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QUIC: A UDP-Based Multiplexed and Secure Transport
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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 [1].

Working Group information can be found at <https://github.com/quicwg> [2]; source code and issues list for this draft can be found at <https://github.com/quicwg/base-drafts/labels/-transport> [3].

Status of This Memo

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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 transport for multiple applications.

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, 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](#)].

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: The 64-bit unsigned number used as an identifier for a QUIC connection.

QUIC packet: A well-formed UDP payload that can be parsed by a QUIC receiver. QUIC packet size in this document refers to the UDP payload size.

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} Indicates that x is encrypted

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 8.1](#)

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

3. A QUIC Overview

This section briefly describes QUIC's key mechanisms and benefits. Key strengths of QUIC include:

- o Low-latency connection establishment
- o Multiplexing without head-of-line blocking
- o Authenticated and encrypted header and payload
- o Rich signaling for congestion control and loss recovery
- o Stream and connection flow control
- o Connection migration and resilience to NAT rebinding
- o Version negotiation

3.1. Low-Latency Connection Establishment

QUIC relies on a combined cryptographic and transport handshake for setting up a secure transport connection. QUIC connections are expected to commonly use 0-RTT handshakes, meaning that for most QUIC connections, data can be sent immediately following the client handshake packet, without waiting for a reply from the server. QUIC

provides a dedicated stream (Stream ID 0) to be used for performing the cryptographic handshake and QUIC options negotiation. The format of the QUIC options and parameters used during negotiation are described in this document, but the handshake protocol that runs on Stream ID 0 is described in the accompanying cryptographic handshake draft [[QUIC-TLS](#)].

[3.2.](#) Stream Multiplexing

When application messages are transported over TCP, independent application messages can suffer from head-of-line blocking. When an application multiplexes many streams atop TCP's single-bytestream abstraction, a loss of a TCP segment results in blocking of all subsequent segments until a retransmission arrives, irrespective of the application streams that are encapsulated in subsequent segments. QUIC ensures that lost packets carrying data for an individual stream only impact that specific stream. Data received on other streams can continue to be reassembled and delivered to the application.

[3.3.](#) Rich Signaling for Congestion Control and Loss Recovery

QUIC's packet framing and acknowledgments carry rich information that help both congestion control and loss recovery in fundamental ways. Each QUIC packet carries a new packet number, including those carrying retransmitted data. This obviates the need for a separate mechanism to distinguish acknowledgments for retransmissions from those for original transmissions, avoiding TCP's retransmission ambiguity problem. QUIC acknowledgments also explicitly encode the delay between the receipt of a packet and its acknowledgment being sent, and together with the monotonically-increasing packet numbers, this allows for precise network roundtrip-time (RTT) calculation. QUIC's ACK frames support multiple ACK blocks, so QUIC is more resilient to reordering than TCP with SACK support, as well as able to keep more bytes on the wire when there is reordering or loss.

[3.4.](#) Stream and Connection Flow Control

QUIC implements stream- and connection-level flow control. At a high level, a QUIC receiver advertises the maximum amount of data that it is willing to receive on each stream. As data is sent, received, and delivered on a particular stream, the receiver sends MAX_STREAM_DATA frames that increase the advertised limit for that stream, allowing the peer to send more data on that stream.

In addition to this stream-level flow control, QUIC implements connection-level flow control to limit the aggregate buffer that a QUIC receiver is willing to allocate to all streams on a connection. Connection-level flow control works in the same way as stream-level

flow control, but the bytes delivered and the limits are aggregated across all streams.

[3.5.](#) Authenticated and Encrypted Header and Payload

TCP headers appear in plaintext on the wire and are not authenticated, causing a plethora of injection and header manipulation issues for TCP, such as receive-window manipulation and sequence-number overwriting. While some of these are mechanisms used by middleboxes to improve TCP performance, others are active attacks. Even "performance-enhancing" middleboxes that routinely interpose on the transport state machine end up limiting the evolvability of the transport protocol, as has been observed in the design of MPTCP [[RFC6824](#)] and in its subsequent deployability issues.

Generally, QUIC packets are always authenticated and the payload is typically fully encrypted. The parts of the packet header which are not encrypted are still authenticated by the receiver, so as to thwart any packet injection or manipulation by third parties. Some early handshake packets, such as the Version Negotiation packet, are not encrypted, but information sent in these unencrypted handshake packets is later verified as part of cryptographic processing.

[3.6.](#) Connection Migration and Resilience to NAT Rebinding

QUIC connections are identified by a Connection ID, a 64-bit unsigned number randomly generated by the server. QUIC's consistent connection ID allows connections to survive changes to the client's IP and port, such as those caused by NAT rebindings or by the client changing network connectivity to a new address. QUIC provides automatic cryptographic verification of a rebound client, since the client continues to use the same session key for encrypting and decrypting packets. The consistent connection ID can be used to allow migration of the connection to a new server IP address as well, since the Connection ID remains consistent across changes in the client's and the server's network addresses.

[3.7.](#) Version Negotiation

QUIC version negotiation allows for multiple versions of the protocol to be deployed and used concurrently. Version negotiation is described in [Section 7.2](#).

[4.](#) 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.

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 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 [[4](#)].

5. 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.

5.1. Long Header

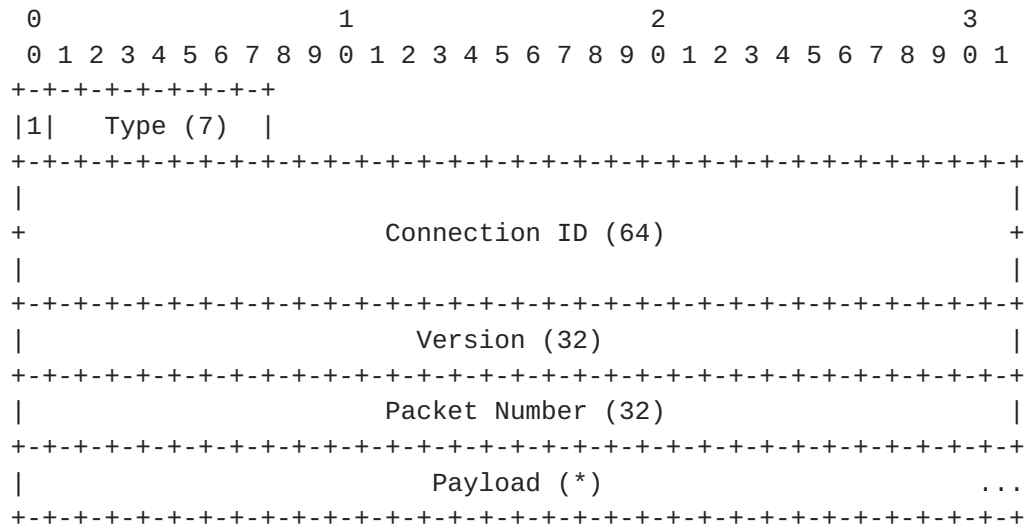


Figure 1: Long Header Format

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 5.2](#)). 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.

Connection ID: Octets 1 through 8 contain the connection ID. [Section 5.6](#) describes the use of this field in more detail.

Version: Octets 9 to 12 contain the selected protocol version. This field indicates which version of QUIC is in use and determines how the rest of the protocol fields are interpreted.

Packet Number: Octets 13 to 16 contain the packet number. [Section 5.7](#) describes the use of packet numbers.

Payload: Octets from 17 onwards (the rest of QUIC packet) are the payload of the packet.

The following packet types are defined:

Type	Name	Section
0x7F	Initial	Section 5.4.1
0x7E	Retry	Section 5.4.2
0x7D	Handshake	Section 5.4.3
0x7C	0-RTT Protected	Section 5.5

Table 1: Long Header Packet Types

The header form, packet type, connection ID, packet number and version fields of a long header packet are version-independent. The types of packets defined in Table 1 are version-specific. See [Section 5.8](#) 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.

5.2. Short Header

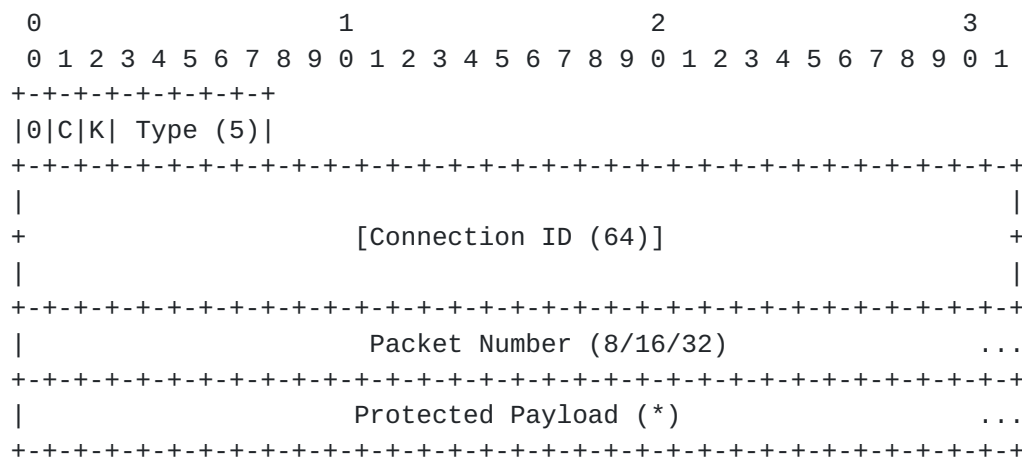


Figure 2: Short Header Format

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.

