Understanding QUIC

John Dellaverson, Tianxiang Li, Yanrong Wang, Jana Iyengar, Alexander Afanasyev, Lixia Zhang

ABSTRACT

QUIC represents the latest transport protocol development with the potential to replace TCP over time. Instead of describing the QUIC operations mechanically by enumerating, step-by-step, how it works, this paper aims to *explain* QUIC from the core ideas that its design is based on. We first describe TCP, the most widely used transport protocol so far, to explain the basic functions performed by a transport protocol and observed issues, and discuss the insights learned from the design of a few other transport protocols. Then, we describe the design of QUIC in detail and focus on the fundamental underpinnings of its most important concepts, and demonstrate how it effectively addresses the identified issues in the existing transport protocols.

1 INTRODUCTION

QUIC is the latest transport protocol with a big uptake. Some people predict that QUIC may eventually replace TCP over time [12]. However, QUIC specs are long and largely describe the protocol operations without necessarily explaining why. For many people who want to learn about QUIC quickly, directly diving into the QUIC specifications does not seem an effective means to reach the goal. This writeup aims to offer a comprehensive and insightful look into QUIC.

QUIC looks very different from TCP that people are familiar with, but exactly what are the differences? And more importantly, why are these differences? Where did the new ideas come from? We note that the QUIC design and development are still in progress, therefore various specific aspects are likely to change in near future. Nevertheless, we expect that the core elements focused on by the paper will remain part of the protocol.

We begin our explanation by examining TCP first, the issues that have been identified, and the lessons learned from years of transport protocol designs (§2). Then, we move into examining the QUIC protocol itself, separated into QUIC connections (§3), QUIC packets (§4), QUIC recovery (§5), QUIC security (§6), and application over QUIC (§7). Finally, we investigate some of the remaining challenges facing both QUIC and future transport protocols in general (§8).

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2 TRANSPORT PROTOCOL 101

In this section, we use TCP as an example to identify the set of basic functions a (unicast) transport protocol must support. People familiar with TCP may skip §2.1 and §2.2 to go directly to §2.3 which describes a few other transport protocols that the QUIC design draws lessons from.

2.1 TCP

To provide reliable data delivery service between two endpoints, every data piece must be uniquely identified, allowing the two ends to figure out whether all the data pieces have been delivered. All transport protocols achieve this goal by first defining a unique connection identifier, and within the connection assigning each data unit a unique identifier, which is a monotonically increasing sequence number in general. With monotonically increasing sequence numbers, the receiver can inform the sender of all the data it has received up to Seq# n by a simple cumulative acknowledgment $ACK(n)$.

TCP uses the combination of the two endpoints' IP addresses and port numbers to create a globally unique connection identifier. However, the use of IP addresses as part of the connection ID makes a TCP connection fragile – it breaks whenever any end changes its IP address. As we show in §3.1, QUIC fixes this problem by replacing the two IP addresses with two unique numbers randomly drawn by each of the two ends.

As a transport protocol, TCP performs the following three basic functions. First, TCP supports the demultiplexing of data. With the usage of port numbers, multiple TCP applications can run at the same time and each application can only receive packets that are intended for it. Second, TCP supports reliable byte stream delivery with window-based flow control. To achieve reliable data delivery, an identifier for each data piece is needed and a reliable connection setup process is used to let both ends agree on the initial sequence number used in a connection. Third, TCP supports congestion control to limit the number of packets in the network.

For connection setup, note that the initiating end can start sending data with the third handshake message, thus there is just one round trip delay. As shown in §3.2, QUIC's initial connection setup follows a similar step, except that TCP uses this RTT just to reach an agreement on an initial sequence number for each sender, while QUIC also establishes a security association.

2.2 TCP's Problems

1. Head of line blocking (HLB): TCP uses window-based flow control with sequential delivery. If a single data piece D is lost, all the subsequent packets that later arrive will be blocked from being delivered to the application until D has been recovered. For instance, in Fig. 1 packet 2 has been delivered to the receiver but packet 1 is lost during transit. Due to sequential delivery, the data of packet 2 cannot be delivered to the application until packet 1 has been retransmitted and received. So in TCP, the loss of one single packet will block the delivery of all subsequent packets until the loss packet has been recovered.

Figure 1: TCP Head of Line Blocking.

2. Congestion control (CC): CC function was patched onto TCP by borrowing the same window mechanism used for flow-control mentioned above. CC's goal is to control the number of packets *inside the network*, N. However whenever any packets are lost, the window adjustment is constrained by waiting for recovery of the lost packets, even when the majority of the packets within the window have been delivered to the receiver node. Therefore the flow control window size no longer reflects the value of N, and the patches of "window inflation, deflation" are applied to mitigate this problem, with limited effectiveness.

3. IP address changes can occur due to host multihoming, or mobility, and/or change of NAT. Because TCP uses the two endpoints' IP addresses and port numbers as the connection identifier, so any change in the IP address would break the existing connection and a new 3-way handshake is required to set up a new one.

4. Cost of 3-way handshake: Without the support of connection context reuse, every time an endpoint wants to communicate with another host, a 3-way handshake is required before application data can be sent. Because TCP lacks the built-in support of security, another 1-RTT is required if TLS is used to secure the channel.

5. Expressiveness of control: TCP packs all non-data-related communication between the two ends into the same 20-byte TCP header: setup, tear down; ACK; and connection reset. When new info needs to be communicated, e.g., SACK, it has to be squeezed into the TCP header option which is limited to 20 bytes max.

