id)) or HKDF
[RFC5869] (for example, using the static key as input keying
material, with instance and connection identifiers as salt). The
output of this function is truncated to 16 octets to produce the
Stateless Reset Token for that connection.

An endpoint that loses state can use the same method to generate a
valid Stateless Reset Token. The connection ID comes from the packet
that the endpoint receives. An instance that receives a packet for
another instance might be able to recover the instance identifier
using the connection ID. Alternatively, the instance identifier
might be omitted from the calculation of the Stateless Reset Token so
that all instances are equally able to generate a stateless reset.

This design relies on the peer always sending a connection ID in its
packets so that the endpoint can use the connection ID from a packet
to reset the connection. An endpoint that uses this design cannot
allow its peers to send packets with a zero-length destination
connection ID.

Revealing the Stateless Reset Token allows any entity to terminate
the connection, so a value can only be used once. This method for

choosing the Stateless Reset Token means that the combination of
instance, connection ID, and static key cannot occur for another
connection. A connection ID from a connection that is reset by
revealing the Stateless Reset Token cannot be reused for new
connections at the same instance without first changing to use a
different static key or instance identifier.

Note that Stateless Reset messages do not have any cryptographic
protection.

7. Frame Types and Formats

As described in Section 5, packets contain one or more frames. This
section describes the format and semantics of the core QUIC frame
types.

7.1. Variable-Length Integer Encoding

QUIC frames commonly use a variable-length encoding for non-negative
integer values. This encoding ensures that smaller integer values
need fewer octets to encode.

The QUIC variable-length integer encoding reserves the two most
significant bits of the first octet to encode the base 2 logarithm of
the integer encoding length in octets. The integer value is encoded
on the remaining bits, in network byte order.

This means that integers are encoded on 1, 2, 4, or 8 octets and can
encode 6, 14, 30, or 62 bit values respectively. Table 4 summarizes
the encoding properties.

```
+------+--------+------------+----------------------+
| 2Bit | Length | Usable Bits | Range               |
+------+--------+------------+----------------------+
| 00   | 1      | 6          | 0-63                 |
|      |        |            |                      |
| 01   | 2      | 14         | 0-16383              |
|      |        |            |                      |
| 10   | 4      | 30         | 0-1073741823         |
|      |        |            |                      |
| 11   | 8      | 62         | 0-4611686018427387903 |
+------+--------+------------+----------------------+
```

Table 4: Summary of Integer Encodings

For example, the eight octet sequence c2 19 7c 5e ff 14 e8 8c (in
hexadecimal) decodes to the decimal value 151288809941952652; the
four octet sequence 9d 7f 3e 7d decodes to 494878333; the two octet

sequence 7b bd decodes to 15293; and the single octet 25 decodes to
37 (as does the two octet sequence 40 25).

Error codes (Section 11.3) are described using integers, but do not
use this encoding.

7.2. PADDING Frame

The PADDING frame (type=0x00) has no semantic value. PADDING frames
can be used to increase the size of a packet. Padding can be used to
increase an initial client packet to the minimum required size, or to
provide protection against traffic analysis for protected packets.

A PADDING frame has no content. That is, a PADDING frame consists of
the single octet that identifies the frame as a PADDING frame.

7.3. RST_STREAM Frame

An endpoint may use a RST_STREAM frame (type=0x01) to abruptly
terminate a stream.

After sending a RST_STREAM, an endpoint ceases transmission and
retransmission of STREAM frames on the identified stream. A receiver
of RST_STREAM can discard any data that it already received on that
stream.

An endpoint that receives a RST_STREAM frame for a send-only stream
MUST terminate the connection with error PROTOCOL_VIOLATION.

The RST_STREAM frame is as follows:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Stream ID (i)                        ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Application Error Code (16)  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Final Offset (i)                     ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

The fields are:

Stream ID: A variable-length integer encoding of the Stream ID of
   the stream being terminated.

Application Protocol Error Code: A 16-bit application protocol error
   code (see Section 11.4) which indicates why the stream is being
   closed.

Final Offset: A variable-length integer indicating the absolute byte
   offset of the end of data written on this stream by the RST_STREAM
   sender.

7.4. CONNECTION_CLOSE frame

An endpoint sends a CONNECTION_CLOSE frame (type=0x02) to notify its
peer that the connection is being closed. CONNECTION_CLOSE is used
to signal errors at the QUIC layer, or the absence of errors (with
the NO_ERROR code).

If there are open streams that haven't been explicitly closed, they
are implicitly closed when the connection is closed.

The CONNECTION_CLOSE frame is as follows:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|           Error Code (16)     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       Frame Type (i)                        ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Reason Phrase Length (i)                 ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                      Reason Phrase (*)                      ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

The fields of a CONNECTION_CLOSE frame are as follows:

Error Code: A 16-bit error code which indicates the reason for
   closing this connection. CONNECTION_CLOSE uses codes from the
   space defined in Section 11.3 (APPLICATION_CLOSE uses codes from
   the application protocol error code space, see Section 11.4).

Frame Type: The type of frame that triggered the error. A value of
   0 (equivalent to the mention of the PADDING frame) is used when
   the frame type is unknown.

Reason Phrase Length: A variable-length integer specifying the
   length of the reason phrase in bytes. Note that a
   CONNECTION_CLOSE frame cannot be split between packets, so in
   practice any limits on packet size will also limit the space
   available for a reason phrase.

   Reason Phrase: A human-readable explanation for why the connection
      was closed. This can be zero length if the sender chooses to not
      give details beyond the Error Code. This SHOULD be a UTF-8
      encoded string [RFC3629].

7.5. APPLICATION_CLOSE frame

   An APPLICATION_CLOSE frame (type=0x03) uses the same format as the
   CONNECTION_CLOSE frame (Section 7.4), except that it uses error codes
   from the application protocol error code space (Section 11.4) instead
   of the transport error code space.

   Other than the error code space, the format and semantics of the
   APPLICATION_CLOSE frame are identical to the CONNECTION_CLOSE frame.

7.6. MAX_DATA Frame

   The MAX_DATA frame (type=0x04) is used in flow control to inform the
   peer of the maximum amount of data that can be sent on the connection
   as a whole.

   The frame is as follows:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Maximum Data (i)                     ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

   The fields in the MAX_DATA frame are as follows:

   Maximum Data: A variable-length integer indicating the maximum
      amount of data that can be sent on the entire connection, in units
      of octets.

   All data sent in STREAM frames counts toward this limit. The sum of
   the largest received offsets on all streams - including streams in
   terminal states - MUST NOT exceed the value advertised by a receiver.
   An endpoint MUST terminate a connection with a
   QUIC_FLOW_CONTROL_RECEIVED_TOO_MUCH_DATA error if it receives more
   data than the maximum data value that it has sent, unless this is a
   result of a change in the initial limits (see Section 6.6.2).

7.7. MAX_STREAM_DATA Frame

   The MAX_STREAM_DATA frame (type=0x05) is used in flow control to
   inform a peer of the maximum amount of data that can be sent on a
   stream.

An endpoint that receives a MAX_STREAM_DATA frame for a receive-only
stream MUST terminate the connection with error PROTOCOL_VIOLATION.

An endpoint that receives a MAX_STREAM_DATA frame for a send-only
stream it has not opened MUST terminate the connection with error
PROTOCOL_VIOLATION.

Note that an endpoint may legally receive a MAX_STREAM_DATA frame on
a bidirectional stream it has not opened.

The frame is as follows:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Stream ID (i)                        ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Maximum Stream Data (i)                  ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

The fields in the MAX_STREAM_DATA frame are as follows:

Stream ID: The stream ID of the stream that is affected encoded as a
   variable-length integer.

Maximum Stream Data: A variable-length integer indicating the
   maximum amount of data that can be sent on the identified stream,
   in units of octets.

When counting data toward this limit, an endpoint accounts for the
largest received offset of data that is sent or received on the
stream. Loss or reordering can mean that the largest received offset
on a stream can be greater than the total size of data received on
that stream. Receiving STREAM frames might not increase the largest
received offset.

The data sent on a stream MUST NOT exceed the largest maximum stream
data value advertised by the receiver. An endpoint MUST terminate a
connection with a FLOW_CONTROL_ERROR error if it receives more data
than the largest maximum stream data that it has sent for the
affected stream, unless this is a result of a change in the initial
limits (see Section 6.6.2).

7.8. MAX_STREAM_ID Frame

The MAX_STREAM_ID frame (type=0x06) informs the peer of the maximum
stream ID that they are permitted to open.

The frame is as follows:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                     Maximum Stream ID (i)                   ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

The fields in the MAX_STREAM_ID frame are as follows:

Maximum Stream ID: ID of the maximum unidirectional or bidirectional
   peer-initiated stream ID for the connection encoded as a variable-
   length integer. The limit applies to unidirectional steams if the
   second least signification bit of the stream ID is 1, and applies
   to bidirectional streams if it is 0.

Loss or reordering can mean that a MAX_STREAM_ID frame can be
received which states a lower stream limit than the client has
previously received. MAX_STREAM_ID frames which do not increase the
maximum stream ID MUST be ignored.

A peer MUST NOT initiate a stream with a higher stream ID than the
greatest maximum stream ID it has received. An endpoint MUST
terminate a connection with a STREAM_ID_ERROR error if a peer
initiates a stream with a higher stream ID than it has sent, unless
this is a result of a change in the initial limits (see
[Section 6.6.2](#)).

7.9. PING Frame

Endpoints can use PING frames (type=0x07) to verify that their peers
are still alive or to check reachability to the peer. The PING frame
contains no additional fields.

The receiver of a PING frame simply needs to acknowledge the packet
containing this frame.

The PING frame can be used to keep a connection alive when an
application or application protocol wishes to prevent the connection
from timing out. An application protocol SHOULD provide guidance
about the conditions under which generating a PING is recommended.
This guidance SHOULD indicate whether it is the client or the server
that is expected to send the PING. Having both endpoints send PING
frames without coordination can produce an excessive number of
packets and poor performance.

A connection will time out if no packets are sent or received for a
period longer than the time specified in the idle_timeout transport

parameter (see Section 6.13). However, state in middleboxes might
time out earlier than that. Though REQ-5 in [RFC4787] recommends a 2
minute timeout interval, experience shows that sending packets every
15 to 30 seconds is necessary to prevent the majority of middleboxes
from losing state for UDP flows.

7.10. BLOCKED Frame

A sender SHOULD send a BLOCKED frame (type=0x08) when it wishes to
send data, but is unable to due to connection-level flow control (see
Section 10.2.1). BLOCKED frames can be used as input to tuning of
flow control algorithms (see Section 10.1.2).

The BLOCKED frame is as follows:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Offset (i)                           ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

The BLOCKED frame contains a single field.

Offset: A variable-length integer indicating the connection-level
   offset at which the blocking occurred.

7.11. STREAM_BLOCKED Frame

A sender SHOULD send a STREAM_BLOCKED frame (type=0x09) when it
wishes to send data, but is unable to due to stream-level flow
control. This frame is analogous to BLOCKED (Section 7.10).

An endpoint that receives a STREAM_BLOCKED frame for a send-only
stream MUST terminate the connection with error PROTOCOL_VIOLATION.

The STREAM_BLOCKED frame is as follows:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       Stream ID (i)                         ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Offset (i)                           ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

The STREAM_BLOCKED frame contains two fields:

   Stream ID: A variable-length integer indicating the stream which is
      flow control blocked.

   Offset: A variable-length integer indicating the offset of the
      stream at which the blocking occurred.

7.12. STREAM_ID_BLOCKED Frame

   A sender MAY send a STREAM_ID_BLOCKED frame (type=0x0a) when it
   wishes to open a stream, but is unable to due to the maximum stream
   ID limit set by its peer (see Section 7.8). This does not open the
   stream, but informs the peer that a new stream was needed, but the
   stream limit prevented the creation of the stream.

   The STREAM_ID_BLOCKED frame is as follows:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Stream ID (i)                        ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

   The STREAM_ID_BLOCKED frame contains a single field.

   Stream ID: A variable-length integer indicating the highest stream
      ID that the sender was permitted to open.

7.13. NEW_CONNECTION_ID Frame

   An endpoint sends a NEW_CONNECTION_ID frame (type=0x0b) to provide
   its peer with alternative connection IDs that can be used to break
   linkability when migrating connections (see Section 6.11.5).

