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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](mailto:quic@ietf.org)), which is archived at [https://mailarchive.ietf.org/arch/search/?email\\_list=quic](https://mailarchive.ietf.org/arch/search/?email_list=quic) .

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

Status of This Memo

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

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## 1. Introduction

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. Using UDP as the substrate, QUIC seeks to be compatible with legacy clients and middleboxes. 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 words "MUST", "MUST NOT", "SHOULD", and "MAY" are used in this document. It's not shouting; when they are capitalized, they have the special meaning defined in [RFC2119].

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 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 [RFC2360] Section 3.1, 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 (\*) ... 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 1) 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 1 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 up to 256 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, closely following HTTP/2's flow control mechanisms. At a high level, a QUIC receiver advertises the absolute byte offset within each stream up to which the receiver is willing to receive data. As data is sent,

received, and delivered on a particular stream, the receiver sends WINDOW\_UPDATE frames that increase the advertised offset 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 highest received offset are all aggregates 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.

PUBLIC\_RESET packets that reset a connection are currently not authenticated.

### 3.6. Connection Migration and Resilience to NAT Rebinding

QUIC connections are identified by a 64-bit Connection ID, randomly generated by the client. 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 7.1.

## 4. Versions

QUIC versions are identified using a 32-bit value.

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

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, and for public resets. Short headers are minimal version-specific headers, which can be used after version negotiation and 1-RTT keys are established.

### 5.1. Long Header

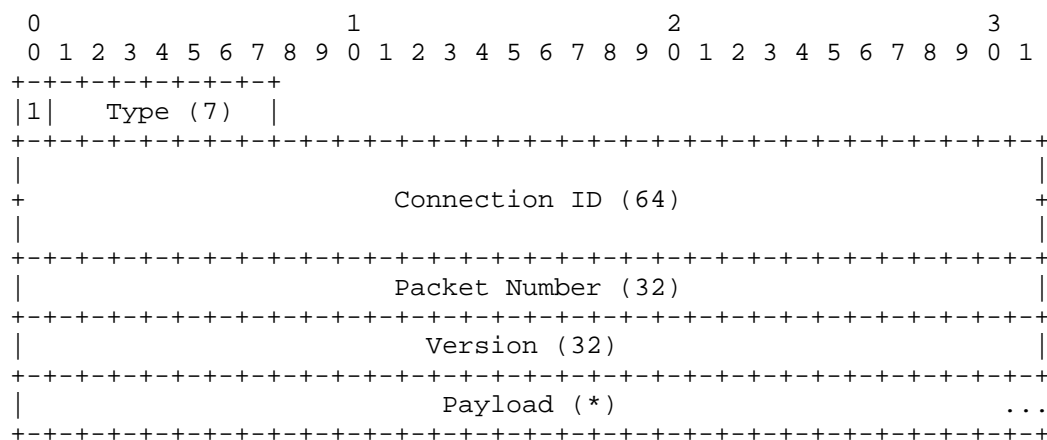


Figure 1: Long Header Format

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 SHOULD switch to sending short-form headers. While inefficient, long headers MAY be used for packets encrypted with 1-RTT keys. The long form allows for special packets, such as the Version Negotiation and the Public Reset packets 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 the first octet is set to 1 for long headers and 0 for short headers.

Long Packet Type: The remaining seven bits of first octet of a long packet is 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 5.7 describes the use of this field in more detail.

Packet Number: Octets 9 to 12 contain the packet number. {{packet-numbers}} describes the use of packet numbers.

Version: Octets 13 to 16 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.

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     |
|------|-------------------------------|-------------|
| 01   | Version Negotiation           | Section 5.3 |
| 02   | Client Cleartext              | Section 5.4 |
| 03   | Non-Final Server Cleartext    | Section 5.4 |
| 04   | Final Server Cleartext        | Section 5.4 |
| 05   | 0-RTT Encrypted               | Section 5.5 |
| 06   | 1-RTT Encrypted (key phase 0) | Section 5.5 |
| 07   | 1-RTT Encrypted (key phase 1) | Section 5.5 |
| 08   | Public Reset                  | Section 5.6 |

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

(TODO: Should the list of packet types be version-independent?)

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 Section 5.3, Section 5.6, Section 5.4, and Section 5.5.

## 5.2. Short Header

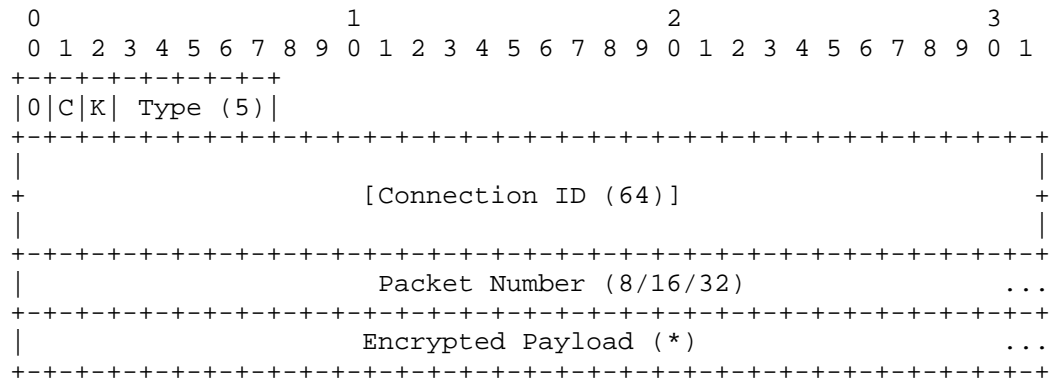


Figure 2: Short Header Format

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 the first octet of a packet is the header form. This bit is set to 0 for the short header.

**Connection ID Flag:** The second bit (0x40) of the first octet indicates whether the Connection ID field is present. If set to 1, then the Connection ID field is present; if set to 0, the Connection ID field is omitted.

**Key Phase Bit:** The third bit (0x20) of the first octet 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 the first octet include one of 32 packet types. Table 2 lists the types that are defined for short packets.

**Connection ID:** If the Connection ID Flag is set, a connection ID occupies octets 1 through 8 of the packet. See Section 5.7 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.

**Encrypted 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 |
|------|--------------------|
| 01   | 1 octet            |
| 02   | 2 octets           |
| 03   | 4 octets           |

Table 2: Short Header Packet Types

The header form, 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 5.9 for details on how packets from different versions of QUIC are interpreted.

### 5.3. Version Negotiation Packet

A Version Negotiation packet is sent only by servers and is a response to a client packet of an unsupported version. It uses a long header and contains:

- o Octet 0: 0x81
- o Octets 1-8: Connection ID (echoed)
- o Octets 9-12: Packet Number (echoed)
- o Octets 13-16: Version (echoed)
- o Octets 17+: Payload

The payload of the Version Negotiation packet is a list of 32-bit versions which the server supports, as shown below.

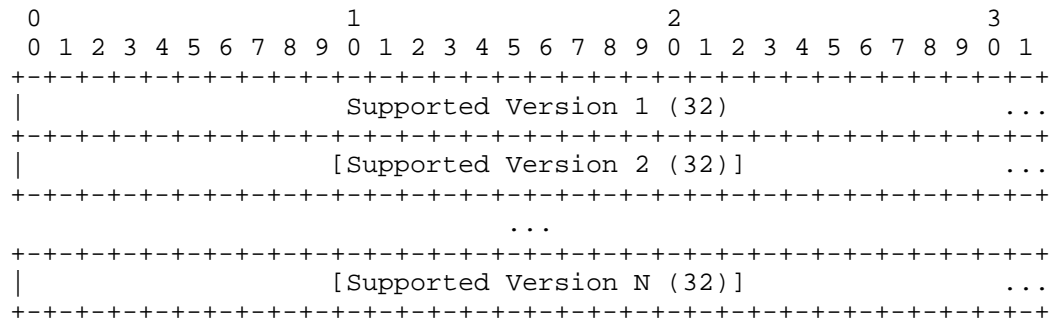


Figure 3: Version Negotiation Packet

See Section 7.1 for a description of the version negotiation process.

#### 5.4. Cleartext Packets

Cleartext packets are sent during the handshake prior to key negotiation. A Client Cleartext packet contains:

- o Octet 0: 0x82
- o Octets 1-8: Connection ID (initial)
- o Octets 9-12: Packet number
- o Octets 13-16: Version
- o Octets 17+: Payload

Non-Final Server Cleartext packets contain:

- o Octet 0: 0x83
- o Octets 1-8: Connection ID (echoed)
- o Octets 9-12: Packet Number
- o Octets 13-16: Version
- o Octets 17+: Payload

Final Server Cleartext packets contains:

- o Octet 0: 0x84
- o Octets 1-8: Connection ID (final)

- o Octets 9-12: Packet Number
- o Octets 13-16: Version
- o Octets 17+: Payload

The client MUST choose a random 64-bit value and use it as the initial Connection ID in all packets until the server replies with the final Connection ID. The server echoes the client's Connection ID in Non-Final Server Cleartext packets. The first Final Server Cleartext and all subsequent packets MUST use the final Connection ID, as described in Section 5.7.