2.3 Other Transport Protocols

Although TCP has been the dominant transport protocol in use by far, several other transport protocols were also developed over the years, each filling some needs missing from TCP.

2.3.1 ***T/TCP****.* T/TCP: Transaction TCP[2], which was developed to mitigate TCP's limitation-4 identified above, by keeping the connection state after the initial establishment. Keeping a persistent connection state adds additional system memory cost, but avoids the 3-way handshake for subsequent short transactions, which may be separated by long idle time periods in between.

2.3.2 ***RTP****.* UDP [13] can be viewed as a NO-OP transport protocol other than using port numbers to demultiplex incoming packets to intended processes, and an optional checksum. However, UDP does offer a likely unnoticed but a rather important advantage: it allows applications to control what data to be packaged into each IP packet, thus enabling the realization of the *application data unit (ADU)* [4].

Real-time Transport Protocol (RTP) [6] is the first widely used transport protocol that runs over UDP, resulting in RTP implementation being *outside the kernel*, allowing RTP to be tightly integrated with apps, and app implementations to utilize ADU.

Transport protocols have traditionally been put in the kernel, one reason is for performance efficiency. Every coin has two sides, here the other side of the story is the lack of control on the data packets and difficulty in making protocol changes. QUIC adopted RTP's way of running over UDP so that it is outside the kernel and supports ADUs.

2.3.3 ***SCTP****.* The design of SCTP [15] preceded QUIC by 10+ years. Its design addresses three of the identified TCP issues.

For **issue #1** HLB, SCTP defines multiple data substreams within a single SCTP connection. This removed the head-of-line blocking problem *between* the data of different substreams, confining the problem to be with each substream which still needs in-order delivery. As we will see in §4.2, QUIC adopted this multi-substream approach to address head-of-line blocking as well. However, SCTP did not fully address the HLB problem: because the whole connection uses one TSN (Transmission Sequence Number) which is used for both reliable delivery and congestion control, it suffers a similar problem as TCP.

SCTP only partially addressed **TCP issue #3** on IP address changes: each end of a SCTP connection (called an association) can have multiple IP addresses, and the set may change.

Nevertheless, SCTP connection identifiers are still bound to IP addresses.

In addressing **issue #5**, SCTP defined multiple *typed chunks*, each chunk with its own header; multiple chunks can be packed into a single SCTP packet within the MTU limit. Each connection command is defined as a separate control chunk; application data are put into data chunks as ADUs, each identified by [stream ID, stream seq#].[1] This design gives SCTP flexibility of defining new connection management options simply by adding a new chunk type, and the SACK chunk is no longer limited by space. QUIC adopted this approach of typed chunks to carry control and data but changed the terminology from *chunk* to *frame*.

2.4 Secure Transport Protocols: TLS and DTLS

Internet applications need crypto protection, which got patched onto the existing transport protocol.

The Transport Layer Security (TLS) protocol is a cryptographic protocol, built upon TCP, designed to provide authenticity and confidentially protection between two communicating peers [14]. TLS runs in the user space and relies on TCP to provide reliable delivery for its own structured data units used for data encryption. Applications can use TLS to send data to the other endpoint, and TLS will encrypt the data and protect it from tampering with. A handshake process is required for TLS to establish parameters to protect a connection before application data can be sent.

Datagram Transport Layer Security (DTLS) protocol [5] is an application protocol based on TLS that is designed for securing datagram-based applications.

2.5 Summary: Transport Protocol Functions over IP

Below we summarize the functions that a transport protocol running over IP should be able to provide:

- **Globally unique connection ID** that binds the two ends of the connection, wishes to be IP address independent but must map to IP addresses reliably.
- **Unique data identifier** that must be reliably exchanged with the other end.
- **Window flow control for reliable delivery**; wish to avoid the head-of-line blocking problem.
- **Using port numbers for demux** inside a host.
- **Congestion control**:[2] needs to control the number of packets inside the network.
- **Control information exchange** between the two ends; wish to have flexibility in defining new control messages.
- **Securing the connection**.[3]

3 QUIC CONNECTION

QUIC is a transport protocol originally designed by Google to improve transport performance for encrypted traffic and to enable rapid deployment and continued evolution of transport mechanisms. [3] QUIC uses UDP as an underlying protocol and its implementation runs in the user space, making it easy for future updates without having to wait for a kernel upgrade. Learning the lessons from previous protocol designs, QUIC addressed TCP's problems identified in §2.2. A QUIC connection is a shared state between a client and a server, which always starts with a handshake process and during which the two endpoints establish the parameters for the connection [7].

3.1 Connection ID

QUIC uses the combination of two numbers, one selected by each end, to form a pair of connection IDs. The connection ID (CID) acts as a unique identifier for the connection, which is used to ensure that changes in addressing at lower protocol layers will not cause packets to be delivered to a wrong recipient. By using the connection ID, QUIC supports the demultiplexing ability similar to the functionality provided by TCP.

Related RFC: QUIC-TRANSPORT[7] §5 Connections.

3.2 QUIC Handshake

QUIC combines transport and cryptographic handshakes together, acquiring the information necessary for both in 1-RTT. More specifically, this entails doing an authenticated TLS 1.3 key exchange along with an authenticated transport parameters exchange at the same time. This minimizes the latency necessary to set up a secured connection. Whereas conventional TCP keeps security and transport parameter exchanges separate, requiring at least 2 RTTs to set up a secure connection.

