A QUIC introduction

Release 2024

Olivier Bonaventure

Mar 13, 2024

CONTENTS:

CHAPTER

ONE

QUIC

QUIC [1] is the latest transport protocol standardized by the IETF. There are several characteristics that distinguish QUIC from other transport protocols:

- QUIC supports multiple streams like SCTP
- QUIC includes various reliability and congestion control mechanisms like TCP
- QUIC directly integrates the security features of TLS 1.3 [2] instead of simply layering TLS above the transport layer
- QUIC can also be used to carry datagrams [3]
- QUIC runs above UDP in contrast with other transport protocols such as TCP, SCTP or DCCP that run above IP

From a pure layering viewpoint, QUIC can be illustrated as shown in Fig. 1.1. It is unusual to layer a transport protocol

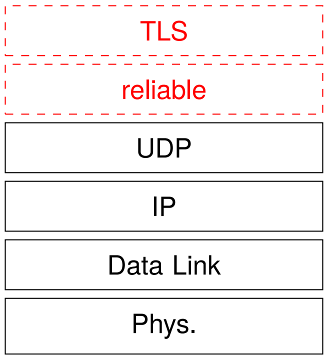


Fig. 1.1: QUIC in the TCP/IP stack

above another one. QUIC opted for this solution for two main reasons. First, on most operating systems, any application can directly use UDP without requiring special privileges. This implies that QUIC can be implemented as a library which can be included directly inside applications. This contrasts with TCP, SCTP or DCCP whose implementations are either part of the operating system kernel or need special privileges to send *raw* packets. The second motivation is that UDP (as well as TCP and ICMP) is supported by most middleboxes while many of them block transport protocols that were not defined when they were designed [4].

It is useful to note that by using UDP, QUIC slightly increases its overhead. Each QUIC packet carries 8 bytes of headers containing the source and destination ports, the length field and a checksum. UDP also comes with a performance penalty compared to TCP. During the last decades, operating system kernels have been optimized to provide high bandwidth using TCP with techniques such as TCP Segmentation Offload (TSO) and Generic Receive Offload (GRO). In parallel, the UDP implementation has not changed significantly and most of the optimizations focused on request-response services such as DNS servers. The situation has changed recently with some effort, notably on Linux, to improve UDP's raw throughput [5].

1.1 Frames and packets

There is an important difference between QUIC and classical protocols like TCP or UDP. TCP and UDP send segments that are composed of a header followed by a sequence of bytes that constitutes the payload. In contrast and like SCTP, a QUIC packet contains a header followed by one or more frames. The QUIC header is much simpler and shorter than the TCP header. It only carries the information which is required in all QUIC packets. We will describe later the short and long QUIC headers. Each QUIC header starts with one byte that contains some flags and a 32 bits version field. QUIC defines different types of frames that we will discuss in this chapter. Some types of QUIC frames carry user data. Other types of QUIC frames carry control information. Some of these frames are used during the handshake only while others such as acknowledgments can be sent at any time. Each QUIC frame is a sequence of byte that starts with a one byte Type field. Fig. 1.2 shows a QUIC packet containing two frames which is placed inside a UDP datagram. Neither the QUIC header nor the QUIC frames need to be aligned on 32 bits boundaries even if this alignment is convenient for :numref:`fig-quic-packet. An important point to note is that a QUIC packet can mix both data and control frames in any order.

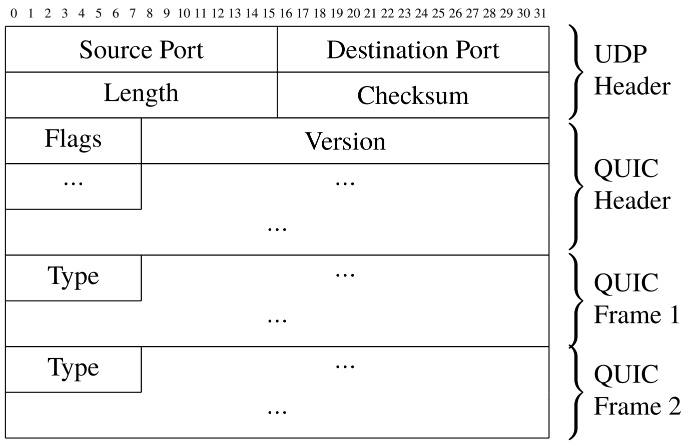


Fig. 1.2: A QUIC packet is sent inside a UDP datagram and contains one or more QUIC frames

1.2 Connection establishment

QUIC uses a four-way handshake to create a QUIC connection. Fig. 1.3 describes this handshake. The QUIC handshake has three main purposes. First, it allows to negotiate the crypto keys required to both encrypt and authenticate the packets that will be sent later on the connection. This is mainly done using TLS 1.3 [2]. Second, it allows to negotiate different options using transport parameters. Third, the server can validate that the client can respond to the address used to send the initial packet. This validation allows to prevent denial of service attacks using spoofed addresses. The client sends an `Initial` packet containing a `CRYPTO` frame. This packet carries the `TLS Client Hello` and the transport parameters proposed by the client for this connection. The server replies with an `Initial` packet containing also a `CRYPTO` frame. This one contains the `TLS Server Hello`. It is immediately followed by one or more `Handshake` packets containing also a `CRYPTO` frame with the `TLS Encrypted Extensions`. The contents of this frame is encrypted using the session key derived from the information contained in the `TLS Client Hello` and the `TLS Server Hello`. It mainly contains the certificate and the transport parameters of the server. This frame can be spread over several QUIC packets. The client replies with a `Handshake` packet that contains a `CRYPTO` frame with the `TLS Finished` message. The server later confirms the end of the TLS handshake by sending a `Handshake_Done` frame.

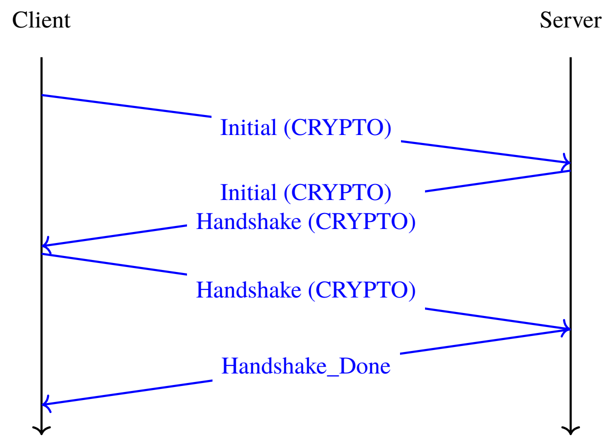


Fig. 1.3: Simplified QUIC Handshake

Before looking at the details of the negotiation of the cryptographic parameters, it is interesting to see how QUIC counters denial of service attacks that use spoofed addresses. During such attack, host x sends packets using the address of host y as their source. The main risk of such attacks is that the server could send a large number of packets towards address y although the host owning this address did not try to establish a QUIC connection with the server. QUIC prevents such attacks by using two distinct techniques. First, and this is unusual for transport protocols, the Initial QUIC packet sent by the client is large. The first packet sent to create a QUIC connection must contain a UDP payload of at least 1200 bytes [1]. Such a packet contains a CRYPTO frame has shown in the figure, but also padding frames to fill the packet. If an attacker wants to send spoofed packets to initiate a connection with a server, it needs to send more than one KByte for each connection attempt. This should be compared with the 40 bytes of the TCP and IPv4 headers that must be sent to initiate a TCP connection. Another advantage of sending a large initial packet, the client can also perform Path MTU discovery and detect routers that could fragment the QUIC packets.

Note: Address spoofing

In theory, an Internet host should only send packets using its IPv4 and IPv6 source addresses. In practice, incorrectly configured hosts can use other addresses than their assigned one. Furthermore, attackers often change their source address to hide some of their activities. A frequent situation are denial of service (DoS) attacks. A simple DoS attack is when a host sends a large volume of packets to a victim. If the attacker sends these packets using another address than its official IP address, it makes it more difficult for the victim to identify the source of the attack.

But there is another category of DoS attack that is more worrisome. If an attacker can send a packets using the source address of the victim to a server, the server would return a response to the victim. These attackers use Internet servers that send a large response, possibly using multiple packets to a single request packet. They have exploited protocols such as DNS, NTP or applications such as memcached . The main problem with such attacks is that the server amplifies the volume of the attack generated by the clients. As there are very powerful servers on the Internet, this can be a huge problem and such attacks have reached volumes of hundreds of Gbps. The IETF and network operators have published recommendations to configure access networks to block spoofed packets [6]. Unfortunately, there are still portions of the Internet where attackers can send spoofed packets [7].

The second mitigation against denial-of-service attacks using spoofed packets operates on the server. When a server receives an initial packet from a client, it may respond with an initial packet as shown in Fig. 1.3. This could for example be the case of an enterprise server that receives a request from a host of a known enterprise subnet. The server could also want to validate the client and verify that the client can receive the packets that it sends. For this, it returns a Retry frame and a Token. This token is an opaque field that is constructed in a way that makes it easy for the server to validate the subsequent client packets and difficult for the client to predict the token that a server will create. A possible approach is to compute a secure hash of a message that contains the source IP addresses and ports used by the client, a secret value only known by the server and possibly some timing information to enable the server to ignore older tokens.

Faced with the same problem, TCP *syn cookies* are encoded using fewer bits and thus inherently less secure. Fig. 1.4 shows a QUIC handshake that includes a validation of the client address. Address validation improves the resilience of

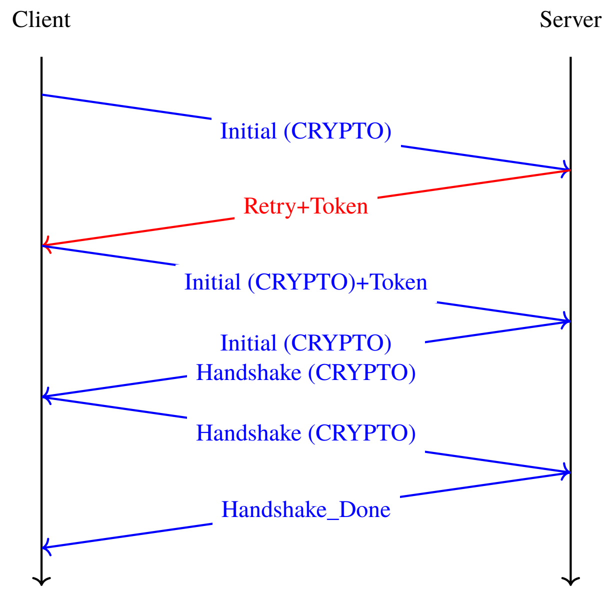


Fig. 1.4: Simplified QUIC Handshake with address validation

servers against denial of service attacks using spoofed addresses, but this comes at the expense of a longer connection establishment delay. QUIC version 1 includes several additional techniques to reduce the impact of address validation while still preventing denial of service attacks.

1.2.1 Identifying QUIC connections

A TCP connection is identified by a four tuple $IP_{Client}, IP_{Server}, Port_{Client}, Port_{Server}$. All packets belonging to a given connection carry this information in their IP and TCP headers. As QUIC runs above UDP, a simple approach could have been to use the UDP four tuple to identify each QUIC connection. Although simple, this solution would have severely restricted the flexibility of QUIC and the scalability of QUIC servers. The QUIC designers have opted for locally unique connection identifiers (CID) that are selected by the client and the server. These identifiers are placed in the QUIC packet headers during the handshake. When sending the Initial packet, the client selects a source CID that uniquely identifies the connection on the client and a random destination CID. Upon reception of this packet, the server selects its own connection identifier. It echoes the client selected CID and returns its selected CID. This is illustrated in Fig. 1.5. The connection identifiers selected by the client and the server uniquely identify the QUIC connection.

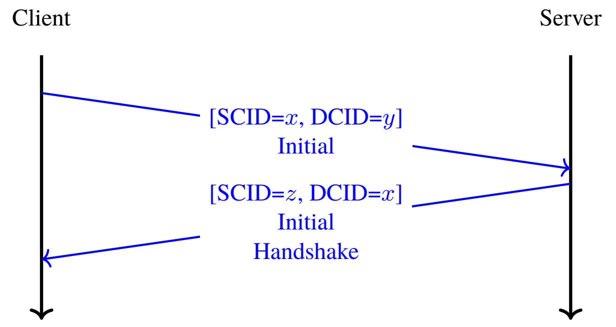


Fig. 1.5: Connection identifiers during a simplified QUIC Handshake

However, in contrast with TCP and UDP, the two identifiers are not present in all packets. Since a host selects a unique identifier for each connection, it only needs this identifier to identify a connection to which a packet belongs. For this reason, the QUIC packets exchanged on a connection after the handshake only contain the destination CID, i.e. the CID selected by the host that receives the packet.

Note: Variable length CIDs

Most transport protocols rely on fixed-length fields because this simplifies the parsing of packet headers. For example, the TCP and UDP port numbers are encoded as a 16 bits field. However, using fixed-length fields also limits the extensibility of the protocol. A TCP server cannot listen to more than 2^{16} different ports.

QUIC has opted for variable length CIDs to support very different use cases. On the server side, the length of the selected connection identifiers will depend on the architecture of the server. Large sites might use a load-balancer that distributes the connections to different physical servers. Such a load-balancer can leverage the CID to direct each incoming packet to the server that handles this connection. A simple CID would be composed of a server identifier chosen by the load balancer, e.g. in the high order bits of the CID, followed by a connection identifier selected by the physical server. Other designs are possible, e.g. by encrypting the CID to prevent attacks where malicious clients try to target a specific server.

One the client side, variable lengths CIDs bring another benefit. As clients typically manage a small number of QUIC connections, they can simply rely on the destination port of the packets that they receive to identify the corresponding QUIC connection. This corresponds to a zero-length connection identifier. Such a CID is never sent by the server after the handshake. This limits the byte overhead of the packets that clients receive.

A last point to note about these CIDs is their encoding inside the QUIC packets. The Initial packet contains the length and the value of both connection identifiers. The maximum length for a CID is 20 bytes. However, after the handshake, the packets that are exchanged over the QUIC connection only contain the destination CID without any field indicating its length. The host that has allocated the CID knows the length of the CIDs that it uses and can thus parse the packets that it receives without an explicit length information.

1.2.2 Security keys

We can now discuss how QUIC leverages TLS 1.3 to negotiate the security keys that are used to authenticate and encrypt the packets exchanged over a connection. As shown in Fig. 1.3, a QUIC connection starts with the exchange of four frames which can be carried in four or more packets. The first packet sent by the client contains the `ClientHello` TLS record. The `ClientHello` contains the information required to derive the session keys using Diffie-Hellman or a similar protocol. TLS 1.3 supports both finite field Diffie-Hellman and Elliptic Curve Diffie-Hellman [2]. The `ClientHello` message also contains TLS or QUIC parameters that the client proposes to use during the connection. The `TLS Server Hello` returned by the server contains the certificate that enables the client to validate the server's identity and the information required to determine the Diffie-Hellman keys. Using these keys, the server also encrypts the `TLS Encrypted Extensions` message that contains the TLS and QUIC parameters that the server has selected based on the ones proposed in the `ClientHello`. The server also constructs the `Finished` message that contains a message authentication code computed over the entire TLS handshake. This message is encrypted and authenticated using the session keys derived from the Diffie-Hellman keys. The client and the server recompute the hash of the entire handshake and verify both `Finished` messages. If one of these messages is incorrect, this indicates that either the key has not been correctly derived or that some of the TLS messages have been tampered. In these situations, the QUIC connection is terminated with an error message. The simplified TLS handshake used by QUIC is illustrated in Fig. 1.6. The TLS messages shown in italics are encrypted using the session keys.

