Encryption in the transport layer: QUIC, TLS1.3, and HTTP/2

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SwiNOG

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mami
measurement and architecture for a middleboxed internet

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Overview
Encryption in the web

- QUIC - New, encrypted transport protocol
  - Optimized for HTTP/2 as an alternative to TCP
  - Designed to be implemented in user space, e.g. in your browser

- TLS 1.3 and DTLS - improved end-to-end encryption
  - Perfect Forward Secrecy (Static RSA and Static Diffie-Hellman cipher suites removed)

- HTTPs uses TLS/TCP or QUIC

Why encryption?

1. Improvements in data and privacy protection (Snowden revelations)
   - "Encrypt it all!“
2. Reaction to ossification
   - Endpoint control about exposure to maintain evolution
   - Increase transparency on in-network handling
   - Middlebox traversal
   - Implementation correctness

Overview

HTTP/2

- Published as IETF RFC7540 in May 2015
- HTTP/2 is based on SPDY as originally proposed by Google
- About 250K domains support HTTP/2 (e.g. see isthewebhttp2yet.com)
  - Deployment driven by big hosting providers

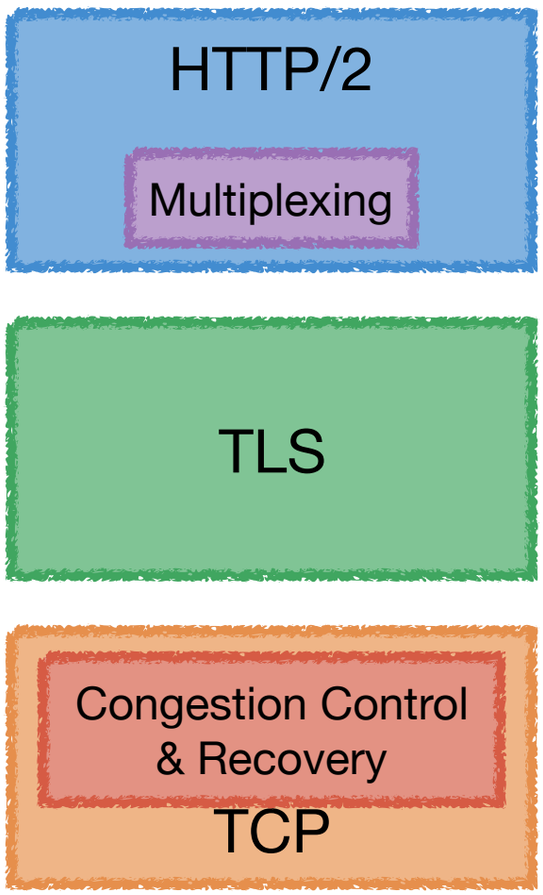
QUIC

- Currently under standardization in the IETF (since Nov'16)
- Originally developed by Google together with SPDY

TLS1.3

- draft-ietf-tls-tls13 (approved for publication by IESG)
- used by QUICv1 as build in encryption protocol

HTTP/2 over QUIC



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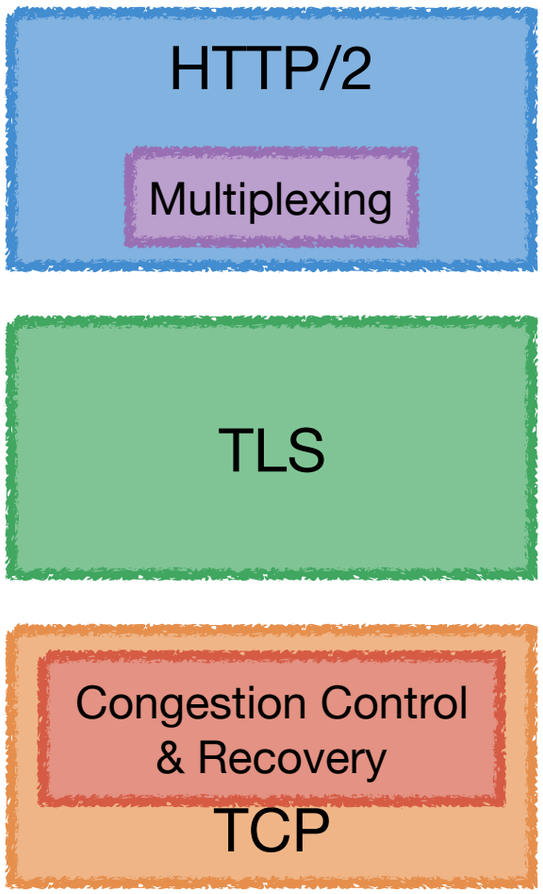

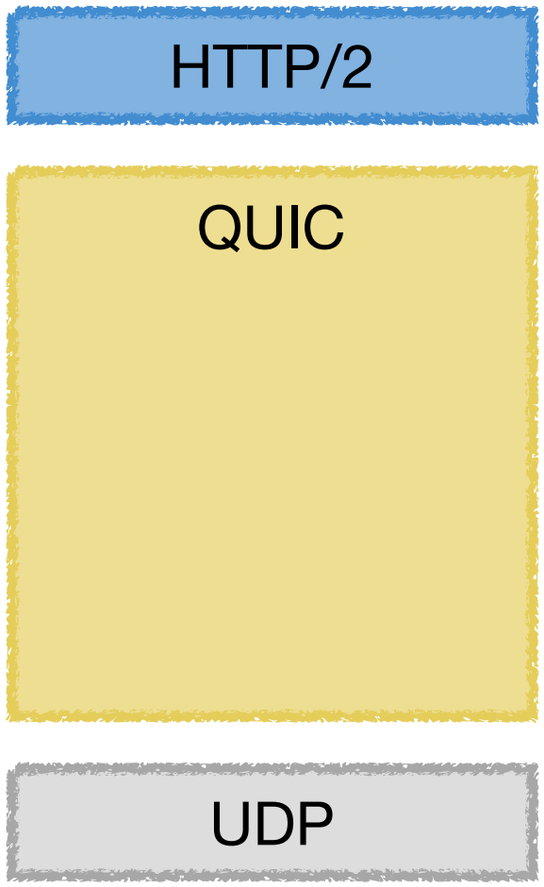

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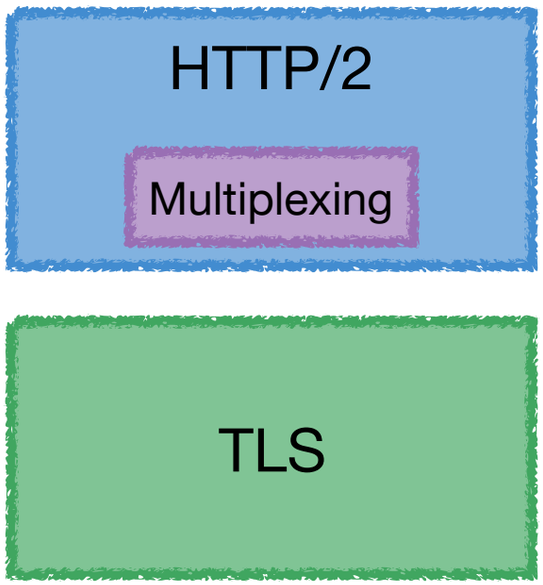
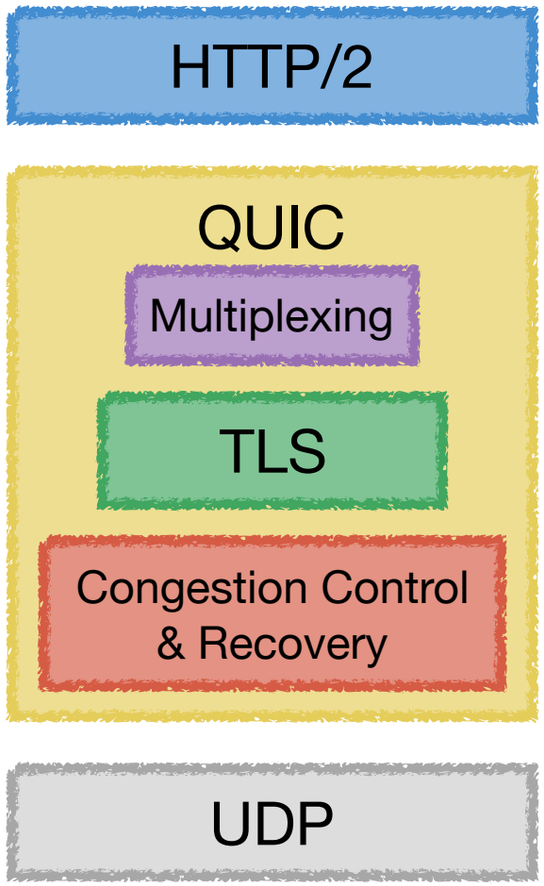




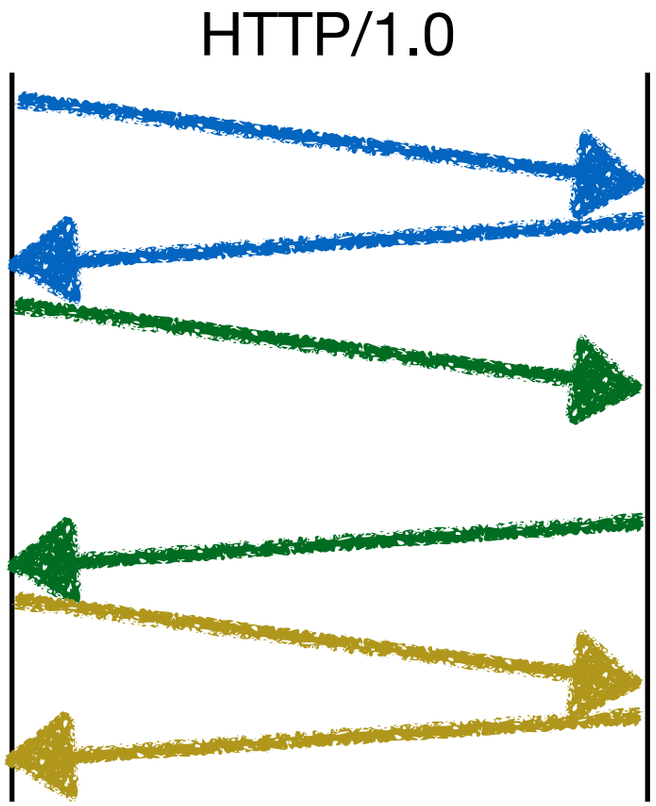
- Stream multiplexing avoids HoL of independent data resources
- Always authenticated and payload is fully encrypted