QUIC uses the Initial packet to negotiate the connection IDs for a new connection. Each endpoint will populate the Source Connection ID field with its chosen value in its Initial

[1] Note that stream seq# identifies a data chunk given by the application, therefore SCTP has to handle data chunk fragmentation and reassembly, as in contrast to TCP's byte stream data model, thus TCP can chop off a segment at any byte boundary.

[2] Ideally CC should be a network layer function, it landed on TCP because IP is open-loop and thus has no effective means to control packet transmission.

[3] To be more specific, people currently view encrypted connections as *network security*, although TLL encrypted channels provide only data confidentiality; remote party authenticity and trust are managed through third-party certificate authorities (CAs).

packet and that ID will be used by the other endpoint to set the Destination Connection ID when sending future packets. Upon receiving an Initial packet, a server can optionally choose to verify a client's address by sending a Retry packet containing a random token, which should be repeated by the client in a new Initial packet to continue the handshake process. TLS 1.3 handshakes messages are also embedded in these Initial packets, which could establish a shared secret to protect the confidentiality and authenticity of future packets in 1-RTT. The chosen connection IDs will be included in the QUIC transport parameters, which will be authenticated during the TLS handshake process. With the negotiation of connection IDs, QUIC supports the reliable setup of a new connection similar to the functionality provided by TCP.

QUIC allows a client to send 0-RTT encrypted application data in its first packet to the server by reusing the negotiated parameters from a previous connection and a TLS 1.3 pre-shared key (PSK) identity issued by the server, though these 0-RTT data are not protected against replay attack. By supporting sending 0-RTT data, QUIC is also able to handle use cases where T/TCP is required. More detail about the cryptographic part of the handshake process is discussed in §6.1.

Related RFC: QUIC-TRANSPORT[7] §7 Cryptographic and Transport Handshake and §8 Address Validation, The Transport Layer Security (TLS) Protocol Version 1.3 [14] §2 Protocol Overview and §4 Handshake Protocol.

3.3 Connection Migration

Unlike TCP where the combination of the two endpoints' IP addresses and port numbers are used as the connection identifier, QUIC connection has the ability to survive changes in underlying protocol addresses with the usage of Connection ID. After a network change, a migrating endpoint can send a packet with previously established connection IDs using its new address to initialize the connection migration process. After the other endpoint received that packet, it will perform path validation to verify the peer's ownership of the new address by sending a special challenge frame containing some random data to the peer's new address and waiting for an echoed response with the same data, and the two endpoints can continue to exchange data after the verification of the new address. To prevent a passive observer from correlating the activity of an endpoint between different network paths, a QUIC endpoint can provide its peer with alternative connection IDs in advance and a migrating endpoint can use different connection IDs when sending data from different addresses.

QUIC also allows a server to accept connections on one IP address and ask the client to migrate to a new server address by using the transport parameters to convey its preferred address during the handshake process. After the handshake is confirmed, the client will perform a path validation on the server's preferred address, and once it succeeds, it will send all future packets to the new server address.

Related RFC: QUIC-TRANSPORT[7] §8 Address Validation and §9 Connection Migration.

4 QUIC PACKET

4.1 Packet Format

Unlike TCP where the packet header format is fixed, QUIC has two types of packet headers. QUIC packets for connection establishment need to contain several pieces of information, it uses the long header format. Once a connection is established, only certain header fields are necessary, the subsequent packets use the short header format for efficiency [12]. The short header format that is used after the handshake is completed is demonstrated in Fig. 3. In each packet, one or more frames can be embedded in it and each frame does not need to be of the same type as long as it is within the MTU limit.

Each packet in a QUIC connection is assigned a unique packet number. This number increases monotonically, indicating the transmission order of packets and is decoupled from loss recovery [4]. Therefore, it can be used to tell easily and accurately about how many packets may be inside the network, as compared to TCP congestion control which shares the same flow control window used for reliability.

QUIC receiver ACKs the largest packet number ever received, together with selective ACK (ACKing all received packets below it, coded in continuous packet number ranges) as shown in Figure 4. The use of purposely defined ACK frames can support up to 256 ACK blocks in one ACK frame, as compared to TCP's 3 SACK ranges due to TCP option field size limit. This allows QUIC to ACK received packets repeatedly in multiple ACK frames, leading to higher resiliency against packet reordering and losses. When a QUIC packet is ACKed, it indicates all the frames carried in that packet have been received.

Related RFC: QUIC-TRANSPORT[7] §12 Packets and Frames, §13 Packetization and Reliability, and §17 Packet Formats.

4.2 Stream

QUIC has adopted several features directly from HTTP/2, and one of them is incorporating stream multiplexing into the transport layer. In the same way that in HTTP/2, multiple

[4]QUIC uses different packet number space for each encryption level (initial packets, handshake, application data). Packet numbers are unique within each packet number space, and packets are acknowledged in their own packet number spaces. This enables cryptographic data separation between different packet spaces.