Note: Encrypting `TLS Client Hello` and `TLS Server Hello`

When TLS 1.3 is used above TCP, the `TLS Client Hello` and `TLS Server Hello` messages are sent in clear because the client and the server have not yet exchanged the session keys. A similar approach could have been used for QUIC, but there was a fear that middleboxes could analyze the contents of these initial QUIC messages and try to interfere

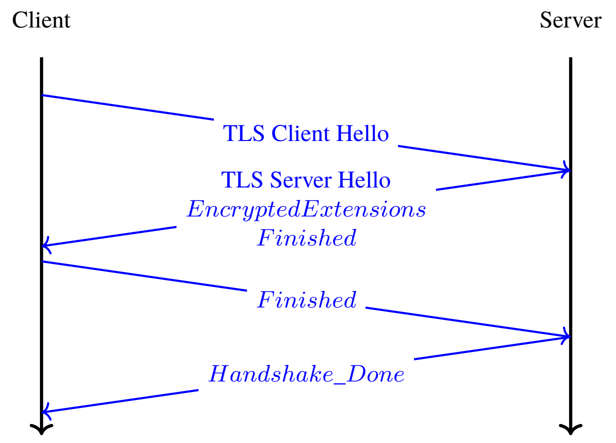


Fig. 1.6: Simplified TLS Handshake within a QUIC connection

with them. To add some burden on these middleboxes, QUIC encrypts the Initial packets using a secret that is derived from the destination connection ID of the client's first Initial packet. The pseudocode below, extracted from [8], shows how the client and the server keys are derived:

```
initial_salt = 0x38762cf7f55934b34d179ae6a4c80cadccbb7f0a
initial_secret = HKDF-Extract(initial_salt,
                              client_dst_connection_id)

client_initial_secret = HKDF-Expand-Label(initial_secret,
               "client in", "", Hash.length)
server_initial_secret = HKDF-Expand-Label(initial_secret,
                               "server in", "",Hash.length)
```

Since the keys used to protect the Initial packets are derived from the destination connection ID, any QUIC implementation, including those used on middleboxes, can decrypt the contents of the Initial packets.

As mentioned earlier, the client and the server can also use the TLS handshake to agree on specific QUIC parameters. These parameters are called *transport parameters* in QUIC [1]. 17 different transport parameters are defined in QUIC version 1 [1] and implementations can define their own transport parameters. We will discuss some of them in different sections of this document. A first example is the `max_udp_payload_size` parameter that indicates the largest UDP payload that an implementation is willing to receive. The minimum value for this parameter is 1200 bytes. QUIC implementations used in a datacenter supporting jumbo Ethernet frames could agree on a much larger `max_udp_payload_size` without risking packet fragmentation.

Another example of QUIC transport parameters are the `initial_source_connection_id` and the `original_destination_connection_id` transport parameters. As explained above, thanks to the `Finished` messages in the TLS handshake, the client and the servers can verify that their messages have not been tampered. Unfortunately, the authentication code included in the `Finished` messages is only computed based on the contents of the TLS messages (i.e. `ClientHello`, `ServerHello`, `EncryptedExtensions` and `Finished`). During the handshake, the client and the servers also propose the source and destination connection identifiers that they plan to use to identify the QUIC session. These identifiers are placed in the packet header and not inside the TLS messages. They are thus not covered by the authentication code included in the `Finished` message. To still authenticate these identifiers, QUIC encodes them as transport parameters that are included in the `ClientHello` and the `EncryptedExtensions` messages. The client copies the source connection identifier in the `initial_source_connection_id` transport parameter in its `ClientHello`. The server does the same when sending the `ServerHello`. It also copies in the `original_destination_connection_id` transport parameter the destination identifier used by the client to send the packet containing the `ClientHello`.

1.2.3 The QUIC packet headers

At this point, the QUIC session and the TLS security keys are known by the client and the server. They can start to exchange data. Before looking at how data is carried inside QUIC packets, it is interesting to explore in more details the packet headers that are placed inside each packet. QUIC uses variable length packet headers. Two different header formats exist. The first header format is the long header. This is the header used for the first packets of a QUIC connection.

Internet protocol specifications usually contain figures to represent the format of the packet headers. This graphical format is useful to get a quick grasp at a header containing fixed size fields. However, when a header contains several variable length fields, the graphical representation can become difficult to follow. The QUIC specification [1] uses the textual representation that was also used for the TLS protocol. As an example, let us consider the well-known TCP header. This header is graphically represented as shown in Fig. 1.7.

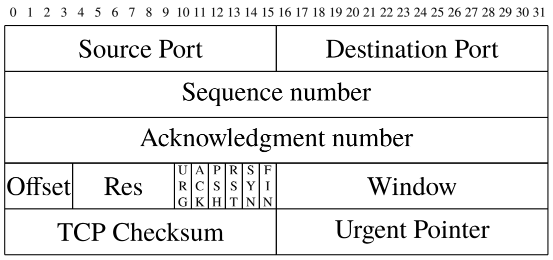


Fig. 1.7: Graphical representation of the TCP header

Listing 1.1: Textual representation of the TCP header

```
TCP Header Packet {
  Source Port (16),
  Destination Port (16),
  Sequence Number (32),
  Acknowledgment Number (32),
  Offset (4),
  Reserved (6),
  Urgent Flag (1),
  ACK Flag (1),
  Push Flag (1),
  RST Flag (1),
  SYN Flag (1),
  FIN Flag(1),
  Window (16),
  TCP Checksum (16),
  Urgent Pointer (16),
  TCP Options (..)
}
```

The attentive reader will easily understand the correspondence between the two formats. When explaining QUIC, we use the textual representation while we stick to the graphical one for TCP.

Listing 1.2 shows the QUIC long header. It starts with one byte containing the header type in the most significant bit, two bits indicating the packet type and four bits that are specific to each packet packet. Then, 32 bits carry the QUIC version number. The current version of QUIC, defined in [1], corresponds to version `0x00000001`. The header then contains the destination and source connection identifiers that were described previously and then a payload that is specific to each type.

Listing 1.2: The QUIC long header

```
Long Header Packet {
  Header Form (1) = 1,                   /* high order bit of the first byte */
  Fixed Bit (1) = 1,                     /* second order bit of the first byte */
  Long Packet Type (2),                  /* third and fourth high order bits of the first␣
↪byte */
  Type-Specific Bits (4),                /* low order four bits of the first byte */
  Version (32),                          /* 32 bits version number */
  Destination Connection ID Length (8), /* 8 bits */
  Destination Connection ID (0..160),   /* variable number from 0 up to 160 bits */
  Source Connection ID Length (8),
  Source Connection ID (0..160),
  Type-Specific Payload (..),            /* variable length */
}
```

Note: Encoding packet numbers

Most transport protocols use fixed fields to encode packet numbers or byte offsets. The size of this field is always a trade-off. On one hand, a small packet number field limits the per packet overhead. On the other hand, a large packet number space is required to ensure that two packets carrying different data do not use the same packet number. TCP uses a 32 bits sequence number field that indicates the position of the first byte of the payload in the bytestream. This 32 bits field became a concern as bandwidth increased to Gbps and beyond [9].

QUIC takes a different approach to sequence numbers. Each packet contains a per-packet sequence number. This number is encoded as a variable-length integer (`varint`). Such a `varint` has a length encoded in the two most significant bits of the first byte. If these bits are set to `00`, then the `varint` is encoded in one byte and can contain values between 0 and $2^6 - 1$. If the two most significant bits are set to `01`, the `varint` can encode values between 0 and $2^{14} - 1$ within two bytes. When the two high order bits are set to `11` the `varint` can encode values between 0 and $2^{62} - 1$ within four bytes.

There are other important differences between QUIC and other transport protocols when considering packet numbers. First, a QUIC sender must *never* reuse the same packet number for two different packets sent over a QUIC connection. If data needs to be retransmitted, it will be resent as a frame inside a new packet. Furthermore, since the largest possible packet number is $2^{62} - 1$, a QUIC sender must close the corresponding connection once it has sent a QUIC packet carrying this packet number. This puts a restriction on the duration of QUIC connections. They cannot last forever in contrast to TCP connections such as those used to support BGP sessions between routers. An application that uses QUIC must be ready to restart a connection from time to time.

This long header is used for the `Initial`, `Handhsake` and `Retry` packets. Some of these packet types add new flags in the first byte and additional information after the connection identifiers. Listing 1.3 shows the long header of the `Initial` packet. It contains two bits in the first byte that indicate the length of the packet number field. The packet specific part contains an option token, a length field, a packet number and a payload. The token length, length and packet number are encoded using variable length integers.

Listing 1.3: The QUIC long header of the Initial packet

```
Initial Packet {
  Header Form (1) = 1,                    /* High order bit first byte */
  Fixed Bit (1) = 1,
  Long Packet Type (2) = 0,
  Reserved Bits (2),
  Packet Number Length (2),               /* Low order 2 bits of first byte */
```

(continues on next page)

(continued from previous page)

```
  Version (32),
  Destination Connection ID Length (8),
  Destination Connection ID (0..160),
  Source Connection ID Length (8),
  Source Connection ID (0..160),
  Token Length (i),
  Token (..),
  Length (i),
  Packet Number (8..32),
  Packet Payload (8..),
}
```

The QUIC short header contains fewer fields. The most significant bit of the first byte is set to 1 to indicate that the packet carries a short header. The other flags will be discussed later. The two least significant bits of this byte contain the length of the packet number field. It is interesting to note that in contrast with the long header, there is no explicit indication of the length of the destination connection identifier. This connection identifier has been assigned by the host that receives this packet and it already knows the length of the connection identifiers that it uses.

Listing 1.4: The QUIC short header used by 1-RTT packets

```
1-RTT Packet {
   Header Form (1) = 0,               /* High order bit of first byte */
   Fixed Bit (1) = 1,
   Spin Bit (1),
   Reserved Bits (2),
   Key Phase (1),
   Packet Number Length (2),          /* Low order bits of first byte */
   Destination Connection ID (0..160),
   Packet Number (8..32),
   Packet Payload (8..),
}
```

The short header format, depicted in Listing 1.4, is used by all QUIC packets once the session keys have been derived. This usually happens after one round-trip-time. These packets are called the 1-RTT packets in the QUIC specification [1]. This notation is used to emphasize the fact that QUIC also supports 0-RTT packets, i.e. packets that carry data and can be exchanged in parallel with the TLS handshake.

Note: Coalescing packets

Besides the connection identifiers, another difference between the short and the long headers is the presence of the `Packet Length` field in the long header. This field might surprise the reader who is familiar with UDP since UDP also contains a Length field. As each QUIC packet is placed inside a UDP message, the QUIC Length field could seem redundant. This Length field was included in the QUIC long header to allow a QUIC sender to coalesce several consecutive and small packets inside a single UDP message. Some of the frames exchanged during the handshake are rather small. Sending a UDP message for each of these frames would be a waste of resources. Furthermore, a mix of `Initial`, `Handshake` and `0-RTT` packets are exchanged when creating a QUIC connection. It would not be wise to require the utilization of one UDP message to send each of these packets. You might observe this optimization when analyzing packet traces collected on QUIC servers.

1.2.4 0-RTT data

Latency is a key concern for transport protocols. The QUIC/TLS handshake that we have described until now allows the client and the server to agree on security keys within one round-trip-time. However, one round-trip-time can be a long delay for some applications. To minimize the impact of the connection setup time, QUIC allows applications to exchange data during the QUIC/TLS handshake. Such data is called 0-RTT data. To ensure that 0-RTT data is exchanged securely, the client and the server must have previously agreed on a key which can be used to encrypt and authenticate the 0-RTT data. Such a 0-RTT key could either be a pre-shared key that the client and the server have shared without using the QUIC protocol or, and this is the most frequent solution, the key that they negotiated during a previous connection. In practice, the server enables 0-RTT by sending a TLS session ticket to the client [2]. A session ticket is an encrypted record that contains information that enables the server to recover all the state information about a session including its session keys. It is also linked to the client's address to enable the server to verify that a given client reuses the tickets that it has received earlier. Usually, these tickets also contain an expiration date. The client places the received ticket in the `TLS CLient Hello` that it sends in the first `Initial` packet. It uses the pre-shared key corresponding to this ticket to encrypt data and place it in one or more `0-RTT` packets. The server uses the information contained in the ticket to recover the key and decrypt the data of the `0-RTT` packet. Listing 1.5 shows the format of QUIC's 0-RTT packet.

Listing 1.5: The QUIC 0-RTT packet

```
0-RTT Packet {
  Header Form (1) = 1,                  /* High order bit of the first byte */
  Fixed Bit (1) = 1,
  Long Packet Type (2) = 1,
  Reserved Bits (2),
  Packet Number Length (2),            /* Low order bits of the first byte */
  Version (32),
  Destination Connection ID Length (8),
  Destination Connection ID (0..160),
  Source Connection ID Length (8),
  Source Connection ID (0..160),
  Length (i),
  Packet Number (8..32),
  Packet Payload (8..),
}
```

The main benefit of these `0-RTT` packets is that the client can immediately send encrypted data while sending its `Initial` packet. This is illustrated in Fig. 1.8 where the frames encrypted with the 0-RTT keys are shown in italics. Note that some of these frames can span several packets. `0-RTT` packets are only sent by the QUIC client since the server can send encrypted data immediately after having sent its `Handshake` frames. As explained earlier, the Initial packets are also encrypted but using keys derived from the connection identifiers.

Note: Replay attacks and 0-RTT packets

Thanks to the 0-RTT packets, a client can send encrypted data to the server before waiting for the secure handshake. This reduces the latency of the data transfer, but with one important caveat. QUIC does not provide any guarantee that 0-RTT data will not be replayed. QUIC's 0-RTT data exchanged is intended for idempotent operations. A detailed discussion of the impact of replay attacks may be found in [10].

To understand the importance of these replay attacks, let us consider a simple HTTP GET request. Such a request could easily fit inside the 0-RTT packet and thus have lower latency. If a web browser uses it to request a static `index.html` file, there is no harm if the request is received twice by the server. However, if the GET request is part of a REST API and has side effects, then problems could occur depending on the type of side effect. Consider a REST API that allows a user to switch off the lights using his or her smartphone. Replaying this request two or three times will always result in the light being switched off. However, if the user requests to increase the room temperature by one °C, then multiple

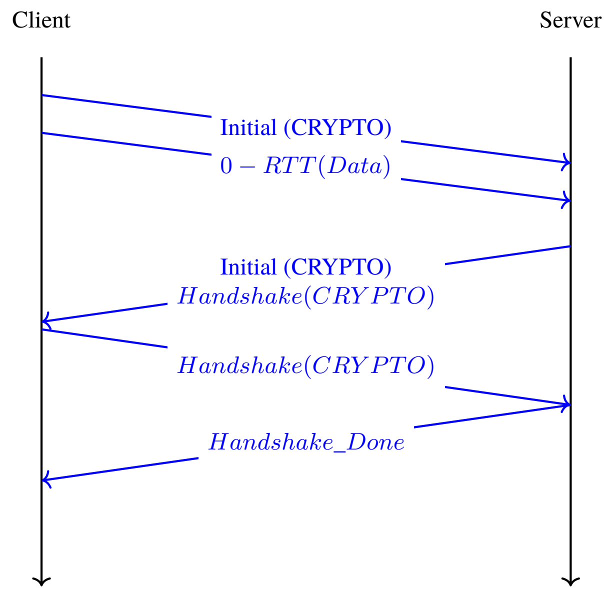


Fig. 1.8: Simplified QUIC Handshake with 0-RTT data

replays will obviously have different consequences.