The payload of a Cleartext packet consists of a sequence of frames, as described in Section 6.

(TODO: Add hash before frames.)

#### 5.5. Encrypted Packets

Packets encrypted with either 0-RTT or 1-RTT keys may be sent with long headers. Different packet types explicitly indicate the encryption level for ease of decryption. These packets contain:

- o Octet 0: 0x85, 0x86 or 0x87
- o Octets 1-8: Connection ID (initial or final)
- o Octets 9-12: Packet Number
- o Octets 13-16: Version
- o Octets 17+: Encrypted Payload

A first octet of 0x85 indicates a 0-RTT packet. After the 1-RTT keys are established, key phases are used by the QUIC packet protection to identify the correct packet protection keys. The initial key phase is 0. See [QUIC-TLS] for more details.

The encrypted payload is both authenticated and encrypted using packet protection keys. [QUIC-TLS] describes packet protection in detail. After decryption, the plaintext consists of a sequence of frames, as described in Section 6.

## 5.6. Public Reset Packet

A Public Reset packet is only sent by servers and is used to abruptly terminate communications. Public Reset is provided as an option of last resort for a server that does not have access to the state of a connection. This is intended for use by a server that has lost state (for example, through a crash or outage). A server that wishes to communicate a fatal connection error **MUST** use a `CONNECTION_CLOSE` frame if it has sufficient state to do so.

A Public Reset packet contains:

- o Octet 0: 0x88
- o Octets 1-8: Echoed data (octets 1-8 of received packet)
- o Octets 9-12: Echoed data (octets 9-12 of received packet)
- o Octets 13-16: Version
- o Octets 17+: Public Reset Proof

For a client that sends a connection ID on every packet, the Connection ID field is simply an echo of the initial Connection ID, and the Packet Number field includes an echo of the client's packet number (and, depending on the client's packet number length, 0, 2, or 3 additional octets from the client's packet).

A Public Reset packet sent by a server indicates that it does not have the state necessary to continue with a connection. In this case, the server will include the fields that prove that it originally participated in the connection (see Section 5.6.1 for details).

Upon receipt of a Public Reset packet that contains a valid proof, a client **MUST** tear down state associated with the connection. The client **MUST** then cease sending packets on the connection and **SHOULD** discard any subsequent packets that arrive. A Public Reset that does not contain a valid proof **MUST** be ignored.

### 5.6.1. Public Reset Proof

TODO: Details to be added.

### 5.7. 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 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.

When a connection is initiated, the client MUST choose a random value and use it as the initial Connection ID until the final value is available. The initial Connection ID is a suggestion to the server. The server echoes this value in all packets until the handshake is successful (see [QUIC-TLS]). On a successful handshake, the server MUST select the final Connection ID for the connection and use it in Final Server Cleartext packets. This final Connection ID MAY be the one proposed by the client or MAY be a new server-selected value. All subsequent packets from the server MUST contain this value. On handshake completion, the client MUST switch to using the final Connection ID for all subsequent packets.

Thus, all Client Cleartext packets, 0-RTT Encrypted packets, and Non-Final Server Cleartext packets MUST use the client's randomly-generated initial Connection ID. Final Server Cleartext packets, 1-RTT Encrypted packets, and all short-header packets MUST use the final Connection ID.

### 5.8. Packet Numbers

The packet number is a 64-bit unsigned number and is used as part of a 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.

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  $2^{64} - 1$ , the sender MUST close the connection by sending a CONNECTION\_CLOSE frame with the error code QUIC\_SEQUENCE\_NUMBER\_LIMIT\_REACHED (connection termination is described in Section 7.6.)

To reduce the number of bits required to represent the packet number over the wire, only the least significant bits of the packet number are transmitted over the wire, up to 32 bits. 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 **MAY** use a larger packet number size to safeguard against such reordering.

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.

#### 5.8.1. Initial Packet Number

The initial value for packet number **MUST** be a 31-bit random number. That is, the value is selected from an uniform random distribution between 0 and  $2^{31}-1$ . [RFC4086] provides guidance on the generation of random values.

The first set of packets sent by an endpoint **MUST** include the low 32-bits of the packet number. Once any packet has been acknowledged, subsequent packets can use a shorter packet number encoding.

#### 5.9. 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 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, and

- o the location and size of the Packet Number field in long headers.

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 cleartext packets and the plaintext after decryption of encrypted payloads consists of a sequence of frames, as shown in Figure 4.

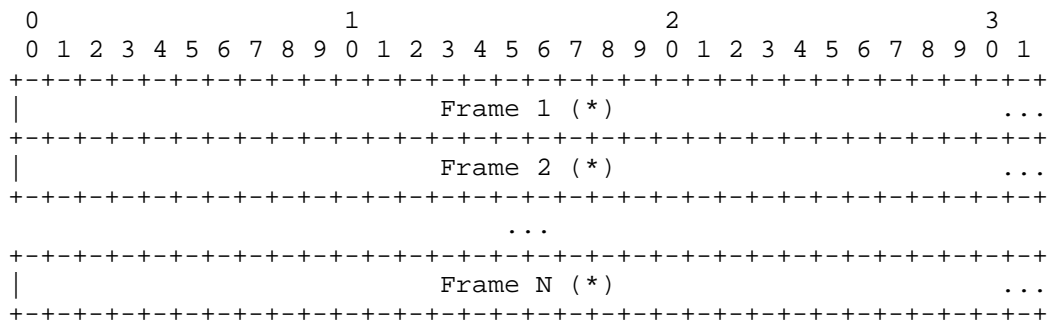


Figure 4: Contents of Encrypted Payload

Encrypted 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:

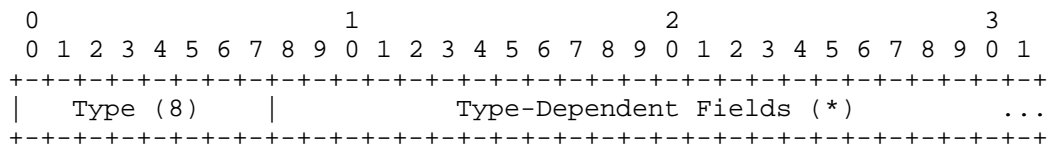


Figure 5: Generic Frame Layout

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-field value | Frame type       | Definition  |
|------------------|------------------|-------------|
| 0x00             | PADDING          | Section 8.6 |
| 0x01             | RST_STREAM       | Section 8.5 |
| 0x02             | CONNECTION_CLOSE | Section 8.8 |
| 0x03             | GOAWAY           | Section 8.9 |
| 0x04             | WINDOW_UPDATE    | Section 8.3 |
| 0x05             | BLOCKED          | Section 8.4 |
| 0x07             | PING             | Section 8.7 |
| 0x40 - 0x7f      | ACK              | Section 8.2 |
| 0x80 - 0xff      | STREAM           | Section 8.1 |

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 7.2. 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 7.5. Finally a connection may be terminated by either endpoint, as described in Section 7.6.

### 7.1. 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 a handshake packet. The details of the handshake mechanisms are described in Section 7.2, but all of the initial packets sent from the client to the server MUST use the long header format and MUST specify the version of the protocol being used.

When the server receives a packet from a client with the long header format, it compares the client's version to the versions it supports.

If the version selected by the client is not acceptable to the server, the server discards the incoming packet and responds with a Version Negotiation packet (Section 5.3). This includes a list of versions that the server will accept. A server **MUST** send a Version Negotiation packet for every packet that it receives with an unacceptable version.

If the packet contains a version that is acceptable to the server, the server proceeds with the handshake (Section 7.2). This commits the server to the version that the client selected.

When the client receives a Version Negotiation packet from the server, it should select an acceptable protocol version. If the server lists an acceptable version, the client selects that version and reattempts to create a connection using that version. Though the contents of a packet 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** ignore Version Negotiation packets on the same connection.

Version negotiation uses unprotected data. The result of the negotiation **MUST** be revalidated as part of the cryptographic handshake (see Section 7.3.4).

#### 7.1.1. 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. However, when the server generates a Version Negotiation packet, it cannot randomly generate a reserved version number. This is because

the server is required to include the same value in its transport parameters (see Section 7.3.4). To avoid the selected version number changing during connection establishment, the reserved version SHOULD be generated as a function of values that will be available to the server when later generating its handshake packets.

A pseudorandom function that takes client address information (IP and port) and the client selected version as input would ensure that there is sufficient variability in the values that a server uses.

