QUIC Security

NDSS QUIPS Workshop, February 2020

Martin Thomson

Overview

QUIC handshake

- key establishment
- denial of service

Packet and header protection

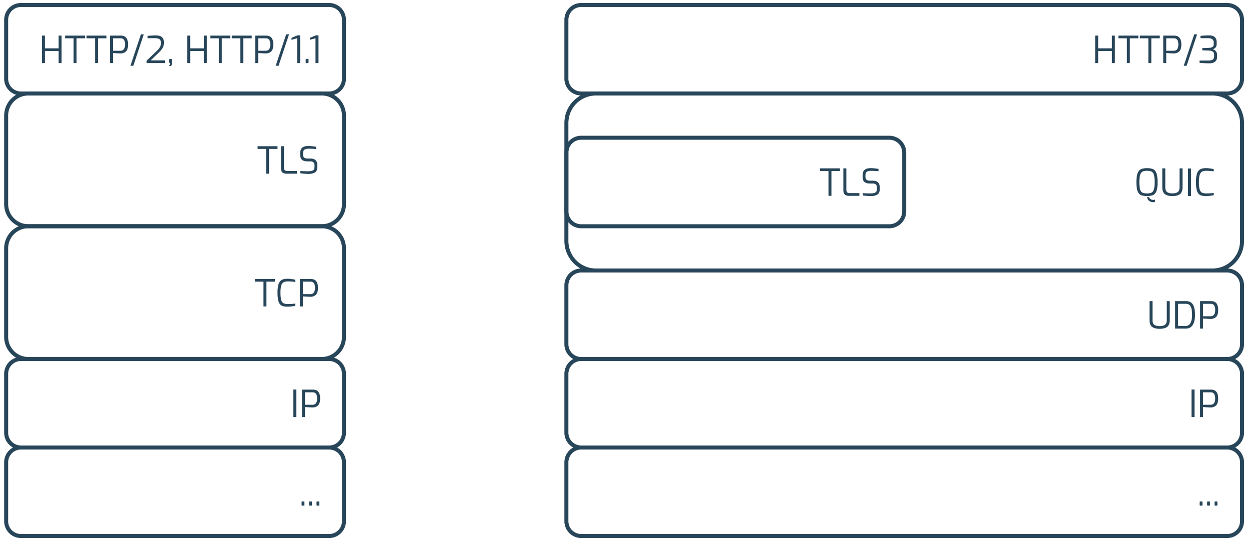
Key update

Migration

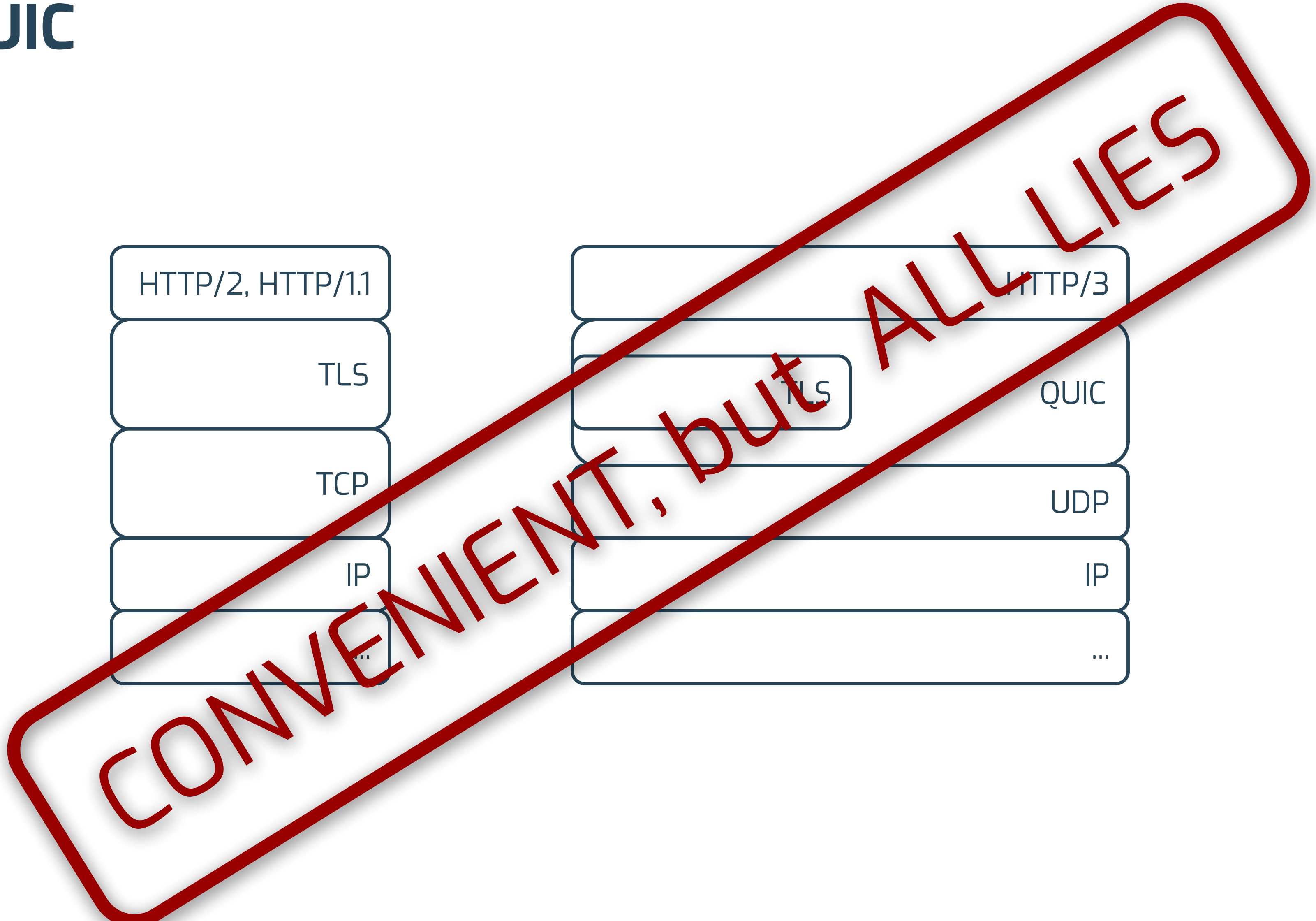
Connection reset

Version negotiation and other stuff

QUIC



QUIC


HTTP/2, HTTP/1.1
TLS
TCP
IP
...
HTTP/3
TLS
QUIC
UDP
IP
...
CONVENIENT, but ALL LIES

QUIC Handshake Overview

QUIC connection setup does what TCP and TLS do

QUIC uses TLS to do most of the TLS bits