1.3 Closing a QUIC connection

Before exploring how data can be exchanged over a QUIC connection, let us now analyze how a QUIC connection can terminate. QUIC supports three different methods to close a QUIC connection. QUIC's approach to terminating connection is very different from the approaches used by traditional transport protocol. Before looking at these techniques, it is important to understand how QUIC interacts with Network Address Translation.

Note: QUIC and Network Address Translation

QUIC runs above UDP and the design of QUIC was heavily influenced by the presence of NATs. NATs, like other middleboxes, maintain per-flow state. For TCP connections, many NATs rely on the `SYN`, `FIN` and `RST` flags to determine when state must be created or removed for a TCP connection. For UDP, this stateful approach is not possible and NATs create a new mapping when they observe the first packet of a flow and remove the mapping once the flow has been idle for sometime. The IETF recommends to maintain NAT mappings during at least two minutes [11], but measurements show that some deployed NATs use shorter timeouts [12, 13]. In practice, UDP flows should probably send a packet every 30 seconds to ensure that the on-path NATs preserve their state.

To prevent NATs from changing the mapping associated to the IP addresses and ports used for a QUIC connection, QUIC hosts will need to regularly send data over each established QUIC connection. QUIC defines a `PING` frame that allows any QUIC endpoint to send a frame that will trigger a response from the other peer. The `PING` frame does not carry data, but the receiver of a `PING` frame needs to acknowledge the packet containing this frame. This creates a bidirectional communication and can prevent NATs from discarding the mapping associated to the QUIC connection.

1.3.1 Implicit termination of QUIC connections

Each QUIC implementation keeps in its connection state the timestamp of the last QUIC packet received over this connection. During the connection establishment, the QUIC hosts can also exchange the `max_idle_timeout` parameter that indicates how long (in seconds) a QUIC connection can remain idle before being automatically closed. The first way to close a QUIC connection is to keep it idle for this period of time.

1.3.2 Explicit termination of a QUIC connection

The second technique to terminate a QUIC connection is to use the `CONNECTION_CLOSE` frame. This frame indicates that this connection has been closed abruptly. The host that receives the `CONNECTION_CLOSE` may respond with one `CONNECTION_CLOSE` frame. After that, it must stop sending any additional frame. It keeps the connection state for some time, but does not accept any new packet nor retransmit others. The host that sends a `CONNECTION_CLOSE` frame indicates that it will neither send nor accept more data. It keeps a subset of the QUIC connection state to be able to retransmit the `CONNECTION_CLOSE` frame if needed.

A host also sends a `CONNECTION_CLOSE` frame to abruptly terminate a connection if it receives an invalid frame or detects a protocol error. In this case, the `CONNECTION_CLOSE` frame contains a variable length integer that indicates the reason for the termination, the type of the frame that triggered the error and additional information encoded as a text string. The QUIC specification also defines a third technique called *stateless reset* to cope with hosts that have lost

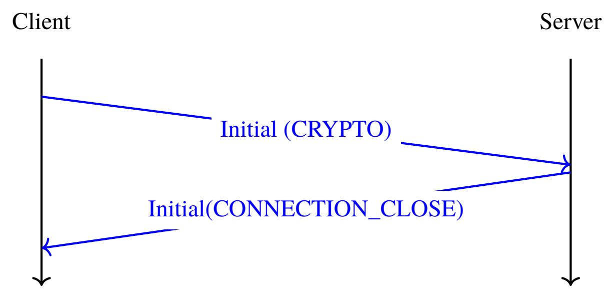


Fig. 1.9: A server that refuses a connection

connection state after a crash or outage. It relies on a 16 bytes stateless token announced together with the connection identifier. See [1] for all the details.

1.4 Exchanging data over a QUIC connection

The data exchanged over is QUIC connection is organized in different streams. A stream is a sequence of bytes. QUIC supports both unidirectional and bidirectional streams. Both the client and the server can create new streams over a QUIC connection. Each stream is identified by a stream identifier. To prevent problems when the client and the server try to create a stream using the same identifier, QUIC restricts the utilization of the stream identifiers based its two low-order bits. A QUIC client can only create streams whose two low order bits are set to `00` (bidirectional stream) or `10` (unidirectional stream). Similarly, the low order bits of the server-initiated streams must be set to `01` (bidirectional stream) or 11 (unidirectional streams). The QUIC streams are created implicitly by sending data over the stream with the chosen identifier. The stream identifiers start at the minimum value, i.e. `0x00` to `0x03` for the respective types. If a host sends stream data for stream `x` before having sent data over the lower-numbered streams of that type, then those streams are implicitly created. The stream identifier is encoded using a variable length integer. The largest possible stream identifier is thus $2^{62} - 1$.

QUIC places all data inside `STREAM` frames that are then placed inside QUIC packets. The structure of a `STREAM` frame is shown in Listing 1.6. This frame contains the following information :

- the Type of the Stream frame[1]
- the identifier of the stream
- the offset, i.e. the position of the first byte of the Stream data in the bytestream
- the length of the data
- the Stream Data

Listing 1.6: The QUIC STREAM frame

```
STREAM Frame {
   Type (i) = 0x08..0x0f,
   Stream ID (i),
   Offset (i),
   Length (i),
   Stream Data (..),
}
```

The STREAM frame carries data, but it can also terminate the corresponding stream. The lowest order bit of the Type field acts as a FIN bit. When set to zero, it indicates that subsequent data will be sent over this stream. When set to one, it indicates that the STREAM frame contains the last bytes sent over that stream. The stream is closed once the last byte of the stream has been delivered to the user application. Once a QUIC stream has been closed, it cannot be reused again over this connection.

Using this information, the receiver can easily reassemble the data received over the different streams. As an illustration, let us consider a server that has created two streams (stream 1 and 5). The server sends ABCD.. over stream 1 and 123 over stream 5 and closes it after having sent the third digit. The data from these streams could be encoded as shown in Listing 1.7.

Listing 1.7: Data sent over two different streams

```
STREAM Frame {
   Type (i) = 0x0e,
   Stream ID = 1,
   Offset = 0
   Length = 2
   Stream Data = AB
}
STREAM Frame {
   Type (i) = 0x0e,
   Stream ID = 5,
   Offset = 0
   Length = 1
   Stream Data = 1
}
STREAM Frame {
   Type (i) = 0x0e,
   Stream ID = 1,
   Offset = 2
   Length = 1
   Stream Data = C
}
```

(continues on next page)

[1] All STREAM frames have a type that starts with 0b0001.... The three low order bits of the STREAM frame indicate the presence of the Offset and Length fields. The lowest order bit is the FIN bit.

(continued from previous page)

```
STREAM Frame {
   Type (i) = 0x0f,   /* FIN bit is set, end of stream */
   Stream ID = 5,
   Offset = 1
   Length = 2
   Stream Data = 23
}
STREAM Frame {
   Type (i) = 0x0e,
   Stream ID = 1,
   Offset = 3
   Length = 4
   Stream Data = DEFG
}
```

The penultimate frame shown in Listing 1.7 has the `FIN` flag set. It marks the end of stream `1` that has transported three bytes in total. The `FIN` flag is the normal way to gracefully close a QUIC stream.

There are however cases where an application might need to cancel a stream abruptly without closing the corresponding connection. First, the sending side of a stream can decide to reset the stream. For this, it sends a `RESET_STREAM` frame that carries the identifier of the stream that is canceled. The receiving side of a stream might also need to stop receiving data over a given stream. Consider for example a web browser that has started to download the different images that compose a web while the user has already clicked on another page from the same server. The streams that correspond to these images become useless. In this case, our browser can send a `STOP_SENDING` frame to indicate that it discards the incoming data over the corresponding streams. Upon reception of this frame, the server sends a `RESET_STREAM` frame to indicate that the corresponding stream has been closed.

1.4.1 Flow control in QUIC

Transport protocols usually allocate some resources to each established connection. Each QUIC connection requires memory to store its state, but also buffers to store the packets arrived out-of-order. In practice, the memory available for QUIC implementations is not unlimited and a QUIC receiver must control the amount of packets that the remote host can send at any time. QUIC supports flow control techniques that operate at different levels.

The first level is the connection level. During the handshake, each host can announce the maximum number of bytes that it agrees to receive initially on the connection using the `initial_max_data` transport parameter. This parameter contains the number of bytes that the sending host agrees to receive without further notice. If the connection uses more bytes than initially agreed, the receiver can update this limit by sending a `MAX_DATA` frame at any time. This frame contains a variable length integer that encodes the maximum amount of stream data that can be sent over the connection.

The utilization of different streams also consumes resources on a QUIC host. A receiver can also restrict the number of streams that the remote host can create. During the handshake, the `initial_max_streams_bidi` and `initial_max_streams_uni` transport parameters announce the maximum number of bidirectional and unidirectional streams that the receiving host can accept. This limit can be modified during the connection by sending a `MAX_STREAMS` frame that updates the limit.

Flow control can also take place at the stream level. During the handshake, several transport parameters allow the hosts to advertise the maximum number of bytes that they agree to receive on each stream. Different transport parameters are used to specify the limits that apply to the local/remote and unidirectional/bidirectional streams. These limits can be updated during the connection by sending `MAX_STREAM_DATA` frames. Each of these frames indicates the maximum amount of stream data that can be accepted on a given stream.

These limits restrict the number of streams that a host can create and the amount of bytes that it can send. If a host is blocked by any of these limits, it may sent a control frame to request the remote host to extend the limit. For each type of flow control, there is an associated control frame which can be used to request an extension of the limit.

A host should send a `DATA_BLOCKED` frame when it reaches the limit on the maximum amount of data set by the `initial_max_data` transport parameter or a previously received `MAX_DATA` frame. The `DATA_BLOCKED` frame contains the connection limit that caused the transmission to be blocked. In practice, a receiving host should increase the connection-level limit by sending `MAX_DATA` frames before reaching the limit. However, since this limit is function of the available memory, a host might not always be able to send a `MAX_DATA` frame. Fig. 1.10 provides an example packet flow with the utilization of these frames. We assume that the `initial_max_data` transport parameter was set to `100` bytes by the client during the handshake and the the server needs to send 900 bytes. The server creates a stream and sends 100 bytes in a `1-RTT` packet carrying a `STREAM` frame. At this point, the server is blocked. The same applies

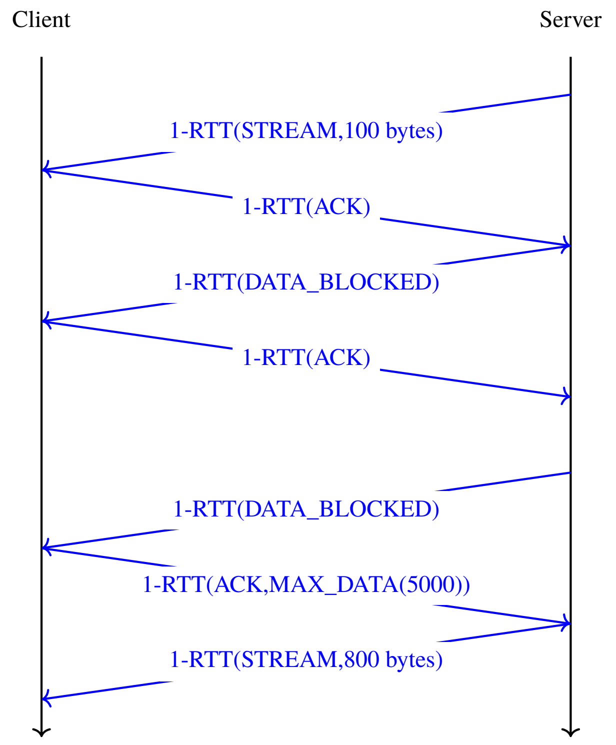


Fig. 1.10: QUIC uses `DATA_BLOCKED` frames when a connection's flow control is blocked

with the `STREAM_DATA_BLOCKED` frame that is sent when a host reaching the per-stream limit. The `STREAMS_BLOCKED` frame is used when a host has reached the maximum number of established streams.

Note: Connections blocked by flow control are not totally idle

If a QUIC host detects that a connection is blocked by flow control, it should regularly send `DATA_BLOCKED` or `STREAM_DATA_BLOCKED` frames to request the remote host to extend the current limit. The QUIC specification [1] does not recommend precisely how often these frames should be sent when a connection is blocked by flow control. Experience with QUIC deployments will enable the QUIC developers to more precisely define how often these frames should be sent.

A measurement study [14] revealed that QUIC implementations used different strategies for flow control. They identified three main types of behaviors :

- Static Flow Control: the receive buffer size stays unchanged and the receiver simply increases the maximum allowance linearly
- Growing Flow Control: the size of the receive buffer increases over time as the connection progresses

- Auto-tuning: the size of the receive buffer is adjusted dynamically based on the estimated bandwidth and round-trip times

In 2020, three quarter of the studied implementations used a Static Flow Control and only one used auto-tuning. Static Flow Control can work, but this is a waste of memory. For example, Google's Chrome starts with a 15 MBytes receive buffer and updates it linearly [14]. This should be contrasted with TCP implementations that usually start with a window of a few tens of KBytes and adjust it with auto-tuning. Auto-tuning is a key feature of modern TCP implementations [15]. It is expected that QUIC implementations will include more advanced heuristics to tune their flow control mechanism.

1.4.2 QUIC Loss Detection

As other transport protocols, QUIC includes mechanisms to detect transmission errors and packet losses. The transmission errors are usually detected by using the UDP checksum or at the datalink layer with the Wi-Fi or Ethernet CRCs. When a transmission error occurs, the corresponding packet is discarded and QUIC considers this error as a packet loss. Researchers have analyzed the performance of checksums and CRCs on real data [16].

Second, since QUIC used AEAD encryption schemes, all QUIC packets are authenticated and a receiver can leverage this AEAD to detect transmission errors that were undetected by the UDP checksum of the CRC of the lower layers. However, these undetected transmission errors are assumed to be rare and if QUIC a detects an invalid AEAD, it will consider that this error was caused by an attack and will stop the connection using a TLS alert [2].

There are several important differences between the loss detection and retransmission mechanisms used by QUIC and other transport protocols. First, QUIC packet numbers always increase monotonically over a QUIC connection. A QUIC sender never sends twice a packet with the same packet number over a given connection. QUIC encodes the packet numbers as variable length integers and it does not support wrap around in contrast with other transport protocols. The QUIC frames contain the valuable information that needs to be delivered reliably. If a QUIC packet is lost, the frames that it contained will be retransmitted in another QUIC packet that uses a different packet number. Thus, the QUIC packet number serves as a unique identifier of a packet. This simplifies some operations such as measuring the round-trip-time which is more difficult in protocols such as TCP when packets are transmitted [17].

Second, QUIC's acknowledgments carry more information than the cumulative or selective acknowledgments used by TCP and related protocols. This enables the receiver to provide a more detailed view of the packets that it received. In contrast with TCP [18], once a receiver has reported that one packet was correctly received in an acknowledgment, the sender of that packet can discard the corresponding frames.

Third, a QUIC sender autonomously decides which frames it sends inside each packet. A QUIC packet may contain both data and control frames, or only data or only control information. If a QUIC packet is lost, the frames that it contained could be retransmitted in different packets. A QUIC implementation thus needs to buffer the frames and mark the in-flight ones to be able to retransmit them if the corresponding packet was lost.