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.

## 7.2. Cryptographic and Transport Handshake

QUIC relies on a combined cryptographic and transport handshake to minimize connection establishment latency. QUIC allocates stream 1 for the cryptographic handshake. This version of QUIC uses TLS 1.3 [QUIC-TLS].

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 7.3)
- o authenticated confirmation of version negotiation (see Section 7.3.4)
- 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 7.4)

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 1280 octet QUIC packet. 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].

### 7.3. 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 {
    stream_fc_offset(0),
    connection_fc_offset(1),
    concurrent_streams(2),
    idle_timeout(3),
    truncate_connection_id(4),
    (65535)
} TransportParameterId;

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

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

            case encrypted_extensions:
                QuicVersion supported_versions<2..2^8-4>;
    };
    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 7.3.4) before the connection establishment is considered properly complete.

Definitions for each of the defined transport parameters are included in Section 7.3.1.

### 7.3.1. Transport Parameter Definitions

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

`stream_fc_offset` (0x0000): The initial stream level flow control offset parameter is encoded as an unsigned 32-bit integer in units of octets. The sender of this parameter indicates that the flow control offset for all stream data sent toward it is this value.

`connection_fc_offset` (0x0001): The connection level flow control offset parameter contains the initial connection flow control window encoded as an unsigned 32-bit integer in units of 1024 octets. That is, the value here is multiplied by 1024 to determine the actual flow control offset. The sender of this parameter sets the byte offset for connection level flow control to this value. This is equivalent to sending a `WINDOW_UPDATE` (Section 8.3) for the connection immediately after completing the handshake.

`concurrent_streams` (0x0002): The maximum number of concurrent streams parameter is encoded as an unsigned 32-bit integer.

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

An endpoint **MAY** use the following transport parameters:

`truncate_connection_id` (0x0004): The truncated connection identifier parameter indicates that packets sent to the peer can omit the connection ID. This can be used by an endpoint where the 5-tuple is sufficient to identify a connection. This parameter is zero length. Omitting the parameter indicates that the endpoint relies on the connection ID being present in every packet.

### 7.3.2. Values of Transport Parameters for 0-RTT

Transport parameters from the server **SHOULD** be remembered by the client for use with 0-RTT data. A client that doesn't remember values from a previous connection can instead assume the following values: `stream_fc_offset` (65535), `connection_fc_offset` (65535), `concurrent_streams` (10), `idle_timeout` (600), `truncate_connection_id` (absent).

If assumed values change as a result of completing the handshake, the client is expected to respect the new values. This introduces some



potential problems, particularly with respect to transport parameters that establish limits:

- o A client might exceed a newly declared connection or stream flow control limit with 0-RTT data. If this occurs, the client ceases transmission as though the flow control limit was reached. Once WINDOW\_UPDATE frames indicating an increase to the affected flow control offsets is received, the client can recommence sending.
- o Similarly, a client might exceed the concurrent stream limit declared by the server. A client MUST reset any streams that exceed this limit. A server SHOULD reset any streams it cannot handle with a code that allows the client to retry any application action bound to those streams.

A server MAY close a connection if remembered or assumed 0-RTT transport parameters cannot be supported, using an error code that is appropriate to the specific condition. For example, a QUIC\_FLOW\_CONTROL\_RECEIVED\_TOO\_MUCH\_DATA might be used to indicate that exceeding flow control limits caused the error. A client that has a connection closed due to an error condition SHOULD NOT attempt 0-RTT when attempting to create a new connection.

#### 7.3.3. 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.

The definition of a transport parameter SHOULD include a default value that a client can use when establishing a new connection. If no default is specified, the value can be assumed to be absent when attempting 0-RTT.

New transport parameters can be registered according to the rules in Section 14.1.

#### 7.3.4. Version Negotiation Validation

The transport parameters include three fields that encode version information. These retroactively authenticate the version negotiation (see Section 7.1) that is performed prior to the cryptographic handshake.

The cryptographic handshake provides integrity protection for the negotiated version as part of the transport parameters (see

Section 7.3). As a result, modification of version negotiation packets by an attacker can be detected.

The client includes two fields in the transport parameters:

- o The `negotiated_version` is the version that was finally selected for use. This MUST be identical to the value that is on the packet that carries the ClientHello. A server that receives a `negotiated_version` that does not match the version of QUIC that is in use MUST terminate the connection with a `QUIC_VERSION_NEGOTIATION_MISMATCH` error code.
- o 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`.

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 and negotiated versions are the same, a stateless server can accept the value.

If the initial version is different from the `negotiated_version`, 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 value of `negotiated_version`, the server MUST terminate the connection with a `QUIC_VERSION_NEGOTIATION_MISMATCH` error.

The server includes a list of versions that it would send in any version negotiation packet (Section 5.3) in `supported_versions`. This value is set even if it did not send a version negotiation packet.

The client can validate 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 `QUIC_VERSION_NEGOTIATION_MISMATCH` error code if the `negotiated_version` value is not included in the `supported_versions` list. A client MUST terminate with a `QUIC_VERSION_NEGOTIATION_MISMATCH` error code if version negotiation occurred but it would have selected a different version based on the value of the `supported_versions` list.

#### 7.4. 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 from a client is padded to at least 1280 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.

##### 7.4.1. 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 7.4.3), 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.

#### 7.4.2. 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 7.5). 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.

#### 7.4.3. 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 `QUIC_ADDRESS_VALIDATION_FAILURE` error code.

#### 7.5. 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. QUIC also provides automatic cryptographic verification of a client which has changed its IP address because the client continues to use the same session key for encrypting and decrypting packets.

DISCUSS: Simultaneous migration. Is this reasonable?

TODO: Perhaps move mitigation techniques from Security Considerations here.

## 7.6. 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:

1. **Explicit Shutdown:** An endpoint sends a `CONNECTION_CLOSE` frame to initiate a connection termination. An endpoint may send a `GOAWAY` frame to the peer prior to a `CONNECTION_CLOSE` to indicate that the connection will soon be terminated. A `GOAWAY` frame signals to the peer that any active streams will continue to be processed, but the sender of the `GOAWAY` will not initiate any additional streams and will not accept any new incoming streams. On termination of the active streams, a `CONNECTION_CLOSE` may be sent. If an endpoint sends a `CONNECTION_CLOSE` frame while unterminated streams are active (no `FIN` bit or `RST_STREAM` frames have been sent or received for one or more streams), then the peer must assume that the streams were incomplete and were abnormally terminated.
2. **Implicit Shutdown:** The default idle timeout for a QUIC connection is 30 seconds, and is a required parameter in connection negotiation. The maximum is 10 minutes. If there is no network activity for the duration of the idle timeout, the connection is closed. By default a `CONNECTION_CLOSE` frame will be sent. A silent close option can be enabled when it is expensive to send an explicit close, such as mobile networks that must wake up the radio.
3. **Abrupt Shutdown:** An endpoint may send a Public Reset packet at any time during the connection to abruptly terminate an active connection. A Public Reset packet **SHOULD** only be used as a final recourse. Commonly, a public reset is expected to be sent when a packet on an established connection is received by an endpoint that is unable to decrypt the packet. For instance, if a server reboots mid-connection and loses any cryptographic state associated with open connections, and then receives a packet on an open connection, it should send a Public Reset packet in return. (TODO: articulate rules around when a public reset should be sent.)

TODO: Connections that are terminated are added to a `TIME_WAIT` list at the server, so as to absorb any straggler packets in the network. Discuss `TIME_WAIT` list.

## 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. STREAM Frame

STREAM frames implicitly create a stream and carry stream data. The type byte for a STREAM frame contains embedded flags, and is formatted as "1FDOOOSS". These bits are parsed as follows:

- o The leftmost bit must be set to 1, indicating that this is a STREAM frame.
- o "F" is the FIN bit, which is used for stream termination.
- o The "D" bit indicates whether a Data Length field is present in the STREAM header. When set to 0, this field indicates that the Stream Data field extends to the end of the packet. When set to 1, this field indicates that Data Length field contains the length (in bytes) of the Stream Data field. The option to omit the length should only be used when the packet is a "full-sized" packet, to avoid the risk of corruption via padding.
- o The "OOO" bits encode the length of the Offset header field as 0, 16, 24, 32, 40, 48, 56, or 64 bits long.
- o The "SS" bits encode the length of the Stream ID header field as 8, 16, 24, or 32 bits. (DISCUSS: Consider making this 8, 16, 32, 64.)

A STREAM frame is shown below.