   The NEW_CONNECTION_ID is as follows:

```
   0                   1                   2                   3
   0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |                       Sequence (i)                        ...
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |  Length (8)   |        Connection ID (32..144)            ...
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |                                                               |
  +                                                               +
  |                                                               |
  +                  Stateless Reset Token (128)                  +
  |                                                               |
  +                                                               +
  |                                                               |
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

The fields are:

Sequence: A variable-length integer. This value starts at 0 and
   increases by 1 for each connection ID that is provided by the
   server. The connection ID that is assigned during the handshake
   is assumed to have a sequence of -1. That is, the value selected
   during the handshake comes immediately before the first value that
   a server can send.

Length: An 8-bit unsigned integer containing the length of the
   connection ID. Values less than 4 and greater than 18 are invalid
   and MUST be treated as a connection error of type
   PROTOCOL_VIOLATION.

Connection ID: A connection ID of the specified length.

Stateless Reset Token: A 128-bit value that will be used to for a
   stateless reset when the associated connection ID is used (see
   Section 6.13.4).

An endpoint MUST NOT send this frame if it currently requires that
its peer send packets with a zero-length Destination Connection ID.
Changing the length of a connection ID to or from zero-length makes
it difficult to identify when the value of the connection ID changed.
An endpoint that is sending packets with a zero-length Destination
Connection ID MUST treat receipt of a NEW_CONNECTION_ID frame as a
connection error of type PROTOCOL_VIOLATION.

7.14. STOP_SENDING Frame

An endpoint may use a STOP_SENDING frame (type=0x0c) to communicate that incoming data is being discarded on receipt at application request. This signals a peer to abruptly terminate transmission on a stream.

Receipt of a STOP_SENDING frame is only valid for a send stream that exists and is not in the "Ready" state (see Section 9.2.1). Receiving a STOP_SENDING frame for a send stream that is "Ready" or non-existent MUST be treated as a connection error of type PROTOCOL_VIOLATION. An endpoint that receives a STOP_SENDING frame for a receive-only stream MUST terminate the connection with error PROTOCOL_VIOLATION.

The STOP_SENDING frame is as follows:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Stream ID (i)                        ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Application Error Code (16)  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

The fields are:

Stream ID: A variable-length integer carrying the Stream ID of the stream being ignored.

Application Error Code: A 16-bit, application-specified reason the sender is ignoring the stream (see Section 11.4).

7.15. ACK Frame

Receivers send ACK frames (type=0x0d) to inform senders which packets they have received and processed. The ACK frame contains any number of ACK blocks. ACK blocks are ranges of acknowledged packets.

QUIC acknowledgements are irrevocable. Once acknowledged, a packet remains acknowledged, even if it does not appear in a future ACK frame. This is unlike TCP SACKs ([RFC2018]).

It is expected that a sender will reuse the same packet number across different packet number spaces. ACK frames only acknowledge the packet numbers that were transmitted by the sender in the same packet number space of the packet that the ACK was received in.

A client MUST NOT acknowledge Retry packets. Retry packets include
the packet number from the Initial packet it responds to. Version
Negotiation packets cannot be acknowledged because they do not
contain a packet number. Rather than relying on ACK frames, these
packets are implicitly acknowledged by the next Initial packet sent
by the client.

An ACK frame is shown below.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                     Largest Acknowledged (i)              ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         ACK Delay (i)                     ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       ACK Block Count (i)                 ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                          ACK Blocks (*)                   ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
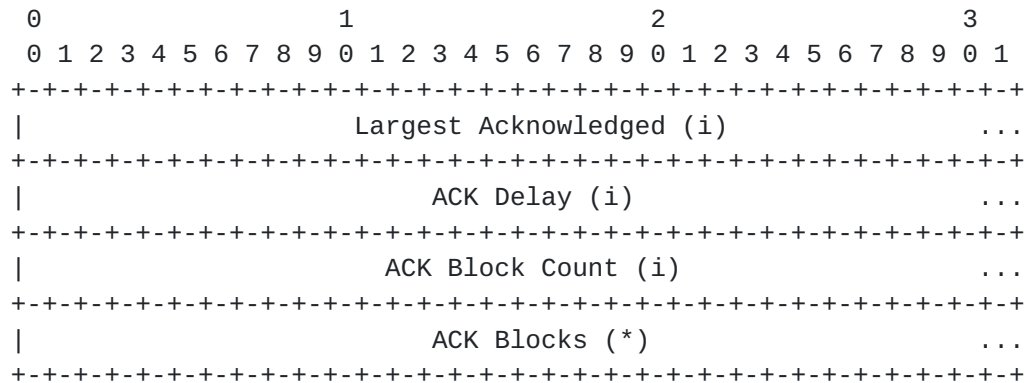
Figure 9: ACK Frame Format

The fields in the ACK frame are as follows:

Largest Acknowledged: A variable-length integer representing the
   largest packet number the peer is acknowledging; this is usually
   the largest packet number that the peer has received prior to
   generating the ACK frame. Unlike the packet number in the QUIC
   long or short header, the value in an ACK frame is not truncated.

ACK Delay: A variable-length integer including the time in
   microseconds that the largest acknowledged packet, as indicated in
   the Largest Acknowledged field, was received by this peer to when
   this ACK was sent. The value of the ACK Delay field is scaled by
   multiplying the encoded value by the 2 to the power of the value
   of the "ack_delay_exponent" transport parameter set by the sender
   of the ACK frame. The "ack_delay_exponent" defaults to 3, or a
   multiplier of 8 (see Section 6.6.1). Scaling in this fashion
   allows for a larger range of values with a shorter encoding at the
   cost of lower resolution.

ACK Block Count: The number of Additional ACK Block (and Gap) fields
   after the First ACK Block.

ACK Blocks: Contains one or more blocks of packet numbers which have
   been successfully received, see Section 7.15.1.

7.15.1. ACK Block Section

   The ACK Block Section consists of alternating Gap and ACK Block
   fields in descending packet number order. A First Ack Block field is
   followed by a variable number of alternating Gap and Additional ACK
   Blocks. The number of Gap and Additional ACK Block fields is
   determined by the ACK Block Count field.

   Gap and ACK Block fields use a relative integer encoding for
   efficiency. Though each encoded value is positive, the values are
   subtracted, so that each ACK Block describes progressively lower-
   numbered packets. As long as contiguous ranges of packets are small,
   the variable-length integer encoding ensures that each range can be
   expressed in a small number of octets.

```
    0                   1                   2                   3
    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                     First ACK Block (i)                     ...
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                          Gap (i)                            ...
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                   Additional ACK Block (i)                  ...
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                          Gap (i)                            ...
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                   Additional ACK Block (i)                  ...
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
                                  ...
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                          Gap (i)                            ...
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                   Additional ACK Block (i)                  ...
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
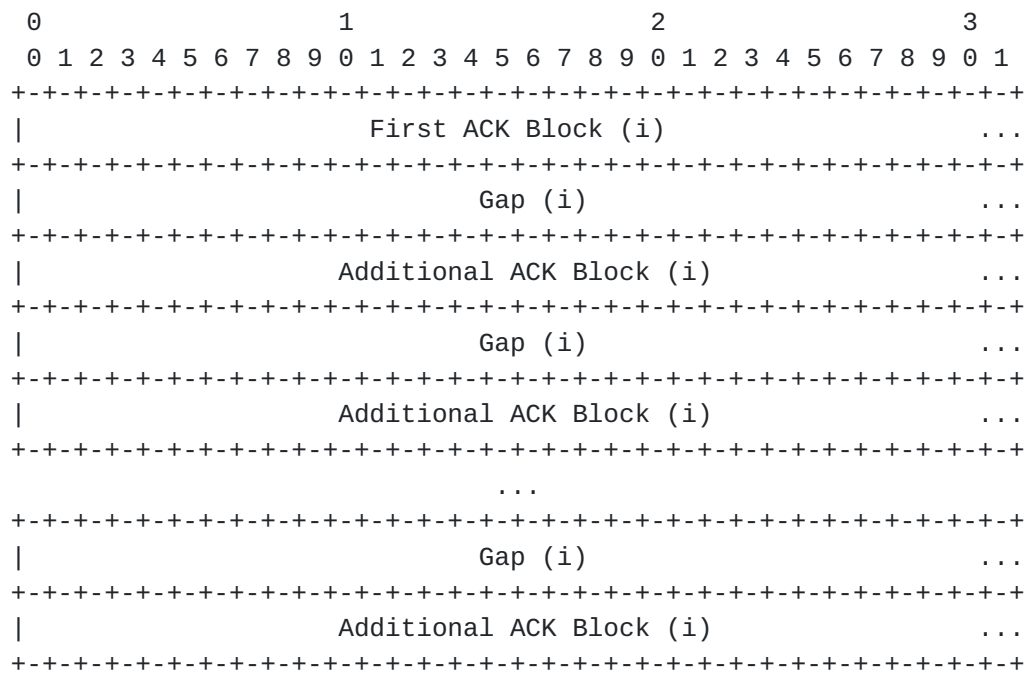
                     Figure 10: ACK Block Section

   Each ACK Block acknowledges a contiguous range of packets by
   indicating the number of acknowledged packets that precede the
   largest packet number in that block. A value of zero indicates that
   only the largest packet number is acknowledged. Larger ACK Block
   values indicate a larger range, with corresponding lower values for
   the smallest packet number in the range. Thus, given a largest
   packet number for the ACK, the smallest value is determined by the
   formula:

      smallest = largest - ack_block

The range of packets that are acknowledged by the ACK block include
the range from the smallest packet number to the largest, inclusive.

The largest value for the First ACK Block is determined by the
Largest Acknowledged field; the largest for Additional ACK Blocks is
determined by cumulatively subtracting the size of all preceding ACK
Blocks and Gaps.

Each Gap indicates a range of packets that are not being
acknowledged. The number of packets in the gap is one higher than
the encoded value of the Gap Field.

The value of the Gap field establishes the largest packet number
value for the ACK block that follows the gap using the following
formula:

      largest = previous_smallest - gap - 2

If the calculated value for largest or smallest packet number for any
ACK Block is negative, an endpoint MUST generate a connection error
of type FRAME_ENCODING_ERROR indicating an error in an ACK frame.

The fields in the ACK Block Section are:

First ACK Block: A variable-length integer indicating the number of
    contiguous packets preceding the Largest Acknowledged that are
    being acknowledged.

Gap (repeated): A variable-length integer indicating the number of
    contiguous unacknowledged packets preceding the packet number one
    lower than the smallest in the preceding ACK Block.

ACK Block (repeated): A variable-length integer indicating the
    number of contiguous acknowledged packets preceding the largest
    packet number, as determined by the preceding Gap.

7.15.2. Sending ACK Frames

Implementations MUST NOT generate packets that only contain ACK
frames in response to packets which only contain ACK frames.
However, they MUST acknowledge packets containing only ACK frames
when sending ACK frames in response to other packets.
Implementations MUST NOT send more than one packet containing only
ACK frames per received packet that contains frames other than ACK
frames. Packets containing non-ACK frames MUST be acknowledged
immediately or when a delayed ack timer expires.

   To limit ACK blocks to those that have not yet been received by the
   sender, the receiver SHOULD track which ACK frames have been
   acknowledged by its peer. Once an ACK frame has been acknowledged,
   the packets it acknowledges SHOULD NOT be acknowledged again.

   Because ACK frames are not sent in response to ACK-only packets, a
   receiver that is only sending ACK frames will only receive
   acknowledgements for its packets if the sender includes them in
   packets with non-ACK frames. A sender SHOULD bundle ACK frames with
   other frames when possible.

   Endpoints can only acknowledge packets sent in a particular packet
   number space by sending ACK frames in packets from the same packet
   number space.

   To limit receiver state or the size of ACK frames, a receiver MAY
   limit the number of ACK blocks it sends. A receiver can do this even
   without receiving acknowledgment of its ACK frames, with the
   knowledge this could cause the sender to unnecessarily retransmit
   some data. Standard QUIC [QUIC-RECOVERY] algorithms declare packets
   lost after sufficiently newer packets are acknowledged. Therefore,
   the receiver SHOULD repeatedly acknowledge newly received packets in
   preference to packets received in the past.

7.15.3. ACK Frames and Packet Protection

   ACK frames MUST only be carried in a packet that has the same packet
   number space as the packet being ACKed (see Section 4.5). For
   instance, packets that are protected with 1-RTT keys MUST be
   acknowledged in packets that are also protected with 1-RTT keys.

   Packets that a client sends with 0-RTT packet protection MUST be
   acknowledged by the server in packets protected by 1-RTT keys. This
   can mean that the client is unable to use these acknowledgments if
   the server cryptographic handshake messages are delayed or lost.
   Note that the same limitation applies to other data sent by the
   server protected by the 1-RTT keys.

   Endpoints SHOULD send acknowledgments for packets containing CRYPTO
   frames with a reduced delay; see Section 3.5.1 of [QUIC-RECOVERY].

7.16. ACK_ECN Frame

   The ACK_ECN frame (type=0x20) is used by an endpoint that supports
   ECN to acknowledge packets received with ECN codepoints of ECT(0),
   ECT(1), or CE in the packet's IP header.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Largest Acknowledged (i)                ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         ACK Delay (i)                      ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       ECT(0) Count (i)                     ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       ECT(1) Count (i)                     ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       ECN-CE Count (i)                     ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                      ACK Block Count (i)                   ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        ACK Blocks (*)                      ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 11: ACK_ECN Frame Format

An ACK_ECN frame contains all the elements of the ACK frame
(Section 7.15) with the addition of three counts following the ACK
Delay field.

ECT(0) Count: A variable-length integer representing the total
   number packets received with the ECT(0) codepoint.

ECT(1) Count: A variable-length integer representing the total
   number packets received with the ECT(1) codepoint.

CE Count: A variable-length integer representing the total number
   packets received with the CE codepoint.

7.17. PATH_CHALLENGE Frame

Endpoints can use PATH_CHALLENGE frames (type=0x0e) to check
reachability to the peer and for path validation during connection
establishment and connection migration.

PATH_CHALLENGE frames contain an 8-byte payload.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                            Data (8)                           +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

   Data: This 8-byte field contains arbitrary data.