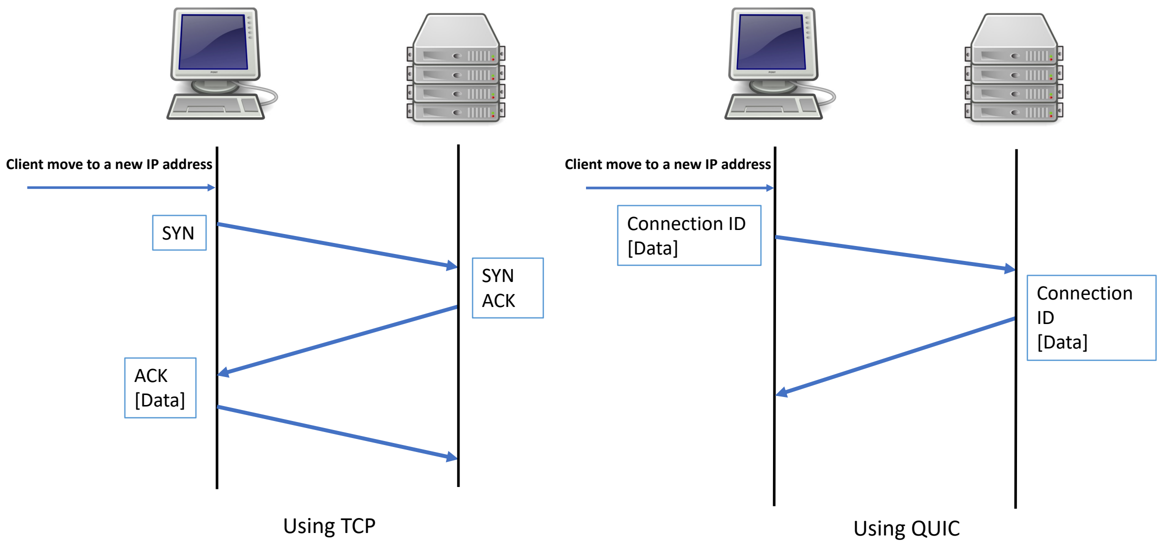

Figure 2: Comparison of TCP and QUIC after having an IP address change. When using TCP, the old connection will be discarded and a new three-way handshake taking 1-RTT will be required before application data can be exchanged. While in QUIC the old connection can be reused and the two peers can directly start sending data if the server has verified the client's address in the past (for example, when the client is moving back to an old address).

```
+-+-+-+-+-+-+-+-+
|    Flags     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+     +-+-+-+-+-+-+-+-+     +-+-+-+-+-+-+-+-+-+-+-+
|   Destination Connection ID        ...          |  Frame 1   |        |   Stream ID      ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+     +-+-+-+-+-+-+-+-+     +-+-+-+-+-+-+-+-+-+-+-+
|         Packet Number              ...          |  Frame 2   |        |   [Offset]       ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+     +-+-+-+-+-+-+-+-+     +-+-+-+-+-+-+-+-+-+-+-+
|         Protected Payload (*)      ...               ...              |   [Length]       ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+     +-+-+-+-+-+-+-+-+     +-+-+-+-+-+-+-+-+-+-+-+
                                                  |  Frame n   |        | Stream Data (*) ...
                                                  +-+-+-+-+-+-+-+-+     +-+-+-+-+-+-+-+-+-+-+-+
```