Omit Connection ID Flag: The second bit (0x40) of octet 0 indicates whether the Connection ID field is omitted. If set to 0, then the Connection ID field is present; if set to 1, the Connection ID field is omitted. The Connection ID field can only be omitted if the `omit_connection_id` transport parameter ([Section 7.4.1](#)) is specified by the intended recipient of the packet.

Key Phase Bit: The third bit (0x20) 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.

Short Packet Type: The remaining 5 bits of octet 0 include one of 32 packet types. Table 2 lists the types that are defined for short packets.

Connection ID: If the Omit Connection ID Flag is not set, a connection ID occupies octets 1 through 8 of the packet. See [Section 5.6](#) for more details.

Packet Number: The length of the packet number field depends on the packet type. This field can be 1, 2 or 4 octets long depending on the short packet type.

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

The packet type in a short header currently determines only the size of the packet number field. Additional types can be used to signal the presence of other fields.

+-----+-----+		
Type	Packet Number Size	
+-----+-----+		
0x1F	1 octet	
0x1E	2 octets	
0x1D	4 octets	
+-----+-----+		

Table 2: Short Header Packet Types

The header form, omit connection ID flag, and connection ID of a short header packet are version-independent. The remaining fields are specific to the selected QUIC version. See [Section 5.8](#) for details on how packets from different versions of QUIC are interpreted.

5.3. Version Negotiation Packet

A Version Negotiation packet is inherently not version-specific, and does not use the packet headers defined above. 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.

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:

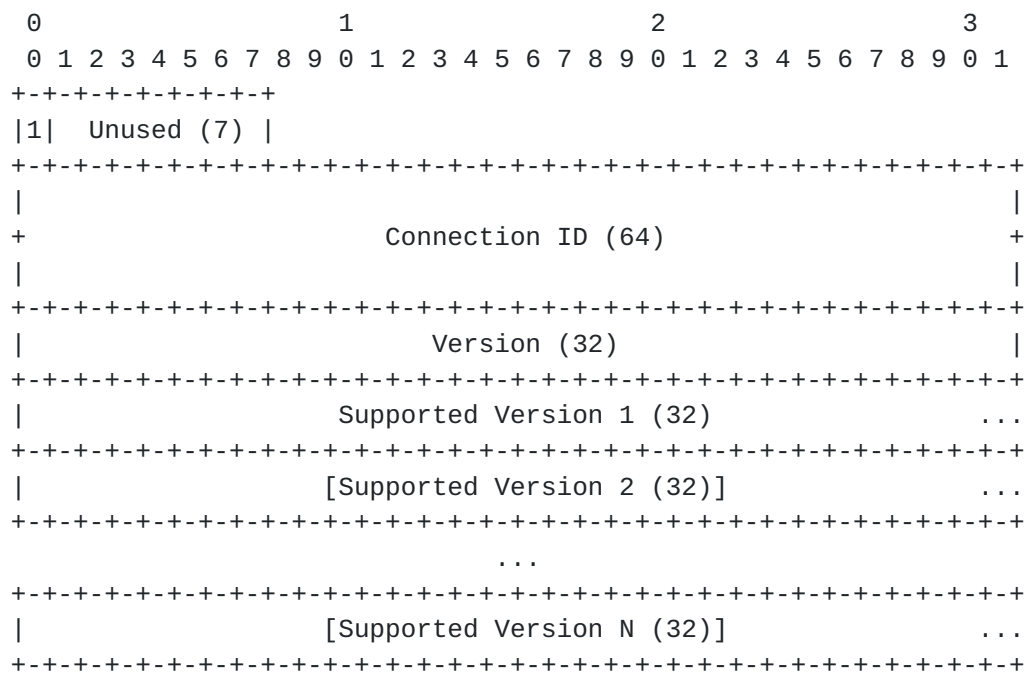


Figure 3: Version Negotiation Packet

The value in the Unused field is selected randomly by the server. The Connection ID field echoes the corresponding value from the triggering client packet. This allows clients some assurance that the server received the packet and that the Version Negotiation packet is in fact from the server. The Version field MUST be set to

0x00000000. 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.

See [Section 7.2](#) for a description of the version negotiation process.

5.4. 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 5.4.1](#)), Retry ([Section 5.4.2](#)) and Handshake ([Section 5.4.3](#)) 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, handshake packets are protected with a connection- and version-specific key, 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.

5.4.1. Initial Packet

The Initial packet uses long headers with a type value of 0x7E. It carries the first cryptographic handshake message sent by the client.

The client populates the connection ID field with randomly selected values, unless it has received a packet from the server. If the client has received a packet from the server, the connection ID field uses the value provided by the server.

The first Initial packet that is sent by a client contains a randomized packet number. All subsequent packets contain a packet number that is incremented by one, see ([Section 5.7](#)).

The payload of a Initial packet consists of a STREAM frame (or frames) for stream 0 containing a cryptographic handshake message, with enough PADDING frames that the packet is at least 1200 octets (see [Section 9](#)). The stream in this packet always starts at an offset of 0 (see [Section 7.5](#)) and the complete cryptographic handshake message MUST fit in a single packet (see [Section 7.3](#)).

The client uses the Initial packet type for any packet that contains an initial cryptographic handshake message. This includes all cases

where a new packet containing the initial cryptographic message needs to be created, this includes the packets sent after receiving a Version Negotiation ([Section 5.3](#)) or Retry packet ([Section 5.4.2](#)).

5.4.2. Retry Packet

A Retry packet uses long headers with a type value of 0x7D. It carries cryptographic handshake messages and acknowledgments. It is used by a server that wishes to perform a stateless retry (see [Section 7.5](#)).

The packet number and connection ID fields echo the corresponding fields from the triggering client packet. This allows a client to verify that the server received its packet.

A Retry packet is never explicitly acknowledged in an ACK frame by a client. Receiving another Initial packet implicitly acknowledges a Retry packet.

After receiving a Retry packet, the client uses a new Initial packet containing the next cryptographic handshake message. The client retains the state of its cryptographic handshake, but discards all transport state. The Initial packet that is generated in response to a Retry packet includes STREAM frames on stream 0 that start again at an offset of 0.

Continuing the cryptographic handshake is necessary to ensure that an attacker cannot force a downgrade of any cryptographic parameters. In addition to continuing the cryptographic handshake, the client MUST remember the results of any version negotiation that occurred (see [Section 7.2](#)). The client MAY also retain any observed RTT or congestion state that it has accumulated for the flow, but other transport state MUST be discarded.

The payload of the Retry packet contains a single STREAM frame on stream 0 with offset 0 containing the server's cryptographic stateless retry material. It MUST NOT contain any other frames. The next STREAM frame sent by the server will also start at stream offset 0.

5.4.3. Handshake Packet

A Handshake packet uses long headers with a type value of 0x7C. It is used to carry acknowledgments and cryptographic handshake messages from the server and client.

The connection ID field in a Handshake packet contains a connection ID that is chosen by the server (see [Section 5.6](#)).

The first Handshake packet sent by a server contains a randomized packet number. This value is increased for each subsequent packet sent by the server as described in [Section 5.7](#). The client increments the packet number from its previous packet by one for each Handshake packet that it sends (which might be an Initial, 0-RTT Protected, or Handshake packet).

The payload of this packet contains STREAM frames and could contain PADDING and ACK frames.

5.5. Protected Packets

Packets that are protected with 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.

Packets protected with 0-RTT keys use a type value of 0x7B. The connection ID field for a 0-RTT packet is selected by the client.

The client can send 0-RTT packets after receiving a Handshake packet ([Section 5.4.3](#)), 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 connection ID selected by the client for 0-RTT packets, see [Section 5.6](#).

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

The packet number field contains a packet number, which increases with each packet sent, see [Section 5.7](#) 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 6](#).

5.6. Connection ID

QUIC connections are identified by their 64-bit Connection ID. All long headers contain a Connection ID. Short headers indicate the presence of a Connection ID using the Omit Connection ID flag. When present, the Connection ID is in the same location in all packet headers, making it straightforward for middleboxes, such as load balancers, to locate and use it.

The client MUST choose a random connection ID and use it in Initial packets ([Section 5.4.1](#)) and 0-RTT packets ([Section 5.5](#)).

When the server receives a Initial packet and decides to proceed with the handshake, it chooses a new value for the connection ID and sends that in a Handshake packet ([Section 5.4.3](#)). The server MAY choose to use the value that the client initially selects.

Once the client receives the connection ID that the server has chosen, it MUST use it for all subsequent Handshake ([Section 5.4.3](#)) and 1-RTT ([Section 5.5](#)) packets but not for 0-RTT packets ([Section 5.5](#)).