QUIC provides all the TCP bits

including providing TLS with reliable, ordered delivery

Security Goals

Core TLS guarantees

- authentication, confidentiality, integrity

Core TCP guarantees

- consent to receive/anti-amplification

Better where possible

TLS Handshake

TLS 1.3 is an optimistic handshake

- Clients guess key agreement parameters to save 1 RT

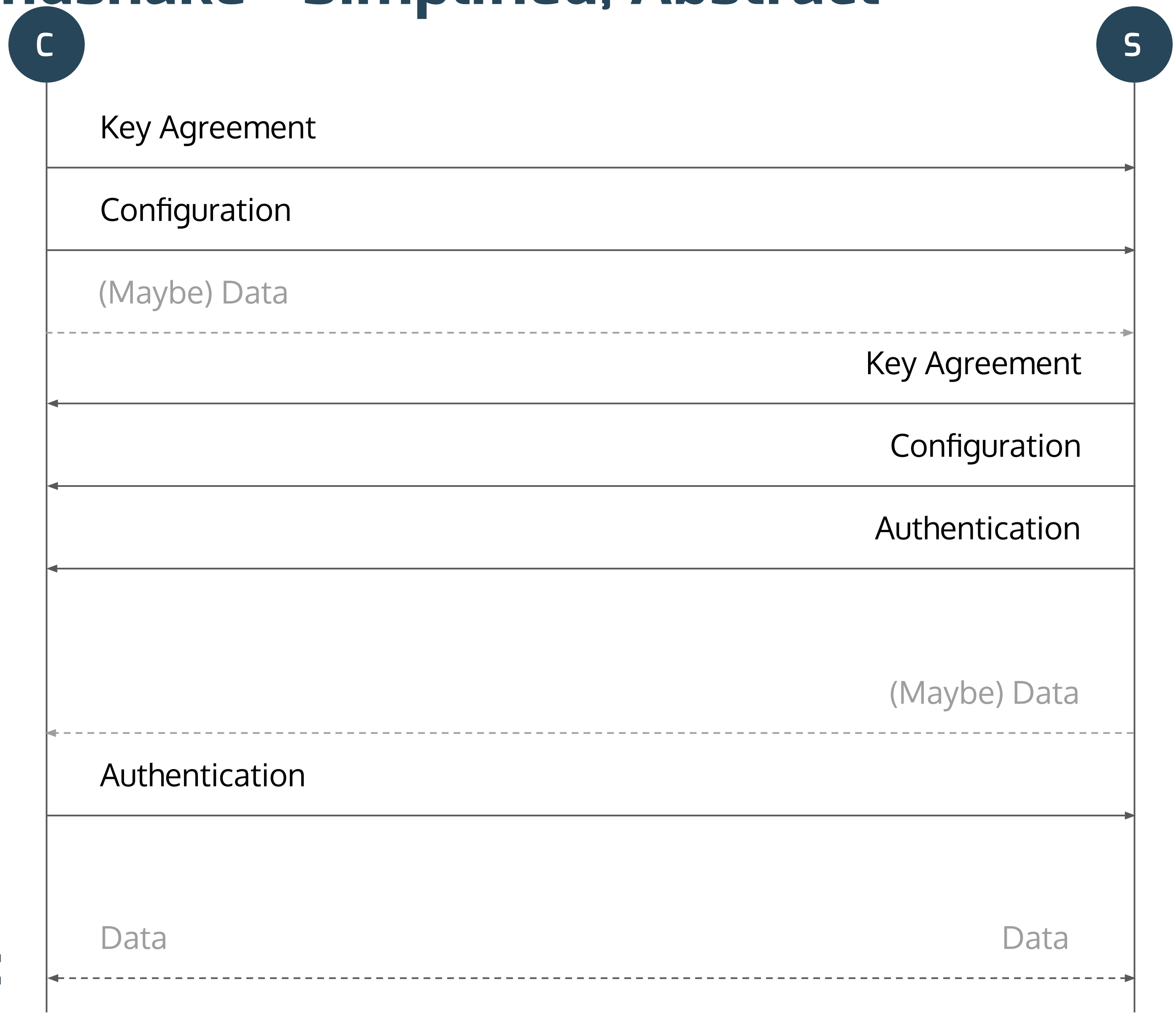
Typical handshake is 3 way / 1.5 RTT

- 1 extra RT if the client guesses wrong

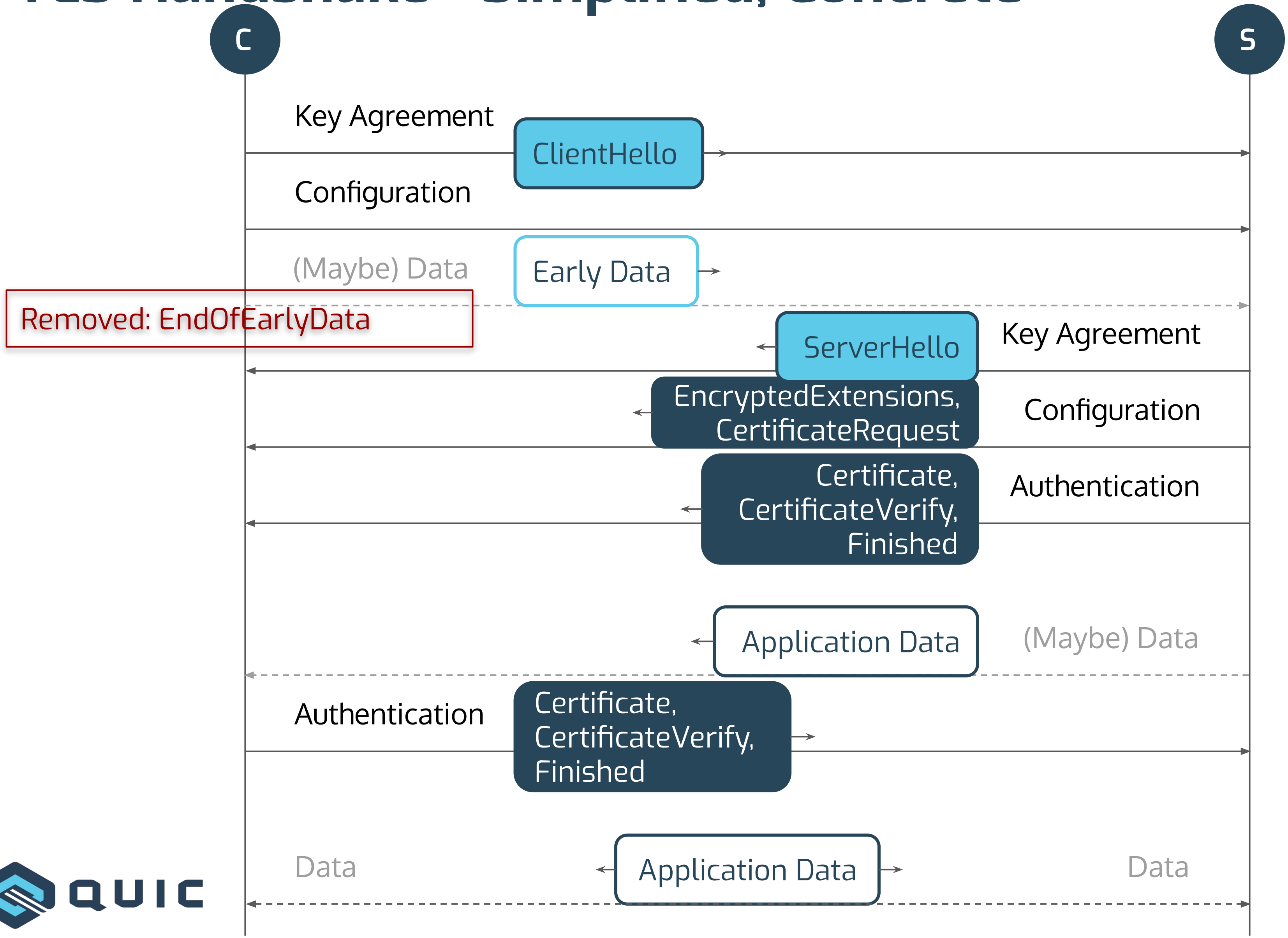
Endpoints can - sometimes - send 1 RT early