Fourth, most QUIC packets are explicitly acknowledged. The only exception are the packets that only contain `ACK`, `PADDING` or `CONNECTION_CLOSE` frames. A packet that contains any other QUIC frame is called an ack-eliciting packet because its delivery will be confirmed by the transmission of an acknowledgment. A QUIC packet that carries both an `ACK` and a `STREAM` frame will thus be acknowledged.

With this in mind, it is interesting to look at the format of the QUIC acknowledgments and then analyze how they can be used. Listing 1.8 provides the format of an ACK frame. It can be sent at any time in a QUIC packet. Two types are used to distinguish between the acknowledgments that contain information about the received ECN flags (type `0x03`) or only regular acknowledgments (type `0x02`). The first information contained in the ACK frame is the largest packet number that is acknowledged by this ACK frame. This is usually the highest packet number received. The second information is the ACK delay. This is the delay in microseconds between the reception of the packet having the largest acknowledged number by the receiver and the transmission of the acknowledgment. This information is important to ensure that round-trip-times are accurately measured, even if a receiver delays acknowledgments. This is illustrated in Fig. 1.11. The `ACK Range Count` field contains the number of `ACK ranges` that are included in the QUIC ACK frame. This number can be set to zero if all packets were received in sequence without any gap. In this case, the `First ACK Range` field contains the number of the packet that arrived before the `Largest Acknowledged` packet number.

Listing 1.8: The QUIC ACK Frame

```
ACK Frame {
   Type (i) = 0x02..0x03,
   Largest Acknowledged (i),
   ACK Delay (i),
   ACK Range Count (i),
   First ACK Range (i),
   ACK Range (..) ...,
   [ECN Counts (..)],
}
```

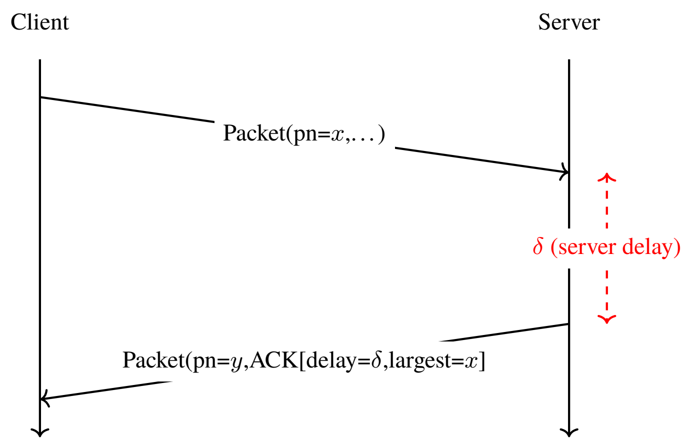


Fig. 1.11: Utilization of the QUIC ACK delay

An `ACK` frame contains 0 or more `ACK Ranges`. The format of an `ACK range` is shown in Listing 1.9. Each range indicates first the number of unacknowledged packets since the smallest acknowledged packet in the preceding range (or the first ACK range). The next field indicates the number of consecutive acknowledged packets.

Listing 1.9: A QUIC ACK range

```
ACK Range {
   Gap (i),
   ACK Range Length (i),
}
```

As an example, consider a host that received the following QUIC packets: `3,4,6,7,8,9,11,14,16,18`. To report all the received packets, it will generate the `ACK` frame shown in Listing 1.10.

Listing 1.10: Sample QUIC ACK Frame

```
ACK Frame {
   Type (i) = 0x02,
   Largest Acknowledged=18,
   ACK Delay=x,
   ACK Range Count=5,
   First ACK Range=0,
```

(continues on next page)

(continued from previous page)

```
    ACK Range #0 [Gap=2, ACK Range Length=1],
    ACK Range #1 [Gap=2, ACK Range Length=1],
    ACK Range #2 [Gap=3, ACK Range Length=1],
    ACK Range #3 [Gap=2, ACK Range Length=4],
    ACK Range #4 [Gap=2, ACK Range Length=2]
}
```

The QUIC specification recommends to send one ACK frame after having received two ack-eliciting packets. This corresponds roughly to TCP's delayed acknowledgments strategy. However, there is ongoing work to allow the sender to provide more guidelines on when and how ACK frames should be sent [19].

Note: When should QUIC hosts send acknowledgments

A measurement study [14] analyzed how QUIC implementations generate acknowledgments. Two of the studied implementations sent acknowledgments every N packets (2 for one implementation and 10 for the other). Other implementations used ack frequencies that varied during the data transfer.

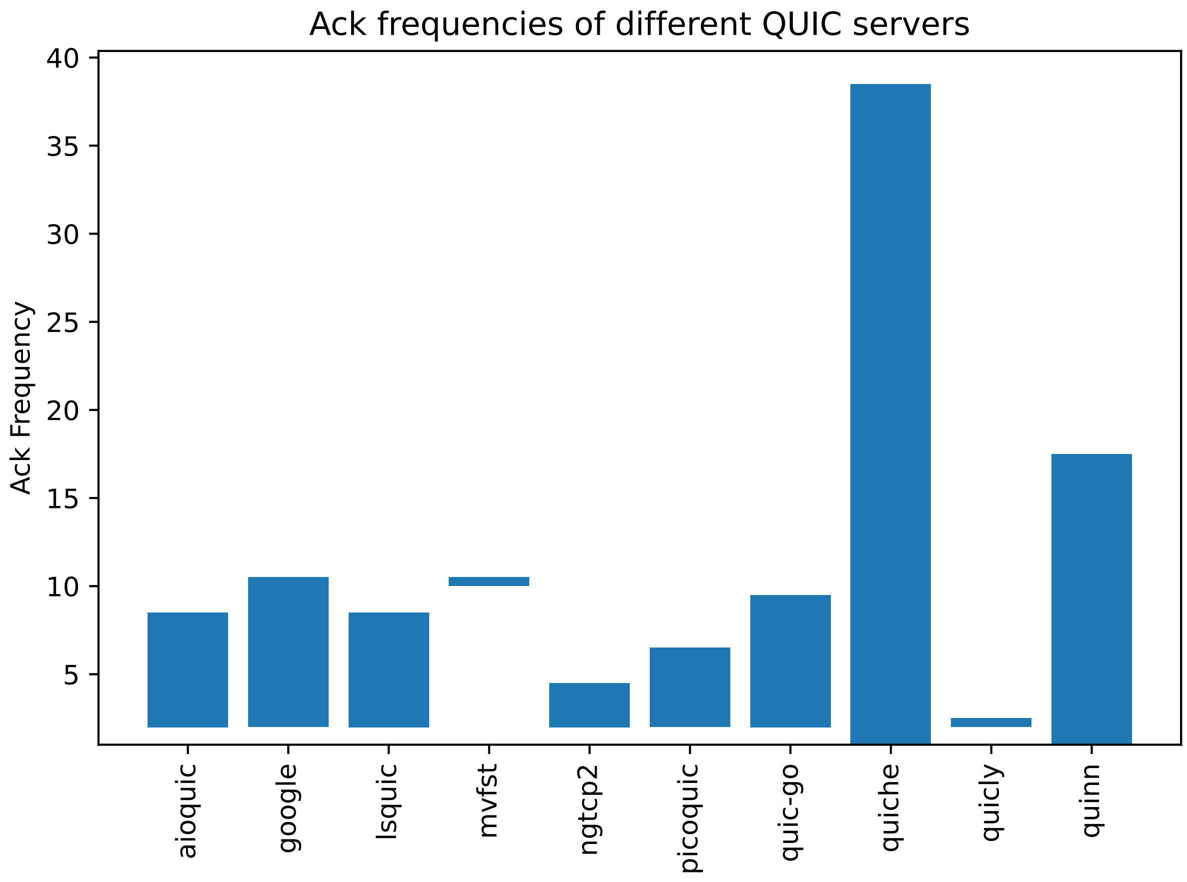


Fig. 1.12: Acknowledgment frequencies for different QUIC servers

The acknowledgment frequencies should be compared with TCP that usually acknowledges every second packet. It is likely that QUIC implementations will tune the generation of their acknowledgments in the coming years based on feedback from deployment.

It is interesting to observe that since the ACK frames are sent inside QUIC packets, they can also be acknowledged. Sending an ACK in response to another ACK could result in an infinite exchange of ACK frames. To prevent this problem, a QUIC sender cannot send an ACK frame in response to a non-eliciting QUIC packet and the ACK frames are one of the non-eliciting frame types. Note that if a receiver that receives many STREAM frames and thus sends many ACK frames wants to obtain information about the reception of its ACK frame, it can simply send one ACK frame inside a packet that contains an eliciting frame, e.g. a PING frame. This frame will trigger the receiver to acknowledge it and the previously sent ACK frames.

In contrast with other reliable transport protocols, QUIC does not use cumulative acknowledgments. As explained earlier, QUIC never retransmits a packet with the same packet number. When a packet is lost, this creates a gap that the receiver reports using an `ACK Range`. Such a gap will never be filled by retransmissions and obviously should not be reported by the receiver forever. In practice, a receiver will send the acknowledgment that corresponds to a given packet number several times and then will assume that the acknowledgment has been received. A receiver can also rely on other heuristics to determine that a given `ACK Range` should not be reported anymore. This is the case if the ACK frame was included in a packet that has been acknowledged by the other peer, but also when the gap was noticed several round-trip times ago.

QUIC also allows a receiver to send information about the ECN flags in the received packets. Two flags of the IP header [20] are reserved to indicate support for Explicit Congestion Notification. The QUIC ECN count field shown in Listing 1.11 contains three counters for the different values of the ECN flags. These counters are incremented upon the reception of each QUIC packet based on the values of the ECN flag of the received packet. Unfortunately, there are still many operational problems when using ECN in the global Internet [21]. Time will tell whether it is easier to deploy ECN with QUIC than with TCP.

Listing 1.11: A QUIC ECN Count

```
ECN Counts {
   ECT0 Count (i),
   ECT1 Count (i),
   ECN-CE Count (i),
}
```

Note: QUIC also acknowledges control frames

Besides the STREAM frames that carry user data, QUIC uses several different frame types to exchange control information. These control frames, like the data frames, are ack-eliciting frames. This implies a host that receives such a frame needs to acknowledge it using an ACK frame.

Fig. 1.13 illustrates the beginning of a QUIC connection with the exchange of the `Initial` packets and the corresponding acknowledgments. The client sends its `TLS Client Hello` inside a CRYPTO frame in an `Initial` packet. This is the first packet sent by the client and thus its packet number is 0. The server replies with a `TLS Server Hello` inside a CRYPTO frame in an `Initial` packet. Since this is the first packet sent by the server, its packet number is also 0. The packet also contains an ACK frame that acknowledges the reception of the packet containing the `TLS Client Hello`.

The `Handshake`, `0-RTT` and `1-RTT` packets are acknowledged similarly using ACK frames. `Handshake` packets are acknowledged in other `Handshake` packets while `0-RTT` and `1-RTT` packets are acknowledged inside `1-RTT` packets.

Note: Not all QUIC servers use 0 as the packet number of their first Initial packet

The example shows a QUIC connection where the client sent its Initial packet with packet number 0 and the server also replied with a packet number set to 0. This is what most QUIC implementations do. However, the QUIC specification does not strictly requires this. In fact, `facebook` servers in October 2022 appear to use random packet numbers for

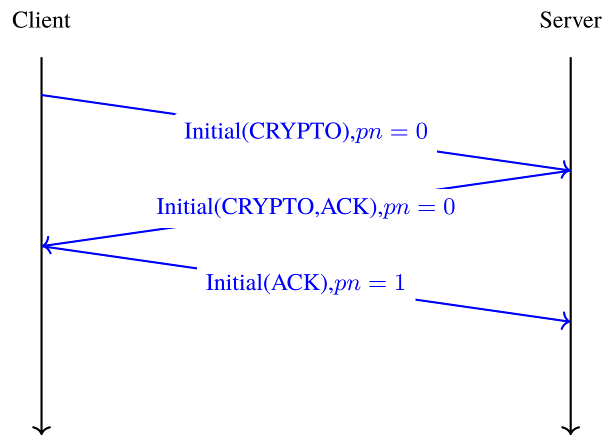


Fig. 1.13: QUIC also acknowledges Initial frames

the Initial packet that they sent in response to a client. This is probably use to detect or mitigate some forms of attacks since the client must receive the server's Initial packet to be able to produce a valid acknowledgment.

To illustrate how QUIC uses acknowledgments, let us consider a simple QUIC connection. The client starts a QUIC connection with a new server, sends a request, receives a response and then closes the connection. There are no losses in this connection. Fig. 1.14 illustrates this connection. The connection starts when the client sends an `Initial` packet containing a `CRYPTO` frame with the `TLS Client Hello`. The server replies with an `Initial` packet that contains an acknowledgment and a `CRYPTO` frame with the `TLS Server Hello`. The server then sends an `Initial` packet containing the `TLS Encrypted Extensions`. Since this is the first `Initial` packet, its packet number is set to 0. In practice, it is likely that the server will need to send several packets to carry the certificates contained in this packet. Note that the server cannot send more than 3 packets in response to the client's `Initial` packet. This limit was introduced in the QUIC specification to restrict the ability of attackers to trigger DDoS attacks by sending spoofed packets to QUIC servers [1]. If the `CRYPTO` frame containing the certificates is too long, the server might need to wait for acknowledgments from the client before sending its last `Handshake` packets. The client confirms the reception of the server's `Initial` packet by sending its last `Initial` packet that contains an `ACK` frame. This is the second `Initial` packet sent by the client and its packet number is thus 1. Since this packet only contains an `ACK` frame, the server does not return an acknowledgment to confirm its reception.

The client replies to the `Handshake` packet with another `Handshake` packet that contains a `CRYPTO` frame and acknowledges the `Handshake` packets sent by the server. The client's `Handshake` packet is acknowledged by the server. The server starts the data exchange by sending a `1-RTT` packet carrying one or more stream frames to create the required streams. Since this is the first `1-RTT` packet sent by the server, its packet number is set to 0. The client then sends its request in a `STREAM` frame. The server replies with a `1-RTT` packet that contains a `STREAM` frame with its response. The client ends the connection by sending a `CONNECTION_CLOSE` frame. In the example, the server replies with a `CONNECTION_CLOSE` frame, but the QUIC specification [1] only indicates that a host may respond with a `CONNECTION_CLOSE` in this case.