Server's Version Negotiation ([Section 5.3](#)) and Retry ([Section 5.4.2](#)) packets MUST use connection ID selected by the client.

5.7. 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. The packet number for sending MUST increase by at least one after sending any packet, unless otherwise specified (see [Section 5.7.1](#)).

A QUIC endpoint MUST NOT reuse a packet number within the same 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; a server MAY send a Stateless Reset ([Section 7.9.4](#)) in response to further packets that it receives.

For the packet header, the number of bits required to represent the packet number are reduced by including only the least significant bits of the packet number. The actual packet number for each packet is reconstructed at the receiver based on the largest packet number received on a successfully authenticated packet.

A 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 16-bit value of 0x1f94 will be decoded as 0xaa831f94.

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 0x6b4264 requires a 16-bit or larger packet number encoding; whereas a 32-bit packet number is needed to send a packet with a number of 0x6bc107.

Version Negotiation ([Section 5.3](#)) and Retry ([Section 5.4.2](#)) packets have special rules for populating the packet number field.

[5.7.1.](#) Initial Packet Number

The initial value for packet number MUST be selected randomly from a range between 0 and $2^{32} - 1025$ (inclusive). This value is selected so that Initial and Handshake packets exercise as many possible values for the Packet Number field as possible.

Limiting the range allows both for loss of packets and for any stateless exchanges. Packet numbers are incremented for subsequent packets, but packet loss and stateless handling can both mean that the first packet sent by an endpoint isn't necessarily the first packet received by its peer. The first packet received by a peer cannot be 2^{32} or greater or the recipient will incorrectly assume a packet number that is 2^{32} values lower and discard the packet.

Use of a secure random number generator [[RFC4086](#)] is not necessary for generating the initial packet number, nor is it necessary that the value be uniformly distributed.

[5.8.](#) Handling Packets from Different Versions

Between different versions the following things are guaranteed to remain constant:

- o the location of the header form flag,
- o the location of the Omit Connection ID flag in short headers,
- o the location and size of the Connection ID field in both header forms,
- o the location and size of the Version field in long headers,

- o the format and semantics of the Version Negotiation packet.

Implementations MUST assume that an unsupported version uses an unknown packet format. All other fields MUST be ignored when processing a packet that contains an unsupported version.

6. 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.

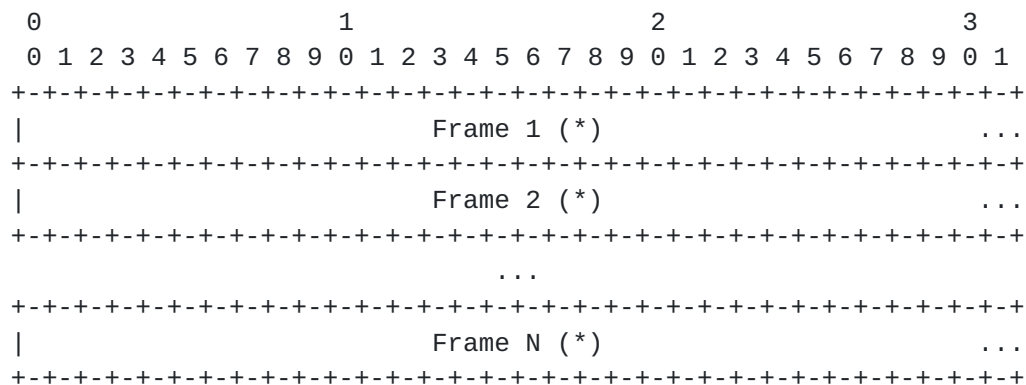


Figure 4: Contents of Protected Payload

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 byte, indicating its type, followed by additional type-dependent fields:

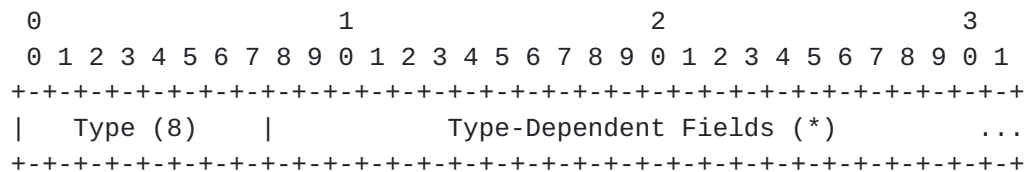


Figure 5: Generic Frame Layout

Frame types are listed in Table 3. Note that the Frame Type byte in STREAM and ACK frames is used to carry other frame-specific flags. For all other frames, the Frame Type byte 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 8.2
0x01	RST_STREAM	Section 8.3
0x02	CONNECTION_CLOSE	Section 8.4
0x03	APPLICATION_CLOSE	Section 8.5
0x04	MAX_DATA	Section 8.6
0x05	MAX_STREAM_DATA	Section 8.7
0x06	MAX_STREAM_ID	Section 8.8
0x07	PING	Section 8.9
0x08	BLOCKED	Section 8.10
0x09	STREAM_BLOCKED	Section 8.11
0x0a	STREAM_ID_BLOCKED	Section 8.12
0x0b	NEW_CONNECTION_ID	Section 8.13
0x0c	STOP_SENDING	Section 8.14
0x0d	PONG	Section 8.15
0x0e	ACK	Section 8.16
0x10 - 0x17	STREAM	Section 8.17

Table 3: Frame Types

7. 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 7.3](#). 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 7.7](#). Finally a connection may be terminated by either endpoint, as described in [Section 7.9](#).

7.1. Matching Packets to Connections

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

Packets that can be associated with an existing connection are handled according to the current state of that connection. Packets are associated with existing connections using connection ID if it is present; this might include connection IDs that were advertised using `NEW_CONNECTION_ID` ([Section 8.13](#)). Packets without connection IDs and long-form packets for connections that have incomplete cryptographic handshakes are associated with an existing connection using the tuple of source and destination IP addresses and ports.

A packet that uses the short header could be associated with an existing connection with an incomplete cryptographic handshake. Such a packet could be a valid packet that has been reordered with respect to the long-form packets that will complete the cryptographic handshake. This might happen after the final set of cryptographic handshake messages from either peer. These packets are expected to be correlated with a connection using the tuple of IP addresses and ports. Packets that might be reordered in this fashion SHOULD be buffered in anticipation of the handshake completing.

0-RTT packets might be received prior to a Client Initial packet at a server. If the version of these packets is acceptable to the server, it MAY buffer these packets in anticipation of receiving a reordered Client Initial packet.

Buffering ensures that data is not lost, which improves performance; conversely, discarding these packets could create false loss signals for the congestion controllers. However, limiting the number and size of buffered packets might be needed to prevent exposure to denial of service.

For clients, any packet that cannot be associated with an existing connection SHOULD be discarded if it is not buffered. Discarded packets MAY be logged for diagnostic or security purposes.

For servers, packets that aren't associated with a connection potentially create a new connection. However, only packets that use the long packet header and that are at least the minimum size defined for the protocol version can be initial packets. A server MAY discard packets with a short header or packets that are smaller than the smallest minimum size for any version that the server supports. A server that discards a packet that cannot be associated with a connection MAY also generate a stateless reset ([Section 7.9.4](#)).

This version of QUIC defines a minimum size for initial packets of 1200 octets (see [Section 9](#)). Versions of QUIC that define smaller minimum initial packet sizes need to be aware that initial packets will be discarded without action by servers that only support versions with larger minimums. Clients that support multiple QUIC versions can avoid this problem by ensuring that they increase the size of their initial packets to the largest minimum size across all of the QUIC versions they support. Servers need to recognize initial packets that are the minimum size of all QUIC versions they support.

[7.2.](#) Version Negotiation

QUIC's connection establishment begins with version negotiation, since all communication between the endpoints, including packet and frame formats, relies on the two endpoints agreeing on a version.

A QUIC connection begins with a client sending an Initial packet ([Section 5.4.1](#)). The details of the handshake mechanisms are described in [Section 7.3](#), but any Initial packet sent from the client to the server **MUST** use the long header format - which includes the version of the protocol being used - and they **MUST** be padded to at least 1200 octets.

The server receives this packet and determines whether it potentially creates a new connection (see [Section 7.1](#)). If the packet might generate a new connection, the server then checks whether it understands the version that the client has selected.

If the packet contains a version that is acceptable to the server, the server proceeds with the handshake ([Section 7.3](#)). This commits the server to the version that the client selected.

[7.2.1.](#) 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 ([Section 5.3](#)). This includes a list of versions that the server will accept.

A server sends a Version Negotiation packet for any packet with an unacceptable version if that packet could create a new connection. This allows a server to process packets with unsupported versions without retaining state. Though either the Client 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.

7.2.2. Handling Version Negotiation Packets

When the client receives a Version Negotiation packet, it first checks that the connection ID matches the connection ID 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 Client 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 7.4.4](#)).

7.2.3. 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 4](#)) 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 7.4.4](#)) 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.