- Client sends 0-RTT if they have a pre-shared key
- Server send at 0.5-RTT if they don't need client auth'n

TLS Handshake - Simplified, Abstract



TLS Handshake - Simplified, Concrete



QUIC

QUIC Handshake

Take TLS messages by type of key

Give handshake messages a packet type each

Initial

Handshake

Treat TLS messages as raw bytes

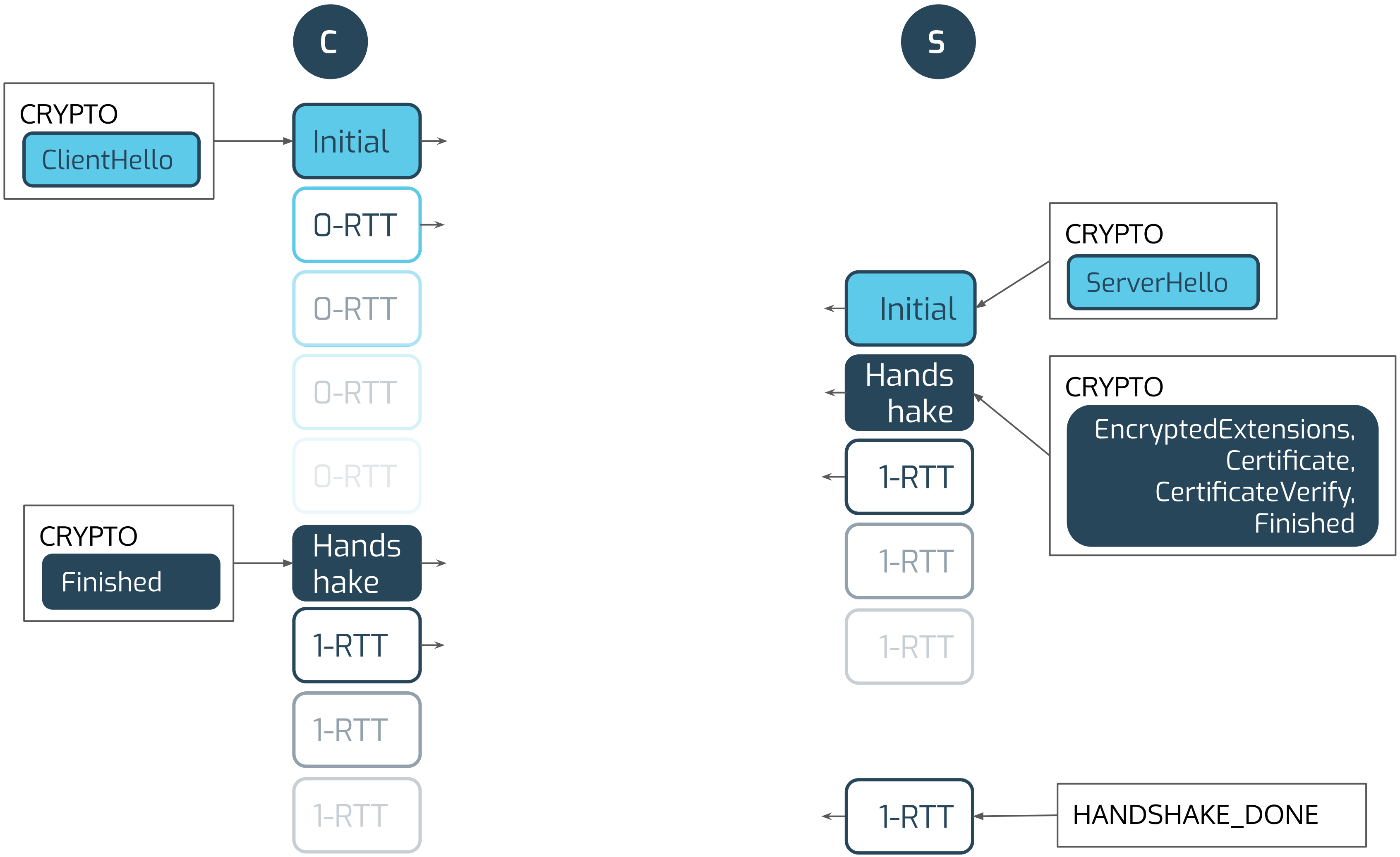
Put those bytes in CRYPTO frames

QUIC doesn’t send data via TLS, but it has the same needs

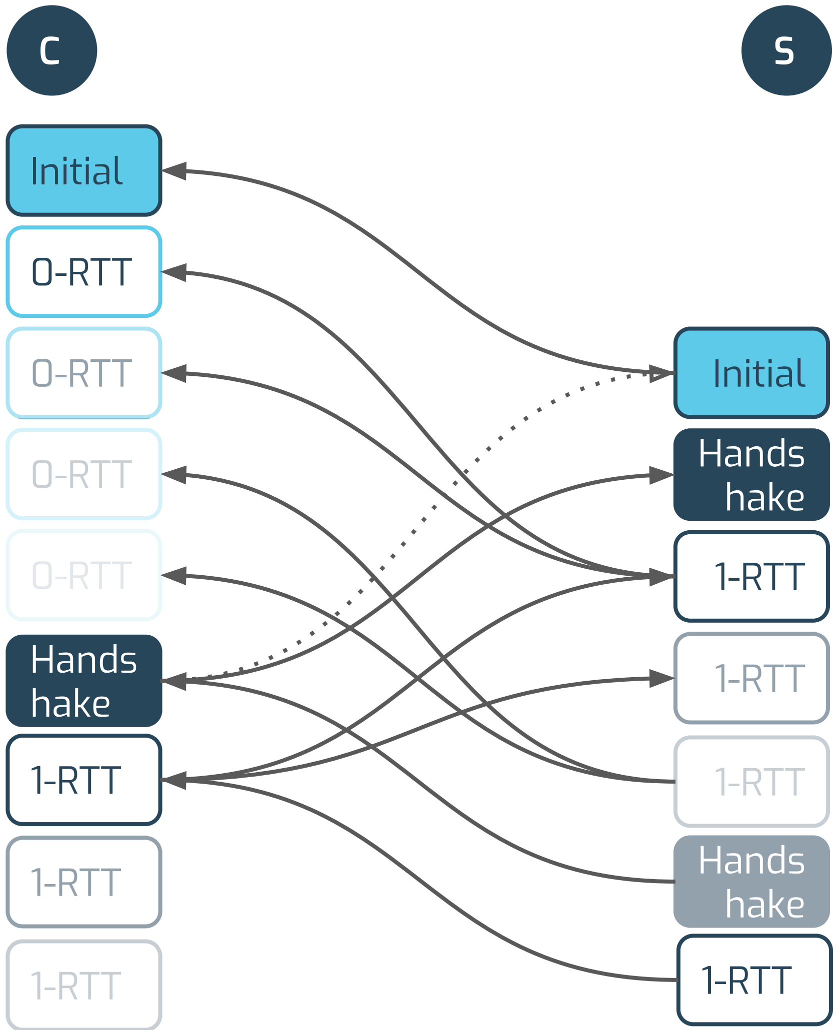
0-RTT

1-RTT (Short)