➡ **Stream & other control information (for e.g. recovery) is not visible to the network anymore!**

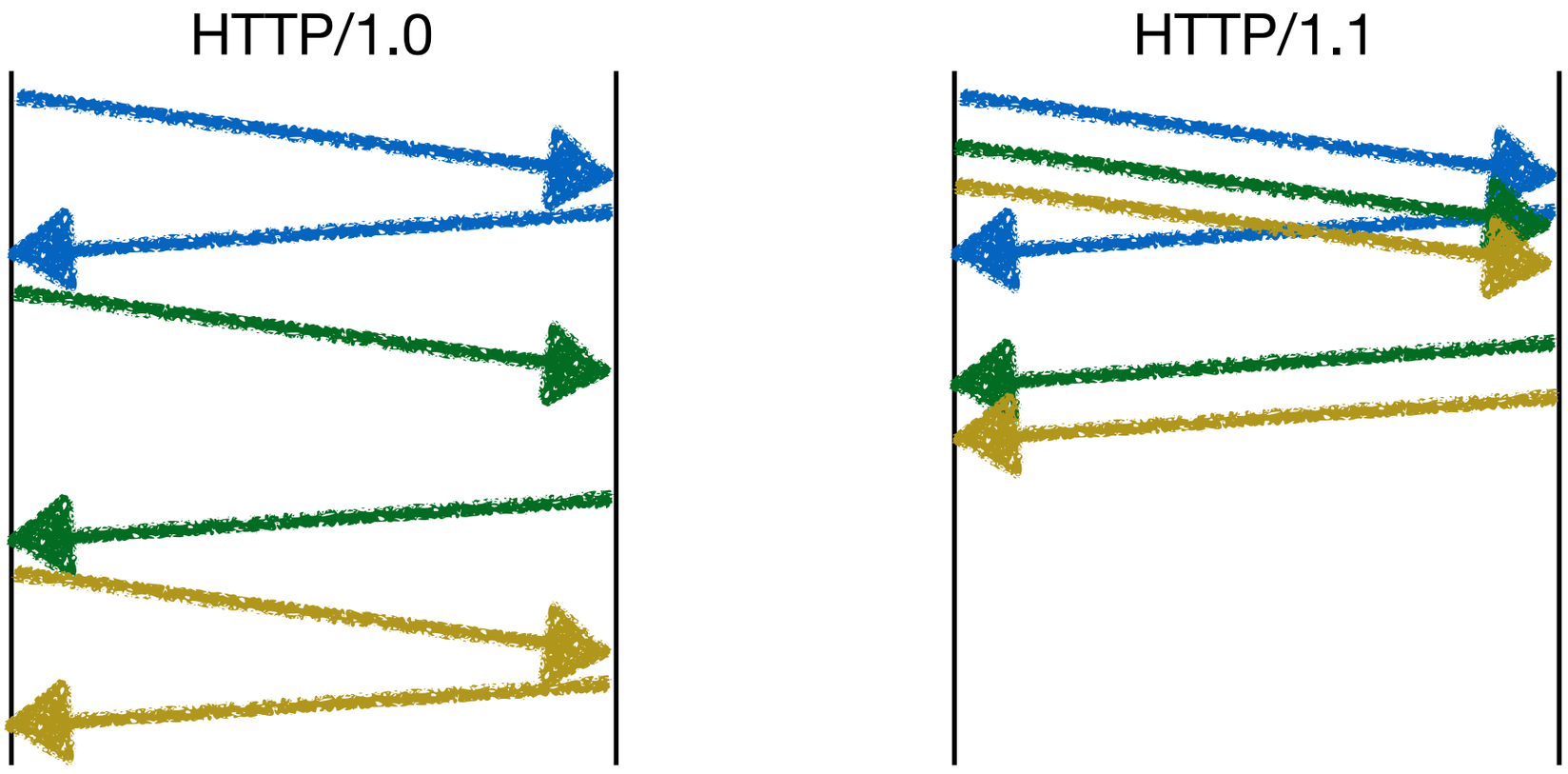
HTTP/2 - Features

- New features to reduce latency of page load time
  - Header compression (HPACK)
  - Server Push
  - Multiplexing of multiple requests over 1 TCP connection
    - avoids Head of Line (HoL) blocking

HTTP/1.1 — Pipelining

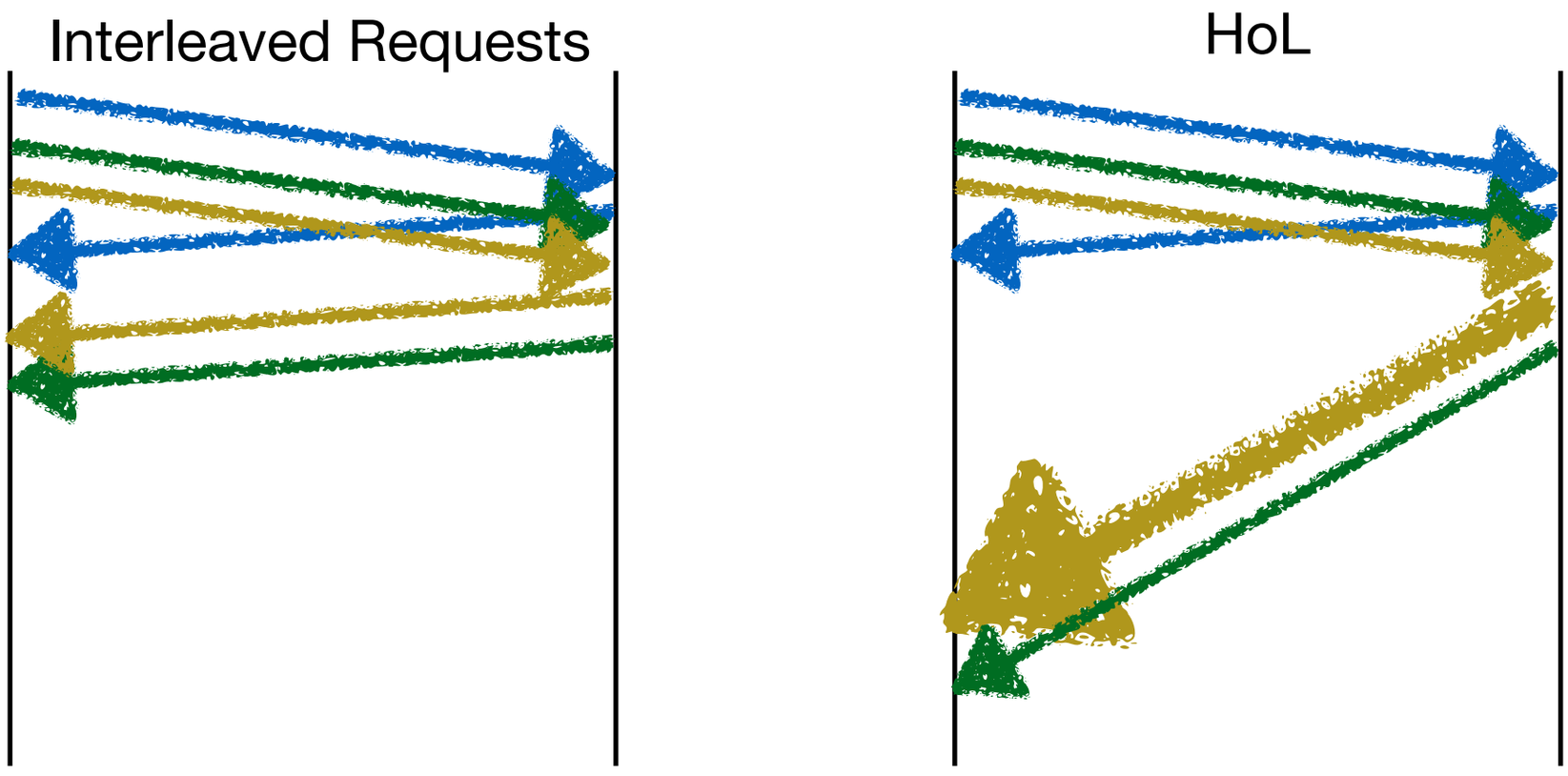


HTTP/1.1 — Pipelining



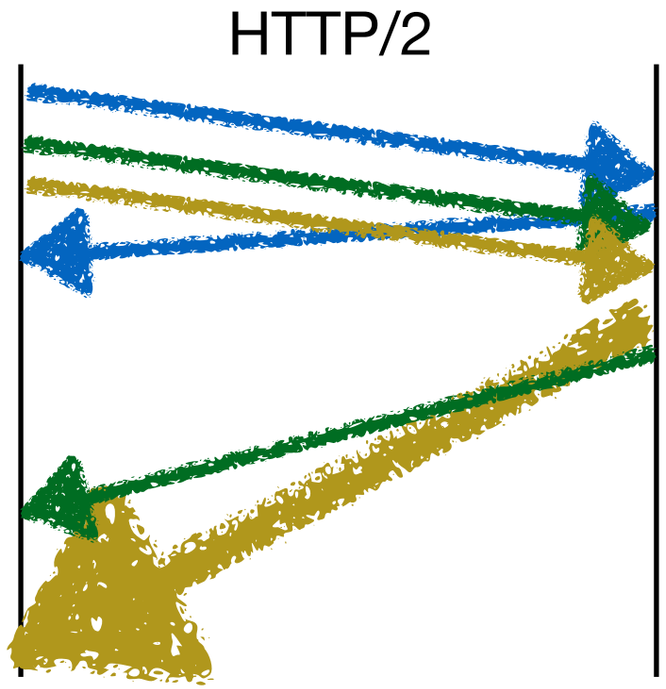
- With pipelining multiple requests can be sent at once
  - ➡ All requests and responses can be sent over the same TCP connection