7.3. Cryptographic and Transport Handshake

QUIC relies on a combined cryptographic and transport handshake to minimize connection establishment latency. QUIC allocates stream 0 for 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 this stream with reliable, ordered delivery of data. In return, the cryptographic handshake provides QUIC with:

- 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 7.4](#))
- o authenticated confirmation of version negotiation (see [Section 7.4.4](#))
- 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 7.6](#))

The initial cryptographic handshake message 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. Reassembling messages requires that a server maintain state prior to establishing a connection, exposing the server to a denial of service risk.

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.

Details of how TLS is integrated with QUIC is provided in more detail in [[QUIC-TLS](#)].

[7.4.](#) 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 6. 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_stream_id_bidi(2),
    idle_timeout(3),
    omit_connection_id(4),
    max_packet_size(5),
    stateless_reset_token(6),
    ack_delay_exponent(7),
    initial_max_stream_id_uni(8),
    (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>;

            case new_session_ticket:
                struct {};
    };
    TransportParameter parameters<30..2^16-1>;
} TransportParameters;
```

Figure 6: 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 7.4.4](#)) before the connection establishment is considered properly complete.

Definitions for each of the defined transport parameters are included in [Section 7.4.1](#). 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`.

[7.4.1](#). 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 8.7](#)) 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 8.6](#)) 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).

A server MUST include the following transport parameters:

`stateless_reset_token (0x0006)`: The Stateless Reset Token is used in verifying a stateless reset, see [Section 7.9.4](#). This parameter is a sequence of 16 octets.

A client MUST NOT include a stateless reset token. A server MUST treat receipt of a `stateless_reset_token` transport parameter as a connection error of type `TRANSPORT_PARAMETER_ERROR`.

An endpoint MAY use the following transport parameters:

`initial_max_stream_id_bidi (0x0002)`: The initial maximum stream ID parameter contains the initial maximum stream number the peer may initiate for bidirectional streams, encoded as an unsigned 32-bit integer. This value MUST be a valid bidirectional stream ID for a peer-initiated stream (that is, the two least significant bits are set to 0 by a server and to 1 by a client). If an invalid value is provided, the recipient MUST generate a connection error of

type `TRANSPORT_PARAMETER_ERROR`. Setting this parameter is equivalent to sending a `MAX_STREAM_ID` ([Section 8.8](#)) immediately after completing the handshake. The maximum bidirectional stream ID is set to 0 if this parameter is absent, preventing the creation of new bidirectional streams until a `MAX_STREAM_ID` frame is sent. Note that a default value of 0 does not prevent the cryptographic handshake stream (that is, stream 0) from being used.

`initial_max_stream_id_uni (0x0008)`: The initial maximum stream ID parameter contains the initial maximum stream number the peer may initiate for unidirectional streams, encoded as an unsigned 32-bit integer. The value **MUST** be a valid unidirectional ID for the recipient (that is, the two least significant bits are set to 2 by a server and to 3 by a client). If an invalid value is provided, the recipient **MUST** generate a connection error of type `TRANSPORT_PARAMETER_ERROR`. Setting this parameter is equivalent to sending a `MAX_STREAM_ID` ([Section 8.8](#)) immediately after completing the handshake. The maximum unidirectional stream ID is set to 0 if this parameter is absent, preventing the creation of new unidirectional streams until a `MAX_STREAM_ID` frame is sent.

`omit_connection_id (0x0004)`: The omit connection identifier parameter indicates that packets sent to the endpoint that advertises this parameter **MAY** omit the connection ID in packets using short header format. This can be used by an endpoint where it knows that source and destination IP address and port are sufficient for it to identify a connection. This parameter is zero length. Absence of this parameter means that the connection ID **MUST** be present in every packet sent to this endpoint.

`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 5.5](#)).

`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 8.16](#). If this value is absent, a default value of 3 is assumed (indicating a multiplier of 8). Values above 20 are invalid.

7.4.2. Values of Transport Parameters for 0-RTT

Transport parameters from the server **MUST** be remembered by the client for use with 0-RTT data. If the TLS NewSessionTicket message includes the quic_transport_parameters extension, then those values are used for the server values when establishing a new connection using that ticket. Otherwise, the transport parameters that the server advertises during connection establishment are used.

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_stream_id_bidi or initial_max_stream_id_uni.

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_stream_id_bidi, initial_max_stream_id_uni, initial_max_data, initial_max_stream_data.

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

7.4.3. 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 14.1](#).

7.4.4. 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 7.2](#)).

The cryptographic handshake provides integrity protection for the negotiated version as part of the transport parameters (see [Section 7.4](#)). 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 5.3](#), 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 5.3](#)) in the `supported_versions` field. The server populates this field even if it did not send a

version negotiation packet. This field is absent if the parameters are included in a NewSessionTicket message.

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.

[7.5.](#) 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 7.6](#)), 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 5.4.2](#)). This packet causes a client to reset its transport state and to continue the connection attempt with new connection state while maintaining the state of the cryptographic handshake.

A server MUST NOT send multiple Retry packets in response to a client handshake packet. Thus, any cryptographic handshake message that is sent MUST fit within a single packet.

In TLS, the Retry packet type is used to carry the HelloRetryRequest message.

[7.6.](#) 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 cryptographic handshake successfully completes. 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 during the establishment of a connection. TLS provides the tools that support the feature, but basic validation is performed by the core transport protocol.

A different type of source address validation is performed after a connection migration, see [Section 7.7.2](#).

[7.6.1](#). 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 cannot be easily guessed (see [Section 7.6.3](#)), if the client is able to return that token, it proves to the server that it received the token.

During the processing of the cryptographic handshake messages from a client, TLS will request that QUIC make a decision about whether to proceed based on the information it has. TLS will provide QUIC with

any token that was provided by the client. For an initial packet, QUIC can decide to abort the connection, allow it to proceed, or request address validation.

If QUIC decides to request address validation, it provides the cryptographic handshake with a token. The contents of this token are consumed by the server that generates the token, so 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 cryptographic handshake is responsible for enacting validation by sending the address validation token to the client. A legitimate client will include a copy of the token when it attempts to continue the handshake. The cryptographic handshake extracts the token then asks QUIC a second time whether the token is acceptable. In response, QUIC 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.

7.6.2. Address Validation on Session Resumption

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.

A different type of token is needed when resuming. Unlike the token that is created during a handshake, 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. 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.

This token can be provided to the cryptographic handshake immediately after establishing a connection. QUIC might also generate an updated token if significant time passes or the client address changes for any reason (see [Section 7.7](#)). The cryptographic handshake is responsible for providing the client with the token. In TLS the

token is included in the ticket that is used for resumption and 0-RTT, which is carried in a NewSessionTicket message.

7.6.3. 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.

In TLS the address validation token is often bundled with the information that TLS requires, such as the resumption secret. In this case, adding integrity protection can be delegated to the cryptographic handshake protocol, avoiding redundant protection. If integrity protection is delegated to the cryptographic handshake, an integrity failure will result in immediate cryptographic handshake failure. If integrity protection is performed by QUIC, QUIC MUST abort the connection if the integrity check fails with a `PROTOCOL_VIOLATION` error code.

7.7. Connection Migration

QUIC connections are identified by their 64-bit Connection ID. QUIC's consistent connection ID allows connections to survive changes to the client's IP and/or port, such as those caused by client or server migrating to a new network. Connection migration allows a client to retain any shared state with a connection when they move networks. This includes state that can be hard to recover such as outstanding requests, which might otherwise be lost with no easy way to retry them.

An endpoint that receives packets that contain a source IP address and port that has not yet been used can start sending new packets with those as a destination IP address and port. Packets exchanged between endpoints can then follow the new path.

Due to variations in path latency or packet reordering, packets from different source addresses might be reordered. The packet with the highest packet number MUST be used to determine which path to use. Endpoints also need to be prepared to receive packets from an older source address.

An endpoint **MUST** validate that its peer can receive packets at the new address before sending any significant quantity of data to that address, or it risks being used for denial of service. See [Section 7.7.2](#) for details.

7.7.1. Privacy Implications of Connection Migration

Using a stable connection ID on multiple network paths allows a passive observer to correlate activity between those paths. A client that moves between networks might not wish to have their activity correlated by any entity other than a server. The `NEW_CONNECTION_ID` message can be sent by a server to provide an unlinkable connection ID for use in case the client wishes to explicitly break linkability between two points of network attachment.

A client might need to send packets on multiple networks without receiving any response from the server. To ensure that the client is not linkable across each of these changes, a new connection ID and packet number gap are needed for each network. To support this, a server sends multiple `NEW_CONNECTION_ID` messages. Each `NEW_CONNECTION_ID` is marked with a sequence number. Connection IDs **MUST** be used in the order in which they are numbered.

A client which wishes to break linkability upon changing networks **MUST** use the connection ID provided by the server as well as incrementing the packet sequence number by an externally unpredictable value computed as described in [Section 7.7.1.1](#). Packet number gaps are cumulative. A client might skip connection IDs, but it **MUST** ensure that it applies the associated packet number gaps for connection IDs that it skips in addition to the packet number gap associated with the connection ID that it does use.

A server that receives a packet that is marked with a new connection ID recovers the packet number by adding the cumulative packet number gap to its expected packet number. A server **SHOULD** discard packets that contain a smaller gap than it advertised.

For instance, a server might provide a packet number gap of 7 associated with a new connection ID. If the server received packet 10 using the previous connection ID, it should expect packets on the new connection ID to start at 18. A packet with the new connection ID and a packet number of 17 is discarded as being in error.

7.7.1.1. Packet Number Gap

In order to avoid linkage, the packet number gap **MUST** be externally indistinguishable from random. The packet number gap for a connection ID with sequence number is computed by encoding the

sequence number as a 32-bit integer in big-endian format, and then computing:

```
Gap = HKDF-Expand-Label(packet_number_secret,  
                        "QUIC packet sequence gap", sequence, 4)
```

The output of HKDF-Expand-Label is interpreted as a big-endian number. "packet_number_secret" is derived from the TLS key exchange, as described in Section 5.6 of [[QUIC-TLS](#)].

7.7.2. Address Validation for Migrated Connections

An endpoint that receives a packet from a new remote IP address and port (or just a new remote port) on packets from its peer is likely seeing a connection migration at the peer.

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

Thus, when seeing a new remote transport address, an endpoint **MUST** verify that its peer can receive and respond to packets at that new address. By providing copies of the data that it receives, the peer proves that it is receiving packets at the new address and consents to receive data.

Prior to validating the new remote address, an endpoint **MUST** limit the amount of data and packets that it sends to its peer. At a minimum, this needs to consider the possibility that packets are sent without congestion feedback.

Once a connection is established, address validation is relatively simple (see [Section 7.6](#) for the process that is used during the handshake). An endpoint validates a remote address by sending a PING frame containing a payload that is hard to guess. This frame **MUST** be sent in a packet that is sent to the new address. Once a PONG frame containing the same payload is received, the address is considered to be valid. The PONG frame can use any path on its return. A PING frame containing 12 randomly generated [[RFC4086](#)] octets is sufficient to ensure that it is easier to receive the packet than it is to guess the value correctly.

If the PING frame is determined to be lost, a new PING frame **SHOULD** be generated. This PING frame **MUST** include a new Data field that is similarly difficult to guess.

If validation of the new remote address fails, after allowing enough time for possible loss and recovery of packets carrying PING and PONG frames, the endpoint **MUST** terminate the connection. When setting this timer, implementations are cautioned that the new path could have a longer round trip time than the original. The endpoint **MUST NOT** send a `CONNECTION_CLOSE` frame in this case; it has to assume that the remote peer does not want to receive any more packets.

If the remote address is validated successfully, the endpoint **MAY** increase the rate that it sends on the new path using the state from the previous path. The capacity available on the new path might not be the same as the old path. An endpoint **MUST NOT** restore its send rate unless it is reasonably sure that the path is the same as the previous path. For instance, a change in only 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 reduce send rates appropriately.

After verifying an address, the endpoint **SHOULD** update any address validation tokens ([Section 7.6](#)) that it has issued to its peer if those are no longer valid based on the changed address.

Address validation using the PING frame **MAY** be used at any time by either peer. For instance, an endpoint might check that a peer is still in possession of its address after a period of quiescence.

Upon seeing a connection migration, an endpoint that sees a new address **MUST** abandon any address validation it is performing with other addresses on the expectation that the validation is likely to fail. Abandoning address validation primarily means not closing the connection when a PONG frame is not received, but it could also mean ceasing retransmissions of the PING frame. An endpoint that doesn't retransmit a PING frame might receive a PONG frame, which it **MUST** ignore.

[7.8](#). Spurious Connection Migrations

A connection migration could be triggered by an attacker that is able to capture and forward a packet such that it arrives before the legitimate copy of that packet. Such a packet will appear to be a legitimate connection migration and the legitimate copy will be dropped as a duplicate.

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 PING frame

that is sent to it, even if it wanted to. Such a spurious connection migration could result in the connection being dropped when the source address validation fails. This grants an attacker the ability to terminate the connection.

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

To ensure that a peer sends packets from the legitimate address before the validation of the new address can fail, an endpoint **SHOULD** attempt to validate the old remote address before attempting to validate the new address. If the connection migration is spurious, then the legitimate address will be used to respond and the connection will migrate back to the old address.

As with any address validation, packets containing retransmissions of the PING frame validating an address **MUST** be sent to the address being validated. Consequently, during a migration of a peer, an endpoint could be sending to multiple remote addresses.

An endpoint **MAY** abandon address validation for an address that it considers to be already valid. That is, if successive connection migrations occur in quick succession with the final remote address being identical to the initial remote address, the endpoint **MAY** abandon address validation for that address.

[7.9.](#) 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 7.9.2](#))
- o immediate close ([Section 7.9.3](#))
- o stateless reset ([Section 7.9.4](#))

[7.9.1.](#) 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 (RTT) interval as defined in [[QUIC-RECOVERY](#)].

An endpoint enters a closing period after initiating an immediate close ([Section 7.9.3](#)) and optionally after an idle timeout ([Section 7.9.2](#)). While closing, an endpoint MUST NOT send packets unless they contain a CONNECTION_CLOSE or APPLICATION_CLOSE frame (see [Section 7.9.3](#) 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 7.9.4](#)) is sent.

7.9.2. Idle Timeout

A connection that remains idle for longer than the idle timeout (see [Section 7.4.1](#)) 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.

7.9.3. Immediate Close

An endpoint sends a closing frame, either CONNECTION_CLOSE or APPLICATION_CLOSE, to terminate the connection immediately. Either 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.

[7.9.4.](#) Stateless Reset

A stateless reset is provided as an option of last resort for a server that does not have access to the state of a connection. A server crash or outage might result in clients continuing to send data to a server that is unable to properly continue the connection. A server 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, the server sends a `stateless_reset_token` value during the handshake in the transport parameters. This value is protected by encryption, so only client and server know this value.

A server 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|C|K|Type (5) |
+---+---+---+---+
|
+           [Connection ID (64)]           +
|
+---+---+---+---+
|           Packet Number (8/16/32)         |
+---+---+---+---+
|           Random Octets (*)               ...
+---+---+---+---+
|
+
|
+           Stateless Reset Token (128)       +
|
+
|
+---+---+---+---+

```

A server copies the connection ID field from the packet that triggers the stateless reset. A server omits the connection ID if explicitly configured to do so, or if the client packet did not include a connection ID.

The Packet Number field is set to a randomized value. The server SHOULD send a packet with a short header and a type of 0x1F. This produces the shortest possible packet number encoding, which minimizes the perceived gap between the last packet that the server sent and this packet. A server MAY use a different short header type, indicating a different packet number length, but a longer packet number encoding might allow this message to be identified as a stateless reset more easily using heuristics.

After the first short header octet and optional connection ID, the server includes the value of the Stateless Reset Token that it included in its transport parameters.

After the Packet Number, the server pads the message with an arbitrary number of octets containing random values.

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

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

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. A server that supports multiple versions of QUIC needs to generate a stateless reset that will be accepted by clients that support any version that the server 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.

7.9.4.1. Detecting a Stateless Reset

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

7.9.4.2. Calculating a Stateless Reset Token

The stateless reset token MUST be difficult to guess. In order to create a Stateless Reset Token, a server could randomly generate [\[RFC4086\]](#) a secret for every connection that it creates. However, this presents a coordination problem when there are multiple servers in a cluster or a storage problem for a server 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, a the connection ID for the connection (see [Section 5.6](#)), and an identifier for the server instance. A server could use HMAC [\[RFC2104\]](#) (for example, `HMAC(static_key, server_id || connection_id)`) or HKDF [\[RFC5869\]](#) (for example, using the static key as input keying material, with server and connection identifiers as salt). The output of this function is truncated to 16 octets to produce the Stateless Reset Token for that connection.

A server that loses state can use the same method to generate a valid Stateless Reset Secret. The connection ID comes from the packet that the server receives.

This design relies on the client always sending a connection ID in its packets so that the server can use the connection ID from a packet to reset the connection. A server that uses this design cannot allow clients to omit a connection ID (that is, it cannot use the `truncate_connection_id` transport parameter [Section 7.4.1](#)).

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 server 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 server without first changing to use a different static key or server identifier.

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

8. Frame Types and Formats

As described in [Section 6](#), Regular packets contain one or more frames. We now describe the various QUIC frame types that can be

present in a Regular packet. The use of these frames and various frame header bits are described in subsequent sections.

8.1. Variable-Length Integer Encoding

QUIC frames use a common variable-length encoding for all 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 12.3](#)) are described using integers, but do not use this encoding.

8.2. 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.

8.3. 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.

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 12.4](#)) 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.

8.4. 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)           | 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 12.3](#) (APPLICATION_CLOSE uses codes from the application protocol error code space, see [Section 12.4](#)).

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](#)].

8.5. APPLICATION_CLOSE frame

An APPLICATION_CLOSE frame (type=0x03) uses the same format as the CONNECTION_CLOSE frame ([Section 8.4](#)), except that it uses error codes from the application protocol error code space ([Section 12.4](#)) 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.

8.6. 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, with the exception of data on stream 0. The sum of the largest received offsets on all streams - including streams in terminal states, but excluding stream 0 - 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 7.4.2](#)).