Figure 3: QUIC Short Header Packet Format. Frame 2 is a Stream frame containing application data.

```
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|      Largest Acknowledged          ...          |            [Gap]                   ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|           ACK Delay                ...          |          [ACK Range]               ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|         ACK Range Count            ...          |            [Gap]                   ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|         First ACK Range            ...          |          [ACK Range]               ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|         ACK Ranges (*)             ...                          ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|          [ECN Counts]              ...          |            [Gap]                   ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
                                                  |          [ACK Range]               ...
                                                  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 4: QUIC ACK Frame Format. The Largest Acknowledged field indicates the largest packet number the sender is acknowledging. An ACK Range indicates the number of continuously acknowledged packets before the largest acknowledged packet number. The gap indicates the number of continuously unacknowledged packets before each ACK Range

streams can exist on one TCP connection, each QUIC connection can have multiple simultaneous flows. This idea also borrows from the structured stream abstraction of SST [11]. Besides, QUIC has also adopted the idea of chopping data into frames and uses those as the basic unit of communication.

Each QUIC stream is identified by a unique stream ID, where its two least significant bits are used to identify which endpoint initiated the stream and whether the stream is bidirectional or unidirectional. Each stream resembles a TCP connection, providing ordered byte-stream delivery. The byte stream is cut to data frames, analogous to TCP segments. **Stream frame offset** is equivalent to TCP seq#, used for data frame delivery ordering and loss detection and retransmission for reliable data delivery. Each data frame is uniquely identified by [stream ID, frame offset]. QUIC uses the STREAM frames to transmit application data and multiple frames from different streams can be packaged into one QUIC packet for transmission.

QUIC endpoints can decide how to allocate bandwidth between different streams, how to prioritize transmission of different stream frames based on information from the application. This ensures effective loss recovery, congestion control, flow control operations, which can significantly impact application performance.

Head-of-Line Blocking: The HTTP/2 protocol used stream multiplexing to solve the HTTP HOL Blocking problem (A HTTP client can only open a limited number of concurrent TCP connections to a server, and when that limit is reached any subsequent requests need to wait for a previous request to finish). However, because HTTP/2 is multiplexing over a single TCP connection it will still suffer from the TCP HOL Blocking problem.

Since QUIC uses multiple independent streams, it avoids the Head-of-Line Blocking problem caused by waiting for recovering lost packets in TCP. When a packet is lost, only the streams with data frames contained in the packet will need to wait for the retransmission of the lost frames. It will not block other streams from moving forward. For instance, in Fig. 5 there are three QUIC streams denoted in red, green, and blue for a single connection. In case there is a packet loss for the red stream, it will not block the delivery of packets for the green stream and the blue stream.

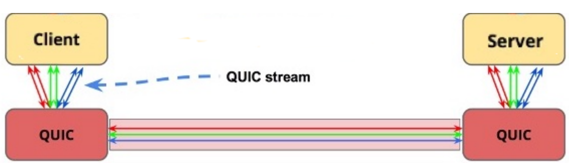

Figure 5: QUIC Solving HOL Blocking Problem.

Related RFC: QUIC-TRANSPORT[7] §2 Streams and §3 Stream States.

4.3 Unreliable Datagram Delivery

Some applications, particularly those that need to transmit real-time data, prefer to transmit data without reliable delivery. Currently one may support these applications by using UDP as the transport protocol, or the secure counterpart DTLS [RFC6347]. QUIC supports the unreliable but secured data delivery with the DATAGRAM frames, which will not be retransmitted upon loss detection[10]. With the support of the unreliable datagram, QUIC could improve the above approach with a reliable and authenticated handshake, followed by secure but unreliable delivery of application datagrams. QUIC packets containing only DATAGRAM frames are also ACK-eliciting, so the application can track whether a DATAGRAM frame is delivered or not.

Related RFC: QUIC-DATAGRAM[10] §3 Transport Parameter, §4 Datagram Frame Type, and §5 Behavior and Usage.

5 QUIC RECOVERY

5.1 Estimating the Round-Trip Time

QUIC ACK frames encode the delay between the receipt of a packet and the transmission of its ACK, which allows the receiver of the ACK to calculate the actual time used in transmitting a packet over the network. So when receiving an ACK frame, a QUIC endpoint can generate an RTT sample of the network path by calculating the time elapsed since the largest acknowledged packet was sent.

QUIC uses the following three values to generate a statistical description of a network path's RTT: the minimum RTT (`min_rtt`), an exponentially weighted moving average RTT (`smoothed_rtt`), and the mean deviation of the observed RTT samples (`rttvar`). With the usage of a monotonically increasing packet number, QUIC retransmission avoids the "retransmission ambiguity" problem in TCP, which is caused by the retransmitted packet carrying the same sequence number as the lost packet.

Related RFC: QUIC-RECOVERY[9] §5 Estimating the Round-Trip Time.

5.2 Congestion Control

Decoupling of congestion control from reliability control: QUIC uses packet numbers for congestion control, and stream frame offset for reliability control.

Incorporating existing algorithms: Similar to TCP congestion control, QUIC utilizes a window-based congestion control scheme that limits the maximum number of bytes the sender might have in transit at any time. QUIC does not aim to develop its own new congestion control *algorithms*, nor use any specific one (e.g., Cubic). QUIC provides generic signals for congestion control, and the sender is free to implement its own congestion control mechanisms. A congestion control algorithm documented in the QUIC standard is described in appendix A.

To avoid unnecessary congestion window reduction, QUIC does not collapse the congestion window unless it detects *persistent congestion*. When two packets requiring acknowledgment are declared to be lost, persistent congestion will be established if none of the packets sent between them is acknowledged, an RTT sample existed before they were sent and the difference between their sent time exceeds the *persistent congestion duration* calculated based on the average RTT (`smoothed_rtt`), the deviation of the RTT samples (`rttvar`) and the maximum time the receiver might delay sending the acknowledgment.

A QUIC sender will pace its sending to reduce the chances of causing short-term congestion by ensuring its inter-packet sending interval exceeds a limit calculated based on the average RTT (`smoothed_rtt`), the congestion window size, and the packet size.