HTTP — Head of Line Blocking (HoL)



- Large resources can delay later, more important resources
  - ➡ Head-of-Line (HoL) blocking is still possible

HTTP/2 — Stream Multiplexing



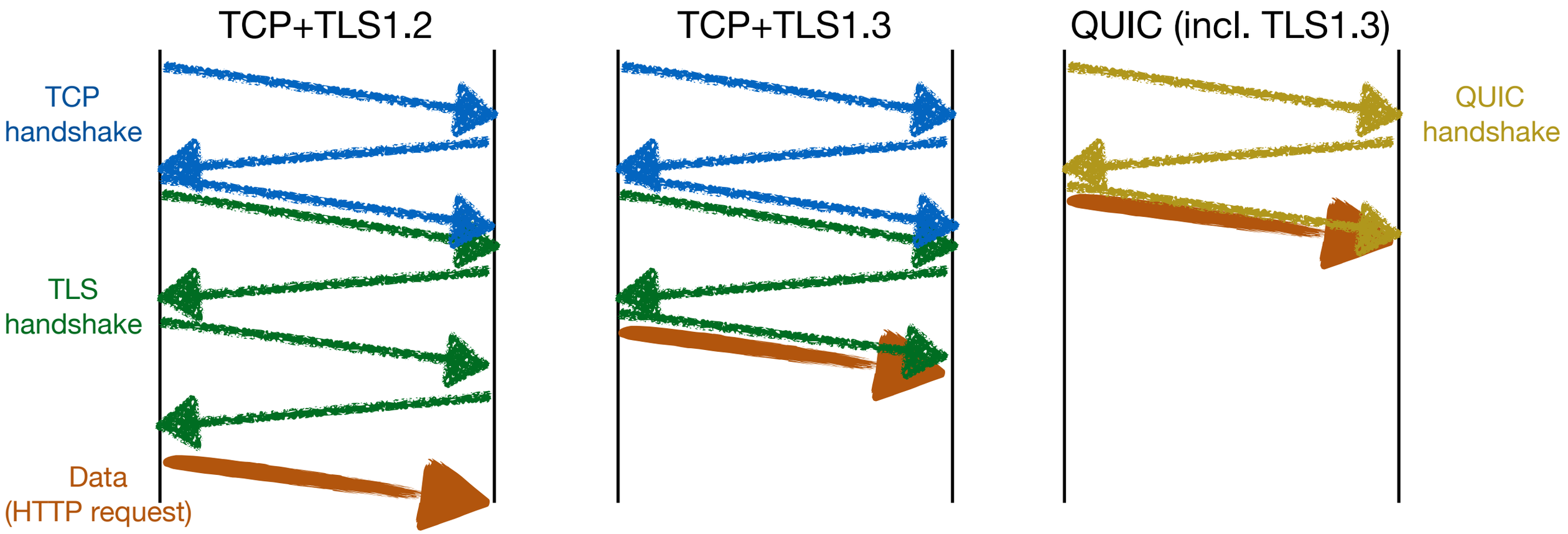
- Requests are send on independent streams in frames

  ➡ Loss or reordering can lead to Head-of-Line (HoL) blocking in the transport layer/TCP

QUIC - Features

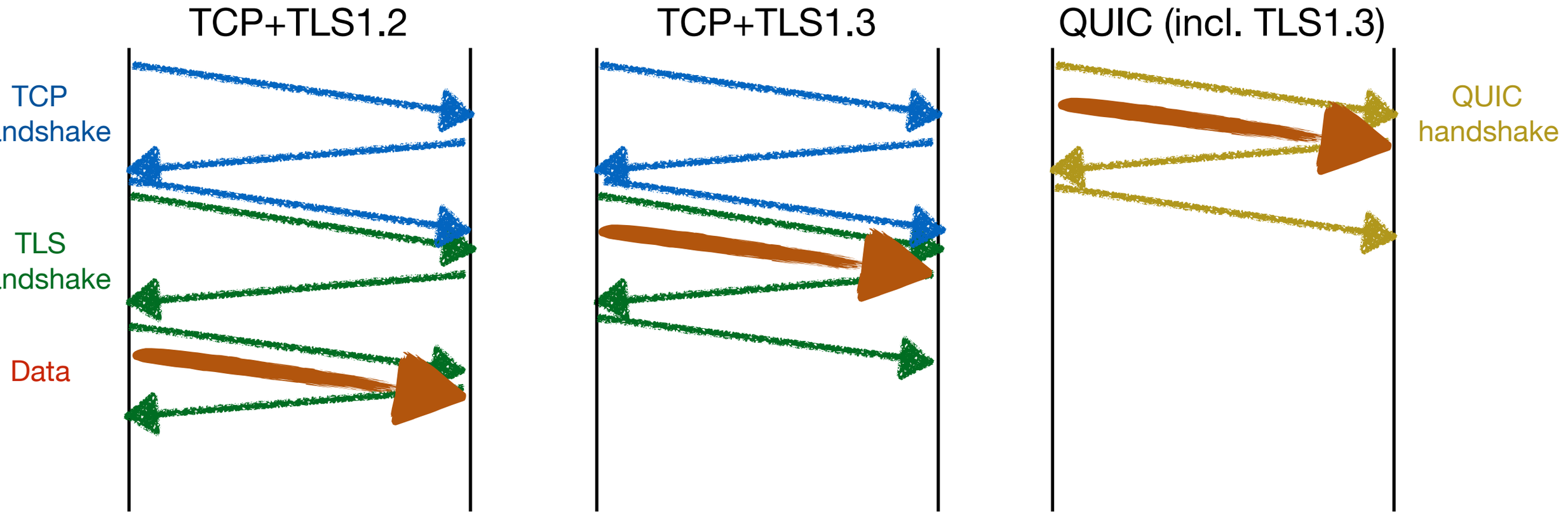
- Stream multiplexing
- Ricer feedback information for enhanced congestion control
- Inherently encrypted using TLS1.3 handshake and control
- 0-RTT low latency support

QUIC — Low Latency Session Establishment



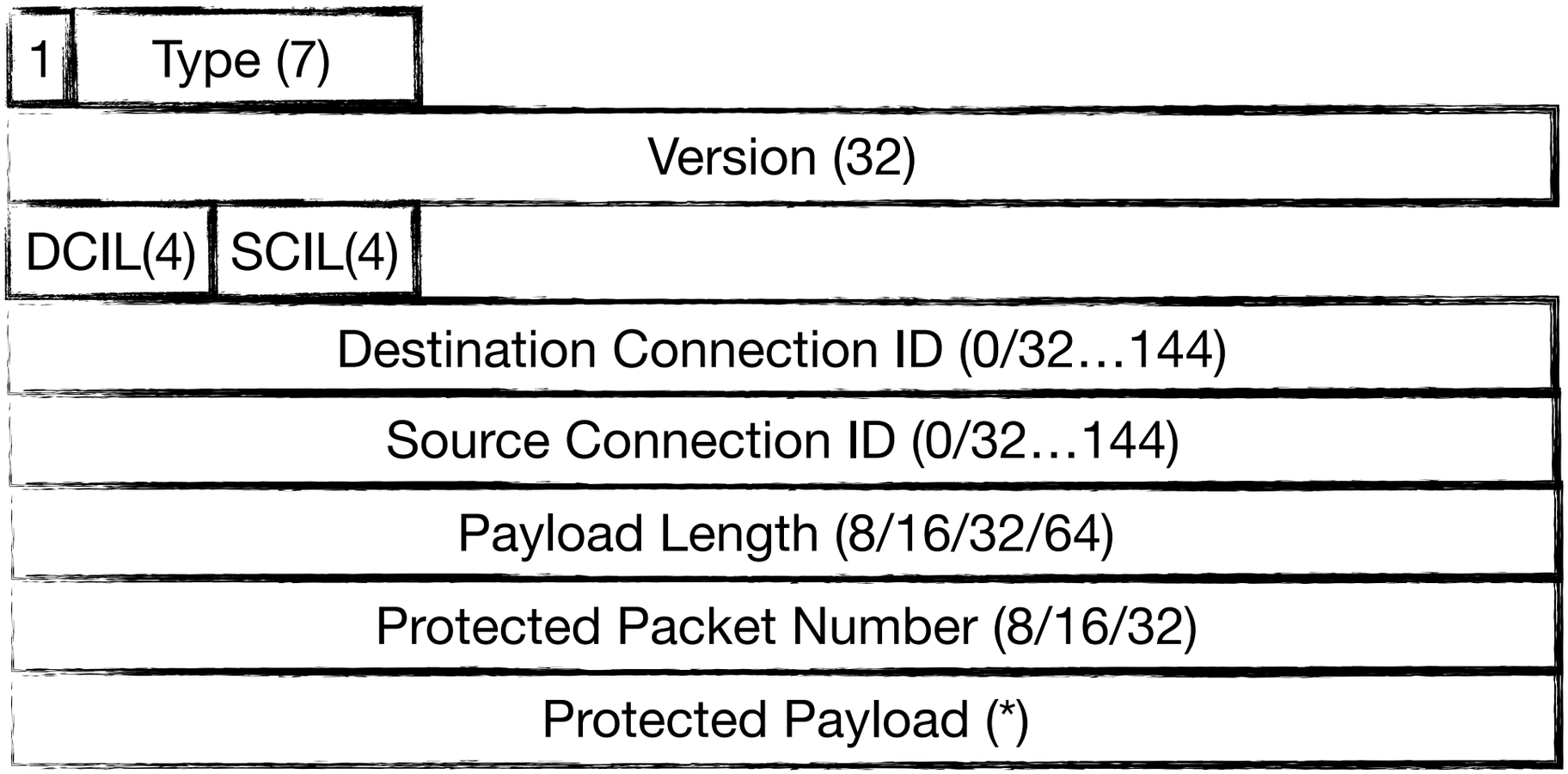
- QUIC combines the transport and crypto handshake
- Handshake packets are not encrypted but verified later