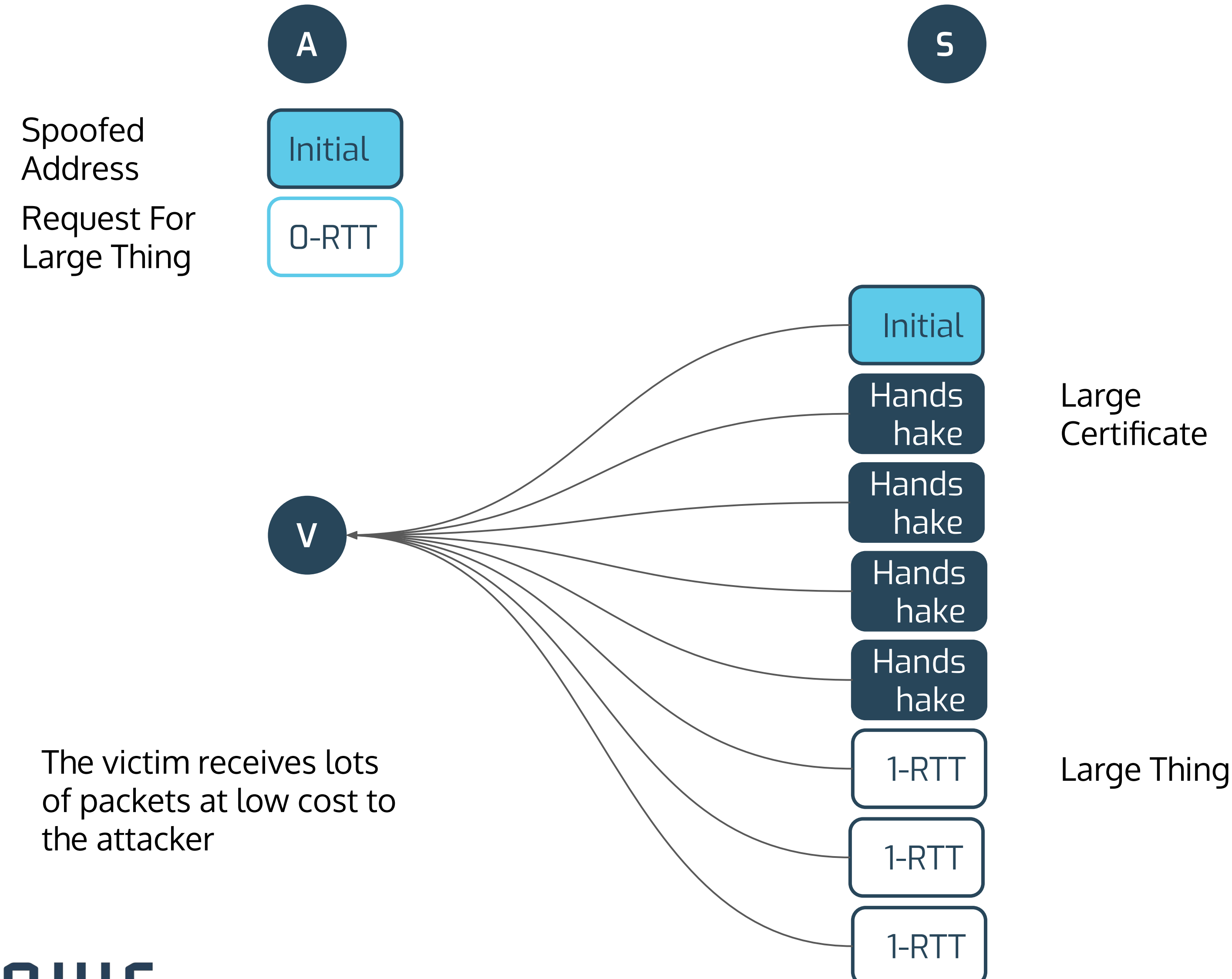
QUIC Handshake - Simplified



QUIC Handshake - With ACKs



Amplification Attack



The victim receives lots of packets at low cost to the attacker

TCP Handshake

TCP also has a 3 way handshake: SYN, SYN+ACK, ACK

For TLS/TCP, this adds 1 RT to setup

TCP confirms willingness to communicate

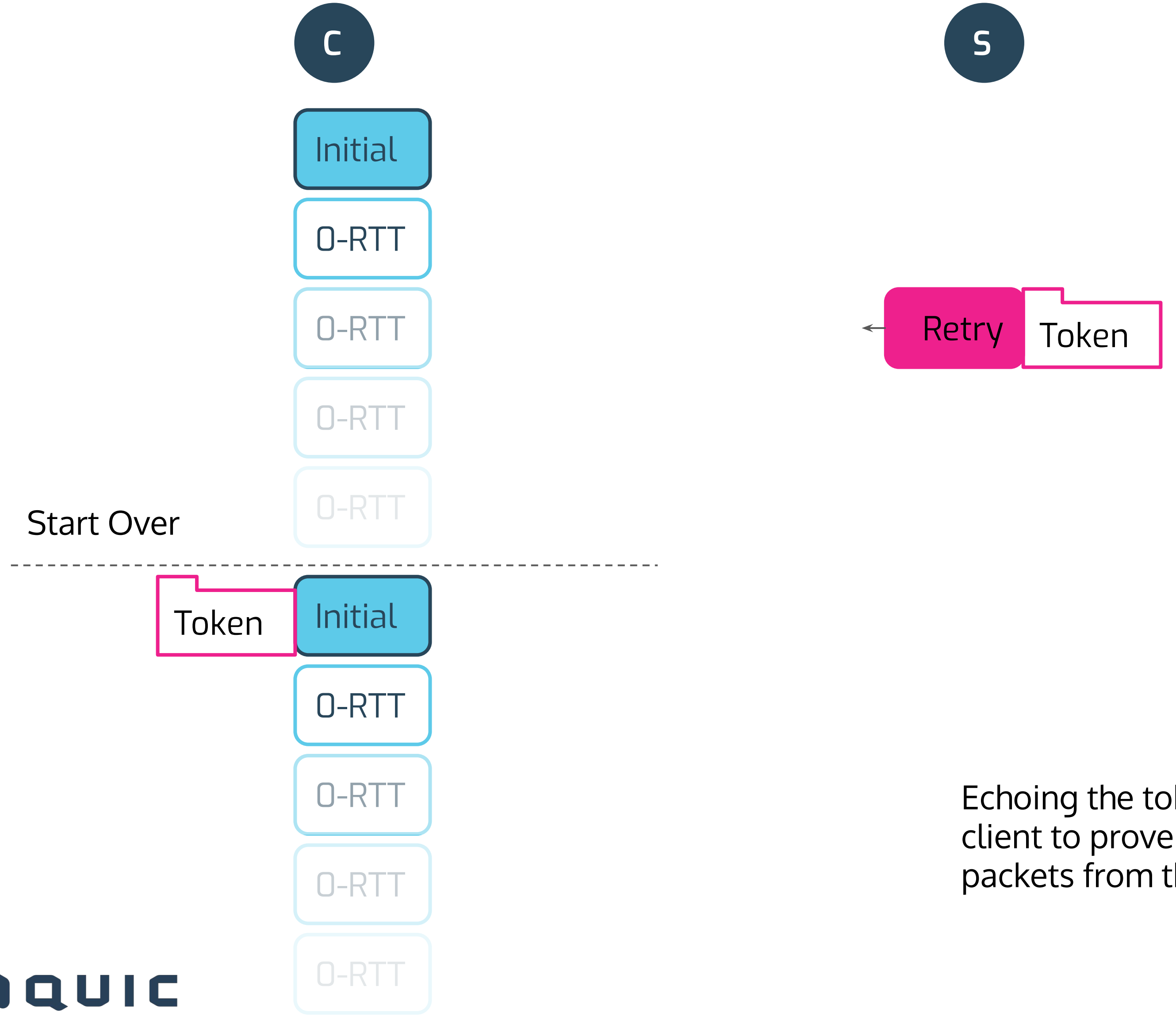
… importantly: before spending CPU on crypto

The simple QUIC handshake does not

so we add Retry

* Retry is optional

QUIC Handshake - Retry