8.7. 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.

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 7.4.2](#)).

8.8. 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 streams 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 7.4.2](#)).

8.9. 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 a variable-length 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
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
| Length(8) |                               Data (*)                               ...
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+

```

Length: This 8-bit value describes the length of the Data field.

Data: This variable-length field contains arbitrary data.

A PING frame with an empty Data field causes the packet containing it to be acknowledged as normal. No other action is required of the recipient.

An empty 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.

If the Data field is not empty, the recipient of this frame MUST generate a PONG frame ([Section 8.15](#)) containing the same Data. A PING frame with data is not appropriate for use in keeping a connection alive, because the PONG frame elicits an acknowledgement, causing the sender of the original PING to send two packets.

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 7.9](#)). 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.

8.10. 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 11.2.1](#)). BLOCKED frames can be used as input to tuning of flow control algorithms (see [Section 11.1.2](#)).

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.

8.11. 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 8.10](#)).

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.

8.12. 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 8.8](#)). 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.

8.13. NEW_CONNECTION_ID Frame

A server sends a NEW_CONNECTION_ID frame (type=0x0b) to provide the client with alternative connection IDs that can be used to break linkability when migrating connections (see [Section 7.7.1](#)).

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)                               ...
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
|                               |
+                               +
|                               |
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
|                               |
+                               +
|                               |
+                               +
|                               |
+                               +
|                               |
+                               +
|                               |
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+

```

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.

Connection ID: A 64-bit connection ID.

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 7.9.4](#)).

8.14. 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.

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 12.4](#)).

8.15. PONG Frame

The PONG frame (type=0x0d) is sent in response to a PING frame that contains data. Its format is identical to the PING frame ([Section 8.9](#)).

An endpoint that receives an unsolicited PONG frame - that is, a PONG frame containing a payload that is empty MUST generate a connection error of type FRAME_ERROR, indicating the PONG frame (that is, 0x10d). If the content of a PONG frame does not match the content of

a PING frame previously sent by the endpoint, the endpoint MAY generate a connection error of type UNSOLICITED_PONG.

8.16. ACK Frame

Receivers send ACK frames (type=0xe) to inform senders which packets they have received and processed. A sent packet that has never been acknowledged is missing. The ACK frame contains any number of ACK blocks. ACK blocks are ranges of acknowledged packets.

Unlike TCP SACKs, QUIC acknowledgements are irrevocable. Once a packet has been acknowledged, even if it does not appear in a future ACK frame, it remains acknowledged.

A client MUST NOT acknowledge Version Negotiation or Retry packets. These packet types contain packet numbers selected by the client, not the server.

A sender MAY intentionally skip packet numbers to introduce entropy into the connection, to avoid opportunistic acknowledgement attacks. The sender SHOULD close the connection if an unsent packet number is acknowledged. The format of the ACK frame is efficient at expressing even long blocks of missing packets, allowing for large, unpredictable gaps.

An ACK frame is shown below.

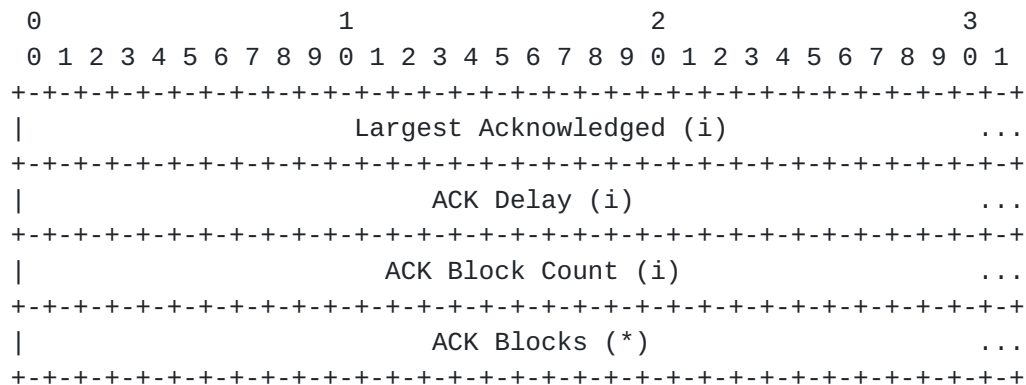


Figure 7: ACK Frame Format

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.

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 7.4.1](#)). 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 8.16.1](#).

[8.16.1](#). 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.

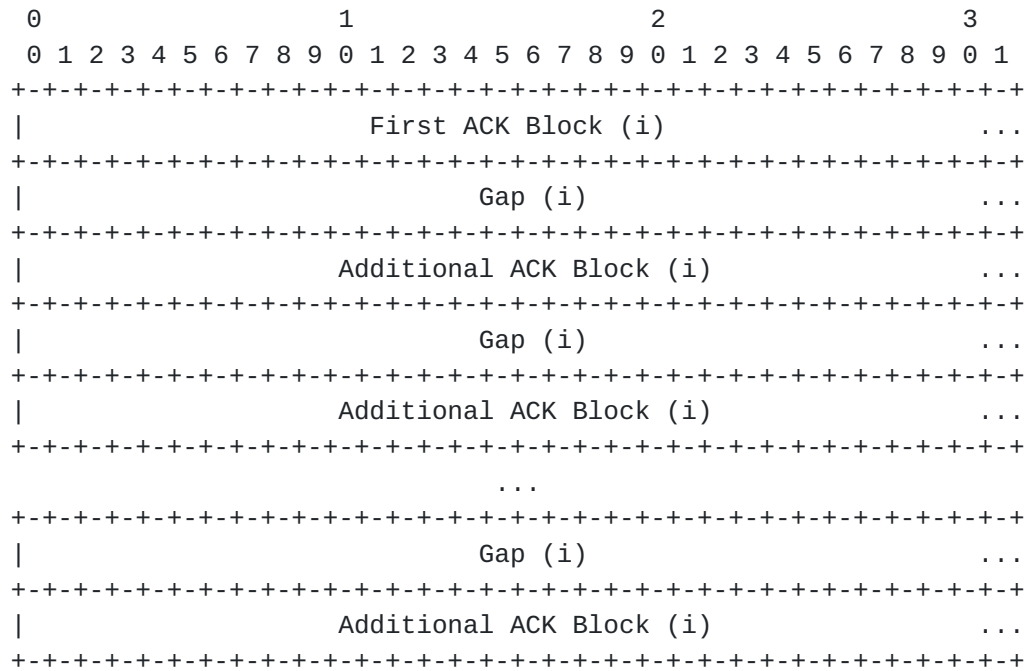


Figure 8: ACK Block Section

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:

$$\text{smallest} = \text{largest} - \text{ack_block}$$

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_ERROR indicating an error in an ACK frame (that is, 0x10d).

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.

8.16.2. 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 ACK frame 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.

A receiver that is only sending ACK frames will not receive acknowledgments for its packets. Sending an occasional MAX_DATA or MAX_STREAM_DATA frame as data is received will ensure that acknowledgments are generated by a peer. Otherwise, an endpoint MAY send a PING frame once per RTT to solicit an acknowledgment.

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.

8.16.3. ACK Frames and Packet Protection

ACK frames that acknowledge protected packets MUST be carried in a packet that has an equivalent or greater level of packet protection.

Packets that are protected with 1-RTT keys MUST be acknowledged in packets that are also protected with 1-RTT keys.

A packet that is not protected and claims to acknowledge a packet number that was sent with packet protection is not valid. An unprotected packet that carries acknowledgments for protected packets MUST be discarded in its entirety.

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.

Unprotected packets, such as those that carry the initial cryptographic handshake messages, MAY be acknowledged in unprotected packets. Unprotected packets are vulnerable to falsification or modification. Unprotected packets can be acknowledged along with protected packets in a protected packet.

An endpoint SHOULD acknowledge packets containing cryptographic handshake messages in the next unprotected packet that it sends, unless it is able to acknowledge those packets in later packets protected by 1-RTT keys. At the completion of the cryptographic handshake, both peers send unprotected packets containing cryptographic handshake messages followed by packets protected by 1-RTT keys. An endpoint SHOULD acknowledge the unprotected packets that complete the cryptographic handshake in a protected packet, because its peer is guaranteed to have access to 1-RTT packet protection keys.

For instance, a server acknowledges a TLS ClientHello in the packet that carries the TLS ServerHello; similarly, a client can acknowledge a TLS HelloRetryRequest in the packet containing a second TLS ClientHello. The complete set of server handshake messages (TLS ServerHello through to Finished) might be acknowledged by a client in protected packets, because it is certain that the server is able to decipher the packet.

8.17. 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 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.
- 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 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).

A STREAM frame is shown below.