QUIC — 0-RTT Session Resumption



- QUIC can send encrypted payload data in the first RTT on session resumption to a previously connected server
- Care must be taken as QUIC/TLS1.3 0-RTT data are not protected against reply attacks

The QUIC wire image — Long header format (handshake & 0-RTT)



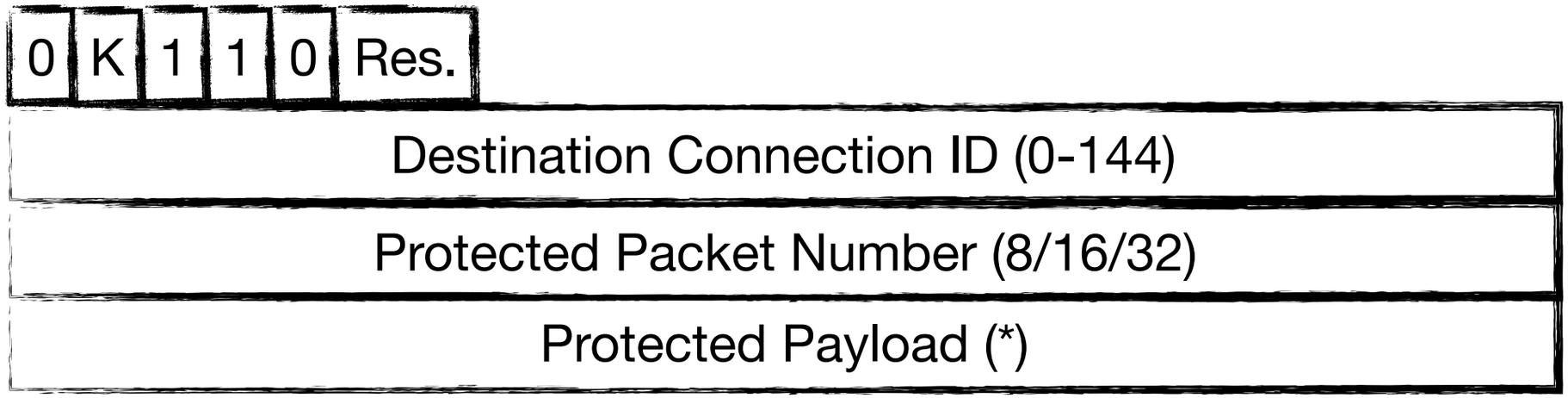
- (Optional) Connection ID for migration and resilience to NAT rebinding
- Packet number is confidentiality protected separate from packet protection (as used as cryptographic nonce for packet encryption)

QUIC Long Header Types

- **Cleartext** packets for (Client) Initial, (Server Stateless) Retry, and (Server/Client) Handshake
- **Encrypted** payload for 0-RTT

Type	Name
0x7F	Initial
0x7E	Retry
0x7D	Handshake
0x7C	0-RTT **Protected**

The QUIC wire image — Short header format (only 1-RTT)



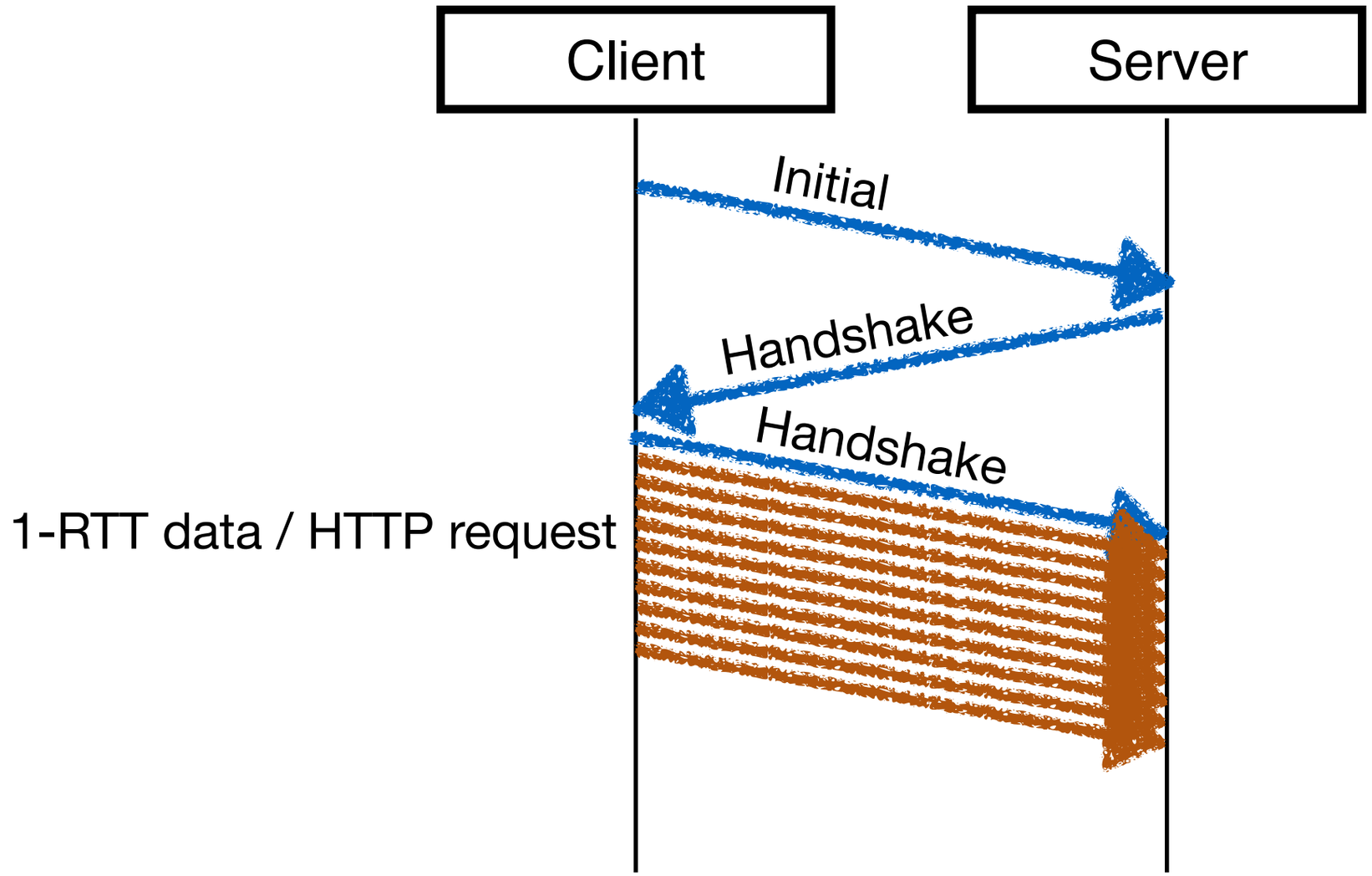
- Only Destination Connection ID or no Connection ID at all
- Payload is always encrypted (K bit indications key phase for decryption)

QUIC Invariants

- Basically everything can change between QUIC version, except a few invariants that are needed for version negotiation!