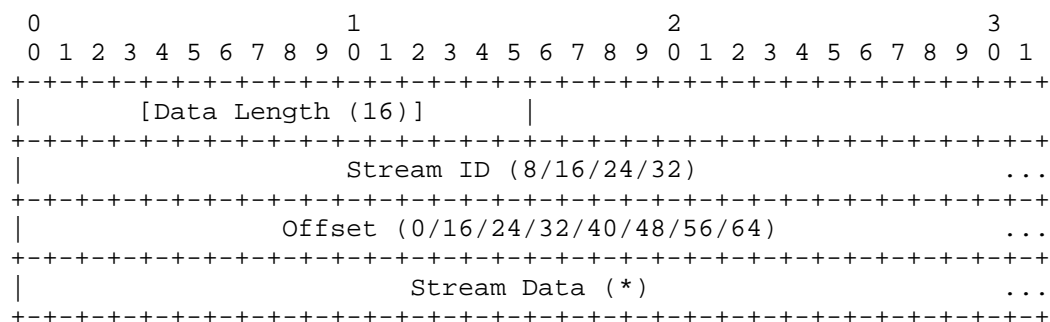


Figure 7: STREAM Frame Format

The STREAM frame contains the following fields:

**Data Length:** An optional 16-bit unsigned number specifying the length of the Stream Data field in this STREAM frame. This field is present when the "D" bit is set to 1.

**Stream ID:** A variable-sized unsigned ID unique to this stream.

**Offset:** A variable-sized unsigned number specifying the byte offset in the stream for the data in this STREAM frame. 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  $2^{64}$ .

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

A STREAM frame MUST have either non-zero data length or the FIN bit set.

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

## 8.2. ACK Frame

Receivers send ACK frames to inform senders which packets they have received and processed, as well as which packets are considered missing. The ACK frame contains between 1 and 256 ACK blocks. ACK blocks are ranges of acknowledged packets.

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. To handle cases where the receiver is only sending ACK frames, and hence will not receive acknowledgments for its packets, it MAY send a PING frame at most once per RTT to explicitly request 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.

Unlike TCP SACKs, QUIC ACK blocks are cumulative and therefore irrevocable. Once a packet has been acknowledged, even if it does not appear in a future ACK frame, it is assumed to be acknowledged.

QUIC ACK frames contain a timestamp section with up to 255 timestamps. Timestamps enable better congestion control, but are not required for correct loss recovery, and old timestamps are less valuable, so it is not guaranteed every timestamp will be received by the sender. A receiver SHOULD send a timestamp exactly once for each received packet containing retransmittable frames. A receiver MAY send timestamps for non-retransmittable packets.

A sender MAY intentionally skip packet numbers to introduce entropy into the connection, to avoid opportunistic acknowledgement attacks. The sender MUST close the connection if an unsent packet number is acknowledged. The format of the ACK frame is efficient at expressing blocks of missing packets; skipping packet numbers between 1 and 255 effectively provides up to 8 bits of efficient entropy on demand, which should be adequate protection against most opportunistic acknowledgement attacks.

The type byte for a ACK frame contains embedded flags, and is formatted as "01NULLMM". These bits are parsed as follows:

- o The first two bits must be set to 01 indicating that this is an ACK frame.
- o The "N" bit indicates whether the frame has more than 1 range of acknowledged packets (i.e., whether the ACK Block Section contains a Num Blocks field).
- o The "U" bit is unused and MUST be set to zero.
- o The two "LL" bits encode the length of the Largest Acknowledged field as 1, 2, 4, or 6 bytes long.
- o The two "MM" bits encode the length of the ACK Block Length fields as 1, 2, 4, or 6 bytes long.

An ACK frame is shown below.

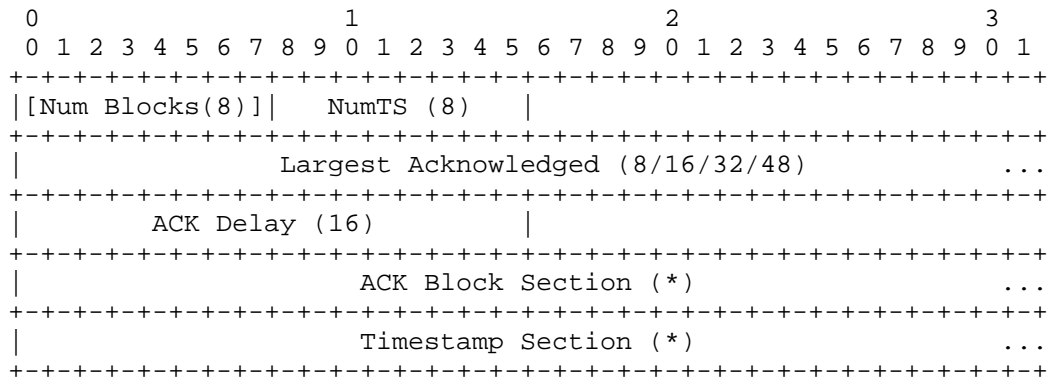


Figure 8: ACK Frame Format

The fields in the ACK frame are as follows:

**Num Blocks (opt):** An optional 8-bit unsigned value specifying the number of additional ACK blocks (besides the required First ACK Block) in this ACK frame. Only present if the 'N' flag bit is 1.

**Num Timestamps:** An unsigned 8-bit number specifying the total number of <packet number, timestamp> pairs in the Timestamp Section.

**Largest Acknowledged:** A variable-sized unsigned value representing the largest packet number the peer is acknowledging in this packet (typically the largest that the peer has seen thus far.)

**ACK Delay:** The time from when the largest acknowledged packet, as indicated in the Largest Acknowledged field, was received by this peer to when this ACK was sent.

**ACK Block Section:** Contains one or more blocks of packet numbers which have been successfully received, see Section 8.2.1.

**Timestamp Section:** Contains zero or more timestamps reporting transit delay of received packets. See Section 8.2.2.

#### 8.2.1. ACK Block Section

The ACK Block Section contains between one and 256 blocks of packet numbers which have been successfully received. If the Num Blocks field is absent, only the First ACK Block length is present in this section. Otherwise, the Num Blocks field indicates how many additional blocks follow the First ACK Block Length field.

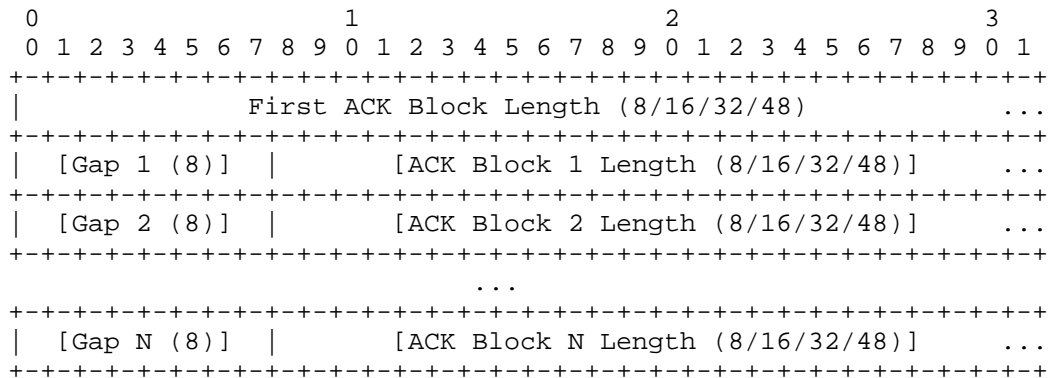


Figure 9: ACK Block Section

The fields in the ACK Block Section are:

**First ACK Block Length:** An unsigned packet number delta that indicates the number of contiguous additional packets being acknowledged starting at the Largest Acknowledged.

**Gap To Next Block (opt, repeated):** An unsigned number specifying the number of contiguous missing packets from the end of the previous ACK block to the start of the next. Repeated "Num Blocks" times.

**ACK Block Length (opt, repeated):** An unsigned packet number delta that indicates the number of contiguous packets being acknowledged starting after the end of the previous gap. Repeated "Num Blocks" times.

#### 8.2.2. Timestamp Section

The Timestamp Section contains between zero and 255 measurements of packet receive times relative to the beginning of the connection.