Related RFC: QUIC-RECOVERY[9] §7 Congestion Control.

5.3 Loss Detection and Recovery

ACK-based loss detection: As elaborated above, QUIC packets each contain several frames, each of which can be considered analogous to an IP packet. QUIC performs loss detection based on these packets (which is to say, the equivalent of a collection of IP packets): for each ACK'd packet, all frames carried in that packet are considered received. The frames carried in a packet are considered lost if that packet is unacknowledged when a later sent packet has been acknowledged, and when a certain threshold is met. QUIC uses two types of thresholds for determining whether an earlier sent packet is lost, (i) packet number based: the in-flight packet's sequence number is smaller than the acknowledged packet by a certain number. For instance, assuming the largest acknowledged packet number is x and the packet reordering threshold is t, then all in-flight packets with a packet number smaller than $x - t$ will be declared lost. (ii) time-based: the in-flight packet was sent at least certain times of the maximum of the current estimated network RTT and the latest sampled RTT before the acknowledged packet. For instance, assuming a packet was acknowledged at time t and the waiting time threshold is t_0, then all in-flight packets sent before time $t - t_0$ will be declared lost. These thresholds provide some grace period for packet reordering and avoid unnecessary retransmissions. It also aims to avoid performance degradation caused by the congestion controller when detecting packet loss.

To detect the loss of tail packets , QUIC will initialize a timer for the Probe Timeout (PTO) period whenever a packet requiring acknowledgment is sent, which includes the estimated network RTT `smoothed_rtt`, the variation in the RTT samples `rttvar`, and the maximum time a receiver might delay sending an acknowledgment. When the PTO timer expires, the sender will send a new packet requiring acknowledgment as a probe, which could repeat some in-flight data to reduce the number of retransmissions.

Loss Recovery: After a loss has been detected, the lost frames are then put into new outgoing packets (which will be assigned new packet numbers, unrelated to the lost packets).

With loss detection and recovery, QUIC supports the reliable ordered byte-stream delivery similar to the functionality provided by TCP.

Related RFC: QUIC-RECOVERY[9] §6 Loss Detection.

6 QUIC SECURITY

QUIC makes security a first-class priority in the protocol. As a result, QUIC encrypts almost everything within the protocol (outside of fields necessary for the network, e.g., source and destination addresses), along with tightly integrating security. Part of this integration is combining the transport and security handshakes: this allows one to cut 1 RTT off from the connection setup time. Though this may naively seem to violate the engineering principle of separating out components, in the vast majority of cases where TCP is used, TLS is used on top of it, making this no sacrifice at all.

6.1 QUIC Cryptographic Handshake

QUIC uses keys derived from a TLS 1.3 handshake to protect the confidentiality and integrity of its packets [8] and the TLS handshake messages are carried in the CRYPTO frames in the Initial and Handshake packets which are coupled with the transport handshake process. The relationship between QUIC and TLS can be described as QUIC taking information from TLS (handshake messages, keys, etc), and in turn providing a reliable stream to TLS. The overall process for a 1-RTT certificate-based cryptographic handshake without client authentication is illustrated in Fig. 6 and proceeds as follows:

- The client initializes the cryptographic handshake process by sending the TLS ClientHello message in its Initial packet, which included the client's supported cipher suites, the public share of its ephemeral Diffie-Helman key, and its QUIC transport parameters. Other TLS extensions like server name indication can also be included in this ClientHello message.
- After the server received the client's Initial packet, it will reply with an Initial packet containing the TLS ServerHello message, which includes the server's chosen cipher suite for the connection, the public share of the server's ephemeral Diffie-Helman key, and possibly other TLS extensions necessary to establish the cryptographic context. At this point, the server can derive the Master Secret with its private key and the client's public key and will use keys derived from the secret to protect all future packets.
  The server will then send a Handshake packet containing the following TLS messages: the EncryptedExtensions message containing the server's QUIC transport parameters and other TLS extensions that are not required to establish the cryptographic context, the Certificate message containing the server's certificate chain, the Certificate Verify message proving the ownership of the certificate's private key, and the Finished message providing authentication of the handshake and the computed keys. [14]
  The server can start sending application data with 1-RTT packets at this point though the liveness of the client has not been verified.
- After the client receives the server's Initial packet and Handshake packet, it can also derive the Master Secret of the connection and calculate the keys to protect all future packets. It will send the TLS Finished message

in a Handshake packet to confirm the handshake. It can also start sending application data to the server with 1-RTT packets.

- After the receipt of the Finished message from the client, the server will send a HANDSHAKE_DONE frame in a 1-RTT packet to confirm the handshake being finished.

Because multiple QUIC packets can be encapsulated into a single UDP datagram, the above handshake process can be finished with only four UDP datagrams.

Sending 0-RTT data QUIC allows a client to send encrypted application data before the handshake is completed by reusing the negotiated parameters from a previous connection. [8] After a connection is established, a QUIC server can issue a pre-shared key (PSK) identity associated with the connection's resumption secret through a TLS NewSessionTicket message with a special maximum early data size to indicate that it will accept 0-RTT data. A QUIC client can remember that PSK identity and its associated secret along with other critical connection parameters so that it can go through the simplified 0-RTT handshake process when connecting to the server next time. The overall process of a 0-RTT handshake is illustrated in Fig. 7 and proceeds as follows:

- The client initializes the handshake process by sending an Initial packet similar to that in the 1-RTT handshake process with a few extra TLS extensions. The client will use the pre_shared_key extension to tell the server the PSK identity it has and use the early_data extension to signal that it has 0-RTT data to send. The application data is included in an 0-RTT packet protected with the resumption secret, which can be encapsulated into a single UDP datagram along with the Initial packet.