   A PATH_CHALLENGE frame containing 8 octets that are hard to guess is
   sufficient to ensure that it is easier to receive the packet than it
   is to guess the value correctly.

   The recipient of this frame MUST generate a PATH_RESPONSE frame
   (Section 7.18) containing the same Data.

7.18. PATH_RESPONSE Frame

   The PATH_RESPONSE frame (type=0x0f) is sent in response to a
   PATH_CHALLENGE frame. Its format is identical to the PATH_CHALLENGE
   frame (Section 7.17).

   If the content of a PATH_RESPONSE frame does not match the content of
   a PATH_CHALLENGE frame previously sent by the endpoint, the endpoint
   MAY generate a connection error of type UNSOLICITED_PATH_RESPONSE.

7.19. NEW_TOKEN frame

   A server sends a NEW_TOKEN frame (type=0x19) to provide the client a
   token to send in a the header of an Initial packet for a future
   connection.

   The NEW_TOKEN frame is as follows:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Token Length (i)  ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         Token (*)                           ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

   The fields of a NEW_TOKEN frame are as follows:

   Token Length: A variable-length integer specifying the length of the
      token in bytes.

   Token: An opaque blob that the client may use with a future Initial
      packet.

7.20. STREAM Frames

   STREAM frames implicitly create a stream and carry stream data. The
   STREAM frame takes the form 0b00010XXX (or the set of values from

0x10 to 0x17). The value of the three low-order bits of the frame
type determine the fields that are present in the frame.

o The OFF bit (0x04) in the frame type is set to indicate that there
   is an Offset field present. When set to 1, the Offset field is
   present; when set to 0, the Offset field is absent and the Stream
   Data starts at an offset of 0 (that is, the frame contains the
   first octets of the stream, or the end of a stream that includes
   no data).

o The LEN bit (0x02) in the frame type is set to indicate that there
   is a Length field present. If this bit is set to 0, the Length
   field is absent and the Stream Data field extends to the end of
   the packet. If this bit is set to 1, the Length field is present.

o The FIN bit (0x01) of the frame type is set only on frames that
   contain the final offset of the stream. Setting this bit
   indicates that the frame marks the end of the stream.

An endpoint that receives a STREAM frame for a send-only stream MUST
terminate the connection with error PROTOCOL_VIOLATION.

A STREAM frame is shown below.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         Stream ID (i)                       ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         [Offset (i)]                        ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         [Length (i)]                        ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Stream Data (*)                      ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

                   Figure 12: STREAM Frame Format
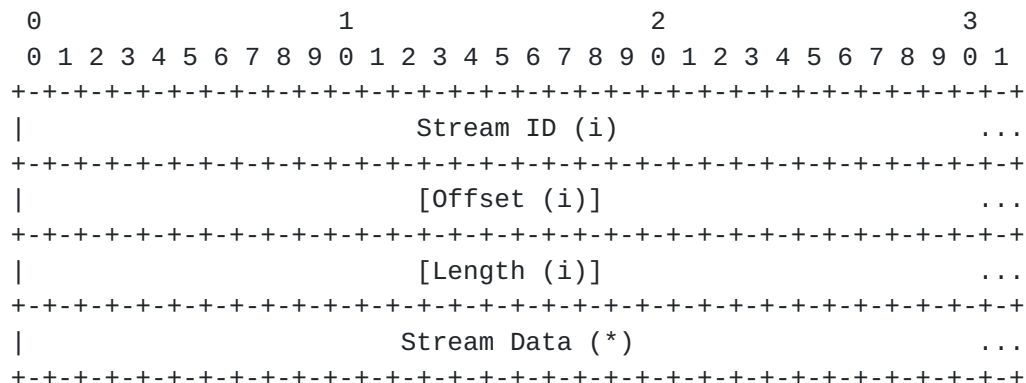
The STREAM frame contains the following fields:

Stream ID: A variable-length integer indicating the stream ID of the
   stream (see Section 9.1).

Offset: A variable-length integer specifying the byte offset in the
   stream for the data in this STREAM frame. This field is present
   when the OFF bit is set to 1. When the Offset field is absent,
   the offset is 0.

   Length: A variable-length integer specifying the length of the
      Stream Data field in this STREAM frame. This field is present
      when the LEN bit is set to 1. When the LEN bit is set to 0, the
      Stream Data field consumes all the remaining octets in the packet.

   Stream Data: The bytes from the designated stream to be delivered.

   When a Stream Data field has a length of 0, the offset in the STREAM
   frame is the offset of the next byte that would be sent.

   The first byte in the stream has an offset of 0. The largest offset
   delivered on a stream - the sum of the re-constructed offset and data
   length - MUST be less than 2^62.

   Stream multiplexing is achieved by interleaving STREAM frames from
   multiple streams into one or more QUIC packets. A single QUIC packet
   can include multiple STREAM frames from one or more streams.

   Implementation note: One of the benefits of QUIC is avoidance of
   head-of-line blocking across multiple streams. When a packet loss
   occurs, only streams with data in that packet are blocked waiting for
   a retransmission to be received, while other streams can continue
   making progress. Note that when data from multiple streams is
   bundled into a single QUIC packet, loss of that packet blocks all
   those streams from making progress. An implementation is therefore
   advised to bundle as few streams as necessary in outgoing packets
   without losing transmission efficiency to underfilled packets.

7.21. CRYPTO Frame

   The CRYPTO frame (type=0x18) is used to transmit cryptographic
   handshake messages. It can be sent in all packet types. The CRYPTO
   frame offers the cryptographic protocol an in-order stream of bytes.
   CRYPTO frames are functionally identical to STREAM frames, except
   that they do not bear a stream identifier; they are not flow
   controlled; and they do not carry markers for optional offset,
   optional length, and the end of the stream.

   A CRYPTO frame is shown below.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                          Offset (i)                        ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                          Length (i)                        ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Crypto Data (*)                     ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
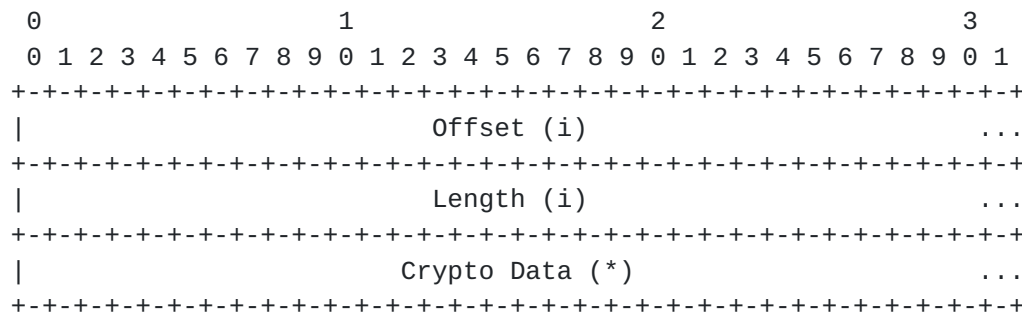
                     Figure 13: CRYPTO Frame Format

The CRYPTO frame contains the following fields:

Offset: A variable-length integer specifying the byte offset in the
   stream for the data in this CRYPTO frame.

Length: A variable-length integer specifying the length of the
   Crypto Data field in this CRYPTO frame.

Crypto Data: The cryptographic message data.

There is a separate flow of cryptographic handshake data in each
encryption level, each of which starts at an offset of 0. This
implies that each encryption level is treated as a separate CRYPTO
stream of data.

Unlike STREAM frames, which include a Stream ID indicating to which
stream the data belongs, the CRYPTO frame carries data for a single
stream per encryption level. The stream does not have an explicit
end, so CRYPTO frames do not have a FIN bit.

8. Packetization and Reliability

A sender bundles one or more frames in a QUIC packet (see Section 5).

A sender SHOULD minimize per-packet bandwidth and computational costs
by bundling as many frames as possible within a QUIC packet. A
sender MAY wait for a short period of time to bundle multiple frames
before sending a packet that is not maximally packed, to avoid
sending out large numbers of small packets. An implementation may
use knowledge about application sending behavior or heuristics to
determine whether and for how long to wait. This waiting period is
an implementation decision, and an implementation should be careful
to delay conservatively, since any delay is likely to increase
application-visible latency.

8.1. Packet Processing and Acknowledgment

A packet MUST NOT be acknowledged until packet protection has been
successfully removed and all frames contained in the packet have been
processed. Any stream state transitions triggered by the frame MUST
have occurred. For STREAM frames, this means the data has been
enqueued in preparation to be received by the application protocol,
but it does not require that data is delivered and consumed.

Once the packet has been fully processed, a receiver acknowledges
receipt by sending one or more ACK frames containing the packet
number of the received packet. To avoid creating an indefinite
feedback loop, an endpoint MUST NOT send an ACK frame in response to
a packet containing only ACK or PADDING frames, even if there are
packet gaps which precede the received packet. The endpoint MUST
acknowledge packets containing only ACK or PADDING frames in the next
ACK frame that it sends.

Strategies and implications of the frequency of generating
acknowledgments are discussed in more detail in [QUIC-RECOVERY].

8.2. Retransmission of Information

QUIC packets that are determined to be lost are not retransmitted
whole. The same applies to the frames that are contained within lost
packets. Instead, the information that might be carried in frames is
sent again in new frames as needed.

New frames and packets are used to carry information that is
determined to have been lost. In general, information is sent again
when a packet containing that information is determined to be lost
and sending ceases when a packet containing that information is
acknowledged.

o Data sent in CRYPTO frames are retransmitted according to the
   rules in [QUIC-RECOVERY], until either all data has been
   acknowledged or the crypto state machine implicitly knows that the
   peer received the data.

o Application data sent in STREAM frames is retransmitted in new
   STREAM frames unless the endpoint has sent a RST_STREAM for that
   stream. Once an endpoint sends a RST_STREAM frame, no further
   STREAM frames are needed.

o The most recent set of acknowledgments are sent in ACK frames. An
   ACK frame SHOULD contain all unacknowledged acknowledgments, as
   described in Section 7.15.2.

o Cancellation of stream transmission, as carried in a RST_STREAM
   frame, is sent until acknowledged or until all stream data is
   acknowledged by the peer (that is, either the "Reset Recvd" or
   "Data Recvd" state is reached on the send stream). The content of
   a RST_STREAM frame MUST NOT change when it is sent again.

o Similarly, a request to cancel stream transmission, as encoded in
   a STOP_SENDING frame, is sent until the receive stream enters
   either a "Data Recvd" or "Reset Recvd" state, see Section 9.3.

o Connection close signals, including those that use
   CONNECTION_CLOSE and APPLICATION_CLOSE frames, are not sent again
   when packet loss is detected, but as described in Section 6.13.

o The current connection maximum data is sent in MAX_DATA frames.
   An updated value is sent in a MAX_DATA frame if the packet
   containing the most recently sent MAX_DATA frame is declared lost,
   or when the endpoint decides to update the limit. Care is
   necessary to avoid sending this frame too often as the limit can
   increase frequently and cause an unnecessarily large number of
   MAX_DATA frames to be sent.

o The current maximum stream data offset is sent in MAX_STREAM_DATA
   frames. Like MAX_DATA, an updated value is sent when the packet
   containing the most recent MAX_STREAM_DATA frame for a stream is
   lost or when the limit is updated, with care taken to prevent the
   frame from being sent too often. An endpoint SHOULD stop sending
   MAX_STREAM_DATA frames when the receive stream enters a "Size
   Known" state.

o The maximum stream ID for a stream of a given type is sent in
   MAX_STREAM_ID frames. Like MAX_DATA, an updated value is sent
   when a packet containing the most recent MAX_STREAM_ID for a
   stream type frame is declared lost or when the limit is updated,
   with care taken to prevent the frame from being sent too often.

o Blocked signals are carried in BLOCKED, STREAM_BLOCKED, and
   STREAM_ID_BLOCKED frames. BLOCKED streams have connection scope,
   STREAM_BLOCKED frames have stream scope, and STREAM_ID_BLOCKED
   frames are scoped to a specific stream type. New frames are sent
   if packets containing the most recent frame for a scope is lost,
   but only while the endpoint is blocked on the corresponding limit.
   These frames always include the limit that is causing blocking at
   the time that they are transmitted.

o A liveness or path validation check using PATH_CHALLENGE frames is
   sent periodically until a matching PATH_RESPONSE frame is received
   or until there is no remaining need for liveness or path

   validation checking. PATH_CHALLENGE frames include a different
   payload each time they are sent.

   o Responses to path validation using PATH_RESPONSE frames are sent
      just once. A new PATH_CHALLENGE frame will be sent if another
      PATH_RESPONSE frame is needed.

   o New connection IDs are sent in NEW_CONNECTION_ID frames and
      retransmitted if the packet containing them is lost.

   o PADDING frames contain no information, so lost PADDING frames do
      not require repair.

   Upon detecting losses, a sender MUST take appropriate congestion
   control action. The details of loss detection and congestion control
   are described in [QUIC-RECOVERY].

8.3. Packet Size

   The QUIC packet size includes the QUIC header and integrity check,
   but not the UDP or IP header.

   Clients MUST pad any Initial packet it sends to have a QUIC packet
   size of at least 1200 octets. Sending an Initial packet of this size
   ensures that the network path supports a reasonably sized packet, and
   helps reduce the amplitude of amplification attacks caused by server
   responses toward an unverified client address.