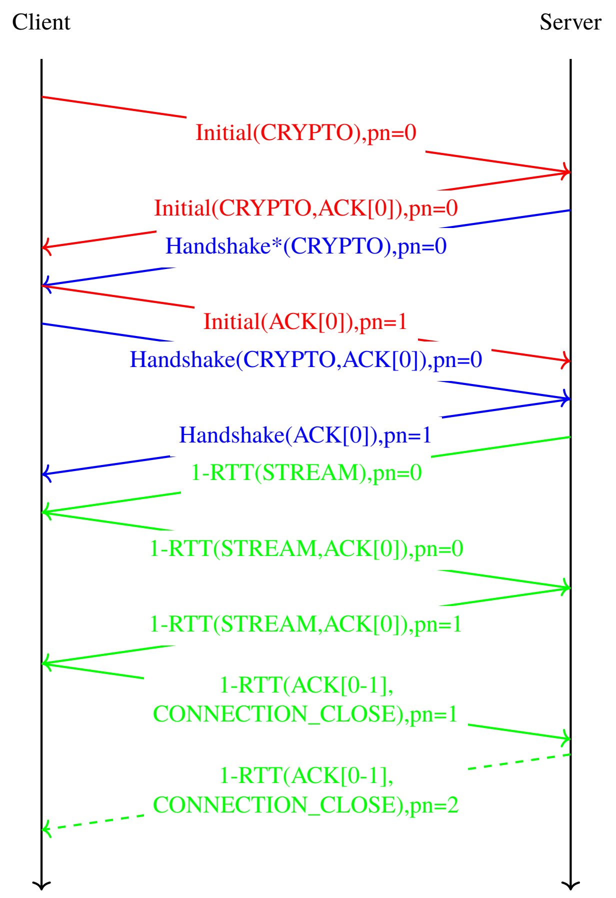
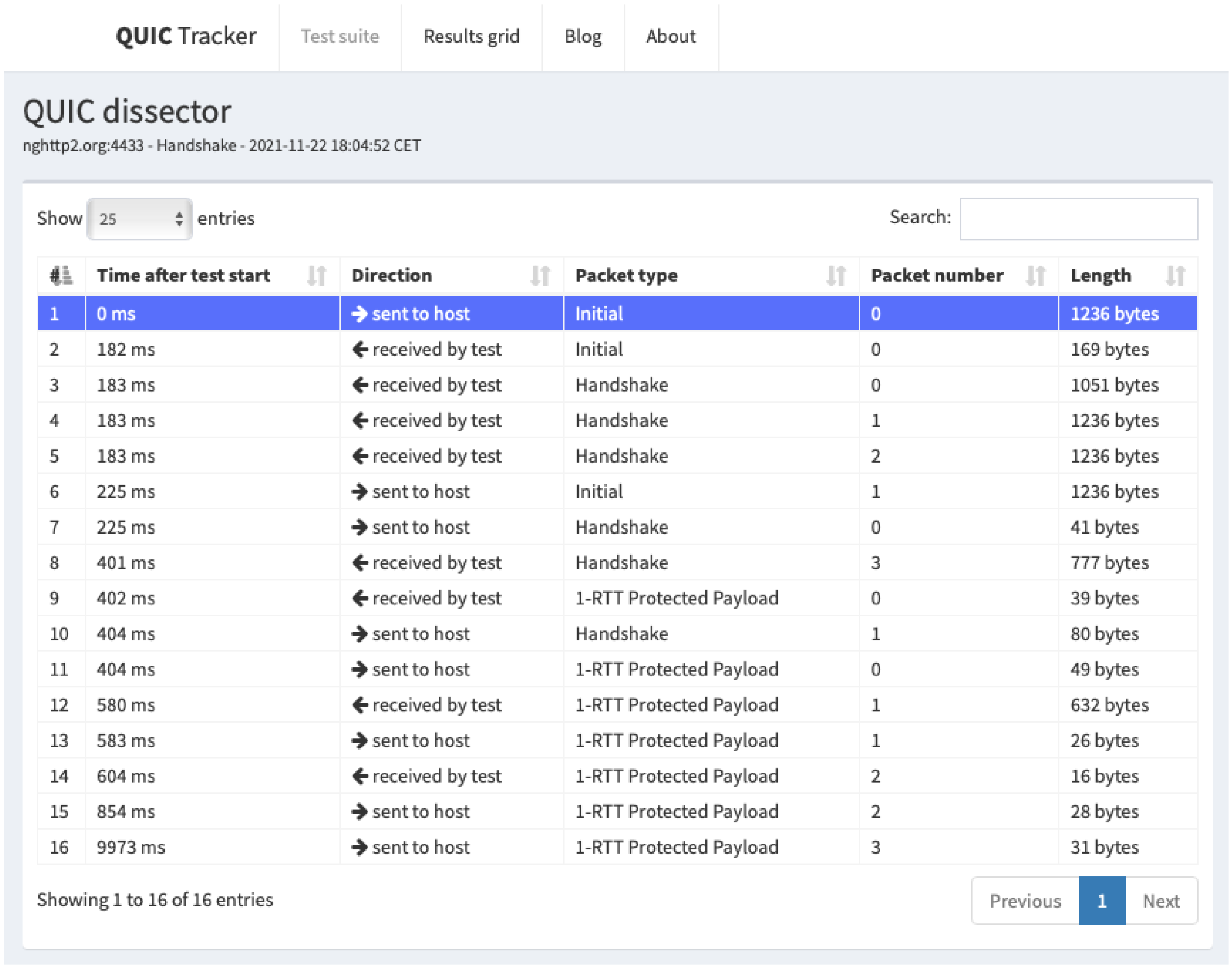


Fig. 1.14: Acknowledgments in a short QUIC connection

1.4.3 Observing QUIC connections

We have now reviewed the main components of the QUIC specification. To illustrate it, let us consider a simple scenario where a client opens a QUIC connection with a server. We leverage Maxime Piraux's QUIC tracker [22]. In this example, we use the packet trace collected using the `nghttp2.org` server on November 22, 2021 at 18:04:52 CET. This trace is available from https://quic-tracker.info.ucl.ac.be/traces/20211122/148. You can see the contents of the packets, download it as a `.pcap` trace or visualize it using QLog/QViz [23] from this web site.

This trace contains 16 packets. The scenario is a simple handshake with an exchange of data.



QUIC dissector

nghttp2.org:4433 - Handshake - 2021-11-22 18:04:52 CET

Show 25 entries   Search:

#	Time after test start	Direction	Packet type	Packet number	Length
1	0 ms	sent to host	Initial	0	1236 bytes
2	182 ms	received by test	Initial	0	169 bytes
3	183 ms	received by test	Handshake	0	1051 bytes
4	183 ms	received by test	Handshake	1	1236 bytes
5	183 ms	received by test	Handshake	2	1236 bytes
6	225 ms	sent to host	Initial	1	1236 bytes
7	225 ms	sent to host	Handshake	0	41 bytes
8	401 ms	received by test	Handshake	3	777 bytes
9	402 ms	received by test	1-RTT Protected Payload	0	39 bytes
10	404 ms	sent to host	Handshake	1	80 bytes
11	404 ms	sent to host	1-RTT Protected Payload	0	49 bytes
12	580 ms	received by test	1-RTT Protected Payload	1	632 bytes
13	583 ms	sent to host	1-RTT Protected Payload	1	26 bytes
14	604 ms	received by test	1-RTT Protected Payload	2	16 bytes
15	854 ms	sent to host	1-RTT Protected Payload	2	28 bytes
16	9973 ms	sent to host	1-RTT Protected Payload	3	31 bytes

Showing 1 to 16 of 16 entries   Previous 1 Next

Fig. 1.15: Sample QUIC tracker trace with `nghttp2.org` containing a successful handshake

To initiate the connection, the client sends an `Initial` QUIC packet. It is interesting to analyze the content of this packet. It starts with a long QUIC header shown in Listing 1.12.

Listing 1.12: The QUIC header of the first packet sent by the client

```
Long Header Packet {
  Header Form (1) = 1,
  Fixed Bit (1) = 1,
  Long Packet Type = 00,
  Type-Specific Bits (4) = 0000,
```

(continues on next page)

(continued from previous page)

```
  Version (32) = 0xff00001d,
  Destination Connection ID Length (8) = 8,
  Destination Connection ID (0..160) = 0x6114ca6ecbe483bb,
  Source Connection ID Length (8) = 8,
  Source Connection ID (0..160) = 0xc9f54d3c298296b9,
  Token Length (i) = 0,
  Length (i) = 1226,
  Packet Number (8..32) = 0,
  Packet Payload (8..) = CRYPTO,
  Type-Specific Payload (..)
}
```

The client proposes a 64 bits connection identifier and uses a random 64 bits identifier for the destination connection identifier. There is no token in this packet since this is the first connection from this client to the server. It is useful to note that the packet number of this `Initial` packet is set to zero. All QUIC connections start with a packet whose packet number is set to zero in contrast with TCP that uses a random sequence number. The packet contains a `CRYPTO` frame shown in Listing 1.13.

Listing 1.13: The CRYPTO frame of the first QUIC packet sent by the client

```
CRYPTO Frame {
   Type (i) = 0x06,
   Offset (i) = 0,
   Length (i) = 245,
   Crypto Data = ClientHello
}
```

The `CRYPTO` frame starts at offset 0 and has a length of `245` bytes. It contains a TLS 1.3 `ClientHello` message whose format is specified in [2]. This `ClientHello` includes a 32 bytes secure random number, a set of proposed cipher suites and a series of TLS extensions. One of these extensions carries the QUIC transport parameters proposed by the client. On this connection, the QUIC tracker client proposed the following ones:

- `initial_max_stream_data_bidi_local` = 0x80004000
- `initial_max_stream_data_uni` = 0x80004000
- `initial_max_data` = 0x80008000
- `initial_max_streams_bidi` = 0x1
- `initial_max_streams_uni` = 0x3
- `max_idle_timeout` = 0x6710
- `active_connection_id_limit` = 0x4
- `max_packet_size` = 0x45c0
- `inital_source_connection_id` = 0xc9f54d3c298296b9

Finally, the first QUIC packet contains a `PADDING` frame with 960 dummy bytes. The entire packet is 1236 bytes long.

The server responds to this `Initial` packet with two packets. The first one is an `Initial` packet. It starts with the header shown in Listing 1.14.

Listing 1.14: The QUIC header of the first packet sent by the client

```
Long Header Packet {
  Header Form (1) = 1,
  Fixed Bit (1) = 1,
  Long Packet Type = 10,
  Type-Specific Bits (4) = 0000,
  Version (32) = 0xff00001d,
  Destination Connection ID Length (8) = 8,
  Destination Connection ID (0..160) = 0xc9f54d3c298296b9,
  Source Connection ID Length (8) = 18,
  Source Connection ID (0..160) = 0x8d3470255ae3b0b3fad3c40515132a813dfa,
  Token Length (i) = 0,
  Length (i) = 149,
  Packet Number (8..32) = 0,
  Packet Payload (...)
}
```

This server uses 18 bytes to encode its connection identifier and proposes the first identifier in the long header. The packet payload contains two frames: an `ACK` frame and a `CRYPTO` frame. The `ACK` frame (Listing 1.15) acknowledges the reception of the `Initial` packet sent by the client. The `CRYPTO` frame contains the TLS ServerHello.

Listing 1.15: The ACK Frame of the first packet sent by the server

```
ACK Frame {
   Type (i) = 0x02,
   Largest Acknowledged = 0,
   ACK Delay = 0,
   ACK Range Count = 0,
   First ACK Range = 0
}
```

The payload of these `Initial` packets is encrypted using the static key derived from the connection identifiers included in the long header.

The server then sends three `Handshake` packets carrying a `CRYPTO` frame that contains the `TLSEncryptedExtensions`. These extensions are encrypted using the TLS key. They mainly contain the server certificate. It is interesting to note that the `packet_number` field of the first `Handshake` packet sent by the server is also set to zero. This is the second, but not the last, packet that we observe with this `packet_number`. QUIC handles packet numbers differently then other protocols. QUIC considers that a QUIC connection is divided in three phases:

1. The exchange of the `Initial` packets
2. The exchange of the `Handshake` packets
3. The exchange of the other packets (`0-RTT`, `1-RTT`, … packets)

A QUIC host restarts the `packet_number` at zero in each phase. This explains why it is possible to observe different packets (of different types) with the same `packet_number` over a QUIC connection.

The three `Handshake` packets sent by the server contain the beginning of the `TLSEncryptedExtensions` sent by the server. To prevent denial of service attacks, the server cannot send more than three full-length packets in response to a packet sent by the client. The server thus needs to wait for an acknowledgment from the client before sending additional packets.

The client sends two packets to carry these acknowledgments. First, it sends an `Initial` packet as the sixth packet of the trace. This packet belongs to the packet numbering space of the `Initial` packets. Its packet number is 1 since this is the second `Initial` packet sent by the client. The next acknowledgment is carried inside an `Handshake` packet. It acknowledges the `Handshake` packets 0-2 sent by the server. Since this is the first `Handshake` packet sent by the client, its packet number is also 0.

The server then sends the eighth packet that contains the last part of the `TLSEncryptedExtensions` in a `CRYPTO` frame. By combining the information contained in the `Handshake` packets and the `Initial` packets, the client can derive the session keys.

The server immediately sends its first `1-RTT` packet. This packet contains a short header shown in Listing 1.16.

Listing 1.16: The QUIC short header of the first 1-RTT packet sent by the server

```
1-RTT Packet {
   Header Form (1) = 0,
   Fixed Bit (1) = 1,
   Spin Bit (1) = 0,
   Reserved Bits (2)= 00,
   Key Phase (1) = 0,
   Packet Number Length (2)= 0,
   Destination Connection ID = 0xc9f54d3c298296b9,
   Packet Number = 0,
}
```

This short header contains the connection identifier proposed by the client in the first `Initial` packet. The payload contains `STREAM` frames that create three streams. The client replies with two packets. The tenth packet of the trace is a `Handshake` packet that carries two frames. The `CRYPTO` frame contains the `TLS Finished` message that finalizes the TLS handshake. The `ACK` frame acknowledges the four `Handshake` packets sent by the server.

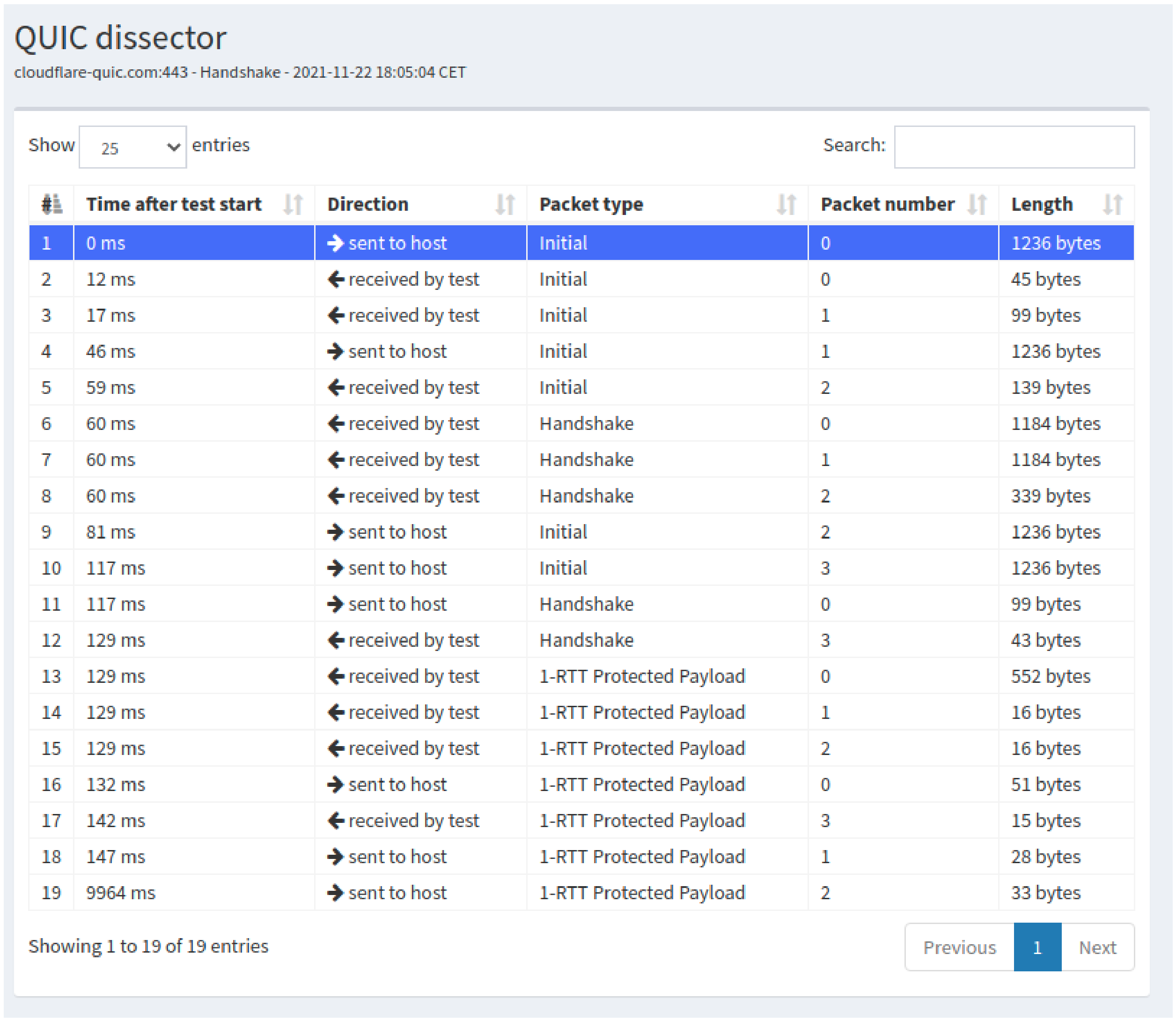
The first `1-RTT` packet sent by the client contains an `ACK` frame that acknowledges the `1-RTT` packet sent by the server and flow control information. The client sends a `MAX_DATA` frame to restrict the amount of data that the server can send and one `MAX_STREAM` frame for each of the three streams created by the server.