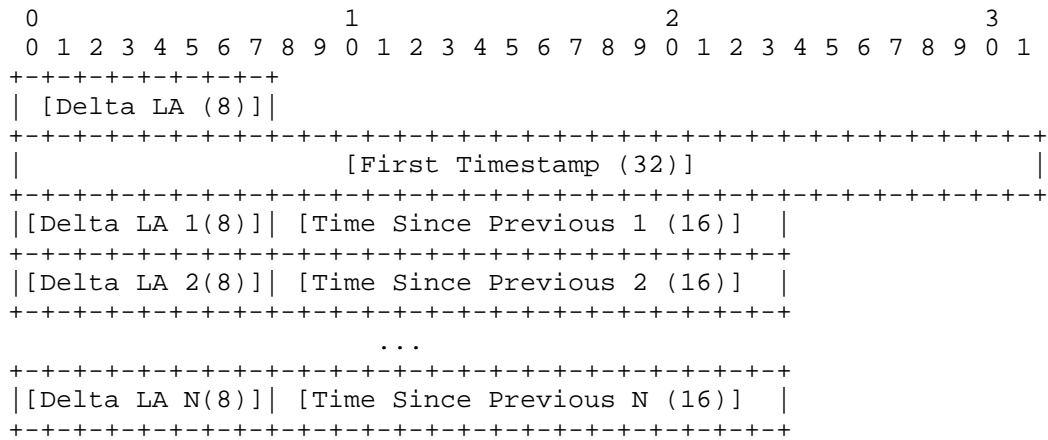


Figure 10: Timestamp Section

The fields in the Timestamp Section are:

**Delta Largest Acknowledged (opt):** An optional 8-bit unsigned packet number delta specifying the delta between the largest acknowledged and the first packet whose timestamp is being reported. In other words, this first packet number may be computed as (Largest Acknowledged - Delta Largest Acknowledged.)

**First Timestamp (opt):** An optional 32-bit unsigned value specifying the time delta in microseconds, from the beginning of the connection to the arrival of the packet indicated by Delta Largest Acknowledged.

**Delta Largest Aced 1..N (opt, repeated):** This field has the same semantics and format as "Delta Largest Acknowledged". Repeated "Num Timestamps - 1" times.

**Time Since Previous Timestamp 1..N(opt, repeated):** An optional 16-bit unsigned value specifying time delta from the previous reported timestamp. It is encoded in the same format as the ACK Delay. Repeated "Num Timestamps - 1" times.

The timestamp section lists packet receipt timestamps ordered by timestamp.

#### 8.2.2.1. Time Format

DISCUSS\_AND\_REPLACE: Perhaps make this format simpler.

The time format used in the ACK frame above is a 16-bit unsigned float with 11 explicit bits of mantissa and 5 bits of explicit exponent, specifying time in microseconds. The bit format is loosely modeled after IEEE 754. For example, 1 microsecond is represented as 0x1, which has an exponent of zero, presented in the 5 high order bits, and mantissa of 1, presented in the 11 low order bits. When the explicit exponent is greater than zero, an implicit high-order 12th bit of 1 is assumed in the mantissa. For example, a floating value of 0x800 has an explicit exponent of 1, as well as an explicit mantissa of 0, but then has an effective mantissa of 4096 (12th bit is assumed to be 1). Additionally, the actual exponent is one-less than the explicit exponent, and the value represents 4096 microseconds. Any values larger than the representable range are clamped to 0xFFFF.

#### 8.2.3. 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.

### 8.3. WINDOW\_UPDATE Frame

The WINDOW\_UPDATE frame (type=0x04) informs the peer of an increase in an endpoint's flow control receive window for either a single stream, or the entire 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
+-----+-----+-----+-----+-----+-----+-----+-----+
|                               Stream ID (32)                               |
+-----+-----+-----+-----+-----+-----+-----+-----+
|                               Flow Control Offset (64)                               |
+-----+-----+-----+-----+-----+-----+-----+-----+

```

The fields in the WINDOW\_UPDATE frame are as follows:

**Stream ID:** ID of the stream whose flow control windows is being updated, or 0 to specify the connection-level flow control window.

**Flow Control Offset:** A 64-bit unsigned integer indicating the flow control offset for the given stream (for a stream ID other than 0) or the entire connection.

The flow control offset is expressed in units of octets for individual streams (for stream identifiers other than 0).

The connection-level flow control offset is expressed in units of 1024 octets (for a stream identifier of 0). That is, the connection-level flow control offset is determined by multiplying the encoded value by 1024.

An endpoint accounts for the maximum offset of data that is sent or received on a stream. Loss or reordering can mean that the maximum offset is greater than the total size of data received on a stream. Similarly, receiving STREAM frames might not increase the maximum offset on a stream. A STREAM frame with a FIN bit set or RST\_STREAM causes the final offset for a stream to be fixed.

The maximum data offset on a stream MUST NOT exceed the stream flow control offset advertised by the receiver. The sum of the maximum data offsets of all streams (including closed streams) MUST NOT exceed the connection flow control offset advertised by the receiver. An endpoint MUST terminate a connection with a QUIC\_FLOW\_CONTROL\_RECEIVED\_TOO\_MUCH\_DATA error if it receives more data than the largest flow control offset that it has sent, unless this is a result of a change in the initial offsets (see Section 7.3.2).

#### 8.4. BLOCKED Frame

A sender sends a BLOCKED frame (type=0x05) when it is ready to send data (and has data to send), but is currently flow control blocked. BLOCKED frames are purely informational frames, but extremely useful for debugging purposes. A receiver of a BLOCKED frame should simply discard it (after possibly printing a helpful log message). 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 (32)                               |
+-----+-----+-----+-----+-----+-----+-----+-----+

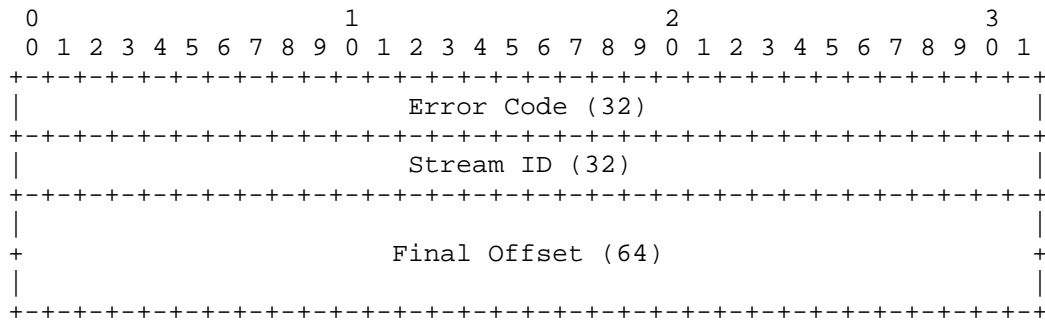
```

The BLOCKED frame contains a single field:

**Stream ID:** A 32-bit unsigned number indicating the stream which is flow control blocked. A non-zero Stream ID field specifies the stream that is flow control blocked. When zero, the Stream ID field indicates that the connection is flow control blocked.

#### 8.5. RST\_STREAM Frame

An endpoint may use a RST\_STREAM frame (type=0x01) to abruptly terminate a stream. The frame is as follows:



The fields are:

Error code: A 32-bit error code which indicates why the stream is being closed.

Stream ID: The 32-bit Stream ID of the stream being terminated.

Final offset: A 64-bit unsigned integer indicating the absolute byte offset of the end of data written on this stream by the RST\_STREAM sender.

#### 8.6. 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.

#### 8.7. PING frame

Endpoints can use PING frames (type=0x07) to verify that their peers are still alive or to check reachability to the peer. The PING frame contains no additional fields. The receiver of a PING frame simply needs to acknowledge the packet containing this frame. The PING frame SHOULD be used to keep a connection alive when a stream is open. The default is to send a PING frame after 15 seconds of quiescence. A PING frame has no additional fields.

#### 8.8. CONNECTION\_CLOSE frame

An endpoint sends a CONNECTION\_CLOSE frame (type=0x02) to notify its peer that the connection is being closed. If there are open streams that haven't been explicitly closed, they are implicitly closed when



the connection is closed. (Ideally, a GOAWAY frame would be sent with enough time that all streams are torn down.) 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
+-----+-----+-----+-----+-----+-----+-----+-----+
|                                     Error Code (32)                                     |
+-----+-----+-----+-----+-----+-----+-----+-----+
| Reason Phrase Length (16) | [Reason Phrase (*)] | ... |
+-----+-----+-----+-----+-----+-----+-----+-----+

```

The fields of a CONNECTION\_CLOSE frame are as follows:

**Error Code:** A 32-bit error code which indicates the reason for closing this connection.

**Reason Phrase Length:** A 16-bit unsigned number specifying the length of the reason phrase. This may be zero if the sender chooses to not give details beyond the Error Code.

**Reason Phrase:** An optional human-readable explanation for why the connection was closed.

## 8.9. GOAWAY Frame

An endpoint uses a GOAWAY frame (type=0x03) to initiate a graceful shutdown of a connection. The endpoints will continue to use any active streams, but the sender of the GOAWAY will not initiate or accept any additional streams beyond those indicated. The GOAWAY 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
+-----+-----+-----+-----+-----+-----+-----+-----+
|                                     Largest Client Stream ID (32)                                     |
+-----+-----+-----+-----+-----+-----+-----+-----+
|                                     Largest Server Stream ID (32)                                     |
+-----+-----+-----+-----+-----+-----+-----+-----+

```

The fields of a GOAWAY frame are:

**Largest Client Stream ID:** The highest-numbered, client-initiated stream on which the endpoint sending the GOAWAY frame either sent data, or received and delivered data. All higher-numbered, client-initiated streams (that is, odd-numbered streams) are implicitly reset by sending or receiving the GOAWAY frame.