   An Initial packet MAY exceed 1200 octets if the client knows that the
   Path Maximum Transmission Unit (PMTU) supports the size that it
   chooses.

   A server MAY send a CONNECTION_CLOSE frame with error code
   PROTOCOL_VIOLATION in response to an Initial packet smaller than 1200
   octets. It MUST NOT send any other frame type in response, or
   otherwise behave as if any part of the offending packet was processed
   as valid.

8.4. Path Maximum Transmission Unit

   The Path Maximum Transmission Unit (PMTU) is the maximum size of the
   entire IP header, UDP header, and UDP payload. The UDP payload
   includes the QUIC packet header, protected payload, and any
   authentication fields.

   All QUIC packets SHOULD be sized to fit within the estimated PMTU to
   avoid IP fragmentation or packet drops. To optimize bandwidth
   efficiency, endpoints SHOULD use Packetization Layer PMTU Discovery

([PLPMTUD]). Endpoints MAY use PMTU Discovery ([PMTUDv4], [PMTUDv6])
for detecting the PMTU, setting the PMTU appropriately, and storing
the result of previous PMTU determinations.

In the absence of these mechanisms, QUIC endpoints SHOULD NOT send IP
packets larger than 1280 octets. Assuming the minimum IP header
size, this results in a QUIC packet size of 1232 octets for IPv6 and
1252 octets for IPv4. Some QUIC implementations MAY wish to be more
conservative in computing allowed QUIC packet size given unknown
tunneling overheads or IP header options.

QUIC endpoints that implement any kind of PMTU discovery SHOULD
maintain an estimate for each combination of local and remote IP
addresses. Each pairing of local and remote addresses could have a
different maximum MTU in the path.

QUIC depends on the network path supporting a MTU of at least 1280
octets. This is the IPv6 minimum MTU and therefore also supported by
most modern IPv4 networks. An endpoint MUST NOT reduce its MTU below
this number, even if it receives signals that indicate a smaller
limit might exist.

If a QUIC endpoint determines that the PMTU between any pair of local
and remote IP addresses has fallen below 1280 octets, it MUST
immediately cease sending QUIC packets on the affected path. This
could result in termination of the connection if an alternative path
cannot be found.

8.4.1. IPv4 PMTU Discovery

Traditional ICMP-based path MTU discovery in IPv4 [PMTUDv4] is
potentially vulnerable to off-path attacks that successfully guess
the IP/port 4-tuple and reduce the MTU to a bandwidth-inefficient
value. TCP connections mitigate this risk by using the (at minimum)
8 bytes of transport header echoed in the ICMP message to validate
the TCP sequence number as valid for the current connection.
However, as QUIC operates over UDP, in IPv4 the echoed information
could consist only of the IP and UDP headers, which usually has
insufficient entropy to mitigate off-path attacks.

As a result, endpoints that implement PMTUD in IPv4 SHOULD take steps
to mitigate this risk. For instance, an application could:

o Set the IPv4 Don't Fragment (DF) bit on a small proportion of
   packets, so that most invalid ICMP messages arrive when there are
   no DF packets outstanding, and can therefore be identified as
   spurious.

   o Store additional information from the IP or UDP headers from DF
      packets (for example, the IP ID or UDP checksum) to further
      authenticate incoming Datagram Too Big messages.

   o Any reduction in PMTU due to a report contained in an ICMP packet
      is provisional until QUIC's loss detection algorithm determines
      that the packet is actually lost.

8.4.2. Special Considerations for Packetization Layer PMTU Discovery

   The PADDING frame provides a useful option for PMTU probe packets.
   PADDING frames generate acknowledgements, but they need not be
   delivered reliably. As a result, the loss of PADDING frames in probe
   packets does not require delay-inducing retransmission. However,
   PADDING frames do consume congestion window, which may delay the
   transmission of subsequent application data.

   When implementing the algorithm in Section 7.2 of [PLPMTUD], the
   initial value of search_low SHOULD be consistent with the IPv6
   minimum packet size. Paths that do not support this size cannot
   deliver Initial packets, and therefore are not QUIC-compliant.

   Section 7.3 of [PLPMTUD] discusses tradeoffs between small and large
   increases in the size of probe packets. As QUIC probe packets need
   not contain application data, aggressive increases in probe size
   carry fewer consequences.

9. Streams: QUIC's Data Structuring Abstraction

   Streams in QUIC provide a lightweight, ordered byte-stream
   abstraction.

   There are two basic types of stream in QUIC. Unidirectional streams
   carry data in one direction only; bidirectional streams allow for
   data to be sent in both directions. Different stream identifiers are
   used to distinguish between unidirectional and bidirectional streams,
   as well as to create a separation between streams that are initiated
   by the client and server (see Section 9.1).

   Either type of stream can be created by either endpoint, can
   concurrently send data interleaved with other streams, and can be
   cancelled.

   Stream offsets allow for the octets on a stream to be placed in
   order. An endpoint MUST be capable of delivering data received on a
   stream in order. Implementations MAY choose to offer the ability to
   deliver data out of order. There is no means of ensuring ordering
   between octets on different streams.

The creation and destruction of streams are expected to have minimal
bandwidth and computational cost. A single STREAM frame may create,
carry data for, and terminate a stream, or a stream may last the
entire duration of a connection.

Streams are individually flow controlled, allowing an endpoint to
limit memory commitment and to apply back pressure. The creation of
streams is also flow controlled, with each peer declaring the maximum
stream ID it is willing to accept at a given time.

An alternative view of QUIC streams is as an elastic "message"
abstraction, similar to the way ephemeral streams are used in SST
[SST], which may be a more appealing description for some
applications.

9.1. Stream Identifiers

Streams are identified by an unsigned 62-bit integer, referred to as
the Stream ID. The least significant two bits of the Stream ID are
used to identify the type of stream (unidirectional or bidirectional)
and the initiator of the stream.

The least significant bit (0x1) of the Stream ID identifies the
initiator of the stream. Clients initiate even-numbered streams
(those with the least significant bit set to 0); servers initiate
odd-numbered streams (with the bit set to 1). Separation of the
stream identifiers ensures that client and server are able to open
streams without the latency imposed by negotiating for an identifier.

If an endpoint receives a frame for a stream that it expects to
initiate (i.e., odd-numbered for the client or even-numbered for the
server), but which it has not yet opened, it MUST close the
connection with error code STREAM_STATE_ERROR.

The second least significant bit (0x2) of the Stream ID
differentiates between unidirectional streams and bidirectional
streams. Unidirectional streams always have this bit set to 1 and
bidirectional streams have this bit set to 0.

The two type bits from a Stream ID therefore identify streams as
summarized in Table 5.

```
+----------+--------------------------------+
| Low Bits | Stream Type                    |
+----------+--------------------------------+
| 0x0      | Client-Initiated, Bidirectional  |
|          |                                |
| 0x1      | Server-Initiated, Bidirectional  |
|          |                                |
| 0x2      | Client-Initiated, Unidirectional |
|          |                                |
| 0x3      | Server-Initiated, Unidirectional |
+----------+--------------------------------+
```

Table 5: Stream ID Types

The first bi-directional stream opened by the client is stream 0.

A QUIC endpoint MUST NOT reuse a Stream ID. Streams can be used in
any order. Streams that are used out of order result in opening all
lower-numbered streams of the same type in the same direction.

Stream IDs are encoded as a variable-length integer (see
Section 7.1).

9.2. Stream States

This section describes the two types of QUIC stream in terms of the
states of their send or receive components. Two state machines are
described: one for streams on which an endpoint transmits data
(Section 9.2.1); another for streams from which an endpoint receives
data (Section 9.2.2).

Unidirectional streams use the applicable state machine directly.
Bidirectional streams use both state machines. For the most part,
the use of these state machines is the same whether the stream is
unidirectional or bidirectional. The conditions for opening a stream
are slightly more complex for a bidirectional stream because the
opening of either send or receive sides causes the stream to open in
both directions.

An endpoint can open streams up to its maximum stream limit in any
order, however endpoints SHOULD open the send side of streams for
each type in order.

Note: These states are largely informative. This document uses
   stream states to describe rules for when and how different types
   of frames can be sent and the reactions that are expected when
   different types of frames are received. Though these state
   machines are intended to be useful in implementing QUIC, these

states aren't intended to constrain implementations. An
implementation can define a different state machine as long as its
behavior is consistent with an implementation that implements
these states.

9.2.1. Send Stream States

Figure 14 shows the states for the part of a stream that sends data
to a peer.

```
       o
       | Create Stream (Sending)
       | Create Bidirectional Stream (Receiving)
       v
   +-------+
   | Ready | Send RST_STREAM
   |       |-----------------------.
   +-------+                       |
       |                           |
       | Send STREAM /             |
       |      STREAM_BLOCKED       |
       v                           |
   +-------+                       |
   | Send  | Send RST_STREAM       |
   |       |---------------------->|
   +-------+                       |
       |                           |
       | Send STREAM + FIN         |
       v                           v
   +-------+               +-------+
   | Data  | Send RST_STREAM  | Reset |
   | Sent  +------------------>| Sent  |
   +-------+               +-------+
       |                       |
       | Recv All ACKs         | Recv ACK
       v                       v
   +-------+               +-------+
   | Data  |               | Reset |
   | Recvd |               | Recvd |
   +-------+               +-------+
```
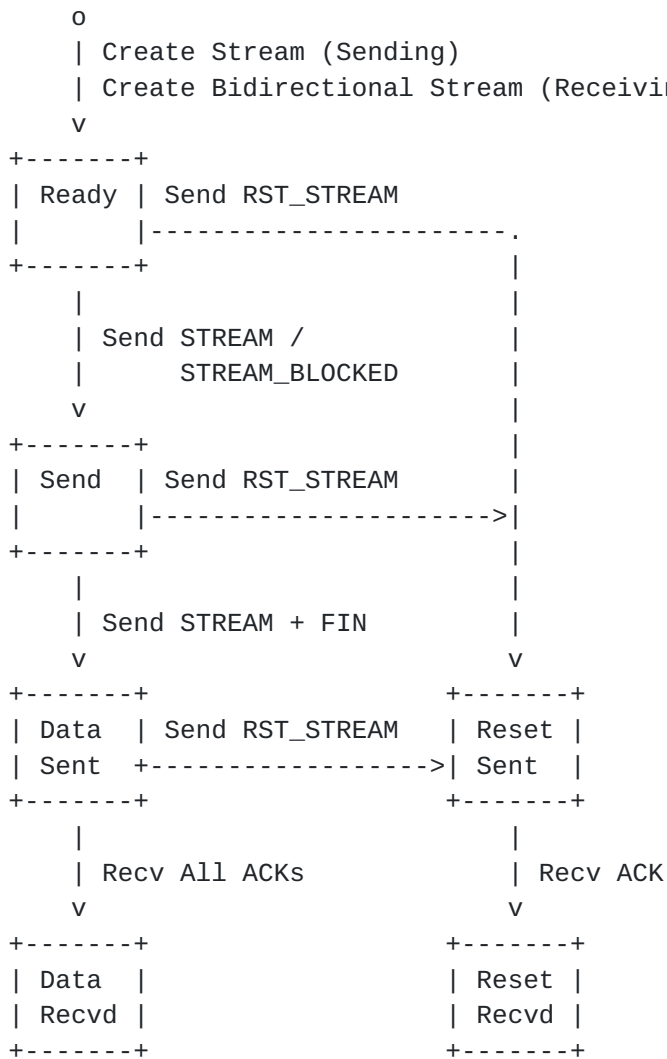
                   Figure 14: States for Send Streams

The sending part of stream that the endpoint initiates (types 0 and 2
for clients, 1 and 3 for servers) is opened by the application or
application protocol. The "Ready" state represents a newly created
stream that is able to accept data from the application. Stream data
might be buffered in this state in preparation for sending.

The sending part of a bidirectional stream initiated by a peer (type
0 for a server, type 1 for a client) enters the "Ready" state if the
receiving part enters the "Recv" state.

Sending the first STREAM or STREAM_BLOCKED frame causes a send stream
to enter the "Send" state. An implementation might choose to defer
allocating a Stream ID to a send stream until it sends the first
frame and enters this state, which can allow for better stream
prioritization.

In the "Send" state, an endpoint transmits - and retransmits as
necessary - data in STREAM frames. The endpoint respects the flow
control limits of its peer, accepting MAX_STREAM_DATA frames. An
endpoint in the "Send" state generates STREAM_BLOCKED frames if it
encounters flow control limits.

After the application indicates that stream data is complete and a
STREAM frame containing the FIN bit is sent, the send stream enters
the "Data Sent" state. From this state, the endpoint only
retransmits stream data as necessary. The endpoint no longer needs
to track flow control limits or send STREAM_BLOCKED frames for a send
stream in this state. The endpoint can ignore any MAX_STREAM_DATA
frames it receives from its peer in this state; MAX_STREAM_DATA
frames might be received until the peer receives the final stream
offset.

Once all stream data has been successfully acknowledged, the send
stream enters the "Data Recvd" state, which is a terminal state.

From any of the "Ready", "Send", or "Data Sent" states, an
application can signal that it wishes to abandon transmission of
stream data. Similarly, the endpoint might receive a STOP_SENDING
frame from its peer. In either case, the endpoint sends a RST_STREAM
frame, which causes the stream to enter the "Reset Sent" state.