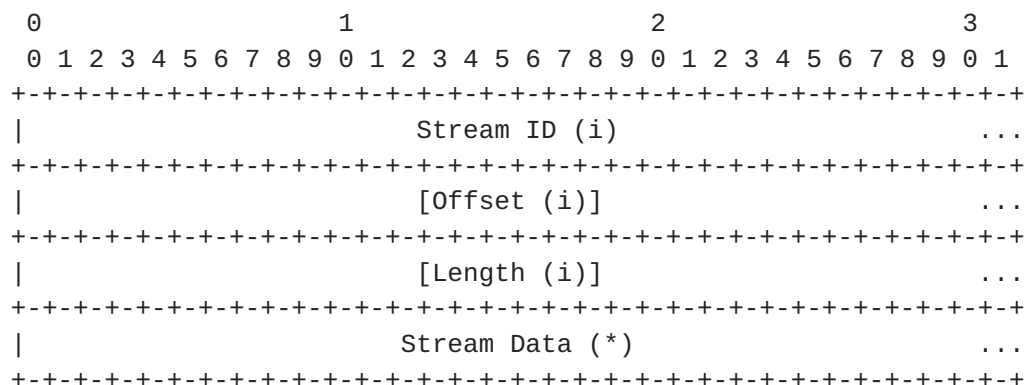


Figure 9: STREAM Frame Format

The STREAM frame contains the following fields:

Stream ID: A variable-length integer indicating the stream ID of the stream (see [Section 10.1](#)).

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.

A stream frame's Stream Data MUST NOT be empty, unless the FIN bit is set. When the FIN flag is sent on an empty STREAM frame, 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.

9. Packetization and Reliability

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](#)]) and 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.

QUIC endpoints that implement any kind of PMTU discovery SHOULD maintain an estimate for each combination of local and remote IP addresses (as each pairing 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 and therefore also supported by most modern IPv4 networks. An endpoint MUST NOT reduce their MTU below this number, even if it receives signals that indicate a smaller limit might exist.

Clients MUST ensure that the first packet in a connection, and any retransmissions of those octets, has a QUIC packet size of least 1200 octets. The packet size for a QUIC packet includes the QUIC header and integrity check, but not the UDP or IP header.

The initial client packet SHOULD be padded to exactly 1200 octets unless the client has a reasonable assurance that the PMTU is larger. Sending a packet of this size ensures that the network path supports an MTU of this size and helps reduce the amplitude of amplification attacks caused by server responses toward an unverified client address.

Servers MUST ignore an initial plaintext packet from a client if its total size is less than 1200 octets.

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.

A sender bundles one or more frames in a Regular QUIC packet (see [Section 6](#)).

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 heuristics about expected application sending behavior 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.

Regular QUIC packets are "containers" of frames; a packet is never retransmitted whole. How an endpoint handles the loss of the frame

depends on the type of the frame. Some frames are simply retransmitted, some have their contents moved to new frames, and others are never retransmitted.

When a packet is detected as lost, the sender re-sends any frames as necessary:

- o All application data sent in STREAM frames MUST be retransmitted, unless the endpoint has sent a RST_STREAM for that stream. When an endpoint sends a RST_STREAM frame, data outstanding on that stream SHOULD NOT be retransmitted, since subsequent data on this stream is expected to not be delivered by the receiver.
- o ACK and PADDING frames MUST NOT be retransmitted. ACK frames containing updated information will be sent as described in [Section 8.16](#).
- o STOP_SENDING frames MUST be retransmitted until the receive stream enters either a "Data Recvd" or "Reset Recvd" state. See [Section 10.3](#).
- o The most recent MAX_STREAM_DATA frame for a stream MUST be retransmitted until the receive stream enters a "Size Known" state. Any previous unacknowledged MAX_STREAM_DATA frame for the same stream SHOULD NOT be retransmitted since a newer MAX_STREAM_DATA frame for a stream obviates the need for delivering older ones. Similarly, the most recent MAX_DATA frame MUST be retransmitted; previous unacknowledged ones SHOULD NOT be retransmitted.
- o BLOCKED, STREAM_BLOCKED, and STREAM_ID_BLOCKED frames SHOULD be retransmitted if the sender is still blocked on the same limit. If the limit has been increased since the frame was originally sent, the frame SHOULD NOT be retransmitted.
- o All other frames MUST be retransmitted.

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

A packet MUST NOT be acknowledged until packet protection has been successfully removed and all frames contained in the packet have been processed. For STREAM frames, this means the data has been queued (but not necessarily delivered to the application). This also means that any stream state transitions triggered by STREAM or RST_STREAM frames have occurred. 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](#)].

9.1. Special Considerations for PMTU Discovery

Traditional ICMP-based path MTU discovery in IPv4 [[RFC1191](#)] 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.

10. 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 10.1](#)).

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

Data that is received on a stream is delivered in order within that stream, but there is no particular delivery order across streams. Transmit ordering among streams is left to the implementation.

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.

[10.1](#). 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

Stream ID 0 (0x0) is a client-initiated, bidirectional stream that is used for the cryptographic handshake. Stream 0 MUST NOT be used for application data.

A QUIC endpoint MUST NOT reuse a Stream ID. Open 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 8.1](#)).

10.2. 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 10.2.1](#)); another for streams from which an endpoint receives data ([Section 10.2.2](#)).

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 causes the stream to open in both directions.

Opening a stream causes all lower-numbered streams of the same type to implicitly open. This includes both send and receive streams if the stream is bidirectional. For bidirectional streams, an endpoint can send data on an implicitly opened stream. On both unidirectional and bidirectional streams, an endpoint MAY send `MAX_STREAM_DATA` or `STOP_SENDING` on implicitly opened streams. An endpoint SHOULD NOT implicitly open streams that it initiates, instead opening streams 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.

[10.2.1.](#) Send Stream States

Figure 10 shows the states for the part of a stream that sends data to a peer.

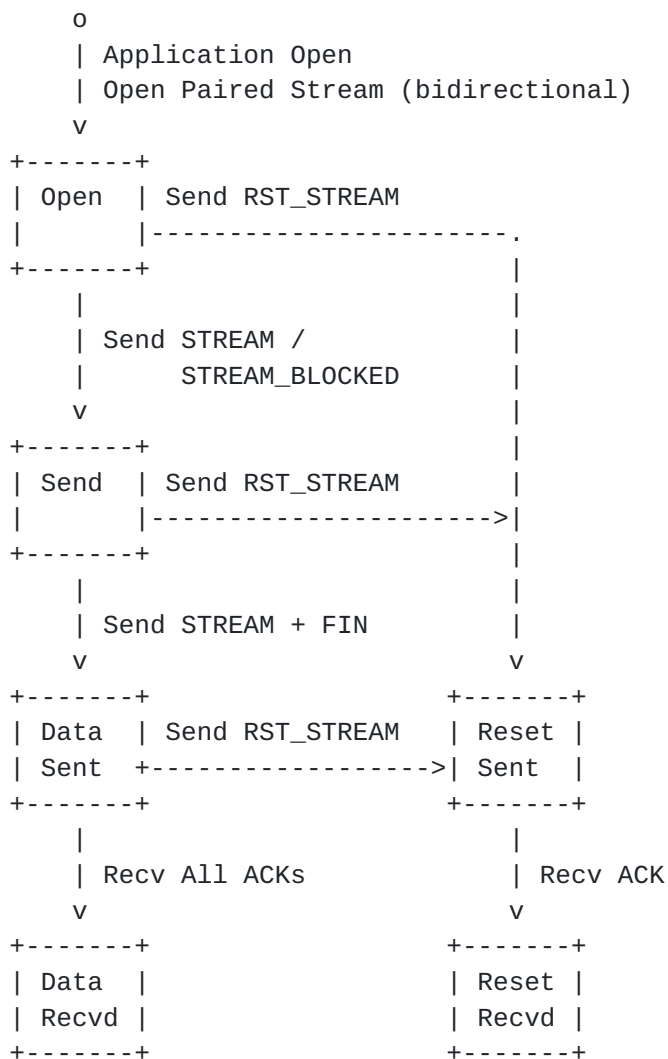


Figure 10: States for Send Streams

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 "Open" 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 "Open" 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 "Open", "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.

10.2.2. Receive Stream States

Figure 11 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 "Open" state; instead, receive streams track the delivery of data to the application or application protocol some of which cannot be observed by the sender.