**Largest Server Stream ID:** The highest-numbered, server-initiated stream on which the endpoint sending the GOAWAY frame either sent data, or received and delivered data. All higher-numbered, server-initiated streams (that is, even-numbered streams) are implicitly reset by sending or receiving the GOAWAY frame.

A GOAWAY frame indicates that any application layer actions on streams with higher numbers than those indicated can be safely retried because no data was exchanged. An endpoint **MUST** set the value of the Largest Client or Server Stream ID to be at least as high as the highest-numbered stream on which it either sent data or received and delivered data to the application protocol that uses QUIC.

An endpoint **MAY** choose a larger stream identifier if it wishes to allow for a number of streams to be created. This is especially valuable for peer-initiated streams where packets creating new streams could be in transit; using a larger stream number allows those streams to complete.

In addition to initiating a graceful shutdown of a connection, GOAWAY **MAY** be sent immediately prior to sending a CONNECTION\_CLOSE frame that is sent as a result of detecting a fatal error. Higher-numbered streams than those indicated in the GOAWAY frame can then be retried.

## 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 public header, encrypted 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 ([RFC4821]) and **MAY** use PMTU Discovery ([RFC1191], [RFC1981]) 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 UDP payload length 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 total size (including IP and UDP headers) of at least 1280 bytes. This might require inclusion of PADDING frames. It is **RECOMMENDED** that a packet be padded to exactly 1280 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 mitigate amplification attacks caused by server responses toward an unverified client address.

Servers **MUST** reject the first plaintext packet received from a client if its total size is less than 1280 octets, to mitigate amplification attacks.

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 between those IP addresses. This may result in abrupt termination of the connection if all pairs are affected. In this case, an endpoint **SHOULD** send a Public Reset packet to indicate the failure. The application **SHOULD** attempt to use TLS over TCP instead.

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 are cumulative, so new frames containing updated information will be sent as described in Section 8.2.
- 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 generate an ACK frame in response to a packet containing only ACK or PADDING frames.

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, and bidirectional byte-stream abstraction modeled closely on HTTP/2 streams [RFC7540].

Streams can be created either by the client or the server, 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.

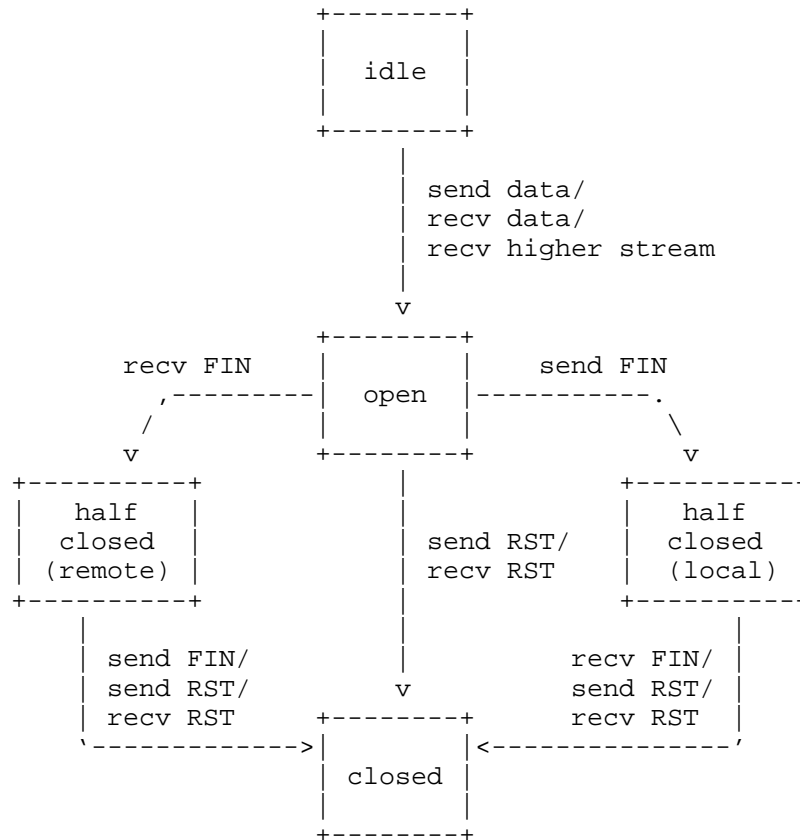
Streams are individually flow controlled, allowing an endpoint to limit memory commitment and to apply back pressure.

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. Life of a Stream

The semantics of QUIC streams is based on HTTP/2 streams, and the lifecycle of a QUIC stream therefore closely follows that of an HTTP/2 stream [RFC7540], with some differences to accommodate the possibility of out-of-order delivery due to the use of multiple

streams in QUIC. The lifecycle of a QUIC stream is shown in the following figure and described below.



send: endpoint sends this frame  
recv: endpoint receives this frame

data: application data in a STREAM frame  
FIN: FIN flag in a STREAM frame  
RST: RST\_STREAM frame

Figure 11: Lifecycle of a stream

Note that this diagram shows stream state transitions and the frames and flags that affect those transitions only. For the purpose of state transitions, the FIN flag is processed as a separate event to the frame that bears it; a STREAM frame with the FIN flag set can cause two state transitions. When the FIN flag is sent on an empty

STREAM frame, the offset in the STREAM frame MUST be one greater than the last data byte sent on this stream.

The recipient of a frame which changes stream state will have a delayed view of the state of a stream while the frame is in transit. Endpoints do not coordinate the creation of streams; they are created unilaterally by either endpoint. The negative consequences of a mismatch in states are limited to the "closed" state after sending RST\_STREAM, where frames might be received for some time after closing. Endpoints can use acknowledgments to understand the peer's subjective view of stream state at any given time.

Streams have the following states:

#### 10.1.1.1. idle

All streams start in the "idle" state.

The following transitions are valid from this state:

Sending or receiving a STREAM frame causes the stream to become "open". The stream identifier is selected as described in Section 10.2. The same STREAM frame can also cause a stream to immediately become "half-closed".

Receiving a STREAM frame on a peer-initiated stream (that is, a packet sent by a server on an even-numbered stream or a client packet on an odd-numbered stream) also causes all lower-numbered "idle" streams in the same direction to become "open". This could occur if a peer begins sending on streams in a different order to their creation, or it could happen if packets are lost or reordered in transit.

Receiving any frame other than STREAM or RST\_STREAM on a stream in this state MUST be treated as a connection error (Section 12) of type YYY.

#### 10.1.1.2. open

A stream in the "open" state may be used by both peers to send frames of any type. In this state, a sending peer must observe the flow-control limit advertised by its receiving peer (Section 11).

From this state, either endpoint can send a frame with the FIN flag set, which causes the stream to transition into one of the "half-closed" states. An endpoint sending an FIN flag causes the stream state to become "half-closed (local)". An endpoint receiving a FIN flag causes the stream state to become "half-closed (remote)" once

all preceding data has arrived. The receiving endpoint MUST NOT consider the stream state to have changed until all data has arrived.

Either endpoint can send a RST\_STREAM frame from this state, causing it to transition immediately to "closed".

#### 10.1.3. half-closed (local)

A stream that is in the "half-closed (local)" state MUST NOT be used for sending STREAM frames; WINDOW\_UPDATE and RST\_STREAM MAY be sent in this state.

A stream transitions from this state to "closed" when a STREAM frame that contains a FIN flag is received and all prior data has arrived, or when either peer sends a RST\_STREAM frame.

An endpoint that closes a stream MUST NOT send data beyond the final offset that it has chosen, see Section 10.1.5 for details.

An endpoint can receive any type of frame in this state. Providing flow-control credit using WINDOW\_UPDATE frames is necessary to continue receiving flow-controlled frames. In this state, a receiver MAY ignore WINDOW\_UPDATE frames for this stream, which might arrive for a short period after a frame bearing the FIN flag is sent.

#### 10.1.4. half-closed (remote)

A stream that is "half-closed (remote)" is no longer being used by the peer to send any data. In this state, a sender is no longer obligated to maintain a receiver stream-level flow-control window.

A stream that is in the "half-closed (remote)" state will have a final offset for received data, see Section 10.1.5 for details.

A stream in this state can be used by the endpoint to send frames of any type. In this state, the endpoint continues to observe advertised stream-level and connection-level flow-control limits (Section 11).

A stream can transition from this state to "closed" by sending a frame that contains a FIN flag or when either peer sends a RST\_STREAM frame.

#### 10.1.5. closed

The "closed" state is the terminal state.