An endpoint MAY send a RST_STREAM as the first frame on a send
stream; this causes the send stream to open and then immediately
transition to the "Reset Sent" state.

Once a packet containing a RST_STREAM has been acknowledged, the send
stream enters the "Reset Recvd" state, which is a terminal state.

9.2.2. Receive Stream States

Figure 15 shows the states for the part of a stream that receives
data from a peer. The states for a receive stream mirror only some
of the states of the send stream at the peer. A receive stream
doesn't track states on the send stream that cannot be observed, such

as the "Ready" state; instead, receive streams track the delivery of
data to the application or application protocol some of which cannot
be observed by the sender.

```
            o
            | Recv STREAM / STREAM_BLOCKED / RST_STREAM
            | Create Bidirectional Stream (Sending)
            | Recv MAX_STREAM_DATA
            v
       +-------+
       | Recv  | Recv RST_STREAM
       |       |----------------------.
       +-------+                      |
           |                          |
           | Recv STREAM + FIN        |
           v                          |
       +-------+                      |
       | Size  | Recv RST_STREAM      |
       | Known +--------------------->|
       +-------+                      |
           |                          |
           | Recv All Data            |
           v                          v
       +-------+              +-------+
       | Data  | Recv RST_STREAM  | Reset |
       | Recvd +<-- (optional) --->| Recvd |
       +-------+              +-------+
           |                      |
           | App Read All Data    | App Read RST
           v                      v
       +-------+              +-------+
       | Data  |              | Reset |
       | Read  |              | Read  |
       +-------+              +-------+
```
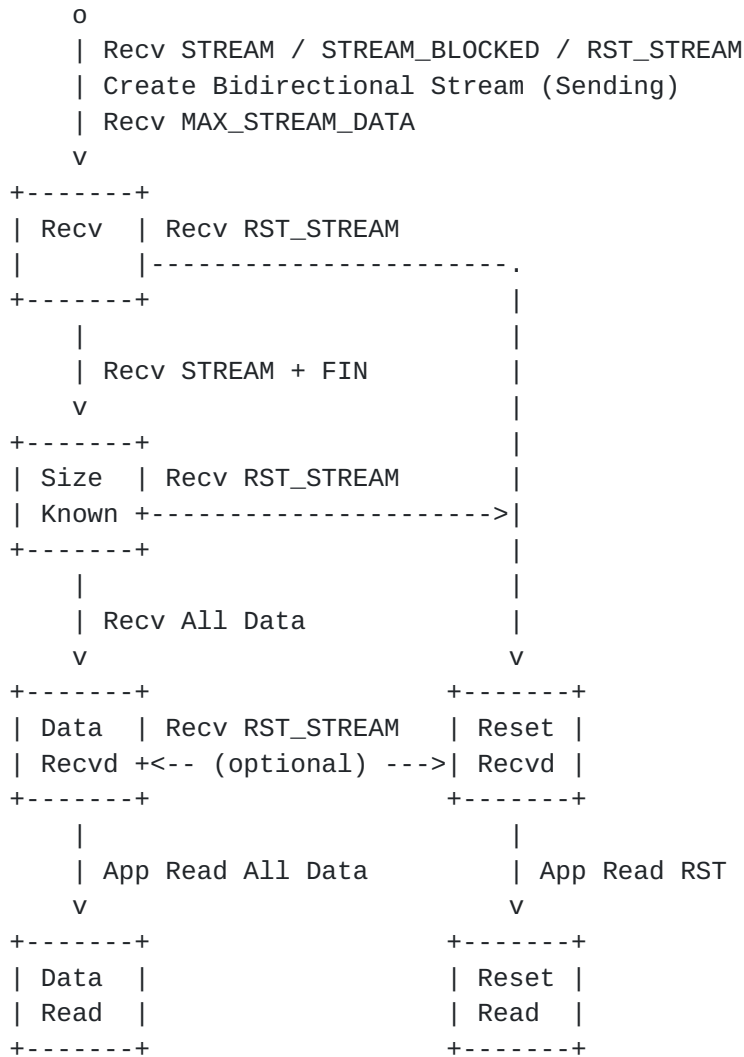
                  Figure 15: States for Receive Streams

   The receiving part of a stream initiated by a peer (types 1 and 3 for
   a client, or 0 and 2 for a server) are created when the first STREAM,
   STREAM_BLOCKED, RST_STREAM, or MAX_STREAM_DATA (bidirectional only,
   see below) is received for that stream. The initial state for a
   receive stream is "Recv". Receiving a RST_STREAM frame causes the
   receive stream to immediately transition to the "Reset Recvd".

   The receive stream enters the "Recv" state when the sending part of a
   bidirectional stream initiated by the endpoint (type 0 for a client,
   type 1 for a server) enters the "Ready" state.

A bidirectional stream also opens when a MAX_STREAM_DATA frame is
received. Receiving a MAX_STREAM_DATA frame implies that the remote
peer has opened the stream and is providing flow control credit. A
MAX_STREAM_DATA frame might arrive before a STREAM or STREAM_BLOCKED
frame if packets are lost or reordered.

In the "Recv" state, the endpoint receives STREAM and STREAM_BLOCKED
frames. Incoming data is buffered and can be reassembled into the
correct order for delivery to the application. As data is consumed
by the application and buffer space becomes available, the endpoint
sends MAX_STREAM_DATA frames to allow the peer to send more data.

When a STREAM frame with a FIN bit is received, the final offset (see
Section 10.3) is known. The receive stream enters the "Size Known"
state. In this state, the endpoint no longer needs to send
MAX_STREAM_DATA frames, it only receives any retransmissions of
stream data.

Once all data for the stream has been received, the receive stream
enters the "Data Recvd" state. This might happen as a result of
receiving the same STREAM frame that causes the transition to "Size
Known". In this state, the endpoint has all stream data. Any STREAM
or STREAM_BLOCKED frames it receives for the stream can be discarded.

The "Data Recvd" state persists until stream data has been delivered
to the application or application protocol. Once stream data has
been delivered, the stream enters the "Data Read" state, which is a
terminal state.

Receiving a RST_STREAM frame in the "Recv" or "Size Known" states
causes the stream to enter the "Reset Recvd" state. This might cause
the delivery of stream data to the application to be interrupted.

It is possible that all stream data is received when a RST_STREAM is
received (that is, from the "Data Recvd" state). Similarly, it is
possible for remaining stream data to arrive after receiving a
RST_STREAM frame (the "Reset Recvd" state). An implementation is
able to manage this situation as they choose. Sending RST_STREAM
means that an endpoint cannot guarantee delivery of stream data;
however there is no requirement that stream data not be delivered if
a RST_STREAM is received. An implementation MAY interrupt delivery
of stream data, discard any data that was not consumed, and signal
the existence of the RST_STREAM immediately. Alternatively, the
RST_STREAM signal might be suppressed or withheld if stream data is
completely received. In the latter case, the receive stream
effectively transitions to "Data Recvd" from "Reset Recvd".

Once the application has been delivered the signal indicating that
the receive stream was reset, the receive stream transitions to the
"Reset Read" state, which is a terminal state.

9.2.3. Permitted Frame Types

The sender of a stream sends just three frame types that affect the
state of a stream at either sender or receiver: STREAM
(Section 7.20), STREAM_BLOCKED (Section 7.11), and RST_STREAM
(Section 7.3).

A sender MUST NOT send any of these frames from a terminal state
("Data Recvd" or "Reset Recvd"). A sender MUST NOT send STREAM or
STREAM_BLOCKED after sending a RST_STREAM; that is, in the "Reset
Sent" state in addition to the terminal states. A receiver could
receive any of these frames in any state, but only due to the
possibility of delayed delivery of packets carrying them.

The receiver of a stream sends MAX_STREAM_DATA (Section 7.7) and
STOP_SENDING frames (Section 7.14).

The receiver only sends MAX_STREAM_DATA in the "Recv" state. A
receiver can send STOP_SENDING in any state where it has not received
a RST_STREAM frame; that is states other than "Reset Recvd" or "Reset
Read". However there is little value in sending a STOP_SENDING frame
after all stream data has been received in the "Data Recvd" state. A
sender could receive these frames in any state as a result of delayed
delivery of packets.

9.2.4. Bidirectional Stream States

A bidirectional stream is composed of a send stream and a receive
stream. Implementations may represent states of the bidirectional
stream as composites of send and receive stream states. The simplest
model presents the stream as "open" when either send or receive
stream is in a non-terminal state and "closed" when both send and
receive streams are in a terminal state.

Table 6 shows a more complex mapping of bidirectional stream states
that loosely correspond to the stream states in HTTP/2 [HTTP2]. This
shows that multiple states on send or receive streams are mapped to
the same composite state. Note that this is just one possibility for
such a mapping; this mapping requires that data is acknowledged
before the transition to a "closed" or "half-closed" state.

Send Stream	Receive Stream	Composite State
No Stream/Ready	No Stream/Recv *1	idle
Ready/Send/Data Sent	Recv/Size Known	open
Ready/Send/Data Sent	Data Recvd/Data Read	half-closed (remote)
Ready/Send/Data Sent	Reset Recvd/Reset Read	half-closed (remote)
Data Recvd	Recv/Size Known	half-closed (local)
Reset Sent/Reset Recvd	Recv/Size Known	half-closed (local)
Data Recvd	Recv/Size Known	half-closed (local)
Reset Sent/Reset Recvd	Data Recvd/Data Read	closed
Reset Sent/Reset Recvd	Reset Recvd/Reset Read	closed
Data Recvd	Data Recvd/Data Read	closed
Data Recvd	Reset Recvd/Reset Read	closed

Table 6: Possible Mapping of Stream States to HTTP/2

Note (*1): A stream is considered "idle" if it has not yet been
   created, or if the receive stream is in the "Recv" state without
   yet having received any frames.

9.3. Solicited State Transitions

If an endpoint is no longer interested in the data it is receiving on
a stream, it MAY send a STOP_SENDING frame identifying that stream to
prompt closure of the stream in the opposite direction. This
typically indicates that the receiving application is no longer
reading data it receives from the stream, but is not a guarantee that
incoming data will be ignored.

STREAM frames received after sending STOP_SENDING are still counted
toward the connection and stream flow-control windows, even though
these frames will be discarded upon receipt. This avoids potential
ambiguity about which STREAM frames count toward flow control.

A STOP_SENDING frame requests that the receiving endpoint send a
RST_STREAM frame. An endpoint that receives a STOP_SENDING frame
MUST send a RST_STREAM frame for that stream, and can use an error
code of STOPPING. If the STOP_SENDING frame is received on a send
stream that is already in the "Data Sent" state, a RST_STREAM frame
MAY still be sent in order to cancel retransmission of previously-
sent STREAM frames.

STOP_SENDING SHOULD only be sent for a receive stream that has not
been reset. STOP_SENDING is most useful for streams in the "Recv" or
"Size Known" states.

An endpoint is expected to send another STOP_SENDING frame if a
packet containing a previous STOP_SENDING is lost. However, once
either all stream data or a RST_STREAM frame has been received for
the stream - that is, the stream is in any state other than "Recv" or
"Size Known" - sending a STOP_SENDING frame is unnecessary.

9.4. Stream Concurrency

An endpoint limits the number of concurrently active incoming streams
by adjusting the maximum stream ID. An initial value is set in the
transport parameters (see Section 6.6.1) and is subsequently
increased by MAX_STREAM_ID frames (see Section 7.8).

The maximum stream ID is specific to each endpoint and applies only
to the peer that receives the setting. That is, clients specify the
maximum stream ID the server can initiate, and servers specify the
maximum stream ID the client can initiate. Each endpoint may respond
on streams initiated by the other peer, regardless of whether it is
permitted to initiated new streams.

Endpoints MUST NOT exceed the limit set by their peer. An endpoint
that receives a STREAM frame with an ID greater than the limit it has
sent MUST treat this as a stream error of type STREAM_ID_ERROR
(Section 11), unless this is a result of a change in the initial
offsets (see Section 6.6.2).

A receiver MUST NOT renege on an advertisement; that is, once a
receiver advertises a stream ID via a MAX_STREAM_ID frame, it MUST
NOT subsequently advertise a smaller maximum ID. A sender may
receive MAX_STREAM_ID frames out of order; a sender MUST therefore
ignore any MAX_STREAM_ID that does not increase the maximum.

9.5. Sending and Receiving Data

Once a stream is created, endpoints may use the stream to send and
receive data. Each endpoint may send a series of STREAM frames
encapsulating data on a stream until the stream is terminated in that
direction. Streams are an ordered byte-stream abstraction, and they
have no other structure within them. STREAM frame boundaries are not
expected to be preserved in retransmissions from the sender or during
delivery to the application at the receiver.

When new data is to be sent on a stream, a sender MUST set the
encapsulating STREAM frame's offset field to the stream offset of the
first byte of this new data. The first octet of data on a stream has
an offset of 0. An endpoint is expected to send every stream octet.
The largest offset delivered on a stream MUST be less than 2^62.

QUIC makes no specific allowances for partial reliability or delivery
of stream data out of order. Endpoints MUST be able to deliver
stream data to an application as an ordered byte-stream. Delivering
an ordered byte-stream requires that an endpoint buffer any data that
is received out of order, up to the advertised flow control limit.