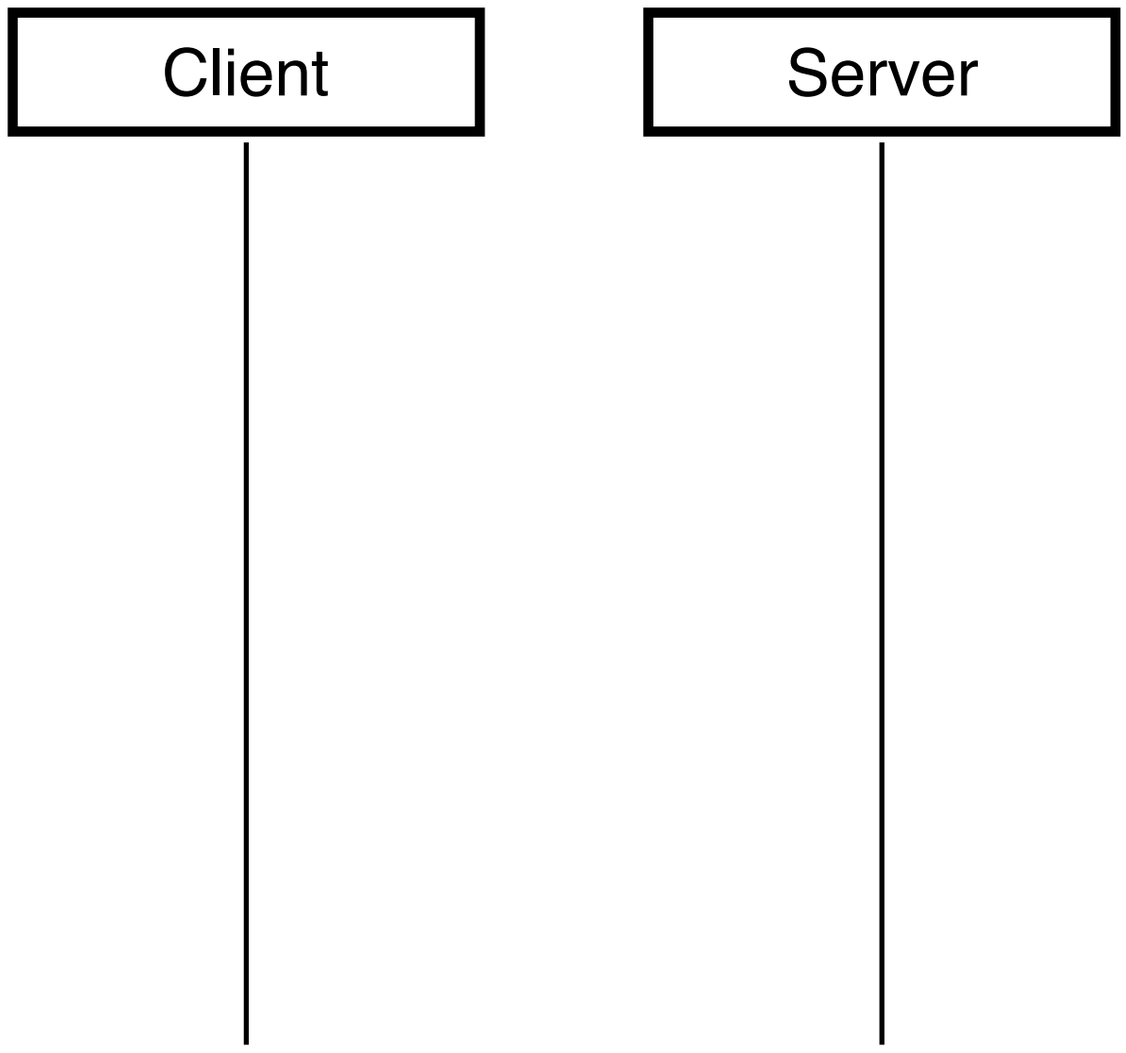
- Only to make version negotiation work, between different versions the following things need to remain the same:
  - the location and meaning of the header form flag,
  - the location and meaning of the Connection ID flag in the short header,
  - the location and size of the Connection ID field in both header forms,
  - the location and size and meaning of the Version field in long headers, and
  - the whole version negotiation packet.

QUIC Handshake



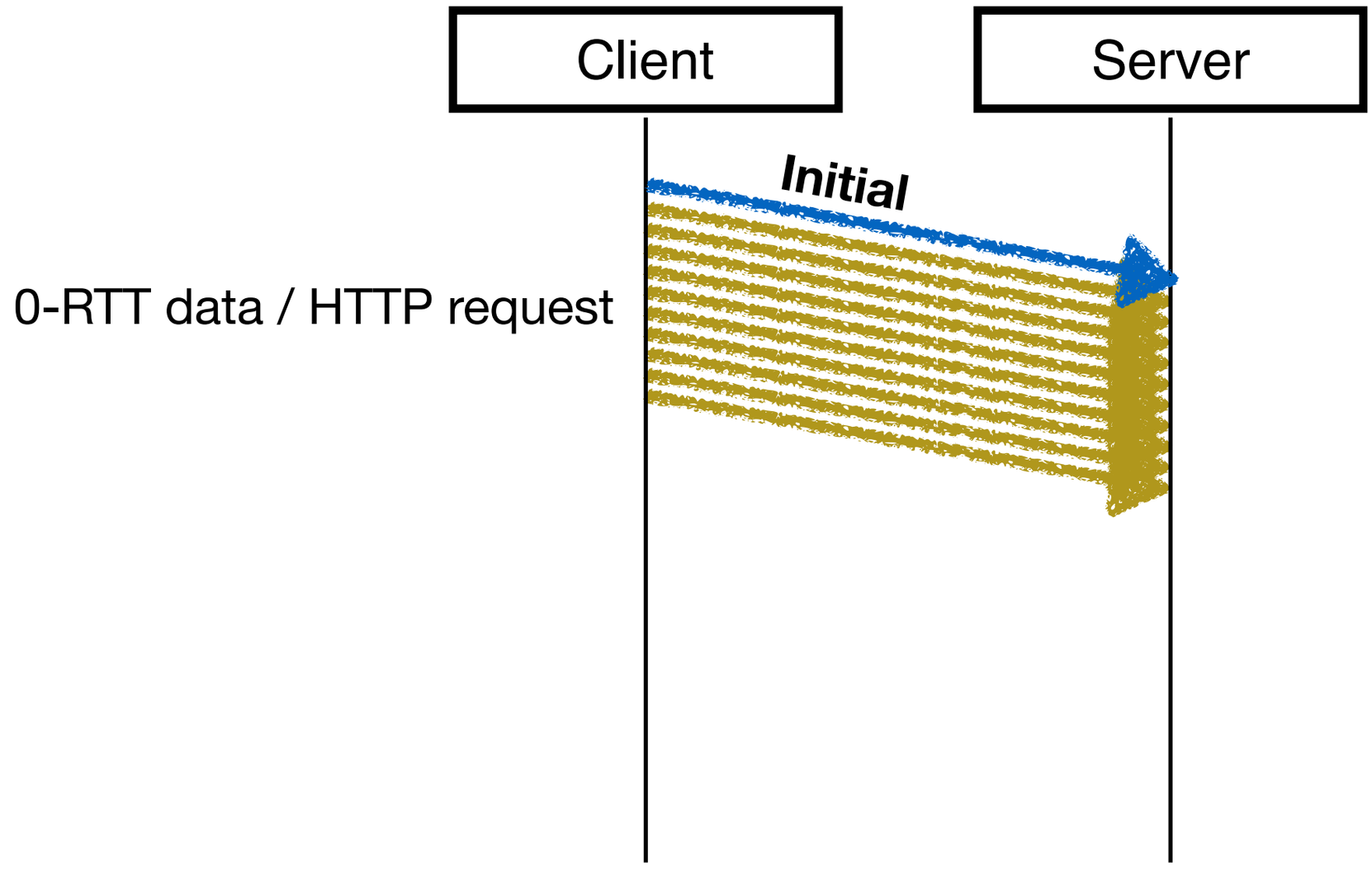
- Copy of the Client Initial and Server Cleartext are included in the encrypted part to verify content

QUIC Handshake — 0-RTT Session Resumption



- Client can send an initial window of data (10 packets) together with Client Initial

QUIC Handshake — 0-RTT Session Resumption



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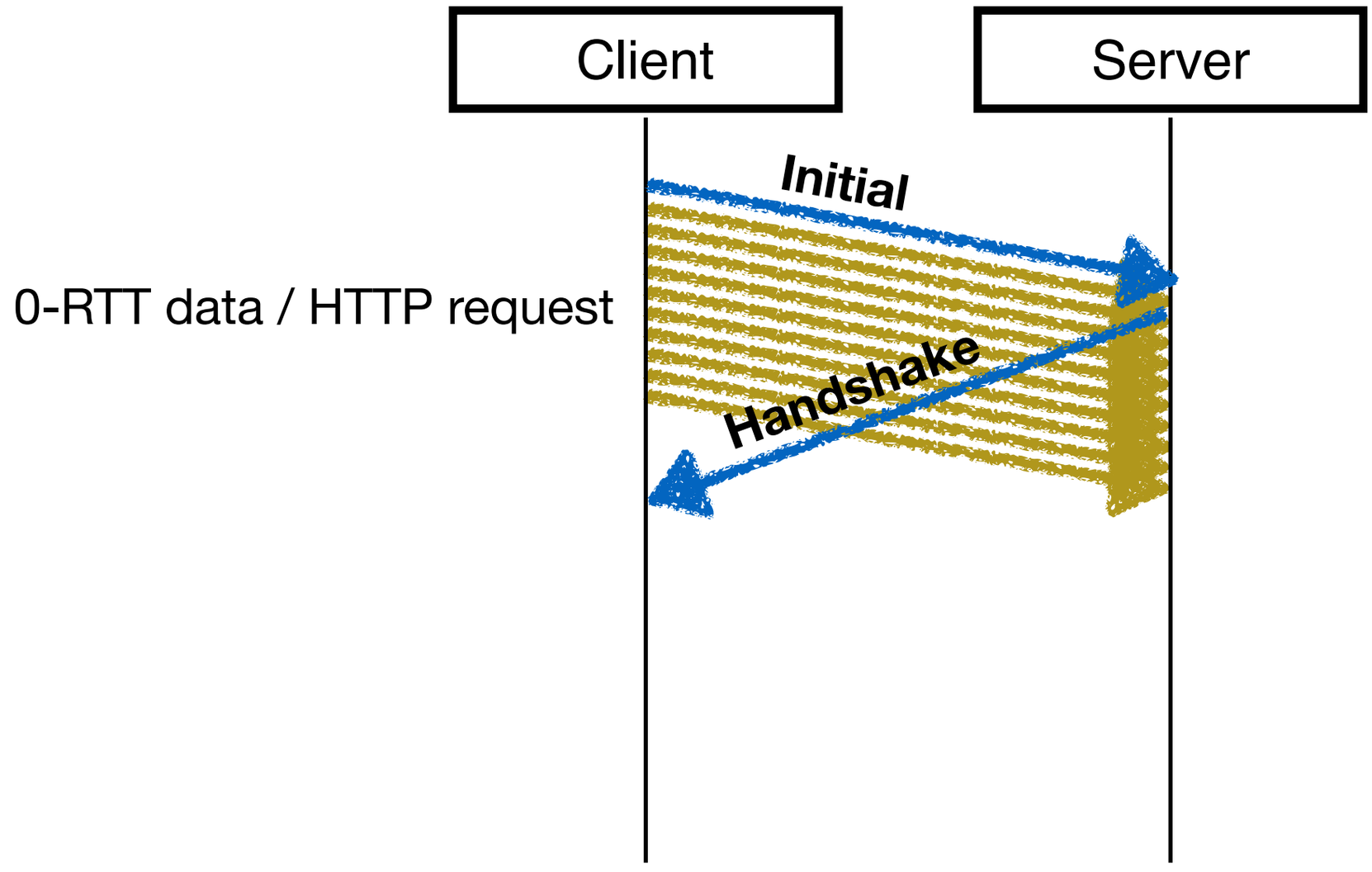