- The Server then uses the TLS stack to check validity (e.g. if the correct cipher-suite was used). If the packet passes this check, the server uses both the QUIC stack and the application protocol to check the packet's validity. Part of the QUIC stack check is ensuring that some additional transport state is associated with the session ticket, above and beyond the TLS 1.3 requirements.

  If the server chooses not to accept the 0-RTT data, it will fall back to the 1-RTT handshake process and no special actions will be needed.
- The server will send an Initial packet and a Handshake packet similar to the 1-RTT handshake with a few changes. In the ServerHello message, the server will include the pre_shared_key extension to indicate that the PSK identity is accepted. In the Handshake packet, the TLS extensions early_data will be added to the EncryptedExtensions message to signal that the 0-RTT data is accepted, and the server does not need to send the Certificate and Certificate Verify message because its identity has already been verified. To provide forward secrecy for the new connection, the server will migrate to a new Master Secret combining both the old resumption secret and the shared secret derived from the new DH key exchange. The server will also send an ACK frame to acknowledge the 0-RTT packet.
- The client will migrate to the new Master Secret after receiving the public share of the server's ephemeral Diffie-Helman key. The remaining process is the same as the 1-RTT handshake.

There are, however, some additional best practices that should be followed. For instance, when using the 0-RTT mode, best practice dictates that the 0-RTT keys should only be used to protect data that is idempotent because 0-RTT packets are not protected against replay attacks. Additionally, in order to reduce security vulnerabilities, when a Client's cached information expires, the Server should reject the 0-RTT connection and send its authorization info as in the first time connection setup. This is built into the QUIC protocol, and the Client should have no trouble moving directly into a 'first time' connection setup.

Related RFC: The Transport Layer Security (TLS) Protocol Version 1.3 [14] §2 Protocol Overview and §4 Handshake Protocol, QUIC-TLS [8] §4 Carrying TLS Messages and §8 QUIC-Specific Adjustments to the TLS Handshake.

6.2 Authenticated and Encrypted Header and Payload

The QUIC protocol has made an intentional choice to encrypt all practical portions of the packet. Though this is a tradeoff – to give a specific example, hiding information from the ISP has both benefits and costs – it enables new protections for end users. To be more specific, QUIC authenticates all of its headers and payload (except version negotiation packets), as well as encrypting most of the data exchanged. Figure 3 shows the QUIC packet format, packet header fields are unencrypted as they are used for routing or performing decryption of the payload. The packet body containing frames is encrypted. Everything in the unencrypted header must remain in plaintext for proper operation. The header contains flags that are needed to specify which fields are included in the header and the length of certain fields. The Connection ID is used for routing the packet to its destination server and simultaneously serves as an identifier for the connection state. The packet number is needed for authentication and decryption, and thus can't be encrypted.

This encryption also has the benefit of ensuring QUIC can remain relatively easy to update. protocol ossification is a well-known problem – middleboxes cannot be easily

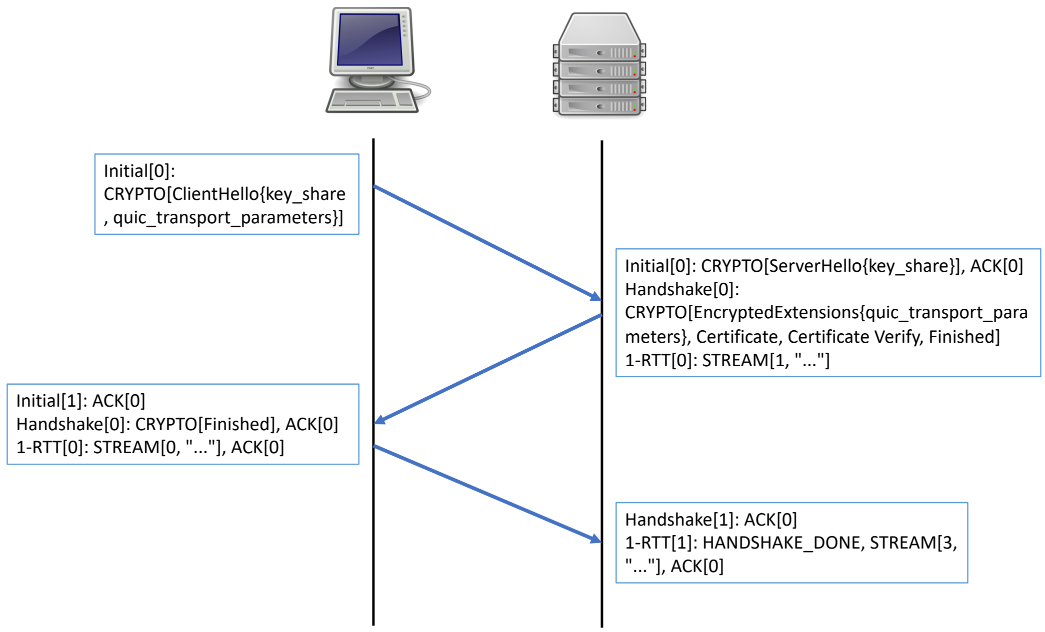

Figure 6: A diagram illustrating the QUIC-TLS 1.3 1-RTT handshake [7].

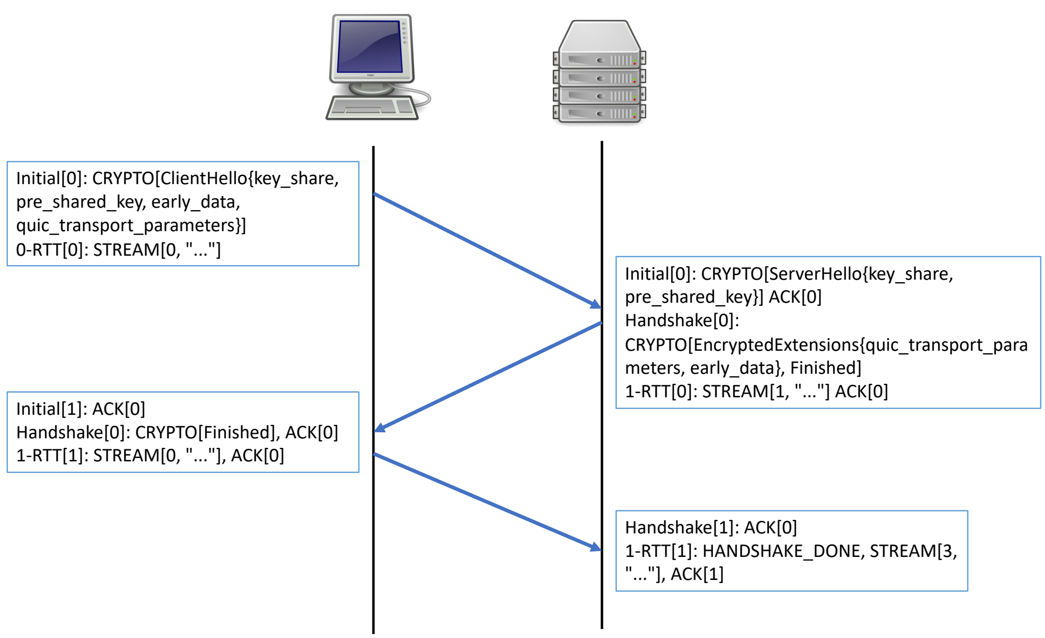

Figure 7: A diagram illustrating the QUIC-TLS 1.3 0-RTT handshake [7].

upgraded to meet protocol changes, which limits the flexibility of network protocol design. QUIC packets are mostly encrypted, which prevents modification by middleboxes, and limits protocol ossification.

Related RFC: QUIC-TLS [8] §5 Packet Protection.

7 APPLICATIONS OVER QUIC: HTTP/3 AS AN EXAMPLE

As an application protocol, HTTP encodes application contents with rich semantics, and the most relevant feature to transport delivery is its request-response message exchange model: a browser client can issue multiple requests in parallel, whose responses often desire different delivery priorities to maximize the viewer experience. However, when HTTP runs over a TCP connection, which supports reliable delivery of a single byte steam only, the order of response contents can only be delivered according to the order in which the server receives the requests.

The QUIC design provides multiple stream support to address the above limitation of TCP being unable to prioritize between different requests. More specifically, HTTP/3, the latest version of HTTP which is designed to run over QUIC, utilizes QUIC's stream semantics to enable each HTTP response being delivered independently and with different priorities."

- As the underlying transport for HTTP/3, QUIC provides reliable in-order delivery at the stream level and congestion control at the connection level. Each HTTP request-response pair is mapped into an independent stream, thus different request-response pairs will not block each other in case of loss. QUIC also provides security matching TLS + TCP, and lower connection setup latency.
- Stream management is handled at the transport layer, QUIC takes care of the reliable delivery and the ordering of the frames then passes the received data to the application.

Related RFC: QUIC-HTTP[1] §4 HTTP Request Lifecycle, §6 Stream Mapping and Usage, and §7 HTTP Framing Layer.

8 CONCLUSION AND FUTURE WORK

QUIC represents the best transport protocol design the community has come out with so far. This is precisely because the basic ideas in the QUIC design did not simply drop out of the sky one day, but rather, QUIC represents an accumulation of lessons learned from networking experimentation and previous protocol designs. For instance, learning from T/TCP, QUIC keeps and reuses connection states to achieve 0-RTT communication. Adopting the ideas from RTP, QUIC runs over UDP to stay outside of the kernel and utilizes the ALF/ADU idea documented in [4]. Similar to SCTP and HTTP/2, QUIC also uses multiple substreams to mitigate head-of-line blocking and typed frames to support a variety of control exchanges. Adopting these ideas and synthesizing them into a single protocol allows the QUIC protocol to minimize latency (often touted as QUICs chief virtue) and minimize other problems (such as those identified in §2.2).

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```
                 New Path or      +------------+
            persistent congestion |   Slow     |
        (O)---------------------->|   Start    |
                                  +------------+
                                        |
                                Loss or |
                        ECN-CE increase |
                                        v
 +------------+     Loss or       +------------+
 | Congestion |  ECN-CE increase  |  Recovery  |
 | Avoidance  |------------------>|   Period   |
 +------------+                   +------------+
           ^                            |
           |                            |
           +----------------------------+
              Acknowledgment of packet
                sent during recovery
```