Echoing the token forces the client to prove that it can receive packets from the server.

Communication Consent w/o Retry

A round trip to confirm that a client is live is expensive

- it’s only good for extreme cases, like DoS

QUIC uses packet protection to achieve the same effect

Client Proves that it saw Server Initial

Once all Initial packets are exchanged

- endpoints have shared keys
- derived from unpredictable key exchange messages

These keys are used to protect Handshake packets

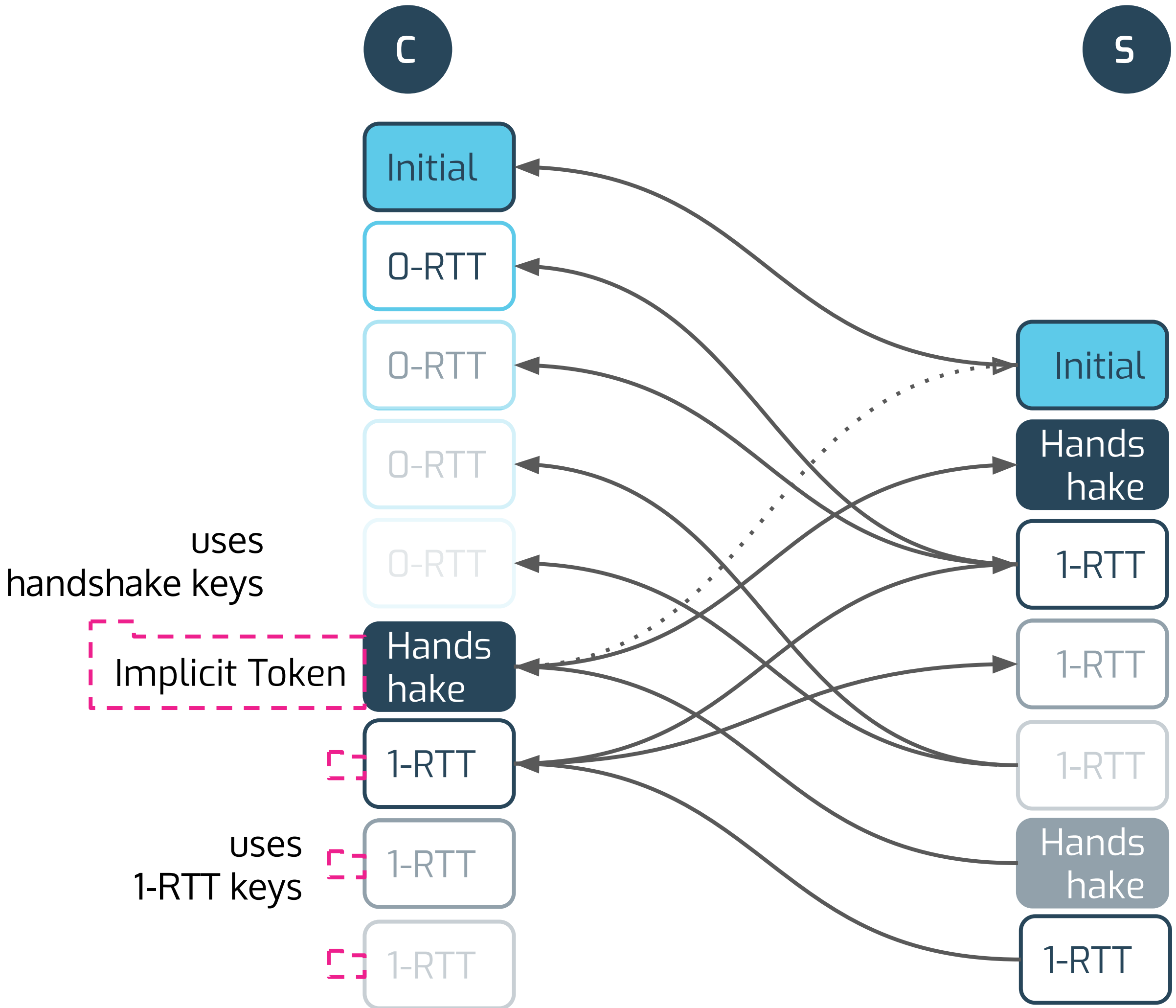
So if the client produces a valid Handshake packet