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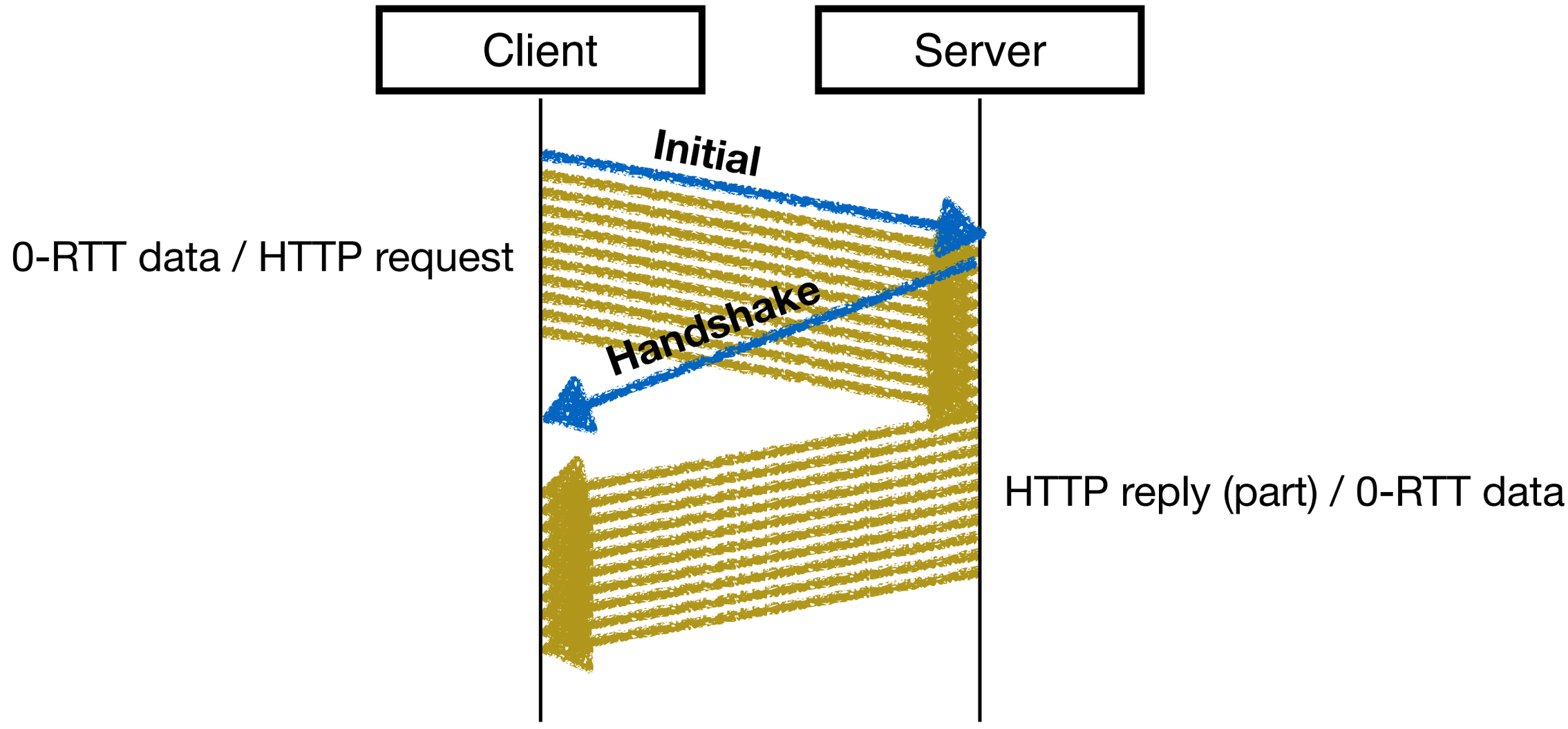

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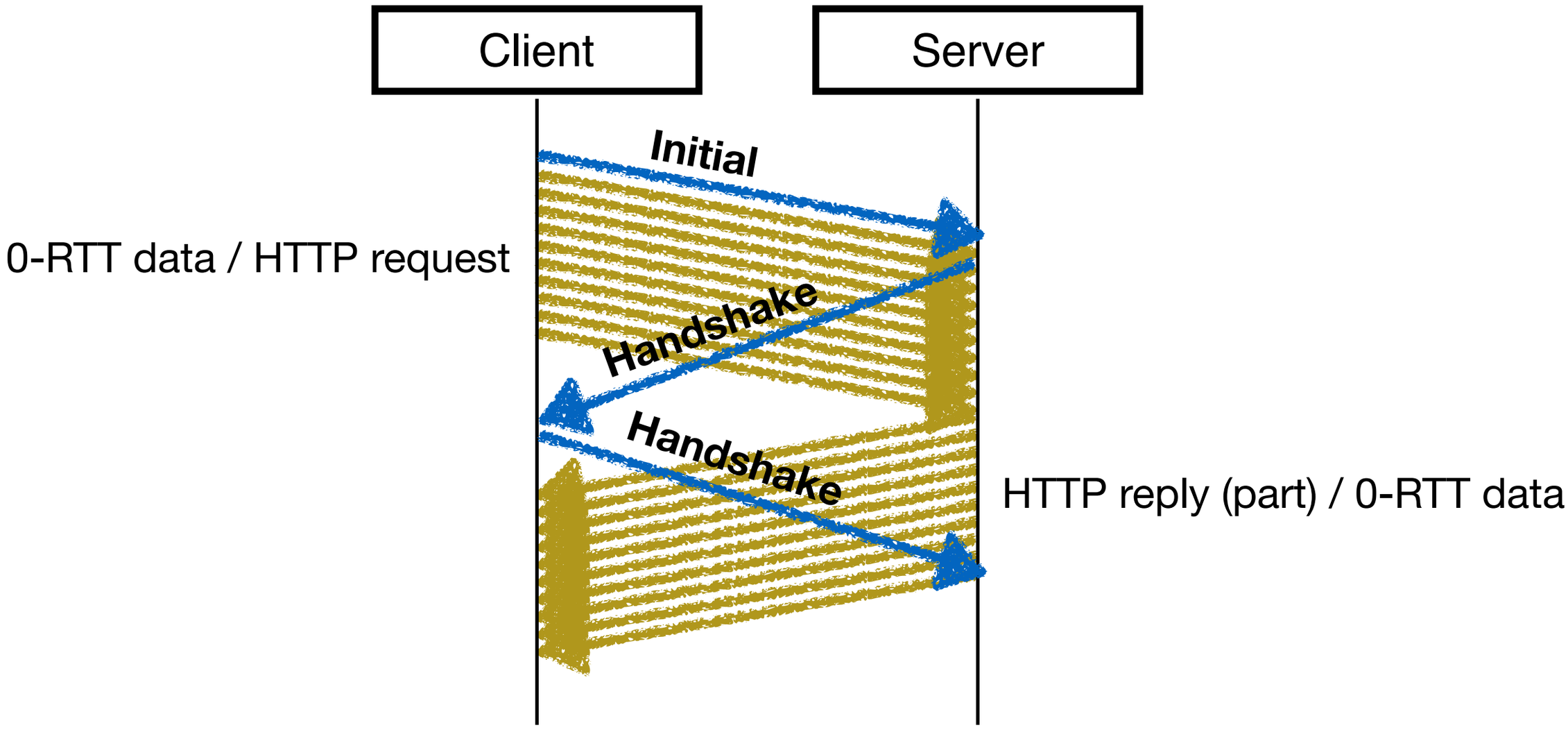