An endpoint could receive the same octets multiple times; octets that
have already been received can be discarded. The value for a given
octet MUST NOT change if it is sent multiple times; an endpoint MAY
treat receipt of a changed octet as a connection error of type
PROTOCOL_VIOLATION.

An endpoint MUST NOT send data on any stream without ensuring that it
is within the data limits set by its peer.

Flow control is described in detail in Section 10, and congestion
control is described in the companion document [QUIC-RECOVERY].

9.6. Stream Prioritization

Stream multiplexing has a significant effect on application
performance if resources allocated to streams are correctly
prioritized. Experience with other multiplexed protocols, such as
HTTP/2 [HTTP2], shows that effective prioritization strategies have a
significant positive impact on performance.

QUIC does not provide frames for exchanging prioritization
information. Instead it relies on receiving priority information
from the application that uses QUIC. Protocols that use QUIC are
able to define any prioritization scheme that suits their application
semantics. A protocol might define explicit messages for signaling
priority, such as those defined in HTTP/2; it could define rules that

allow an endpoint to determine priority based on context; or it could
leave the determination to the application.

A QUIC implementation SHOULD provide ways in which an application can
indicate the relative priority of streams. When deciding which
streams to dedicate resources to, QUIC SHOULD use the information
provided by the application. Failure to account for priority of
streams can result in suboptimal performance.

Stream priority is most relevant when deciding which stream data will
be transmitted. Often, there will be limits on what can be
transmitted as a result of connection flow control or the current
congestion controller state.

Giving preference to the transmission of its own management frames
ensures that the protocol functions efficiently. That is,
prioritizing frames other than STREAM frames ensures that loss
recovery, congestion control, and flow control operate effectively.

CRYPTO frames SHOULD be prioritized over other streams prior to the
completion of the cryptographic handshake. This includes the
retransmission of the second flight of client handshake messages,
that is, the TLS Finished and any client authentication messages.

STREAM data in frames determined to be lost SHOULD be retransmitted
before sending new data, unless application priorities indicate
otherwise. Retransmitting lost stream data can fill in gaps, which
allows the peer to consume already received data and free up flow
control window.

10. Flow Control

It is necessary to limit the amount of data that a sender may have
outstanding at any time, so as to prevent a fast sender from
overwhelming a slow receiver, or to prevent a malicious sender from
consuming significant resources at a receiver. This section
describes QUIC's flow-control mechanisms.

QUIC employs a credit-based flow-control scheme similar to HTTP/2's
flow control [HTTP2]. A receiver advertises the number of octets it
is prepared to receive on a given stream and for the entire
connection. This leads to two levels of flow control in QUIC: (i)
Connection flow control, which prevents senders from exceeding a
receiver's buffer capacity for the connection, and (ii) Stream flow
control, which prevents a single stream from consuming the entire
receive buffer for a connection.

A data receiver sends MAX_STREAM_DATA or MAX_DATA frames to the
sender to advertise additional credit. MAX_STREAM_DATA frames send
the maximum absolute byte offset of a stream, while MAX_DATA sends
the maximum of the sum of the absolute byte offsets of all streams.

A receiver MAY advertise a larger offset at any point by sending
MAX_DATA or MAX_STREAM_DATA frames. A receiver MUST NOT renege on an
advertisement; that is, once a receiver advertises an offset, it MUST
NOT subsequently advertise a smaller offset. A sender could receive
MAX_DATA or MAX_STREAM_DATA frames out of order; a sender MUST
therefore ignore any flow control offset that does not move the
window forward.

A receiver MUST close the connection with a FLOW_CONTROL_ERROR error
(Section 11) if the peer violates the advertised connection or stream
data limits.

A sender SHOULD send BLOCKED or STREAM_BLOCKED frames to indicate it
has data to write but is blocked by flow control limits. These
frames are expected to be sent infrequently in common cases, but they
are considered useful for debugging and monitoring purposes.

A receiver advertises credit for a stream by sending a
MAX_STREAM_DATA frame with the Stream ID set appropriately. A
receiver could use the current offset of data consumed to determine
the flow control offset to be advertised. A receiver MAY send
MAX_STREAM_DATA frames in multiple packets in order to make sure that
the sender receives an update before running out of flow control
credit, even if one of the packets is lost.

Connection flow control is a limit to the total bytes of stream data
sent in STREAM frames on all streams. A receiver advertises credit
for a connection by sending a MAX_DATA frame. A receiver maintains a
cumulative sum of bytes received on all contributing streams, which
are used to check for flow control violations. A receiver might use
a sum of bytes consumed on all contributing streams to determine the
maximum data limit to be advertised.

10.1. Edge Cases and Other Considerations

There are some edge cases which must be considered when dealing with
stream and connection level flow control. Given enough time, both
endpoints must agree on flow control state. If one end believes it
can send more than the other end is willing to receive, the
connection will be torn down when too much data arrives.

Conversely if a sender believes it is blocked, while endpoint B
expects more data can be received, then the connection can be in a

deadlock, with the sender waiting for a MAX_DATA or MAX_STREAM_DATA
frame which will never come.

On receipt of a RST_STREAM frame, an endpoint will tear down state
for the matching stream and ignore further data arriving on that
stream. This could result in the endpoints getting out of sync,
since the RST_STREAM frame may have arrived out of order and there
may be further bytes in flight. The data sender would have counted
the data against its connection level flow control budget, but a
receiver that has not received these bytes would not know to include
them as well. The receiver must learn the number of bytes that were
sent on the stream to make the same adjustment in its connection flow
controller.

To avoid this de-synchronization, a RST_STREAM sender MUST include
the final byte offset sent on the stream in the RST_STREAM frame. On
receiving a RST_STREAM frame, a receiver definitively knows how many
bytes were sent on that stream before the RST_STREAM frame, and the
receiver MUST use the final offset to account for all bytes sent on
the stream in its connection level flow controller.

10.1.1. Response to a RST_STREAM

RST_STREAM terminates one direction of a stream abruptly. Whether
any action or response can or should be taken on the data already
received is an application-specific issue, but it will often be the
case that upon receipt of a RST_STREAM an endpoint will choose to
stop sending data in its own direction. If the sender of a
RST_STREAM wishes to explicitly state that no future data will be
processed, that endpoint MAY send a STOP_SENDING frame at the same
time.

10.1.2. Data Limit Increments

This document leaves when and how many bytes to advertise in a
MAX_DATA or MAX_STREAM_DATA to implementations, but offers a few
considerations. These frames contribute to connection overhead.
Therefore frequently sending frames with small changes is
undesirable. At the same time, infrequent updates require larger
increments to limits if blocking is to be avoided. Thus, larger
updates require a receiver to commit to larger resource commitments.
Thus there is a tradeoff between resource commitment and overhead
when determining how large a limit is advertised.

A receiver MAY use an autotuning mechanism to tune the frequency and
amount that it increases data limits based on a round-trip time
estimate and the rate at which the receiving application consumes
data, similar to common TCP implementations.

10.2. Stream Limit Increment

   As with flow control, this document leaves when and how many streams
   to make available to a peer via MAX_STREAM_ID to implementations, but
   offers a few considerations. MAX_STREAM_ID frames constitute minimal
   overhead, while withholding MAX_STREAM_ID frames can prevent the peer
   from using the available parallelism.

   Implementations will likely want to increase the maximum stream ID as
   peer-initiated streams close. A receiver MAY also advance the
   maximum stream ID based on current activity, system conditions, and
   other environmental factors.

10.2.1. Blocking on Flow Control

   If a sender does not receive a MAX_DATA or MAX_STREAM_DATA frame when
   it has run out of flow control credit, the sender will be blocked and
   SHOULD send a BLOCKED or STREAM_BLOCKED frame. These frames are
   expected to be useful for debugging at the receiver; they do not
   require any other action. A receiver SHOULD NOT wait for a BLOCKED
   or STREAM_BLOCKED frame before sending MAX_DATA or MAX_STREAM_DATA,
   since doing so will mean that a sender is unable to send for an
   entire round trip.

   For smooth operation of the congestion controller, it is generally
   considered best to not let the sender go into quiescence if
   avoidable. To avoid blocking a sender, and to reasonably account for
   the possibiity of loss, a receiver should send a MAX_DATA or
   MAX_STREAM_DATA frame at least two round trips before it expects the
   sender to get blocked.

   A sender sends a single BLOCKED or STREAM_BLOCKED frame only once
   when it reaches a data limit. A sender SHOULD NOT send multiple
   BLOCKED or STREAM_BLOCKED frames for the same data limit, unless the
   original frame is determined to be lost. Another BLOCKED or
   STREAM_BLOCKED frame can be sent after the data limit is increased.

10.3. Stream Final Offset

   The final offset is the count of the number of octets that are
   transmitted on a stream. For a stream that is reset, the final
   offset is carried explicitly in a RST_STREAM frame. Otherwise, the
   final offset is the offset of the end of the data carried in a STREAM
   frame marked with a FIN flag, or 0 in the case of incoming
   unidirectional streams.

   An endpoint will know the final offset for a stream when the receive
   stream enters the "Size Known" or "Reset Recvd" state.

An endpoint MUST NOT send data on a stream at or beyond the final
offset.

Once a final offset for a stream is known, it cannot change. If a
RST_STREAM or STREAM frame causes the final offset to change for a
stream, an endpoint SHOULD respond with a FINAL_OFFSET_ERROR error
(see Section 11). A receiver SHOULD treat receipt of data at or
beyond the final offset as a FINAL_OFFSET_ERROR error, even after a
stream is closed. Generating these errors is not mandatory, but only
because requiring that an endpoint generate these errors also means
that the endpoint needs to maintain the final offset state for closed
streams, which could mean a significant state commitment.

10.4. Flow Control for Crytographic Handshake

Data sent in CRYPTO frames is not flow controlled in the same way as
STREAM frames. QUIC relies on the cryptographic protocol
implementation to avoid excessive buffering of data, see [QUIC-TLS].
The implementation SHOULD provide an interface to QUIC to tell it
about its buffering limits so that there is not excessive buffering
at multiple layers.

11. Error Handling

An endpoint that detects an error SHOULD signal the existence of that
error to its peer. Both transport-level and application-level errors
can affect an entire connection (see Section 11.1), while only
application-level errors can be isolated to a single stream (see
Section 11.2).

The most appropriate error code (Section 11.3) SHOULD be included in
the frame that signals the error. Where this specification
identifies error conditions, it also identifies the error code that
is used.

A stateless reset (Section 6.13.4) is not suitable for any error that
can be signaled with a CONNECTION_CLOSE, APPLICATION_CLOSE, or
RST_STREAM frame. A stateless reset MUST NOT be used by an endpoint
that has the state necessary to send a frame on the connection.

11.1. Connection Errors

Errors that result in the connection being unusable, such as an
obvious violation of protocol semantics or corruption of state that
affects an entire connection, MUST be signaled using a
CONNECTION_CLOSE or APPLICATION_CLOSE frame (Section 7.4,
Section 7.5). An endpoint MAY close the connection in this manner
even if the error only affects a single stream.

Application protocols can signal application-specific protocol errors
using the APPLICATION_CLOSE frame. Errors that are specific to the
transport, including all those described in this document, are
carried in a CONNECTION_CLOSE frame. Other than the type of error
code they carry, these frames are identical in format and semantics.

A CONNECTION_CLOSE or APPLICATION_CLOSE frame could be sent in a
packet that is lost. An endpoint SHOULD be prepared to retransmit a
packet containing either frame type if it receives more packets on a
terminated connection. Limiting the number of retransmissions and
the time over which this final packet is sent limits the effort
expended on terminated connections.

An endpoint that chooses not to retransmit packets containing
CONNECTION_CLOSE or APPLICATION_CLOSE risks a peer missing the first
such packet. The only mechanism available to an endpoint that
continues to receive data for a terminated connection is to use the
stateless reset process (Section 6.13.4).

An endpoint that receives an invalid CONNECTION_CLOSE or
APPLICATION_CLOSE frame MUST NOT signal the existence of the error to
its peer.

11.2. Stream Errors

If an application-level error affects a single stream, but otherwise
leaves the connection in a recoverable state, the endpoint can send a
RST_STREAM frame (Section 7.3) with an appropriate error code to
terminate just the affected stream.

Other than STOPPING (Section 9.3), RST_STREAM MUST be instigated by
the application and MUST carry an application error code. Resetting
a stream without knowledge of the application protocol could cause
the protocol to enter an unrecoverable state. Application protocols
might require certain streams to be reliably delivered in order to
guarantee consistent state between endpoints.

11.3. Transport Error Codes

QUIC error codes are 16-bit unsigned integers.

This section lists the defined QUIC transport error codes that may be
used in a CONNECTION_CLOSE frame. These errors apply to the entire
connection.

NO_ERROR (0x0): An endpoint uses this with CONNECTION_CLOSE to
   signal that the connection is being closed abruptly in the absence
   of any error.

INTERNAL_ERROR (0x1): The endpoint encountered an internal error and
   cannot continue with the connection.

SERVER_BUSY (0x2): The server is currently busy and does not accept
   any new connections.

FLOW_CONTROL_ERROR (0x3): An endpoint received more data than it
   permitted in its advertised data limits (see Section 10).