- (or a token that was sent in a Retry)
- the server is sure that the client has seen its packets

Until then, the server has to limit the data it sends

- Rule: no more than 3 bytes out for every byte received

Client Implicit Token



server has to limit what it sends until it validates the client token (3x rule)

Server Proves that it saw Client Initial

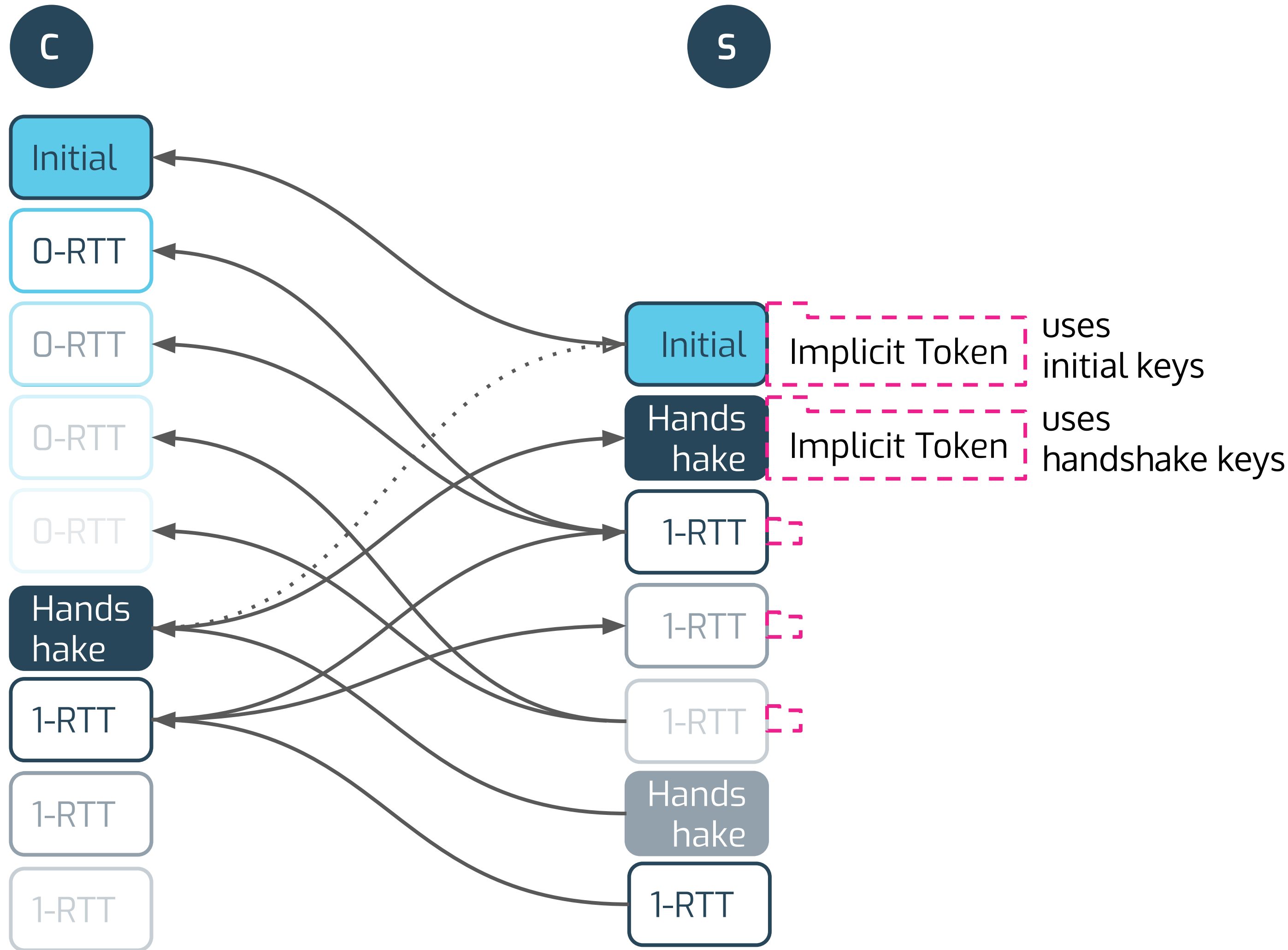
The client encrypts their Initial packet

The key is derived from an unpredictable value
 the “Destination Connection ID”

The server proves that it saw this by
 using the same value to encrypt its Initial packet

Retry includes the value in its integrity check to prove receipt
 the value is not transmitted

Server Implicit Token



Lessons Learned

Getting this far was **hard**

Lots of deadlocks discovered in the process

The protocol state machines are complex

No formal verification to support correctness

Version negotiation added more complexity

- not confident in it either functionality or security
- deferred decision to add downgrade prevention

QUIC Handshake Performance Degradation

+1 RTT if version negotiation if the QUIC version is wrong*

+1 RTT if the server wants to validate the client with Retry

+1 RTT for TLS HelloRetryRequest for a new client key share

+n RTTs if data needs to exceed anti-amplification limits (PQ)

- if client data exceeds initial congestion limit
- if server handshake exceeds 3x client data