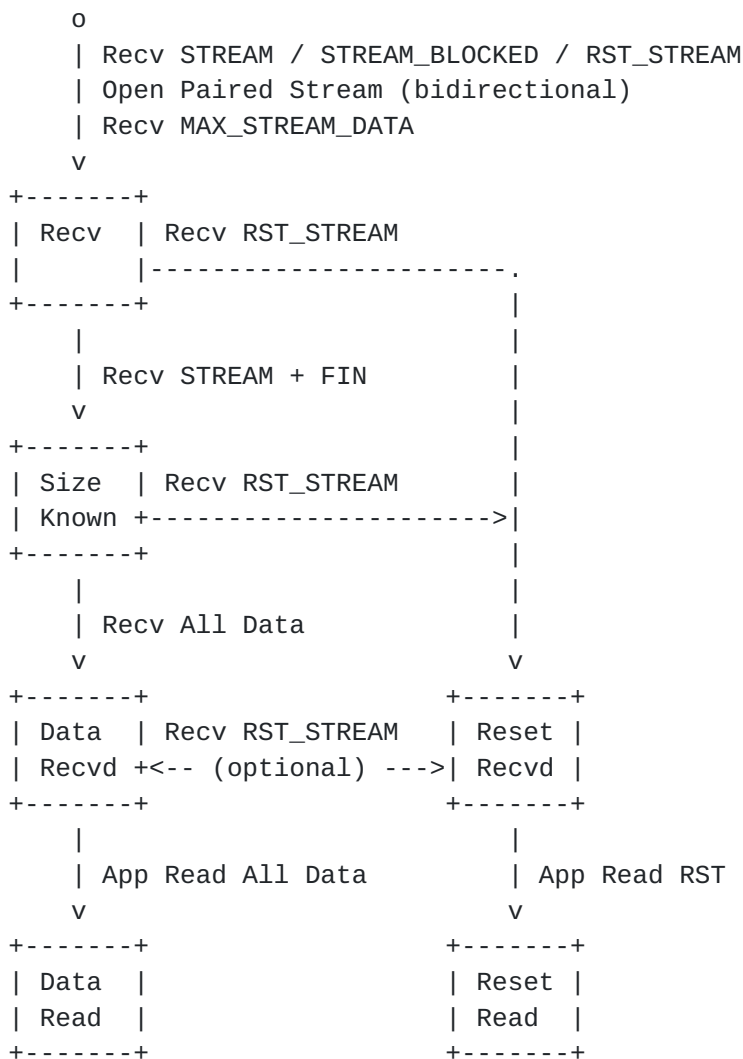


Figure 11: States for Receive Streams

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 "Open" 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 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 11.3](#)) 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.

10.2.3. 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 8.17](#)), STREAM_BLOCKED ([Section 8.11](#)), and RST_STREAM ([Section 8.3](#)).

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 8.7](#)) and STOP_SENDING frames ([Section 8.14](#)).

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.

10.2.4. 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/Open	No Stream/Recv *1	idle
Open/Send/Data Sent	Recv/Size Known	open
Open/Send/Data Sent	Data Recvd/Data Read	half-closed (remote)
Open/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.

10.3. 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.

10.4. 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 7.4.1](#)) and is subsequently increased by MAX_STREAM_ID frames (see [Section 8.8](#)).

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 initiate 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 12](#)), unless this is a result of a change in the initial offsets (see [Section 7.4.2](#)).

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.

10.5. 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 byte of data that is sent on a stream has the stream offset 0. The largest offset delivered on a stream **MUST** be less than 2^{62} . A receiver **MUST** ensure that received stream data is delivered to the application as an ordered byte-stream. Data received out of order **MUST** be buffered for later delivery, as long as it is not in violation of the receiver's flow control limits.

An endpoint **MUST NOT** send data on any stream without ensuring that it is within the data limits set by its peer. The cryptographic handshake stream, Stream 0, is exempt from the connection-level data limits established by MAX_DATA. Data on stream 0 other than the initial cryptographic handshake message is still subject to stream-level data limits and MAX_STREAM_DATA. This message is exempt from flow control because it needs to be sent in a single packet regardless of the server's flow control state. This rule applies even for 0-RTT handshakes where the remembered value of MAX_STREAM_DATA would not permit sending a full initial cryptographic handshake message.

Flow control is described in detail in [Section 11](#), and congestion control is described in the companion document [\[QUIC-RECOVERY\]](#).

10.6. 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.

Stream 0 MUST 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 frames that are 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.

11. 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 the maximum absolute byte offset of a stream, while MAX_DATA sends the maximum sum of the absolute byte offsets of all streams other than stream 0.

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 12](#)) 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 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.

11.1. 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.

11.1.1. 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.

11.1.2. 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 roundtrip time

estimate and the rate at which the receiving application consumes data, similar to common TCP implementations.

11.2. 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.

11.2.1. 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 possibility of loss, a receiver should send a `MAX_DATA` or `MAX_STREAM_DATA` frame at least two roundtrips 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.

11.3. 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 12](#)). 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.

[12.](#) Error Handling

An endpoint that detects an error SHOULD signal the existence of that error to its peer. Errors can affect an entire connection (see [Section 12.1](#)), or a single stream (see [Section 12.2](#)).

The most appropriate error code ([Section 12.3](#)) 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 7.9.4](#)) 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.

[12.1.](#) 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 8.4](#), [Section 8.5](#)). 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 7.9.4](#)).

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

[12.2.](#) Stream Errors

If the error affects a single stream, but otherwise leaves the connection in a recoverable state, the endpoint can send a RST_STREAM frame ([Section 8.3](#)) with an appropriate error code to terminate just the affected stream.

Stream 0 is critical to the functioning of the entire connection. If stream 0 is closed with either a RST_STREAM or STREAM frame bearing the FIN flag, an endpoint MUST generate a connection error of type `PROTOCOL_VIOLATION`.

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.

[12.3.](#) 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.

FLOW_CONTROL_ERROR (0x3): An endpoint received more data than it permitted in its advertised data limits (see [Section 11](#)).

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 10.2](#)).

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_FORMAT_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. This is a generic error code; an endpoint SHOULD use the more specific frame format error codes (0x1XX) if possible.

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_PONG (0xB): An endpoint received a PONG frame that did not correspond to any PING frame that it previously sent.

FRAME_ERROR (0x1XX): An endpoint detected an error in a specific frame type. The frame type is included as the last octet of the

error code. For example, an error in a MAX_STREAM_ID frame would be indicated with the code (0x106).

See [Section 14.2](#) for details of registering new error codes.

[12.4.](#) 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 8.3](#)) and APPLICATION_CLOSE ([Section 8.5](#)) 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.

[13.](#) Security and Privacy Considerations

[13.1.](#) Spoofed ACK Attack

An attacker receives an STK from the server and then releases the IP address on which it received the STK. 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 then spoofs ACK frames to the server which cause the server to potentially drown the victim in data.

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.

13.2. 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.

13.3. 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.

13.4. 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 10.1](#). 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 10.4](#). 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.

[14.](#) IANA Considerations

[14.1.](#) 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. The 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 7.4.1
0x0001	initial_max_data	Section 7.4.1
0x0002	initial_max_stream_id_bidi	Section 7.4.1
0x0003	idle_timeout	Section 7.4.1
0x0004	omit_connection_id	Section 7.4.1
0x0005	max_packet_size	Section 7.4.1
0x0006	stateless_reset_token	Section 7.4.1
0x0007	ack_delay_exponent	Section 7.4.1
0x0008	initial_max_stream_id_uni	Section 7.4.1

Table 7: Initial QUIC Transport Parameters Entries

14.2. 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 0xffeff).

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. Note that FRAME_ERROR takes the range from 0x100 to 0x1FF and private use occupies the range from 0xFE00 to 0xFFFF.

Value	Error	Description	Specification
0x0	NO_ERROR	No error	Section 12.3
0x1	INTERNAL_ERROR	Implementation error	Section 12.3
0x3	FLOW_CONTROL_ERROR	Flow control error	Section 12.3
0x4	STREAM_ID_ERROR	Invalid stream ID	Section 12.3
0x5	STREAM_STATE_ERROR	Frame received in invalid stream state	Section 12.3
0x6	FINAL_OFFSET_ERROR	Change to final stream offset	Section 12.3
0x7	FRAME_FORMAT_ERROR	Generic frame format error	Section 12.3
0x8	TRANSPORT_PARAMETER_ERROR	Error in transport parameters	Section 12.3
0x9	VERSION_NEGOTIATION_ERROR	Version negotiation failure	Section 12.3
0xA	PROTOCOL_VIOLATION	Generic protocol violation	Section 12.3
0xB	UNSOLICITED_PONG	Unsolicited PONG frame	Section 12.3
0x100-0x1FF	FRAME_ERROR	Specific frame format error	Section 12.3

Table 8: Initial QUIC Transport Error Codes Entries

15. References

15.1. Normative References

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[Appendix A. Contributors](#)

The original authors of this specification were Ryan Hamilton, Jana Iyengar, Ian Swett, and Alyssa Wilk.

The original design and rationale behind this protocol draw significantly from work by Jim Roskind [[EARLY-DESIGN](#)]. In alphabetical order, the contributors to the pre-IETF QUIC project at Google are: Britt Cyr, Jeremy Dorfman, Ryan Hamilton, Jana Iyengar, Fedor Kouranov, Charles Krasnic, Jo Kulik, Adam Langley, Jim Roskind, Robbie Shade, Satyam Shekhar, Cherie Shi, Ian Swett, Raman Tenneti, Victor Vasiliev, Antonio Vicente, Patrik Westin, Alyssa Wilk, Dale Worley, Fan Yang, Dan Zhang, Daniel Ziegler.

[Appendix B. Acknowledgments](#)

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Appendix C. 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.

C.1. Since [draft-ietf-quic-transport-07](#)

- o Employ variable-length integer encodings throughout (#595)
- o Draining period can terminate early (#869)

C.2. 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)

C.3. 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)

C.4. 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)

C.5. Since [draft-ietf-quic-transport-03](#)

- o Change STREAM and RST_STREAM layout
- o Add MAX_STREAM_ID settings

C.6. 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)

C.7. 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)

C.8. 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

C.9. 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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