STREAM_ID_ERROR (0x4): An endpoint received a frame for a stream
   identifier that exceeded its advertised maximum stream ID.

STREAM_STATE_ERROR (0x5): An endpoint received a frame for a stream
   that was not in a state that permitted that frame (see
   Section 9.2).

FINAL_OFFSET_ERROR (0x6): An endpoint received a STREAM frame
   containing data that exceeded the previously established final
   offset. Or an endpoint received a RST_STREAM frame containing a
   final offset that was lower than the maximum offset of data that
   was already received. Or an endpoint received a RST_STREAM frame
   containing a different final offset to the one already
   established.

FRAME_ENCODING_ERROR (0x7): An endpoint received a frame that was
   badly formatted. For instance, an empty STREAM frame that omitted
   the FIN flag, or an ACK frame that has more acknowledgment ranges
   than the remainder of the packet could carry.

TRANSPORT_PARAMETER_ERROR (0x8): An endpoint received transport
   parameters that were badly formatted, included an invalid value,
   was absent even though it is mandatory, was present though it is
   forbidden, or is otherwise in error.

VERSION_NEGOTIATION_ERROR (0x9): An endpoint received transport
   parameters that contained version negotiation parameters that
   disagreed with the version negotiation that it performed. This
   error code indicates a potential version downgrade attack.

PROTOCOL_VIOLATION (0xA): An endpoint detected an error with
   protocol compliance that was not covered by more specific error
   codes.

UNSOLICITED_PATH_RESPONSE (0xB): An endpoint received a
   PATH_RESPONSE frame that did not correspond to any PATH_CHALLENGE
   frame that it previously sent.

INVALID_MIGRATION (0xC): A peer has migrated to a different network
    when the endpoint had disabled migration.

CRYPTO_ERROR (0x1XX): The cryptographic handshake failed. A range
    of 256 values is reserved for carrying error codes specific to the
    cryptographic handshake that is used. Codes for errors occuring
    when TLS is used for the crypto handshake are defined in
    Section 11 of [QUIC-TLS].

See Section 13.3 for details of registering new error codes.

11.4. Application Protocol Error Codes

Application protocol error codes are 16-bit unsigned integers, but
the management of application error codes are left to application
protocols. Application protocol error codes are used for the
RST_STREAM (Section 7.3) and APPLICATION_CLOSE (Section 7.5) frames.

There is no restriction on the use of the 16-bit error code space for
application protocols. However, QUIC reserves the error code with a
value of 0 to mean STOPPING. The application error code of STOPPING
(0) is used by the transport to cancel a stream in response to
receipt of a STOP_SENDING frame.

12. Security Considerations

12.1. Handshake Denial of Service

As an encrypted and authenticated transport QUIC provides a range of
protections against denial of service. Once the cryptographic
handshake is complete, QUIC endpoints discard most packets that are
not authenticated, greatly limiting the ability of an attacker to
interfere with existing connections.

Once a connection is established QUIC endpoints might accept some
unauthenticated ICMP packets (see Section 8.4.1), but the use of
these packets is extremely limited. The only other type of packet
that an endpoint might accept is a stateless reset (Section 6.13.4)
which relies on the token being kept secret until it is used.

During the creation of a connection, QUIC only provides protection
against attack from off the network path. All QUIC packets contain
proof that the recipient saw a preceding packet from its peer.

The first mechanism used is the source and destination connection
IDs, which are required to match those set by a peer. Except for an
Initial and stateless reset packets, an endpoint only accepts packets
that include a destination connection that matches a connection ID

the endpoint previously chose. This is the only protection offered
for Version Negotiation packets.

The destination connection ID in an Initial packet is selected by a
client to be unpredictable, which serves an additional purpose. The
packets that carry the cryptographic handshake are protected with a
key that is derived from this connection ID and salt specific to the
QUIC version. This allows endpoints to use the same process for
authenticating packets that they receive as they use after the
cryptographic handshake completes. Packets that cannot be
authenticated are discarded. Protecting packets in this fashion
provides a strong assurance that the sender of the packet saw the
Initial packet and understood it.

These protections are not intended to be effective against an
attacker that is able to receive QUIC packets prior to the connection
being established. Such an attacker can potentially send packets
that will be accepted by QUIC endpoints. This version of QUIC
attempts to detect this sort of attack, but it expects that endpoints
will fail to establish a connection rather than recovering. For the
most part, the cryptographic handshake protocol [QUIC-TLS] is
responsible for detecting tampering during the handshake, though
additional validation is required for version negotiation (see
Section 6.6.4).

Endpoints are permitted to use other methods to detect and attempt to
recover from interference with the handshake. Invalid packets may be
identified and discarded using other methods, but no specific method
is mandated in this document.

12.2. Spoofed ACK Attack

An attacker might be able to receive an address validation token
(Section 6.9) from the server and then release the IP address it used
to acquire that token. The attacker may, in the future, spoof this
same address (which now presumably addresses a different endpoint),
and initiate a 0-RTT connection with a server on the victim's behalf.
The attacker can then spoof ACK frames to the server which cause the
server to send excessive amounts of data toward the new owner of the
IP address.

There are two possible mitigations to this attack. The simplest one
is that a server can unilaterally create a gap in packet-number
space. In the non-attack scenario, the client will send an ACK frame
with the larger value for largest acknowledged. In the attack
scenario, the attacker could acknowledge a packet in the gap. If the
server sees an acknowledgment for a packet that was never sent, the
connection can be aborted.

The second mitigation is that the server can require that
acknowledgments for sent packets match the encryption level of the
sent packet. This mitigation is useful if the connection has an
ephemeral forward-secure key that is generated and used for every new
connection. If a packet sent is protected with a forward-secure key,
then any acknowledgments that are received for them MUST also be
forward-secure protected. Since the attacker will not have the
forward secure key, the attacker will not be able to generate
forward-secure protected packets with ACK frames.

12.3. Optimistic ACK Attack

An endpoint that acknowledges packets it has not received might cause
a congestion controller to permit sending at rates beyond what the
network supports. An endpoint MAY skip packet numbers when sending
packets to detect this behavior. An endpoint can then immediately
close the connection with a connection error of type
PROTOCOL_VIOLATION (see Section 6.13.3).

12.4. Slowloris Attacks

The attacks commonly known as Slowloris [SLOWLORIS] try to keep many
connections to the target endpoint open and hold them open as long as
possible. These attacks can be executed against a QUIC endpoint by
generating the minimum amount of activity necessary to avoid being
closed for inactivity. This might involve sending small amounts of
data, gradually opening flow control windows in order to control the
sender rate, or manufacturing ACK frames that simulate a high loss
rate.

QUIC deployments SHOULD provide mitigations for the Slowloris
attacks, such as increasing the maximum number of clients the server
will allow, limiting the number of connections a single IP address is
allowed to make, imposing restrictions on the minimum transfer speed
a connection is allowed to have, and restricting the length of time
an endpoint is allowed to stay connected.

12.5. Stream Fragmentation and Reassembly Attacks

An adversarial endpoint might intentionally fragment the data on
stream buffers in order to cause disproportionate memory commitment.
An adversarial endpoint could open a stream and send some STREAM
frames containing arbitrary fragments of the stream content.

The attack is mitigated if flow control windows correspond to
available memory. However, some receivers will over-commit memory
and advertise flow control offsets in the aggregate that exceed
actual available memory. The over-commitment strategy can lead to

better performance when endpoints are well behaved, but renders
endpoints vulnerable to the stream fragmentation attack.

QUIC deployments SHOULD provide mitigations against the stream
fragmentation attack. Mitigations could consist of avoiding over-
committing memory, delaying reassembly of STREAM frames, implementing
heuristics based on the age and duration of reassembly holes, or some
combination.

12.6. Stream Commitment Attack

An adversarial endpoint can open lots of streams, exhausting state on
an endpoint. The adversarial endpoint could repeat the process on a
large number of connections, in a manner similar to SYN flooding
attacks in TCP.

Normally, clients will open streams sequentially, as explained in
Section 9.1. However, when several streams are initiated at short
intervals, transmission error may cause STREAM DATA frames opening
streams to be received out of sequence. A receiver is obligated to
open intervening streams if a higher-numbered stream ID is received.
Thus, on a new connection, opening stream 2000001 opens 1 million
streams, as required by the specification.

The number of active streams is limited by the concurrent stream
limit transport parameter, as explained in Section 9.4. If chosen
judiciously, this limit mitigates the effect of the stream
commitment attack. However, setting the limit too low could affect
performance when applications expect to open large number of streams.

12.7. Explicit Congestion Notification Attacks

An on-path attacker could manipulate the value of ECN codepoints in
the IP header to influence the sender's rate. [RFC3168] discusses
manipulations and their effects in more detail.

An on-the-side attacker can duplicate and send packets with modified
ECN codepoints to affect the sender's rate. If duplicate packets are
discarded by a receiver, an off-path attacker will need to race the
duplicate packet against the original to be successful in this
attack. Therefore, QUIC receivers ignore ECN codepoints set in
duplicate packets (see Section 6.8).

13. IANA Considerations

13.1. **QUIC Transport Parameter Registry**

   IANA [SHALL add/has added] a registry for "QUIC Transport Parameters"
   under a "QUIC Protocol" heading.

   The "QUIC Transport Parameters" registry governs a 16-bit space.
   This space is split into two spaces that are governed by different
   policies. Values with the first byte in the range 0x00 to 0xfe (in
   hexadecimal) are assigned via the Specification Required policy
   [RFC8126]. Values with the first byte 0xff are reserved for Private
   Use [RFC8126].

   Registrations MUST include the following fields:

   Value: The numeric value of the assignment (registrations will be
      between 0x0000 and 0xfeff).

   Parameter Name: A short mnemonic for the parameter.

   Specification: A reference to a publicly available specification for
      the value.

   The nominated expert(s) verify that a specification exists and is
   readily accessible. Expert(s) are encouraged to be biased towards
   approving registrations unless they are abusive, frivolous, or
   actively harmful (not merely aesthetically displeasing, or
   architecturally dubious).

   The initial contents of this registry are shown in Table 7.

```
+--------+--------------------------+--------------+
| Value  | Parameter Name           | Specification |
+--------+--------------------------+--------------+
| 0x0000 | initial_max_stream_data  | Section 6.6.1 |
|        |                          |               |
| 0x0001 | initial_max_data         | Section 6.6.1 |
|        |                          |               |
| 0x0002 | initial_max_bidi_streams | Section 6.6.1 |
|        |                          |               |
| 0x0003 | idle_timeout             | Section 6.6.1 |
|        |                          |               |
| 0x0004 | preferred_address        | Section 6.6.1 |
|        |                          |               |
| 0x0005 | max_packet_size          | Section 6.6.1 |
|        |                          |               |
| 0x0006 | stateless_reset_token    | Section 6.6.1 |
|        |                          |               |
| 0x0007 | ack_delay_exponent       | Section 6.6.1 |
|        |                          |               |
| 0x0008 | initial_max_uni_streams  | Section 6.6.1 |
+--------+--------------------------+--------------+
```

Table 7: Initial QUIC Transport Parameters Entries

13.2. QUIC Frame Type Registry

IANA [SHALL add/has added] a registry for "QUIC Frame Types" under a
"QUIC Protocol" heading.

The "QUIC Frame Types" registry governs a 62-bit space. This space
is split into three spaces that are governed by different policies.
Values between 0x00 and 0x3f (in hexadecimal) are assigned via the
Standards Action or IESG Review policies [RFC8126]. Values from 0x40
to 0x3fff operate on the Specification Required policy [RFC8126].
All other values are assigned to Private Use [RFC8126].

Registrations MUST include the following fields:

Value: The numeric value of the assignment (registrations will be
   between 0x00 and 0x3fff). A range of values MAY be assigned.

Frame Name: A short mnemonic for the frame type.

Specification: A reference to a publicly available specification for
   the value.

The nominated expert(s) verify that a specification exists and is
readily accessible. Specifications for new registrations need to

describe the means by which an endpoint might determine that it can
send the identified type of frame. An accompanying transport
parameter registration (see Section 13.1) is expected for most
registrations. The specification needs to describe the format and
assigned semantics of any fields in the frame.

Expert(s) are encouraged to be biased towards approving registrations
unless they are abusive, frivolous, or actively harmful (not merely
aesthetically displeasing, or architecturally dubious).

The initial contents of this registry are tabulated in Table 3.

13.3. QUIC Transport Error Codes Registry

IANA [SHALL add/has added] a registry for "QUIC Transport Error
Codes" under a "QUIC Protocol" heading.

The "QUIC Transport Error Codes" registry governs a 16-bit space.
This space is split into two spaces that are governed by different
policies. Values with the first byte in the range 0x00 to 0xfe (in
hexadecimal) are assigned via the Specification Required policy
[RFC8126]. Values with the first byte 0xff are reserved for Private
Use [RFC8126].

Registrations MUST include the following fields:

Value: The numeric value of the assignment (registrations will be
   between 0x0000 and 0xfeff).

Code: A short mnemonic for the parameter.

Description: A brief description of the error code semantics, which
   MAY be a summary if a specification reference is provided.

Specification: A reference to a publicly available specification for
   the value.

The initial contents of this registry are shown in Table 8. Values
from 0xFF00 to 0xFFFF are reserved for Private Use [RFC8126].