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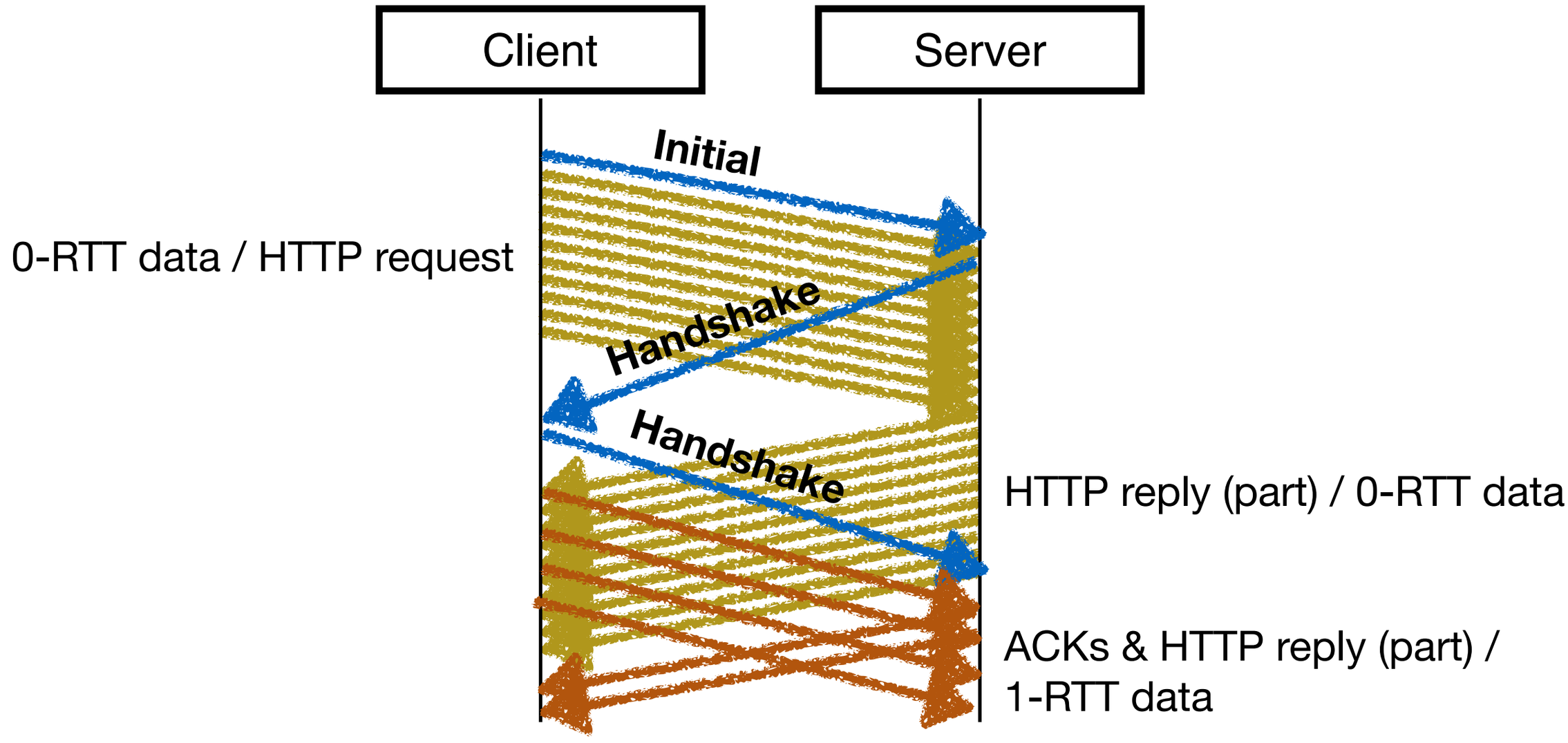
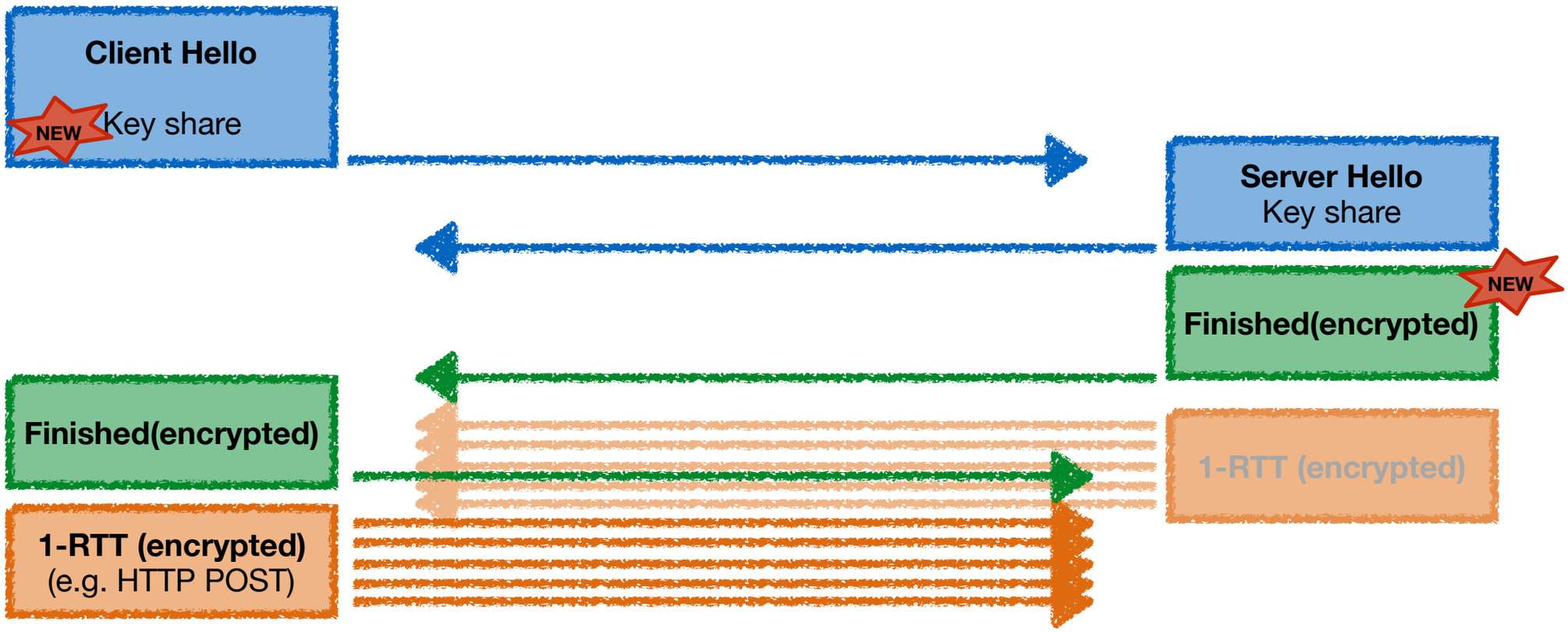


- Client can send an initial window of data (10 packets) together with Client Initial

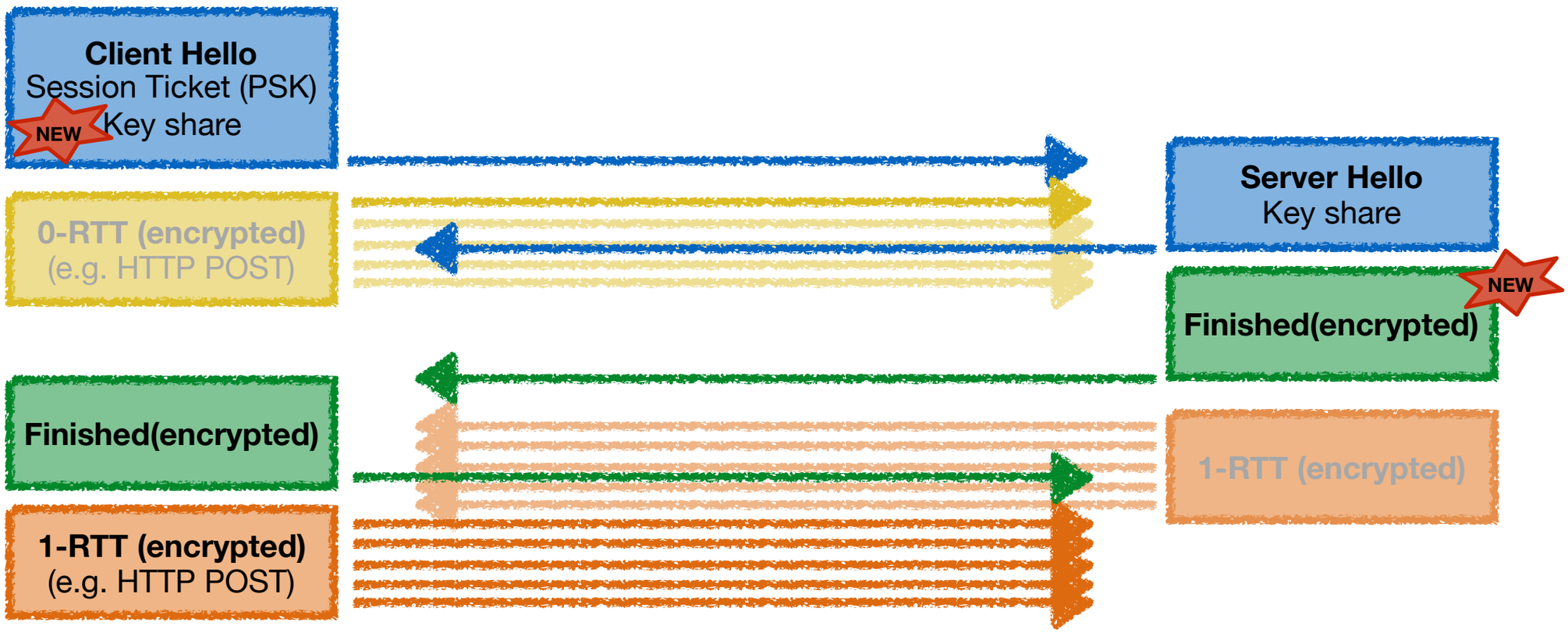
TLS1.3 - Features

- Use of Authenticated Encryption with Associated Data (AEAD)
- Perfect Forward Secrecy
  - Static RSA and static Diffie-Hellman cipher suites removed
- All handshake messages after the ServerHello now encrypted
- New version negotiation mechanism based on extension due for (server and network) compatibility
- Session resumption in 0-RTT mode

TLS 1.3 Handshake



TLS 1.3 Handshake



- Session Tickets servers are stateless
  - 0-RTT PSK provides no Forward Secrecy if Session Ticket key is compromised
  - Replay attack requires idempotent data for 0-RTT

TLS1.3 Interception

- see also draft-camwinget-tls-use-cases

- Perfect Forward Secrecy
  - Keys cannot be shared apriori with middlebox
  - (see also draft-green-tls-static-dh-in-tls13)
- Encrypted Server Certificate
  - Server Identity hidden (as Server Name Identification (SNI) might not match)
- Downgrade Protection
  - detects stripping of "supported_versions" extension