Figure 8: State Machine of the New Reno Algorithm. [9]

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A THE NEWRENO ALGORITHM

The state machine of the *NewReno* algorithm documented in the QUIC standard [9] is shown in Figure 8. In addition to the congestion window, the *NewReno* algorithm will also maintain another variable named Slow Start Threshold, which will be initialized to infinity. The *NewReno* algorithm has the following three states:

Slow Start: A QUIC sender will start at the Slow Start state and will reenter it when persistent congestion is declared. During this state, the congestion window will grow exponentially and is increased by the number of newly acknowledged bytes. The sender will enter the Recovery state when a packet is declared lost or when the ECN-CE counter has been increased.

Recovery: Each time the sender enters the Recovery state, the congestion window will be reduced by half and the Slow Start Threshold will be set to the new congestion window size. The sender will enter the Congestion Avoidance state when a packet sent during the Recovery state is acknowledged by its peer.

Congestion Avoidance: During this state, the Additive Increase Multiplicative Decrease (AIMD) approach will be used, and for each congestion window acknowledgment, the increase of the window size will be limited to the maximum size of one datagram. The sender will enter the Recovery state when a packet is declared lost or when the ECN-CE counter has been increased.

Handling Persistent Congestion: When persistent congestion is declared, the congestion window will be reduced to the minimum congestion window size and the sender will reenter the Slow Start state.

Related RFC: QUIC-RECOVERY[9] §7 Congestion Control.

B VERSION NEGOTIATION

Unlike traditional transport protocols, QUIC supports the co-existence of different protocol versions. In order to carry out this feature, the client and server can negotiate a mutually supported protocol version before establishing a connection. This is useful for the protocol to continuously evolve while allowing endpoints to negotiate which version to use. For clients that support multiple QUIC versions, QUIC should choose the largest of the minimum packet sizes across all the supported versions as the size of its first packet. If the server does not accept the version selected by the client, it will send an additional Version Negotiation packet to the client listing its accepted versions. This will introduce an additional 1-RTT latency to the QUIC handshake process.

Related RFC: QUIC-TRANSPORT[7] §6 Version Negotiation.