Value	Error	Description	Specification
0x0	NO_ERROR	No error	Section 11.3
0x1	INTERNAL_ERROR	Implementation error	Section 11.3

0x2	SERVER_BUSY	Server currently busy	Section 11.3
0x3	FLOW_CONTROL_ERROR	Flow control error	Section 11.3
0x4	STREAM_ID_ERROR	Invalid stream ID	Section 11.3
0x5	STREAM_STATE_ERROR	Frame received in invalid stream state	Section 11.3
0x6	FINAL_OFFSET_ERROR	Change to final stream offset	Section 11.3
0x7	FRAME_ENCODING_ERROR	Frame encoding error	Section 11.3
0x8	TRANSPORT_PARAMETER_ERROR	Error in transport parameters	Section 11.3
0x9	VERSION_NEGOTIATION_ERROR	Version negotiation failure	Section 11.3
0xA	PROTOCOL_VIOLATION	Generic protocol violation	Section 11.3
0xB	UNSOLICITED_PATH_RESPONSE	Unsolicited PATH_RESPONSE frame	Section 11.3
0xC	INVALID_MIGRATION	Violated disabled migration	Section 11.3

Table 8: Initial QUIC Transport Error Codes Entries

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Appendix A. Change Log

   RFC Editor's Note: Please remove this section prior to
   publication of a final version of this document.

   Issue and pull request numbers are listed with a leading octothorp.

A.1. Since draft-ietf-quic-transport-12

   o Changes to integration of the TLS handshake (#829, #1018, #1094,
      #1165, #1190, #1233, #1242, #1252, #1450)

      * The cryptographic handshake uses CRYPTO frames, not stream 0

      * QUIC packet protection is used in place of TLS record
         protection

      * Separate QUIC packet number spaces are used for the handshake

      * Changed Retry to be independent of the cryptographic handshake

      * Added NEW_TOKEN frame and Token fields to Initial packet

* Limit the use of HelloRetryRequest to address TLS needs (like key shares)

o Enable server to transition connections to a preferred address (#560, #1251, #1373)

o Added ECN feedback mechanisms and handling; new ACK_ECN frame (#804, #805, #1372)

o Changed rules and recommendations for use of new connection IDs (#1258, #1264, #1276, #1280, #1419, #1452, #1453, #1465)

o Added a transport parameter to disable intentional connection migration (#1271, #1447)

o Packets from different connection ID can't be coalesced (#1287, #1423)

o Fixed sampling method for packet number encryption; the length field in long headers includes the packet number field in addition to the packet payload (#1387, #1389)

o Stateless Reset is now symmetric and subject to size constraints (#466, #1346)

o Added frame type extension mechanism (#58, #1473)

A.2. Since draft-ietf-quic-transport-11

o Enable server to transition connections to a preferred address (#560, #1251)

o Packet numbers are encrypted (#1174, #1043, #1048, #1034, #850, #990, #734, #1317, #1267, #1079)

o Packet numbers use a variable-length encoding (#989, #1334)

o STREAM frames can now be empty (#1350)

A.3. Since draft-ietf-quic-transport-10

o Swap payload length and packed number fields in long header (#1294)

o Clarified that CONNECTION_CLOSE is allowed in Handshake packet (#1274)

o Spin bit reserved (#1283)

o Coalescing multiple QUIC packets in a UDP datagram (#1262, #1285)

o A more complete connection migration (#1249)

o Refine opportunistic ACK defense text (#305, #1030, #1185)

o A Stateless Reset Token isn't mandatory (#818, #1191)

o Removed implicit stream opening (#896, #1193)

o An empty STREAM frame can be used to open a stream without sending
   data (#901, #1194)

o Define stream counts in transport parameters rather than a maximum
   stream ID (#1023, #1065)

o STOP_SENDING is now prohibited before streams are used (#1050)

o Recommend including ACK in Retry packets and allow PADDING (#1067,
   #882)

o Endpoints now become closing after an idle timeout (#1178, #1179)

o Remove implication that Version Negotiation is sent when a packet
   of the wrong version is received (#1197)

A.4. Since draft-ietf-quic-transport-09

o Added PATH_CHALLENGE and PATH_RESPONSE frames to replace PING with
   Data and PONG frame. Changed ACK frame type from 0x0e to 0x0d.
   (#1091, #725, #1086)

o A server can now only send 3 packets without validating the client
   address (#38, #1090)

o Delivery order of stream data is no longer strongly specified
   (#252, #1070)

o Rework of packet handling and version negotiation (#1038)

o Stream 0 is now exempt from flow control until the handshake
   completes (#1074, #725, #825, #1082)

o Improved retransmission rules for all frame types: information is
   retransmitted, not packets or frames (#463, #765, #1095, #1053)

o Added an error code for server busy signals (#1137)

o Endpoints now set the connection ID that their peer uses.
   Connection IDs are variable length. Removed the
   omit_connection_id transport parameter and the corresponding short
   header flag. (#1089, #1052, #1146, #821, #745, #821, #1166, #1151)

A.5. Since draft-ietf-quic-transport-08

o Clarified requirements for BLOCKED usage (#65, #924)

o BLOCKED frame now includes reason for blocking (#452, #924, #927,
   #928)

o GAP limitation in ACK Frame (#613)

o Improved PMTUD description (#614, #1036)

o Clarified stream state machine (#634, #662, #743, #894)

o Reserved versions don't need to be generated deterministically
   (#831, #931)

o You don't always need the draining period (#871)

o Stateless reset clarified as version-specific (#930, #986)

o initial_max_stream_id_x transport parameters are optional (#970,
   #971)

o Ack Delay assumes a default value during the handshake (#1007,
   #1009)

o Removed transport parameters from NewSessionTicket (#1015)

A.6. Since draft-ietf-quic-transport-07

o The long header now has version before packet number (#926, #939)

o Rename and consolidate packet types (#846, #822, #847)

o Packet types are assigned new codepoints and the Connection ID
   Flag is inverted (#426, #956)

o Removed type for Version Negotiation and use Version 0 (#963,
   #968)

o Streams are split into unidirectional and bidirectional (#643,
   #656, #720, #872, #175, #885)

   * Stream limits now have separate uni- and bi-directinal
      transport parameters (#909, #958)

   * Stream limit transport parameters are now optional and default
      to 0 (#970, #971)

o The stream state machine has been split into read and write (#634,
   #894)

o Employ variable-length integer encodings throughout (#595)

o Improvements to connection close

   * Added distinct closing and draining states (#899, #871)

   * Draining period can terminate early (#869, #870)

   * Clarifications about stateless reset (#889, #890)

o Address validation for connection migration (#161, #732, #878)

o Clearly defined retransmission rules for BLOCKED (#452, #65, #924)

o negotiated_version is sent in server transport parameters (#710,
   #959)

o Increased the range over which packet numbers are randomized
   (#864, #850, #964)

A.7. Since draft-ietf-quic-transport-06

o Replaced FNV-1a with AES-GCM for all "Cleartext" packets (#554)

o Split error code space between application and transport (#485)

o Stateless reset token moved to end (#820)

o 1-RTT-protected long header types removed (#848)

o No acknowledgments during draining period (#852)

o Remove "application close" as a separate close type (#854)

o Remove timestamps from the ACK frame (#841)

o Require transport parameters to only appear once (#792)

A.8. Since draft-ietf-quic-transport-05

   o Stateless token is server-only (#726)

   o Refactor section on connection termination (#733, #748, #328,
      #177)

   o Limit size of Version Negotiation packet (#585)

   o Clarify when and what to ack (#736)

   o Renamed STREAM_ID_NEEDED to STREAM_ID_BLOCKED

   o Clarify Keep-alive requirements (#729)

A.9. Since draft-ietf-quic-transport-04

   o Introduce STOP_SENDING frame, RST_STREAM only resets in one
      direction (#165)

   o Removed GOAWAY; application protocols are responsible for graceful
      shutdown (#696)

   o Reduced the number of error codes (#96, #177, #184, #211)

   o Version validation fields can't move or change (#121)

   o Removed versions from the transport parameters in a
      NewSessionTicket message (#547)

   o Clarify the meaning of "bytes in flight" (#550)

   o Public reset is now stateless reset and not visible to the path
      (#215)

   o Reordered bits and fields in STREAM frame (#620)

   o Clarifications to the stream state machine (#572, #571)

   o Increased the maximum length of the Largest Acknowledged field in
      ACK frames to 64 bits (#629)

   o truncate_connection_id is renamed to omit_connection_id (#659)

   o CONNECTION_CLOSE terminates the connection like TCP RST (#330,
      #328)

   o Update labels used in HKDF-Expand-Label to match TLS 1.3 (#642)

A.10. Since draft-ietf-quic-transport-03

   o Change STREAM and RST_STREAM layout

   o Add MAX_STREAM_ID settings

A.11. Since draft-ietf-quic-transport-02

   o The size of the initial packet payload has a fixed minimum (#267,
      #472)

   o Define when Version Negotiation packets are ignored (#284, #294,
      #241, #143, #474)

   o The 64-bit FNV-1a algorithm is used for integrity protection of
      unprotected packets (#167, #480, #481, #517)

   o Rework initial packet types to change how the connection ID is
      chosen (#482, #442, #493)

   o No timestamps are forbidden in unprotected packets (#542, #429)

   o Cryptographic handshake is now on stream 0 (#456)

   o Remove congestion control exemption for cryptographic handshake
      (#248, #476)

   o Version 1 of QUIC uses TLS; a new version is needed to use a
      different handshake protocol (#516)

   o STREAM frames have a reduced number of offset lengths (#543, #430)

   o Split some frames into separate connection- and stream- level
      frames (#443)

      * WINDOW_UPDATE split into MAX_DATA and MAX_STREAM_DATA (#450)

      * BLOCKED split to match WINDOW_UPDATE split (#454)

      * Define STREAM_ID_NEEDED frame (#455)

   o A NEW_CONNECTION_ID frame supports connection migration without
      linkability (#232, #491, #496)

   o Transport parameters for 0-RTT are retained from a previous
      connection (#405, #513, #512)

      * A client in 0-RTT no longer required to reset excess streams
         (#425, #479)

   o Expanded security considerations (#440, #444, #445, #448)

A.12. Since draft-ietf-quic-transport-01

   o Defined short and long packet headers (#40, #148, #361)

   o Defined a versioning scheme and stable fields (#51, #361)

   o Define reserved version values for "greasing" negotiation (#112,
      #278)

   o The initial packet number is randomized (#35, #283)

   o Narrow the packet number encoding range requirement (#67, #286,
      #299, #323, #356)

   o Defined client address validation (#52, #118, #120, #275)

   o Define transport parameters as a TLS extension (#49, #122)

   o SCUP and COPT parameters are no longer valid (#116, #117)

   o Transport parameters for 0-RTT are either remembered from before,
      or assume default values (#126)

   o The server chooses connection IDs in its final flight (#119, #349,
      #361)

   o The server echoes the Connection ID and packet number fields when
      sending a Version Negotiation packet (#133, #295, #244)

   o Defined a minimum packet size for the initial handshake packet
      from the client (#69, #136, #139, #164)

   o Path MTU Discovery (#64, #106)

   o The initial handshake packet from the client needs to fit in a
      single packet (#338)

   o Forbid acknowledgment of packets containing only ACK and PADDING
      (#291)

   o Require that frames are processed when packets are acknowledged
      (#381, #341)

o Removed the STOP_WAITING frame (#66)

o Don't require retransmission of old timestamps for lost ACK frames
   (#308)

o Clarified that frames are not retransmitted, but the information
   in them can be (#157, #298)

o Error handling definitions (#335)

o Split error codes into four sections (#74)

o Forbid the use of Public Reset where CONNECTION_CLOSE is possible
   (#289)

o Define packet protection rules (#336)

o Require that stream be entirely delivered or reset, including
   acknowledgment of all STREAM frames or the RST_STREAM, before it
   closes (#381)

o Remove stream reservation from state machine (#174, #280)

o Only stream 1 does not contribute to connection-level flow control
   (#204)

o Stream 1 counts towards the maximum concurrent stream limit (#201,
   #282)

o Remove connection-level flow control exclusion for some streams
   (except 1) (#246)

o RST_STREAM affects connection-level flow control (#162, #163)

o Flow control accounting uses the maximum data offset on each
   stream, rather than bytes received (#378)

o Moved length-determining fields to the start of STREAM and ACK
   (#168, #277)

o Added the ability to pad between frames (#158, #276)

o Remove error code and reason phrase from GOAWAY (#352, #355)

o GOAWAY includes a final stream number for both directions (#347)

o Error codes for RST_STREAM and CONNECTION_CLOSE are now at a
   consistent offset (#249)

o Defined priority as the responsibility of the application protocol
   (#104, #303)

A.13. Since draft-ietf-quic-transport-00

o Replaced DIVERSIFICATION_NONCE flag with KEY_PHASE flag

o Defined versioning

o Reworked description of packet and frame layout

o Error code space is divided into regions for each component

o Use big endian for all numeric values

A.14. Since draft-hamilton-quic-transport-protocol-01

o Adopted as base for draft-ietf-quic-tls

o Updated authors/editors list

o Added IANA Considerations section

o Moved Contributors and Acknowledgments to appendices

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