Servers do the first two statelessly

QUIC

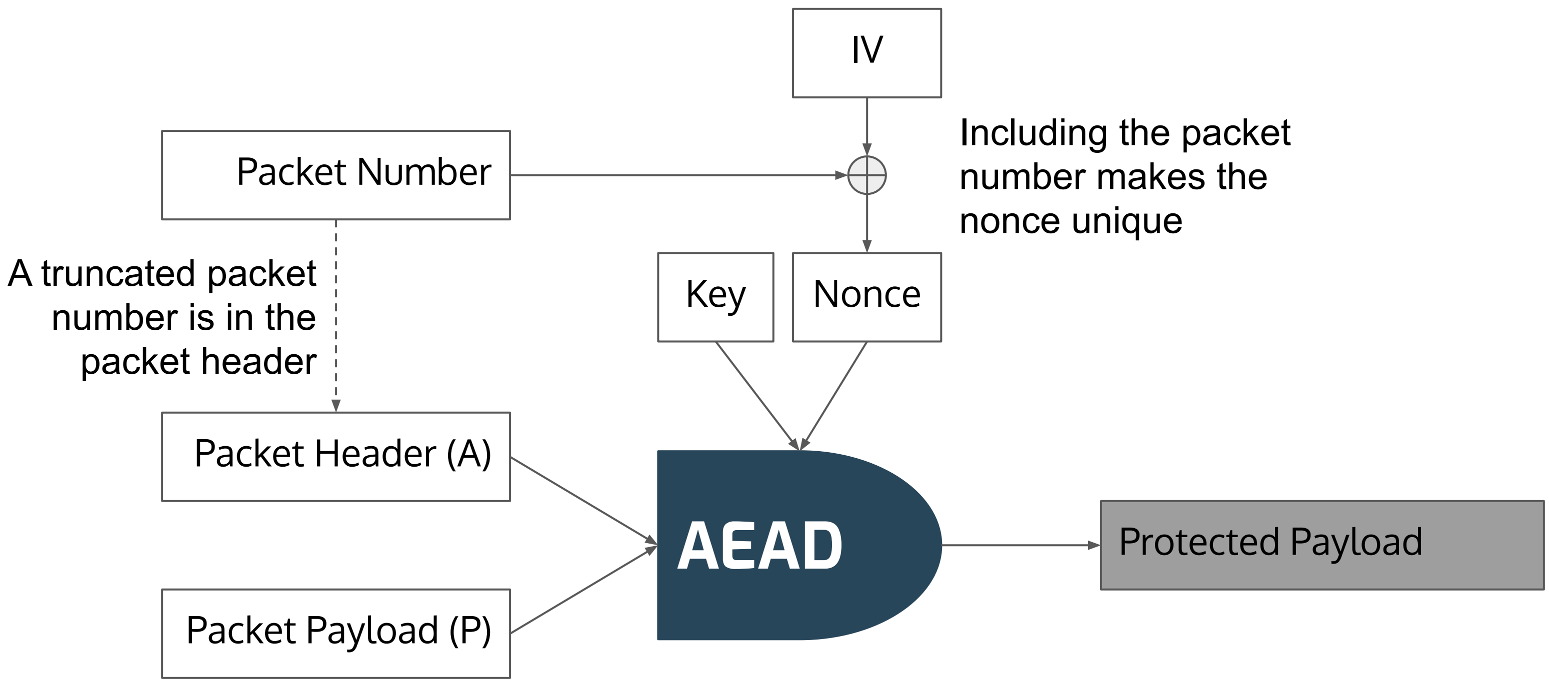
Packet Protection

Everything in QUIC is protected, except

- Version Negotiation - has to be version independent
- Retry - integrity protection only, with fixed keys
- Initial - protected, but with fixed keys
- 0-RTT - protected, but without replay protection
- Handshake - protected, but not fully authenticated

Protected packets all use the same basic scheme

QUIC Packet Protection



We could just send this now...

… but we're not done yet...

Header Linkability

The QUIC packet header contains linkable fields

- connection ID
- key phase
- packet number

0	1	S	R	R	K	P	P
Connection ID ...							
Packet Number ...							

If packets from the same connection are sent on two network paths, these could be used to match those packets

These could allow people to be tracked as they move

Header Protection Lessons

For linkability with Connection IDs we use new values

We tried that for packet numbers, but it didn't work well

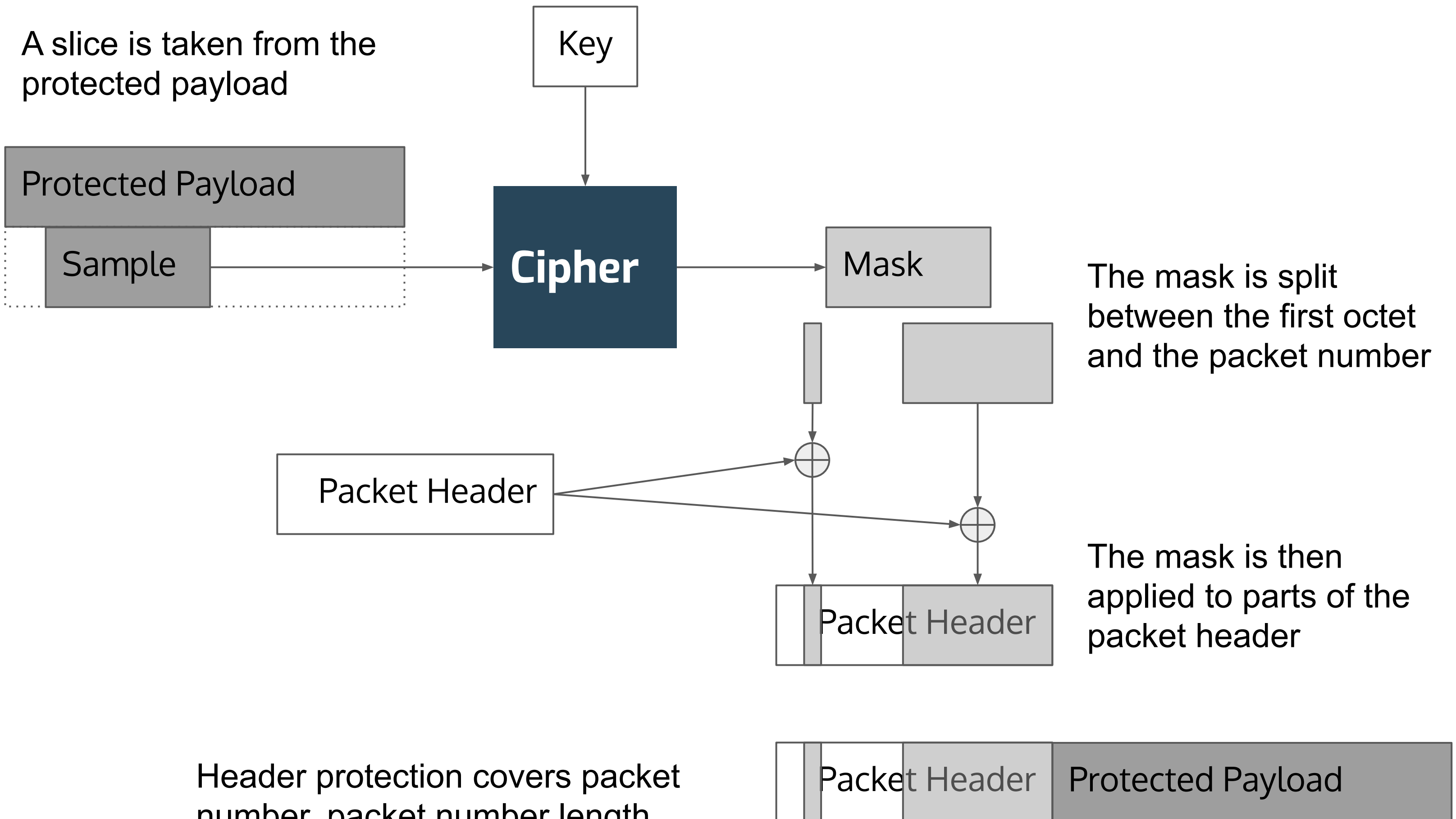
- it always ended up looking like bad encryption

Idea: the protected packet payload is essentially random

- use that as a nonce and just encrypt the packet number
- now we just cite Nonces are Noticed

QUIC Header Protection

A slice is taken from the protected payload



The mask is split between the first octet and the packet number

The mask is then applied to parts of the packet header

Header protection covers packet number, packet number length, key phase, two unused bits.