The twelfth packet of the trace is more interesting. It contains five different frames that are sent by the server. First, the server send two `NEW_CONNECTION_ID` frames that advertise two 18 bytes long connection identifiers which can be used by the client to migrate the connection later. The next frame is the `HANDSHAKE_DONE` frame that confirms the TLS handshake. The server also sends a `NEW_TOKEN` frame that contains a 57 bytes long token that the client will be able to use in subsequent connections with the server. The last frame is a `CRYPTO` frame that contains two `TLS New Session Tickets`.

A closer look at other QUIC handshakes

It is interesting to analyze how different servers perform the handshake using QUIC tracker. Let us first explore the trace collected with cloudflare-quic.com on the same day shown in Fig. 1.16. There are several differences with the nghttp2 trace that we analyzed above. First, the server sends two small packets in response to the client's `Initial`. The first packet only contains an `ACK` frame. It advertises a 20 bytes long connection identifier. The second packet contains a `CRYPTO` frame with a `TLS Hello Retry Request`. This message indicates that the server did not agree with the `key_share` parameter of the `TLS Client Hello` sent in the first packet. The client acknowledges this packet and sends a new `TLS Client Hello` in the fourth packet. The server replies with a `TLS Server Hello` and then the `TLSEncryptedExtensions` in three QUIC packets. The certificate used by `cloudflare-quic.com` is more compact than the one used by `nghttp2.org`.

The `1-RTT` packets are also slightly different. The first `1-RTT` packet sent by the server contains the `HANDSHAKE_DONE` frame, a `CRYPTO` frame with two `TLS New Session Ticket` messages and a `STREAM` frame that creates one stream. The server then sends two short packet. Each of these packets contains a `STREAM` frame that creates a new stream. These



QUIC dissector

cloudflare-quic.com:443 - Handshake - 2021-11-22 18:05:04 CET

Show 25 entries   Search:

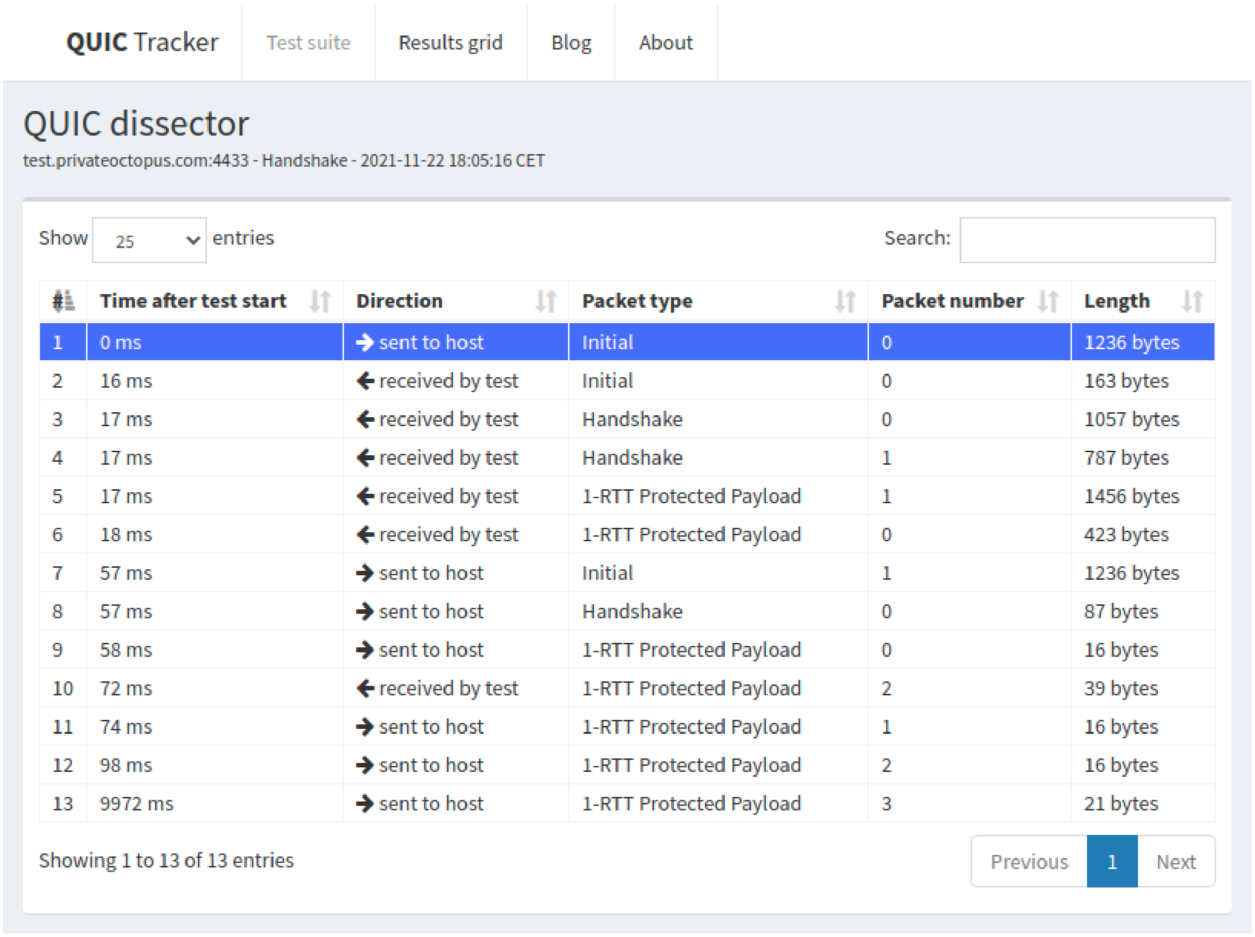
#	Time after test start	Direction	Packet type	Packet number	Length
1	0 ms	→ sent to host	Initial	0	1236 bytes
2	12 ms	← received by test	Initial	0	45 bytes
3	17 ms	← received by test	Initial	1	99 bytes
4	46 ms	→ sent to host	Initial	1	1236 bytes
5	59 ms	← received by test	Initial	2	139 bytes
6	60 ms	← received by test	Handshake	0	1184 bytes
7	60 ms	← received by test	Handshake	1	1184 bytes
8	60 ms	← received by test	Handshake	2	339 bytes
9	81 ms	→ sent to host	Initial	2	1236 bytes
10	117 ms	→ sent to host	Initial	3	1236 bytes
11	117 ms	→ sent to host	Handshake	0	99 bytes
12	129 ms	← received by test	Handshake	3	43 bytes
13	129 ms	← received by test	1-RTT Protected Payload	0	552 bytes
14	129 ms	← received by test	1-RTT Protected Payload	1	16 bytes
15	129 ms	← received by test	1-RTT Protected Payload	2	16 bytes
16	132 ms	→ sent to host	1-RTT Protected Payload	0	51 bytes
17	142 ms	← received by test	1-RTT Protected Payload	3	15 bytes
18	147 ms	→ sent to host	1-RTT Protected Payload	1	28 bytes
19	9964 ms	→ sent to host	1-RTT Protected Payload	2	33 bytes

Showing 1 to 19 of 19 entries

Fig. 1.16: Sample quic tracker trace from cloudflare-quic.com with a successful handshake

two short packets could have been packed in the first `1-RTT` packet sent by the server. In contrast with `nghttp2.org`, `cloudflare-quic.com` does advertise new connection identifiers.

Our third example is picoquic. The QUIC tracker trace with test.privateoctopus.com contains 13 packets.



QUIC dissector

test.privateoctopus.com:4433 - Handshake - 2021-11-22 18:05:16 CET

#	Time after test start	Direction	Packet type	Packet number	Length
1	0 ms	→ sent to host	Initial	0	1236 bytes
2	16 ms	← received by test	Initial	0	163 bytes
3	17 ms	← received by test	Handshake	0	1057 bytes
4	17 ms	← received by test	Handshake	1	787 bytes
5	17 ms	← received by test	1-RTT Protected Payload	1	1456 bytes
6	18 ms	← received by test	1-RTT Protected Payload	0	423 bytes
7	57 ms	→ sent to host	Initial	1	1236 bytes
8	57 ms	→ sent to host	Handshake	0	87 bytes
9	58 ms	→ sent to host	1-RTT Protected Payload	0	16 bytes
10	72 ms	← received by test	1-RTT Protected Payload	2	39 bytes
11	74 ms	→ sent to host	1-RTT Protected Payload	1	16 bytes
12	98 ms	→ sent to host	1-RTT Protected Payload	2	16 bytes
13	9972 ms	→ sent to host	1-RTT Protected Payload	3	21 bytes

Showing 1 to 13 of 13 entries

Fig. 1.17: Sample QUIC tracker trace from `test.privateoctopus.com` with a successful handshake

picoquic uses 64 bits long connection identifiers. It manages to fit its `TLS Encrypted Extensions` within two `Handshake` packets. The first `1-RTT` packet that it sends contains a `PING` frame. The second `1-RTT` packet contains one `CRYPTO` frame that advertises one `TLS New Session Ticket`, three `NEW_CONNECTION_ID` frames and a `NEW_TOKEN` frame. This test server does not try to create new streams in contrast with the two others.

Note: Comparing QUIC servers

It is interesting to use the traces collected by QUIC tracker to analyze how different servers have selected some of the optional features of QUIC. A first difference between the servers is the length of the server-selected connection identifiers. The graph below shows that in November 2021 many servers advertised 8 bytes CIDs, but some have opted for much longer CIDs.

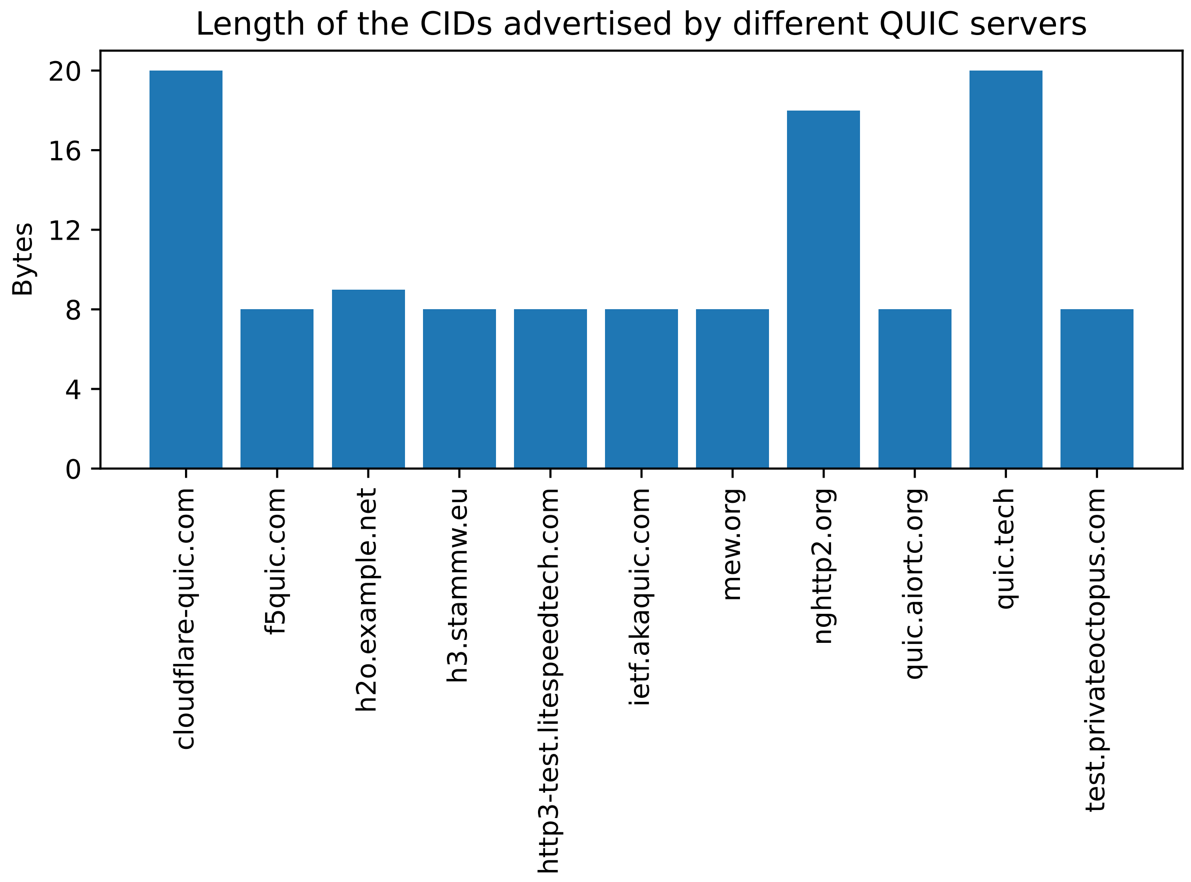
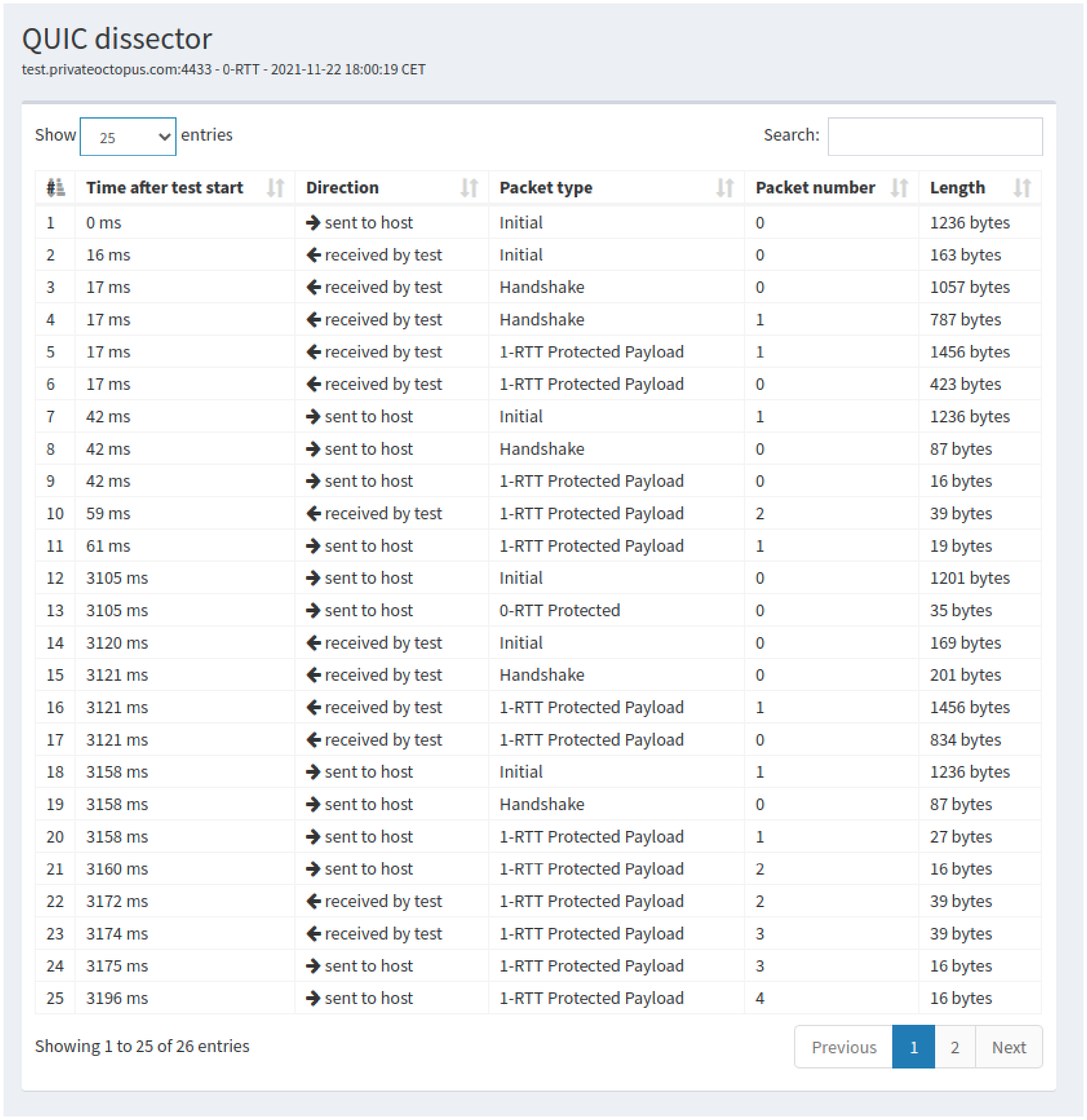