An endpoint will learn the final offset of the data it receives on a stream when it enters the "half-closed (remote)" or "closed" state. The final offset is carried explicitly in the RST\_STREAM frame; otherwise, the final offset is the offset of the end of the data carried in STREAM frame marked with a FIN flag.

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 QUIC\_STREAM\_DATA\_AFTER\_TERMINATION error (see Section 12). A receiver SHOULD treat receipt of data at or beyond the final offset as a QUIC\_STREAM\_DATA\_AFTER\_TERMINATION error. 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.

An endpoint that receives a RST\_STREAM frame (and which has not sent a FIN or a RST\_STREAM) MUST immediately respond with a RST\_STREAM frame, and MUST NOT send any more data on the stream. This endpoint may continue receiving frames for the stream on which a RST\_STREAM is received.

If this state is reached as a result of sending a RST\_STREAM frame, the peer that receives the RST\_STREAM frame might have already sent - or enqueued for sending - frames on the stream that cannot be withdrawn. An endpoint MUST ignore frames that it receives on closed streams after it has sent a RST\_STREAM frame. An endpoint MAY choose to limit the period over which it ignores frames and treat frames that arrive after this time as being in error.

STREAM frames received after sending RST\_STREAM are counted toward the connection and stream flow-control windows. Even though these frames might be ignored, because they are sent before their sender receives the RST\_STREAM, the sender will consider the frames to count against its flow-control windows.

In the absence of more specific guidance elsewhere in this document, implementations SHOULD treat the receipt of a frame that is not expressly permitted in the description of a state as a connection error (Section 12). Frames of unknown types are ignored.

(TODO: QUIC\_STREAM\_NO\_ERROR is a special case. Write it up.)

## 10.2. Stream Identifiers

Streams are identified by an unsigned 32-bit integer, referred to as the StreamID. To avoid StreamID collision, clients MUST initiate streams using odd-numbered StreamIDs; streams initiated by the server MUST use even-numbered StreamIDs.

A StreamID of zero (0x0) is reserved and used for connection-level flow control frames (Section 11); the StreamID of zero cannot be used to establish a new stream.

StreamID 1 (0x1) is reserved for the cryptographic handshake. StreamID 1 MUST NOT be used for application data, and MUST be the first client-initiated stream.

A QUIC endpoint cannot reuse a StreamID on a given connection. Streams MUST be created in sequential order. Open streams can be used in any order. Streams that are used out of order result in lower-numbered streams in the same direction being counted as open.

All streams, including stream 1, count toward this limit. Thus, a concurrent stream limit of 0 will cause a connection to be unusable. Application protocols that use QUIC might require a certain minimum number of streams to function correctly. If a peer advertises a concurrent stream limit (concurrent\_streams) that is too small for the selected application protocol to function, an endpoint MUST terminate the connection with an error of type QUIC\_TOO\_MANY\_OPEN\_STREAMS (Section 12).

## 10.3. Stream Concurrency

An endpoint limits the number of concurrently active incoming streams by setting the concurrent stream limit (see Section 7.3.1) in the transport parameters. The maximum concurrent streams setting is specific to each endpoint and applies only to the peer that receives the setting. That is, clients specify the maximum number of concurrent streams the server can initiate, and servers specify the maximum number of concurrent streams the client can initiate.

Streams that are in the "open" state or in either of the "half-closed" states count toward the maximum number of streams that an endpoint is permitted to open. Streams in any of these three states count toward the limit advertised in the concurrent stream limit.

A recently closed stream MUST also be considered to count toward this limit until packets containing all frames required to close the stream have been acknowledged. For a stream which closed cleanly, this means all STREAM frames have been acknowledged; for a stream

which closed abruptly, this means the RST\_STREAM frame has been acknowledged.

Endpoints MUST NOT exceed the limit set by their peer. An endpoint that receives a STREAM frame that causes its advertised concurrent stream limit to be exceeded MUST treat this as a stream error of type QUIC\_TOO\_MANY\_OPEN\_STREAMS (Section 12).

#### 10.4. 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  $2^{64}$ . 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.

The cryptographic handshake stream, Stream 1, MUST NOT be subject to congestion control or connection-level flow control, but MUST be subject to stream-level flow control. An endpoint MUST NOT send data on any other stream without consulting the congestion controller and the flow controller.

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

#### 10.5. 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 [RFC7540], 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 1 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 frames 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 [RFC7540]. 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 receiver sends WINDOW\_UPDATE frames to the sender to advertise additional credit by sending the absolute byte offset in the stream or in the connection which it is willing to receive.

The initial flow control credit is 65536 bytes for both the stream and connection flow controllers.

A receiver MAY advertise a larger offset at any point in the connection by sending a WINDOW\_UPDATE frame. A receiver MUST NOT renege on an advertisement; that is, once a receiver advertises an offset via a WINDOW\_UPDATE frame, it MUST NOT subsequently advertise a smaller offset. A sender may receive WINDOW\_UPDATE frames out of order; a sender MUST therefore ignore any WINDOW\_UPDATE that does not move the window forward.

A receiver MUST close the connection with a QUIC\_FLOW\_CONTROL\_RECEIVED\_TOO\_MUCH\_DATA error (Section 12) if the peer violates the advertised stream or connection flow control windows.

A sender MUST send BLOCKED frames to indicate it has data to write but is blocked by lack of connection or stream flow control credit. BLOCKED 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 WINDOW\_UPDATE frame with the StreamID set appropriately. A receiver may use the current offset of data consumed to determine the flow control offset to be advertised. A receiver MAY send copies of a WINDOW\_UPDATE frame in multiple packets in order to make sure that the sender receives it 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 contributing to connection flow control. A receiver advertises credit for a connection by sending a WINDOW\_UPDATE frame with the StreamID set to zero (0x00). A receiver maintains a cumulative sum of bytes received on all streams contributing to connection-level flow control, to check for flow control violations. A receiver may maintain a cumulative sum of bytes consumed on all contributing streams to determine the connection-level flow control offset 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 WINDOW\_UPDATE which will never come.

#### 11.1.1. Mid-stream RST\_STREAM

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.

#### 11.1.2. Response to a RST\_STREAM

Since streams are bidirectional, a sender of a RST\_STREAM needs to know how many bytes the peer has sent on the stream. If an endpoint receives a RST\_STREAM frame and has sent neither a FIN nor a RST\_STREAM, it MUST send a RST\_STREAM in response, bearing the offset of the last byte sent on this stream as the final offset.

#### 11.1.3. Offset Increment

This document leaves when and how many bytes to advertise in a WINDOW\_UPDATE to the implementation, but offers a few considerations. WINDOW\_UPDATE frames constitute overhead, and therefore, sending a WINDOW\_UPDATE with small offset increments is undesirable. At the same time, sending WINDOW\_UPDATES with large offset increments requires the sender to commit to that amount of buffer.

Implementations must find the correct tradeoff between these sides to determine how large an offset increment to send in a WINDOW\_UPDATE.

A receiver MAY use an autotuning mechanism to tune the size of the offset increment to advertise based on a roundtrip time estimate and the rate at which the receiving application consumes data, similar to common TCP implementations.

#### 11.1.4. BLOCKED frames

If a sender does not receive a WINDOW\_UPDATE frame when it has run out of flow control credit, the sender will be blocked and MUST send a BLOCKED frame. A BLOCKED frame is expected to be useful for debugging at the receiver. A receiver SHOULD NOT wait for a BLOCKED frame before sending a WINDOW\_UPDATE, since doing so will cause at least one roundtrip of quiescence. 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 WINDOW\_UPDATE frame at least two roundtrips before it expects the sender to get blocked.

### 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.

Public Reset is not suitable for any error that can be signaled with a CONNECTION\_CLOSE or RST\_STREAM frame. Public Reset MUST NOT be sent 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 frame (Section 8.8). An endpoint MAY close the connection in this manner, even if the error only affects a single stream.

A `CONNECTION_CLOSE` frame could be sent in a packet that is lost. An endpoint **SHOULD** be prepared to retransmit a packet containing a `CONNECTION_CLOSE` frame 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` 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 send a Public Reset packet.

## 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 8.5) with an appropriate error code to terminate just the affected stream.

Stream 1 is critical to the functioning of the entire connection. If stream 1 is closed with either a `RST_STREAM` or `STREAM` frame bearing the `FIN` flag, an endpoint **MUST** generate a connection error of type `QUIC_CLOSED_CRITICAL_STREAM`.

Some application protocols make other streams critical to that protocol. An application protocol does not need to inform the transport that a stream is critical; it can instead generate appropriate errors in response to being notified that the critical stream is closed.

An endpoint **MAY** send a `RST_STREAM` frame in the same packet as a `CONNECTION_CLOSE` frame.

## 12.3. Error Codes

Error codes are 32 bits long, with the first two bits indicating the source of the error code:

0x00000000-0x3FFFFFFF: Application-specific error codes. Defined by each application-layer protocol.