Cleartext Parts of QUIC Packets

The first two bits (0b11 = long, 0b01 = short)

Version, Type, and Length (long header)

Destination Connection ID

Source Connection ID and connection ID lengths (long)

Spin bit (short)

Address validation token and its length (Initial packets)

All of Retry and Version Negotiation packets

Key Update

Lock-step protocol for updating keys

- 1-bit signal indicates which keys are used
- updates blocked until peer confirms update

Keying based on TLS design:

- separate read and write secrets are run through HKDF
- new AEAD key and nonce derived from each
- discard old secrets

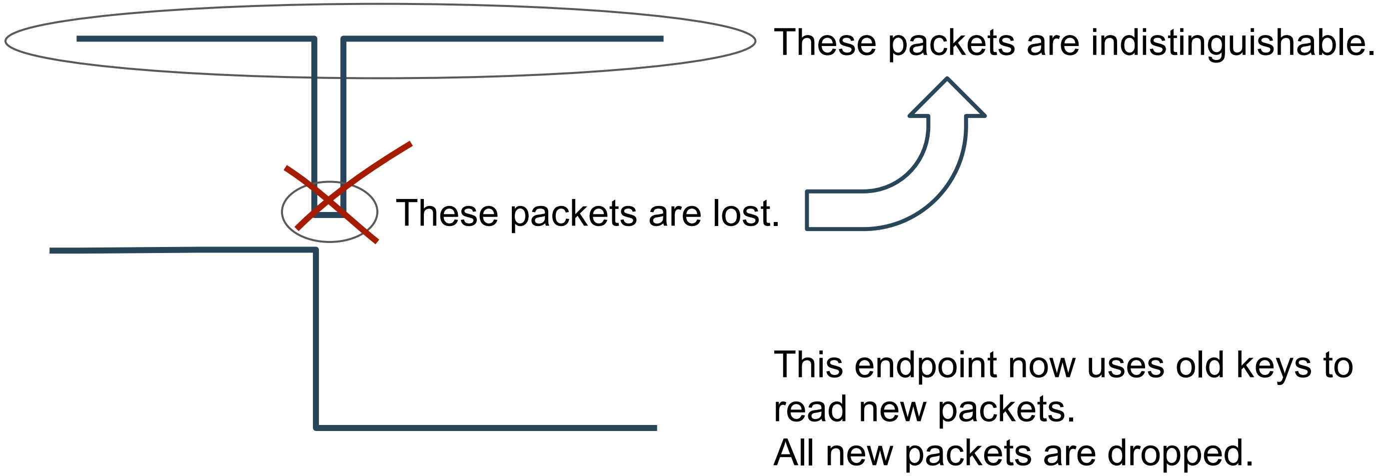
Header protection keys aren’t updated

- these are used to protect the 1-bit signal

Key Update Deadlocks

Original protocol had deadlocks

- Either side can update at any time.
- packets from one endpoint are unreadable



Fix: require acknowledgment of an update, not use of keys

Migration

Desire to deal with NAT binding changes

Desire to allow moving connection to new paths

Desire to prevent attacker from forcing unwanted migration

Desire to prevent attacker from blocking migration

Dolev-Yao model says attacker can rewrite addresses

We can’t integrity protect or QUIC wouldn’t deploy (NAT!)

Hard problem

Not completely confident in solution

Design

Anti-amplification applies to any new remote address

new paths require validation to remove limits

PATH_CHALLENGE to test; PATH_RESPONSE to confirm

Also validate old path

in case old path is good and attacker is forwarding

Limit deliberate migrations to client only

special case: server can request migration

to a preferred address after handshake completion

New paths need new connection IDs to avoid linkability

Terminating Connections Safely

Use case: server reboots and loses state

- connections will eventually time out
- but that isn't efficient

TCP provides RST for this case

- but TCP RST can be sent by any on-path element
- that is a denial of service risk

QUIC provides a secure stateless reset

QUIC Stateless Reset

Every connection ID has an associated stateless reset token

This token is shared secretly (a frame in a protected packet)

Sending a packet containing this secret kills the connection

These can’t be generated by path elements

- they don’t know the secret

These can’t be detected by path elements

- the packet looks like a regular packet, mostly

Generating a Stateless Reset

How does a server generate a stateless reset?

- it might have just rebooted and lost connection state

Keep a secret that is semi-permanent

- all server instances have the same secret

The stateless reset token is KDF(secret, connection ID)

The connection ID is taken from the incoming packet

Need to ensure that connection IDs aren't reused

Stateless Reset

C

S

Server is configured with a static secret.

Initial

Initial

Handshake

Stateless reset token is sent to the client under encryption:
token = f(secret, cid)

Server Reboots

1-RTT

Server doesn't know about this connection!

Reset

Recalculate:
token = f(secret, cid)

The packet looks normal but can't be decrypted.
However it contains the token.
The client abandons the connection.

Stateless Reset Challenges

Stateless reset oracles in clusters

- misrouting might cause node to reset live connections
- creates coupling between routing logic and node config

Key rotation challenges

- limited space to embed information in connection ID

Stateless resets aren't truly indistinguishable from normal

- can only really create uncertainty for middleboxes

Version Negotiation (tentative)

Two modes compatible and incompatible

Compatible can be performed with no additional round trips

- Client sends Initial[vX] containing a signal that vY is OK
- Server knows **F : Initial[vX]** → **Initial[vY]**
- Server completes handshake with vY

Incompatible requires a rejection using Version Negotiation packet

- Client might start over with a different version

Version Negotiation Properties

Server picks between compatible versions

Client picks between incompatible versions

Authenticate final choice by describing choices and outcomes in TLS handshake and authenticating that

Other Potential Sources

HTTP/3 compression is interesting

Flow control deadlocks might have security implications

Effect of network-controlled signals on internal state

- path MTU discovery
- packet loss
- ECN-CE marking