Fig. 1.18: Length of the connection identifiers advertised by different QUIC servers (Nov 2021)

Observing 0-RTT data in QUIC

The ability to send data immediately was one of the requirements for the design of QUIC. It is interesting to observe how QUIC uses the `0-RTT` packets for this purpose. We use a trace collected between QUIC tracker and picoquic as our example. This trace covers two QUIC connections shown in Fig. 1.19.

During the first QUIC connection, QUIC tracker receives one TLS session ticket in the `CRYPTO` frame contained in the 1-RTT packet that the server sent with packet number set to 0. This ticket contains all the information required by the server to retrieve the key in a subsequent connection. QUIC tracker starts the second connection by sending an `Initial` packet. This packet contains a `CRYPTO` frame that contains the `TLS Client Hello` message. A comparison between this `TLS Client Hello` and the one sent to create the first connection shows that the latter contains the `psk_key_exchange_modes` TLS extension. This extension contains the information that enables the server to recover the key required to decrypt the `0-RTT` packet. In this example, the client sends a `0-RTT` that contains the beginning of a simple `HTTP GET`.



QUIC dissector

test.privateoctopus.com:4433 - 0-RTT - 2021-11-22 18:00:19 CET

Show 25 entries

Search:

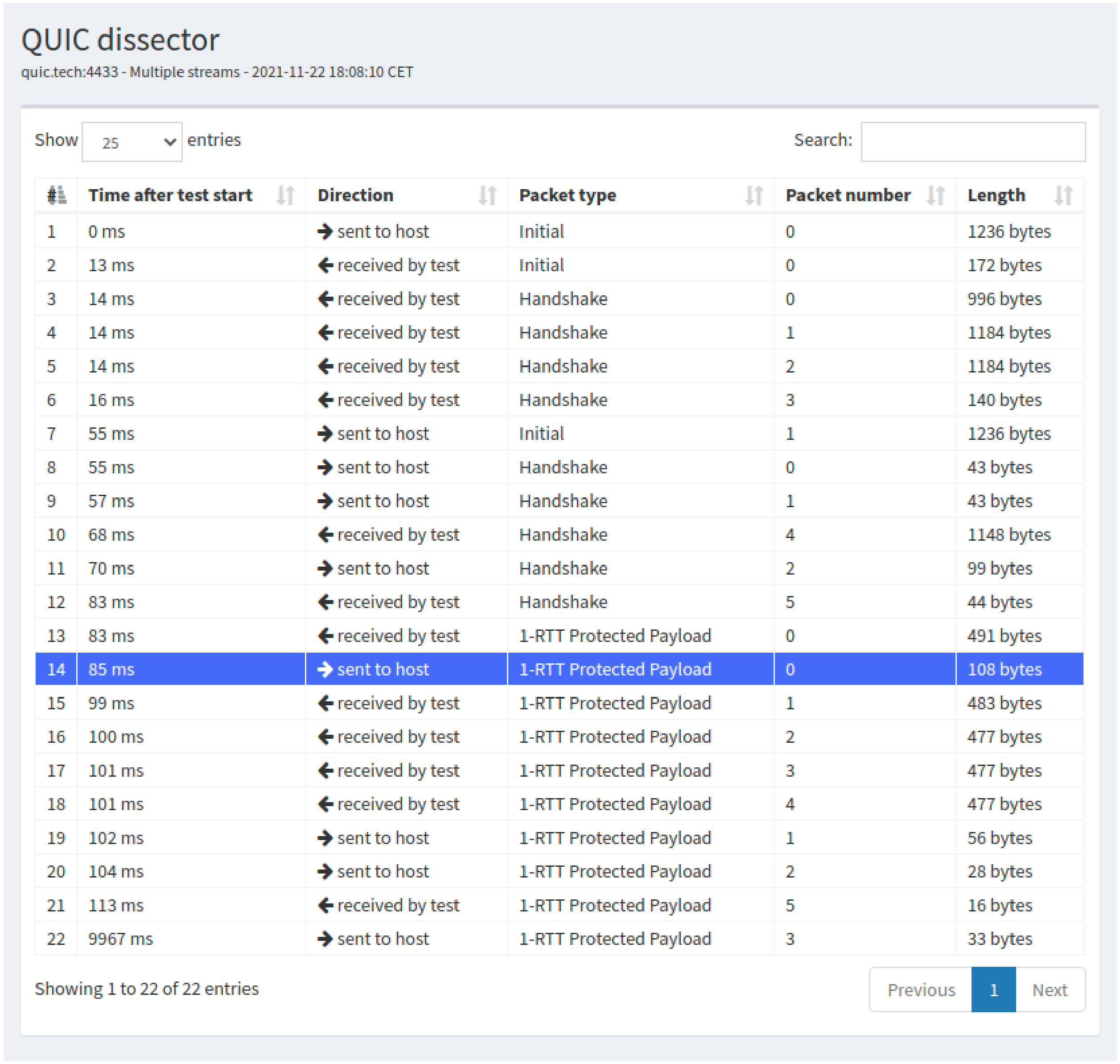
#	Time after test start	Direction	Packet type	Packet number	Length
1	0 ms	→ sent to host	Initial	0	1236 bytes
2	16 ms	← received by test	Initial	0	163 bytes
3	17 ms	← received by test	Handshake	0	1057 bytes
4	17 ms	← received by test	Handshake	1	787 bytes
5	17 ms	← received by test	1-RTT Protected Payload	1	1456 bytes
6	17 ms	← received by test	1-RTT Protected Payload	0	423 bytes
7	42 ms	→ sent to host	Initial	1	1236 bytes
8	42 ms	→ sent to host	Handshake	0	87 bytes
9	42 ms	→ sent to host	1-RTT Protected Payload	0	16 bytes
10	59 ms	← received by test	1-RTT Protected Payload	2	39 bytes
11	61 ms	→ sent to host	1-RTT Protected Payload	1	19 bytes
12	3105 ms	→ sent to host	Initial	0	1201 bytes
13	3105 ms	→ sent to host	0-RTT Protected	0	35 bytes
14	3120 ms	← received by test	Initial	0	169 bytes
15	3121 ms	← received by test	Handshake	0	201 bytes
16	3121 ms	← received by test	1-RTT Protected Payload	1	1456 bytes
17	3121 ms	← received by test	1-RTT Protected Payload	0	834 bytes
18	3158 ms	→ sent to host	Initial	1	1236 bytes
19	3158 ms	→ sent to host	Handshake	0	87 bytes
20	3158 ms	→ sent to host	1-RTT Protected Payload	1	27 bytes
21	3160 ms	→ sent to host	1-RTT Protected Payload	2	16 bytes
22	3172 ms	← received by test	1-RTT Protected Payload	2	39 bytes
23	3174 ms	← received by test	1-RTT Protected Payload	3	39 bytes
24	3175 ms	→ sent to host	1-RTT Protected Payload	3	16 bytes
25	3196 ms	→ sent to host	1-RTT Protected Payload	4	16 bytes

Showing 1 to 25 of 26 entries

Fig. 1.19: Sample QUIC trace with `test.privateoctopus.com` with 0-RTT packets

QUIC streams

As QUIC support multiple streams, it is interesting to analyze how the streams are managed over a real QUIC connection. For this example, we use a trace between QUIC tracker and quic.tech summarized in Fig. 1.20. In the example, the QUIC tracker creates four streams and sends one HTTP GET request over each of them.



QUIC dissector

quic.tech:4433 - Multiple streams - 2021-11-22 18:08:10 CET

Show 25 entries Search:

#	Time after test start	Direction	Packet type	Packet number	Length
1	0 ms	→ sent to host	Initial	0	1236 bytes
2	13 ms	← received by test	Initial	0	172 bytes
3	14 ms	← received by test	Handshake	0	996 bytes
4	14 ms	← received by test	Handshake	1	1184 bytes
5	14 ms	← received by test	Handshake	2	1184 bytes
6	16 ms	← received by test	Handshake	3	140 bytes
7	55 ms	→ sent to host	Initial	1	1236 bytes
8	55 ms	→ sent to host	Handshake	0	43 bytes
9	57 ms	→ sent to host	Handshake	1	43 bytes
10	68 ms	← received by test	Handshake	4	1148 bytes
11	70 ms	→ sent to host	Handshake	2	99 bytes
12	83 ms	← received by test	Handshake	5	44 bytes
13	83 ms	← received by test	1-RTT Protected Payload	0	491 bytes
14	85 ms	→ sent to host	1-RTT Protected Payload	0	108 bytes
15	99 ms	← received by test	1-RTT Protected Payload	1	483 bytes
16	100 ms	← received by test	1-RTT Protected Payload	2	477 bytes
17	101 ms	← received by test	1-RTT Protected Payload	3	477 bytes
18	101 ms	← received by test	1-RTT Protected Payload	4	477 bytes
19	102 ms	→ sent to host	1-RTT Protected Payload	1	56 bytes
20	104 ms	→ sent to host	1-RTT Protected Payload	2	28 bytes
21	113 ms	← received by test	1-RTT Protected Payload	5	16 bytes
22	9967 ms	→ sent to host	1-RTT Protected Payload	3	33 bytes

Showing 1 to 22 of 22 entries

Fig. 1.20: Sample QUIC trace with quic.tech using multiple streams

In this trace, the client creates four streams in its first `STREAM` frame sent in the first `1-RTT` packet. Listing 1.17 shows the first of these `STREAM` frames. The `Type` of the `STREAM` is one octet structured as `0b00001OLF` where `O` is set to 1 if the `STREAM` frame contains an `Offset` field. Bit `L` is set to 1 if the frame contains a `Length` field. Finally, the `F` is set to 1 to mark the end of the `STREAM`. In this test, QUIC Tracker sends 17 bytes over each stream and closes it.

Listing 1.17: The first QUIC STREAM frame sent by QUIC Tracker

```
STREAM Frame {
   Type (i) = 0b00001011,  # Offset=0, Length=1, FIN=1
   Stream ID = 8,
   Length = 17,
   Stream Data = GET /index.html\r\n
}
```

The server sends each response in a `STREAM` frame. Listing 1.18 shows the frame returned by the server. Its `Offset` bit is set to 1. It carries the entire HTML page and its `Offset` field could have been ignored since this is the first frame of the stream.

Listing 1.18: The QUIC STREAM frame returned by the server

```
STREAM Frame {
   Type (i) = 0b00001111,  # Offset=1, Length=1, FIN=1
   Stream ID = 8,
   Offset = 0,
   Length = 462,
   Stream Data = <!DOCTYPE html>...
}
```

CHAPTER

TWO

QUIC CONNECTION MIGRATION

As explained in *QUIC*, QUIC uses connection identifiers. These connection identifiers are used for different purposes. On the server side, they were initially proposed to allow load-balancers to spread the packets of different connections to different servers without having to maintain any state. In addition, QUIC ‘s connection identifiers also enable clients to migrate connections from one path to another or even on the same path.

QUIC connection migrations occur in two steps. As an example, we consider client triggered migrations. These are the most important from a deployment viewpoint. A client can decide to migrate its connection for various reasons, including privacy and performance. A common scenario is a smartphone that moves and goes progressively out of reach of its Wi-Fi access point. When the smartphone notices a decrease in performance of the Wi-Fi network (lower signal to noise ratio, more losses or retransmissions, . . .), it can decide to migrate the QUIC connection over the cellular interface. A naive solution would be to simply move the QUIC packets from one interface to another using the same connection identifiers. This is illustrated in Fig. 2.1. The QUIC connection was established from the client IP address, IP_α, to the server's IP address, IP_S. The first two packets show a simple exchange over this connection. Before sending its second packet, the client decides to switch to the cellular interface. This interface is illustrated in red and its IP address is IP_β. Unfortunately, this naive approach is not secure. Consider a server that receives a QUIC packet from

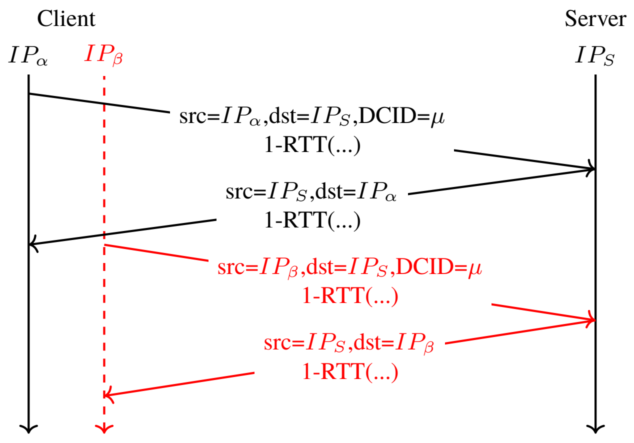

Client
Server
IP_α
IP_β
IP_S
src=IP_α,dst=IP_S,DCID=μ
1-RTT(...)
src=IP_S,dst=IP_α
1-RTT(...)
src=IP_β,dst=IP_S,DCID=μ
1-RTT(...)
src=IP_S,dst=IP_β
1-RTT(...)