0x40000000-0x7FFFFFFF: Reserved for host-local error codes. These codes **MUST NOT** be sent to a peer, but **MAY** be used in API return codes and logs.

0x80000000-0xBFFFFFFF: QUIC transport error codes, including packet protection errors. Applicable to all uses of QUIC.



0xC0000000-0xFFFFFFFF: Cryptographic error codes. Defined by the cryptographic handshake protocol in use.

This section lists the defined QUIC transport error codes that may be used in a CONNECTION\_CLOSE or RST\_STREAM frame. Error codes share a common code space. Some error codes apply only to either streams or the entire connection and have no defined semantics in the other context.

QUIC\_INTERNAL\_ERROR (0x80000001): Connection has reached an invalid state.

QUIC\_STREAM\_DATA\_AFTER\_TERMINATION (0x80000002): There were data frames after the a fin or reset.

QUIC\_INVALID\_PACKET\_HEADER (0x80000003): Control frame is malformed.

QUIC\_INVALID\_FRAME\_DATA (0x80000004): Frame data is malformed.

QUIC\_MULTIPLE\_TERMINATION\_OFFSETS (0x80000005): Multiple final offset values were received on the same stream

QUIC\_STREAM\_CANCELLED (0x80000006): The stream was cancelled

QUIC\_CLOSED\_CRITICAL\_STREAM (0x80000007): A stream that is critical to the protocol was closed.

QUIC\_MISSING\_PAYLOAD (0x80000030): The packet contained no payload.

QUIC\_INVALID\_STREAM\_DATA (0x8000002E): STREAM frame data is malformed.

QUIC\_UNENCRYPTED\_STREAM\_DATA (0x8000003D): Received STREAM frame data is not encrypted.

QUIC\_MAYBE\_CORRUPTED\_MEMORY (0x80000059): Received a frame which is likely the result of memory corruption.

QUIC\_INVALID\_RST\_STREAM\_DATA (0x80000006): RST\_STREAM frame data is malformed.

QUIC\_INVALID\_CONNECTION\_CLOSE\_DATA (0x80000007): CONNECTION\_CLOSE frame data is malformed.

QUIC\_INVALID\_GOAWAY\_DATA (0x80000008): GOAWAY frame data is malformed.

QUIC\_INVALID\_WINDOW\_UPDATE\_DATA (0x80000039): WINDOW\_UPDATE frame data is malformed.

QUIC\_INVALID\_BLOCKED\_DATA (0x8000003A): BLOCKED frame data is malformed.

QUIC\_INVALID\_PATH\_CLOSE\_DATA (0x8000004E): PATH\_CLOSE frame data is malformed.

QUIC\_INVALID\_ACK\_DATA (0x80000009): ACK frame data is malformed.

QUIC\_INVALID\_VERSION\_NEGOTIATION\_PACKET (0x8000000A): Version negotiation packet is malformed.

QUIC\_INVALID\_PUBLIC\_RST\_PACKET (0x8000000b): Public RST packet is malformed.

QUIC\_DECRYPTION\_FAILURE (0x8000000c): There was an error decrypting.

QUIC\_ENCRYPTION\_FAILURE (0x8000000d): There was an error encrypting.

QUIC\_PACKET\_TOO\_LARGE (0x8000000e): The packet exceeded kMaxPacketSize.

QUIC\_PEER\_GOING\_AWAY (0x80000010): The peer is going away. May be a client or server.

QUIC\_INVALID\_STREAM\_ID (0x80000011): A stream ID was invalid.

QUIC\_INVALID\_PRIORITY (0x80000031): A priority was invalid.

QUIC\_TOO\_MANY\_OPEN\_STREAMS (0x80000012): Too many streams already open.

QUIC\_TOO\_MANY\_AVAILABLE\_STREAMS (0x8000004c): The peer created too many available streams.

QUIC\_PUBLIC\_RESET (0x80000013): Received public reset for this connection.

QUIC\_INVALID\_VERSION (0x80000014): Invalid protocol version.

QUIC\_INVALID\_HEADER\_ID (0x80000016): The Header ID for a stream was too far from the previous.

QUIC\_INVALID\_NEGOTIATED\_VALUE (0x80000017): Negotiable parameter received during handshake had invalid value.

QUIC\_DECOMPRESSION\_FAILURE (0x80000018): There was an error decompressing data.

QUIC\_NETWORK\_IDLE\_TIMEOUT (0x80000019): The connection timed out due to no network activity.

QUIC\_HANDSHAKE\_TIMEOUT (0x80000043): The connection timed out waiting for the handshake to complete.

QUIC\_ERROR\_MIGRATING\_ADDRESS (0x8000001a): There was an error encountered migrating addresses.

QUIC\_ERROR\_MIGRATING\_PORT (0x80000056): There was an error encountered migrating port only.

QUIC\_EMPTY\_STREAM\_FRAME\_NO\_FIN (0x80000032): We received a STREAM\_FRAME with no data and no fin flag set.

QUIC\_FLOW\_CONTROL\_RECEIVED\_TOO\_MUCH\_DATA (0x8000003b): The peer received too much data, violating flow control.

QUIC\_FLOW\_CONTROL\_SENT\_TOO\_MUCH\_DATA (0x8000003f): The peer sent too much data, violating flow control.

QUIC\_FLOW\_CONTROL\_INVALID\_WINDOW (0x80000040): The peer received an invalid flow control window.

QUIC\_CONNECTION\_IP\_POOLED (0x8000003e): The connection has been IP pooled into an existing connection.

QUIC\_TOO\_MANY\_OUTSTANDING\_SENT\_PACKETS (0x80000044): The connection has too many outstanding sent packets.

QUIC\_TOO\_MANY\_OUTSTANDING\_RECEIVED\_PACKETS (0x80000045): The connection has too many outstanding received packets.

QUIC\_CONNECTION\_CANCELLED (0x80000046): The QUIC connection has been cancelled.

QUIC\_BAD\_PACKET\_LOSS\_RATE (0x80000047): Disabled QUIC because of high packet loss rate.

QUIC\_PUBLIC\_RESETS\_POST\_HANDSHAKE (0x80000049): Disabled QUIC because of too many PUBLIC\_RESETs post handshake.

QUIC\_TIMEOUTS\_WITH\_OPEN\_STREAMS (0x8000004a): Disabled QUIC because of too many timeouts with streams open.

QUIC\_TOO\_MANY\_RTOS (0x80000055): QUIC timed out after too many RTOs.

QUIC\_ENCRYPTION\_LEVEL\_INCORRECT (0x8000002c): A packet was received with the wrong encryption level (i.e. it should have been encrypted but was not.)

QUIC\_VERSION\_NEGOTIATION\_MISMATCH (0x80000037): This connection involved a version negotiation which appears to have been tampered with.

QUIC\_IP\_ADDRESS\_CHANGED (0x80000050): IP address changed causing connection close.

QUIC\_ADDRESS\_VALIDATION\_FAILURE (0x80000051): Client address validation failed.

QUIC\_TOO\_MANY\_FRAME\_GAPS (0x8000005d): Stream frames arrived too discontinuously so that stream sequencer buffer maintains too many gaps.

QUIC\_TOO\_MANY\_SESSIONS\_ON\_SERVER (0x80000060): Connection closed because server hit max number of sessions allowed.

### 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 encrypted with a forward-secure key,

then any acknowledgments that are received for them MUST also be forward-secure encrypted. Since the attacker will not have the forward secure key, the attacker will not be able to generate forward-secure encrypted packets with ACK frames.

## 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 [RFC5226]. Values with the first byte 0xff are reserved for Private Use [RFC5226].

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 4.

| Value  | Parameter Name         | Specification |
|--------|------------------------|---------------|
| 0x0000 | stream_fc_offset       | Section 7.3.1 |
| 0x0001 | connection_fc_offset   | Section 7.3.1 |
| 0x0002 | concurrent_streams     | Section 7.3.1 |
| 0x0003 | idle_timeout           | Section 7.3.1 |
| 0x0004 | truncate_connection_id | Section 7.3.1 |

Table 4: Initial QUIC Transport Parameters Entries

## 15. References

### 15.1. Normative References

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 Thomson, M., Ed. and S. Turner, Ed., "Using Transport Layer Security (TLS) to Secure QUIC".
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## 15.2. Informative References

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### 15.3. URIs

[1] <https://github.com/quicwg/base-drafts/wiki/QUIC-Versions>

## 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 Krasic, 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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This document has benefited immensely from various private discussions and public ones on the [quic@ietf.org](mailto:quic@ietf.org) and [proto-quic@chromium.org](mailto:proto-quic@chromium.org) mailing lists. Our thanks to all.

## 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-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 (#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 0 does not contributing 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.2. 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.3. 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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