Fig. 2.1: A naive approach to migrate a QUIC connection from Wi-Fi to cellular

the smartphone's cellular interface. This packet originates from a different IP address, but contains the same connection identifier. If the server accepts this packet and decides to reply over the cellular path, this creates several security risks. First, consider an attacker who managed to capture a packet sent by the client over the Wi-Fi network. By sending again this unmodified QUIC packet from its own IP address, the attacker could disrupt the ongoing connection by forcing the server to send replies to its own IP address. Furthermore, this also opens a risk of denial of service attacks if the packet copied by the attacker contains a request for a large object. QUIC copes with these problems by using path-specific connection identifiers and the path validation mechanism.

A QUIC connection identifier is always bound to a specific IP address. When a QUIC host receives a QUIC packet, it verifies that the packet originates from the associated source. The QUIC specification does not prescribe how this verification can be done, but a simple approach is to encode a hash of the source IP address inside the connection identifier.

When a QUIC connection starts the server verifies that the client receives the packets that it sends to prevent attacks from spoofed addresses. This verification is part of the handshake and may in some cases involve the utilization of `RETRY` packets. Consider a malicious client using address IP_α but wishes to create a denial of service attack against address IP_μ. This client could initiate a connection with a server using address IP_α, request a large object and send a packet spoofing address IP_μ to force the server to send all reply packets to the victim. To cope with this attack, a QUIC server must first validate a new client address before sending a large number of packets. To validate a new client address, the server simply needs to send a `PATH_CHALLENGE` frame that contains a random number. This frame is encrypted using the connection keys, like all QUIC frames. Upon reception of this frame, the client can extract the random number and return it in a `PATH_RESPONSE` frame to the server. Upon reception of this frame, the server has the confirmation that the client can also receive packets on the new address and thus it can safely be used. The client can also validate a path as shown below.

To enable a client to migrate a QUIC connection, the server must first advertise at least one different connection identifier. This is done with the `NEW_CONNECTION_ID` frame. The client uses the additional connection identifier advertised by the server to try to move the connection to a new path. The client cannot use a new path before having the guarantee that the server can reply over the new path. To verify that the new path is bidirectional, the client sends a `PATH_CHALLENGE` frame in a QUIC packet that uses the new connection identifier over the new path. This frame mainly contains a 64 bits random nonce that must be echoed by the server. It also includes some padding to check the path's MTU as done during the handshake. Upon reception of this packet, the server detects an attempt to use a new path with the new connection identifier. It replies with a `PATH_RESPONSE` frame that echoes the client nonce. The server may also perform its own path validation by sending a `PATH_CHALLENGE` with a different nonce in the same packet as the `PATH_RESPONSE`. The client considers that the path has been validated upon reception of the valid `PATH_RESPONSE` frame. The packets that contain the `PATH_CHALLENGE` and `PATH_RESPONSE` frames are usually padded with `PADDING` frames. The client then switches to the new connection identifier and the new path for all the frames that it sends. It may still continue to receive packets over the former path for some time. The server will switch to the new path once it has received a response to its `PATH_CHALLENGE` if it decided to validate the new path. Otherwise, the reception of a QUIC packet that contains other frames than `PATH_CHALLENGE`, `PATH_RESPONSE`, `NEW_CONNECTION_ID` or `PADDING` also indicates that the path is active. The client could send a `NEW_CONNECTION_ID` frame together with the `PATH_CHALLENGE` frame if the client uses a non-null connection identifier and it has not sent a `NEW_CONNECTION_ID` frame before. This is illustrated in Fig. 2.2. The examples above showed a connection that migrates from one network

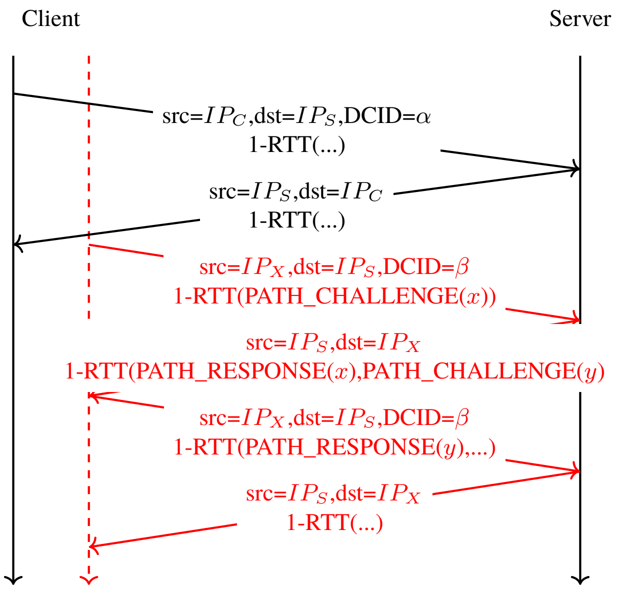

Client
Server
src=IP_C,dst=IP_S,DCID=α
1-RTT(...)
src=IP_S,dst=IP_C
1-RTT(...)
src=IP_X,dst=IP_S,DCID=β
1-RTT(PATH_CHALLENGE(x))
src=IP_S,dst=IP_X
1-RTT(PATH_RESPONSE(x),PATH_CHALLENGE(y)
src=IP_X,dst=IP_S,DCID=β
1-RTT(PATH_RESPONSE(y),...)
src=IP_S,dst=IP_X
1-RTT(...)

Fig. 2.2: A QUIC connection migration initiated by the client

interface to another. This is expected to be a frequent situation for smartphones that move. However, there are also scenarios where the client can trigger a connection migration even if it uses a single network interface. First, the client application can decide to migrate its QUIC connection every n minutes. This could be useful for an application that provides a VPN-like service as proposed [24]. By regularly changing their connection identifiers, such VPN services could prevent some middleboxes from detecting and blocking them. Another scenario are the unintended migrations caused by NAT.

Note: Unintended QUIC connection migrations

We have described how QUIC clients can trigger connection migrations. There are situations when connection migration occurs without being triggered by the client. A classical example is when there is a NAT on the path between the client and the server. The QUIC connection has been idle for some time and the NAT has removed the mapping from the client's private IP address to a public one. When the client sends the next packet over the connection, the NAT creates a new mapping and thus assigns a different IP address to the client. The server receives a packet that uses the same connection identifier but comes from a different IP address than the initial one. This is illustrated in Fig. 2.3. Upon reception of the QUIC packet coming from the new IP address (shown in red in Fig. 2.3, the server triggers a path validation. Once the path has been validated, the QUIC connection can continue.

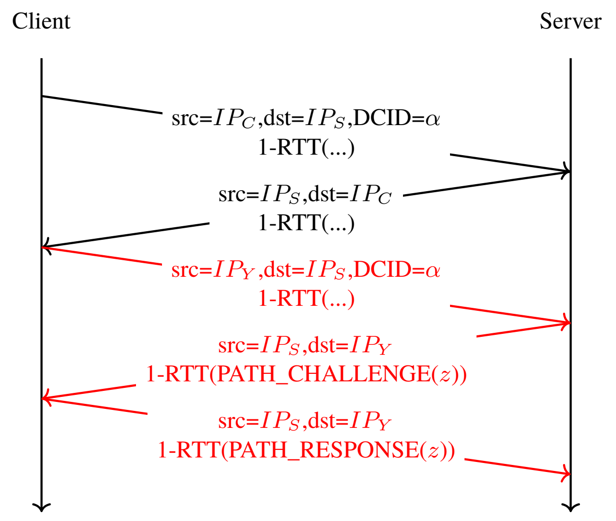

Client
Server
src=IP_C,dst=IP_S,DCID=α
1-RTT(...)
src=IP_S,dst=IP_C
1-RTT(...)
src=IP_Y,dst=IP_S,DCID=α
1-RTT(...)
src=IP_S,dst=IP_Y
1-RTT(PATH_CHALLENGE(z))
src=IP_S,dst=IP_Y
1-RTT(PATH_RESPONSE(z))

Fig. 2.3: A QUIC connection migration triggered by a NAT

The previous examples have shown that a client can trigger a connection migration to improve performance or for privacy reasons. Our examples have considered that the clients can use different IP addresses while the servers have a stable IP address. This corresponds to most deployments, but not all of them. Today, many servers are dual-stack. They support both IPv4 and IPv6. When a client starts a QUIC connection over one address family, it could be useful for the client to learn the other server address to be able to switch to this address if the other fails. Another interesting type of deployments are the server farms where each server has both an anycast address and a unicast one. All servers use the same anycast address and this address is the one advertised using the DNS. When a client initiates a QUIC connection, it targets the anycast address. The `Initial` QUIC packet is load-balanced to one of the servers of the farm and all subsequent packets of this connection are load-balanced to the same server. In this deployment, all packets must be processed by the load-balancer before reaching the server. When the load is high, the load-balancer could become a bottleneck and it would be useful to allow QUIC connections to migrate to the unicast address of their servers since unicast address bypasses the load-balancer. The first version of QUIC provides partial support for this bypass by allowing the server to advertise its preferred unicast addresses (IPv4 and IPv6) using the `preferred_address` transport parameter during the handshake. However, according to QUIC specification [1], a client SHOULD, but is not forced to, migrate to one of the preferred addresses announced by the server. This migration can only be triggered by the client, there is no way for the server to impose a migration.

CHAPTER

THREE

BIBLIOGRAPHY

CHAPTER

FOUR

INDICES AND TABLES

- genindex
- modindex
- search

BIBLIOGRAPHY

[1] J. Iyengar (Ed.) and M. Thomson (Ed.). QUIC: A UDP-Based Multiplexed and Secure Transport. RFC 9000 (Proposed Standard), May 2021. URL: https://www.rfc-editor.org/rfc/rfc9000.txt, doi:10.17487/RFC9000.

[2] E. Rescorla. The Transport Layer Security (TLS) Protocol Version 1.3. RFC 8446 (Proposed Standard), August 2018. URL: https://www.rfc-editor.org/rfc/rfc8446.txt, doi:10.17487/RFC8446.

[3] Tommy Pauly, Eric Kinnear, and David Schinazi. An Unreliable Datagram Extension to QUIC. Internet-Draft draft-ietf-quic-datagram-06, Internet Engineering Task Force, October 2021. Work in Progress. URL: https://datatracker.ietf.org/doc/html/draft-ietf-quic-datagram-06.

[4] Runa Barik, Michael Welzl, Gorry Fairhurst, Ahmed Elmokashfi, Thomas Dreibholz, and Stein Gjessing. On the usability of transport protocols other than tcp: a home gateway and internet path traversal study. *Computer Networks*, 173:107211, 2020.

[5] Willem de Bruijn and Eric Dumazet. Optimizing udp for content delivery: gso, pacing and zerocopy. In *Linux Plumbers Conference*. 2018.

[6] P. Ferguson and D. Senie. Network Ingress Filtering: Defeating Denial of Service Attacks which employ IP Source Address Spoofing. RFC 2827 (Best Current Practice), May 2000. Updated by RFC 3704. URL: https://www.rfc-editor.org/rfc/rfc2827.txt, doi:10.17487/RFC2827.

[7] Matthew Luckie, Robert Beverly, Ryan Koga, Ken Keys, Joshua A Kroll, and K Claffy. Network hygiene, incentives, and regulation: deployment of source address validation in the internet. In *Proceedings of the 2019 ACM SIGSAC Conference on Computer and Communications Security*, 465–480. 2019.

[8] M. Thomson (Ed.) and S. Turner (Ed.). Using TLS to Secure QUIC. RFC 9001 (Proposed Standard), May 2021. URL: https://www.rfc-editor.org/rfc/rfc9001.txt, doi:10.17487/RFC9001.

[9] D. Borman, B. Braden, V. Jacobson, and R. Scheffenegger (Ed.). TCP Extensions for High Performance. RFC 7323 (Proposed Standard), September 2014. URL: https://www.rfc-editor.org/rfc/rfc7323.txt, doi:10.17487/RFC7323.

[10] C. MacCarthaigh. Security review of TLS1.3 0-RTT. https://github.com/tlswg/tls13-spec/issues/1001.

[11] F. Audet (Ed.) and C. Jennings. Network Address Translation (NAT) Behavioral Requirements for Unicast UDP. RFC 4787 (Best Current Practice), January 2007. Updated by RFCs 6888, 7857. URL: https://www.rfc-editor.org/rfc/rfc4787.txt, doi:10.17487/RFC4787.

[12] Philipp Richter, Florian Wohlfart, Narseo Vallina-Rodriguez, Mark Allman, Randy Bush, Anja Feldmann, Christian Kreibich, Nicholas Weaver, and Vern Paxson. A multi-perspective analysis of carrier-grade nat deployment. In *Proceedings of the 2016 Internet Measurement Conference*, 215–229. 2016.

[13] Seppo Hätönen, Aki Nyrhinen, Lars Eggert, Stephen Strowes, Pasi Sarolahti, and Markku Kojo. An experimental study of home gateway characteristics. In *Proceedings of the 10th ACM SIGCOMM conference on Internet measurement*, 260–266. 2010.

[14] Robin Marx, Joris Herbots, Wim Lamotte, and Peter Quax. Same standards, different decisions: a study of quic and http/3 implementation diversity. In *Proceedings of the Workshop on the Evolution, Performance, and Interoperability of QUIC*, 14–20. 2020.

[15] Jeffrey Semke, Jamshid Mahdavi, and Matthew Mathis. Automatic tcp buffer tuning. In *Proceedings of the ACM SIGCOMM'98 conference on Applications, technologies, architectures, and protocols for computer communication*, 315–323. 1998.

[16] Jonathan Stone, Michael Greenwald, Craig Partridge, and James Hughes. Performance of checksums and crcs over real data. *IEEE/ACM Transactions on Networking*, 6(5):529–543, 1998.

[17] Phil Karn and Craig Partridge. Improving round-trip time estimates in reliable transport protocols. *ACM SIGCOMM Computer Communication Review*, 17(5):2–7, 1987.

[18] M. Mathis, J. Mahdavi, S. Floyd, and A. Romanow. TCP Selective Acknowledgment Options. RFC 2018 (Proposed Standard), October 1996. URL: https://www.rfc-editor.org/rfc/rfc2018.txt, doi:10.17487/RFC2018.

[19] Jana Iyengar and Ian Swett. QUIC Acknowledgement Frequency. Internet-Draft draft-ietf-quic-ack-frequency-01, Internet Engineering Task Force, October 2021. Work in Progress. URL: https://datatracker.ietf.org/doc/html/draft-ietf-quic-ack-frequency-01.

[20] K. Ramakrishnan, S. Floyd, and D. Black. The Addition of Explicit Congestion Notification (ECN) to IP. RFC 3168 (Proposed Standard), September 2001. Updated by RFCs 4301, 6040, 8311. URL: https://www.rfc-editor.org/rfc/rfc3168.txt, doi:10.17487/RFC3168.

[21] Anna Maria Mandalari, Andra Lutu, Bob Briscoe, Marcelo Bagnulo, and Ozgu Alay. Measuring ecn++: good news for++, bad news for ecn over mobile. *IEEE Communications Magazine*, 56(3):180–186, 2018.

[22] Maxime Piraux, Quentin De Coninck, and Olivier Bonaventure. Observing the evolution of quic implementations. In *Proceedings of the Workshop on the Evolution, Performance, and Interoperability of QUIC*, 8–14. 2018.

[23] Robin Marx, Maxime Piraux, Peter Quax, and Wim Lamotte. Debugging quic and http/3 with qlog and qvis. In *Proceedings of the Applied Networking Research Workshop*, 58–66. 2020.

[24] Quentin De Coninck, François Michel, Maxime Piraux, Florentin Rochet, Thomas Given-Wilson, Axel Legay, Olivier Pereira, and Olivier Bonaventure. Pluginizing quic. In *Proceedings of the ACM Special Interest Group on Data Communication*, pages 59–74. 2019.