- Certificate pinning
  - see also draft-sheffer-tls-pinning-ticket

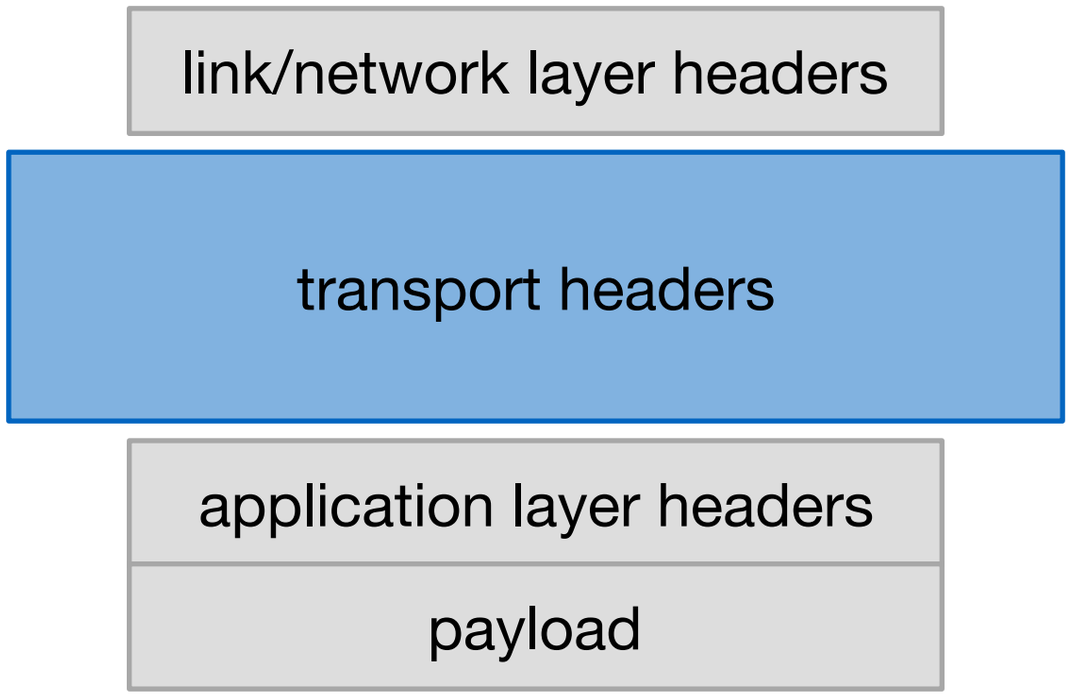
QUIC wire image — Measurements and Monitoring

- **Round-Trip Time (RTT)** can be estimated during the handshake
  - ➡ No easy way to correlate two packets in each direction during the rest of the connection

- Packet Number is now encrypted and cannot be utilized for measurement anymore

- Retransmissions and ECN congestion indications are not visible to the path (to estimate whole-path congestion)

Transport protocol design, 1990s style



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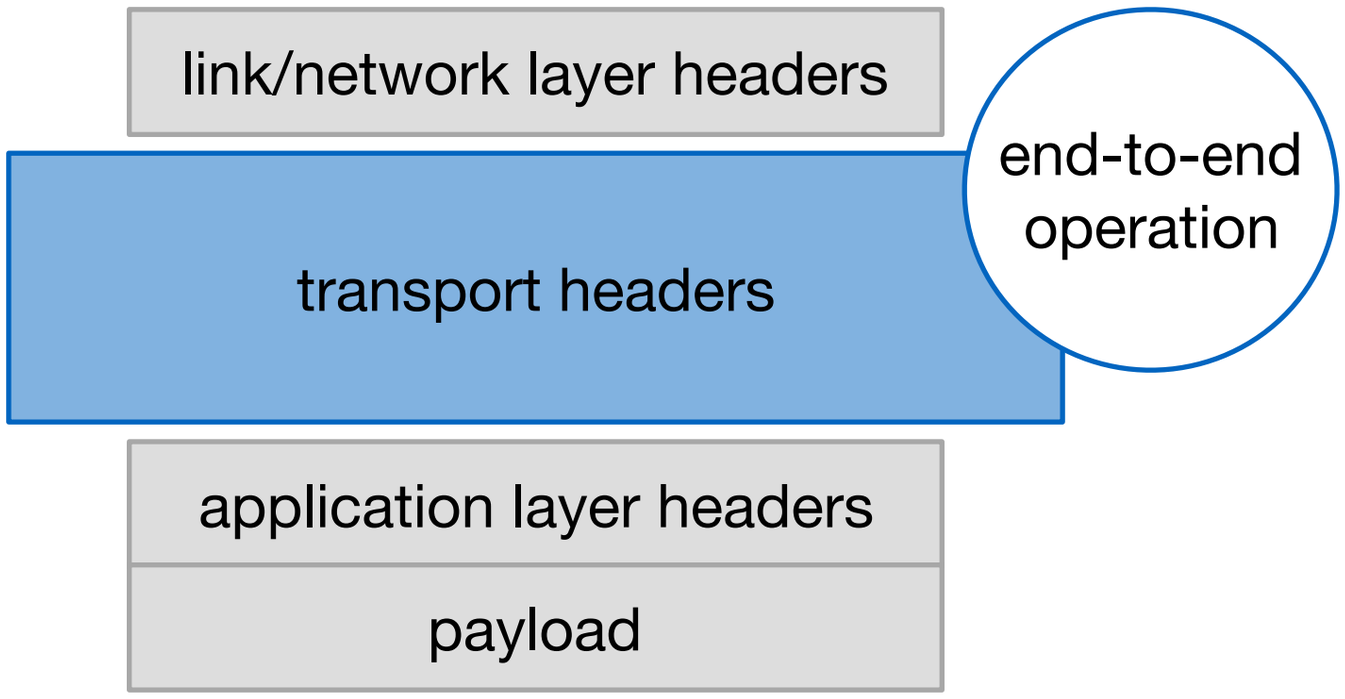

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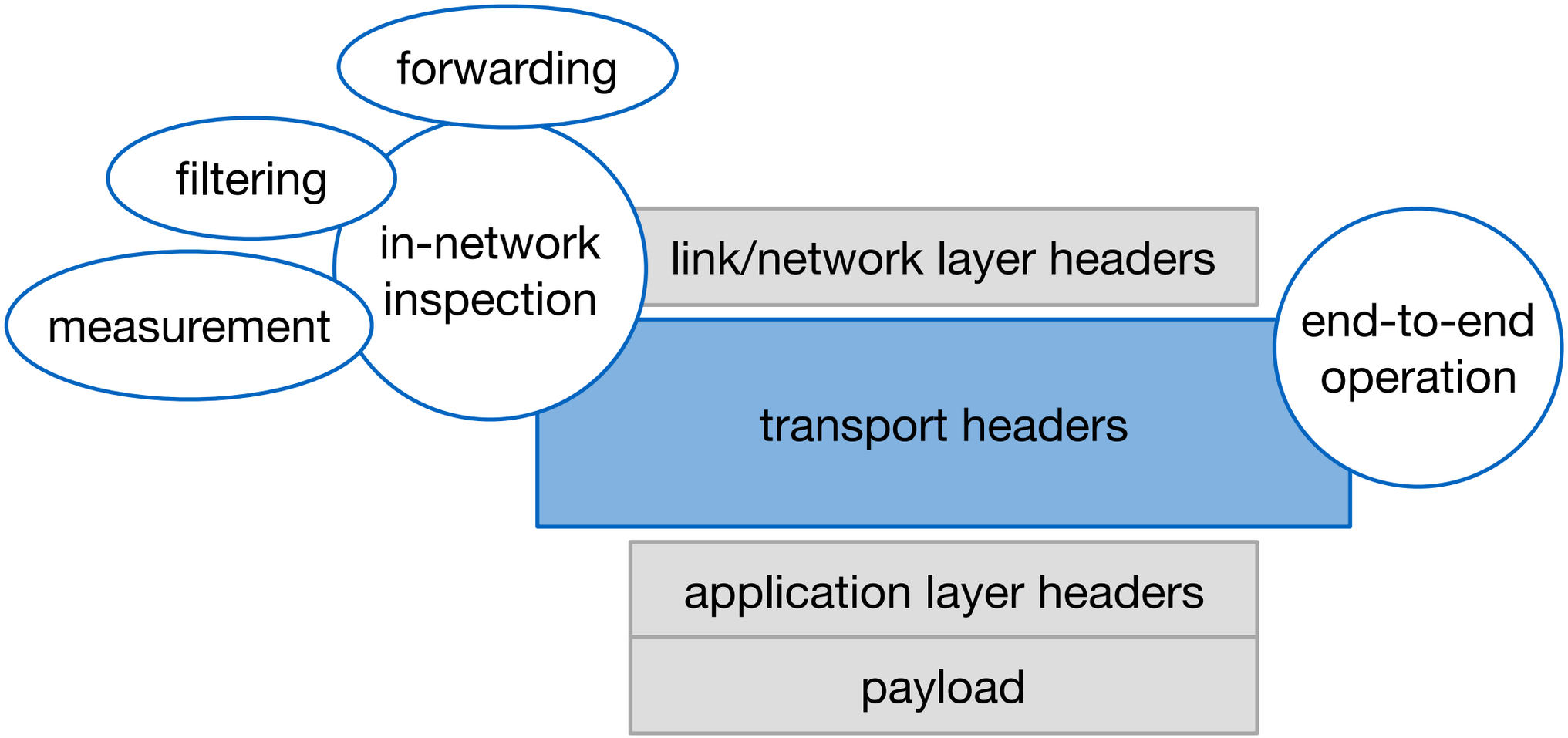

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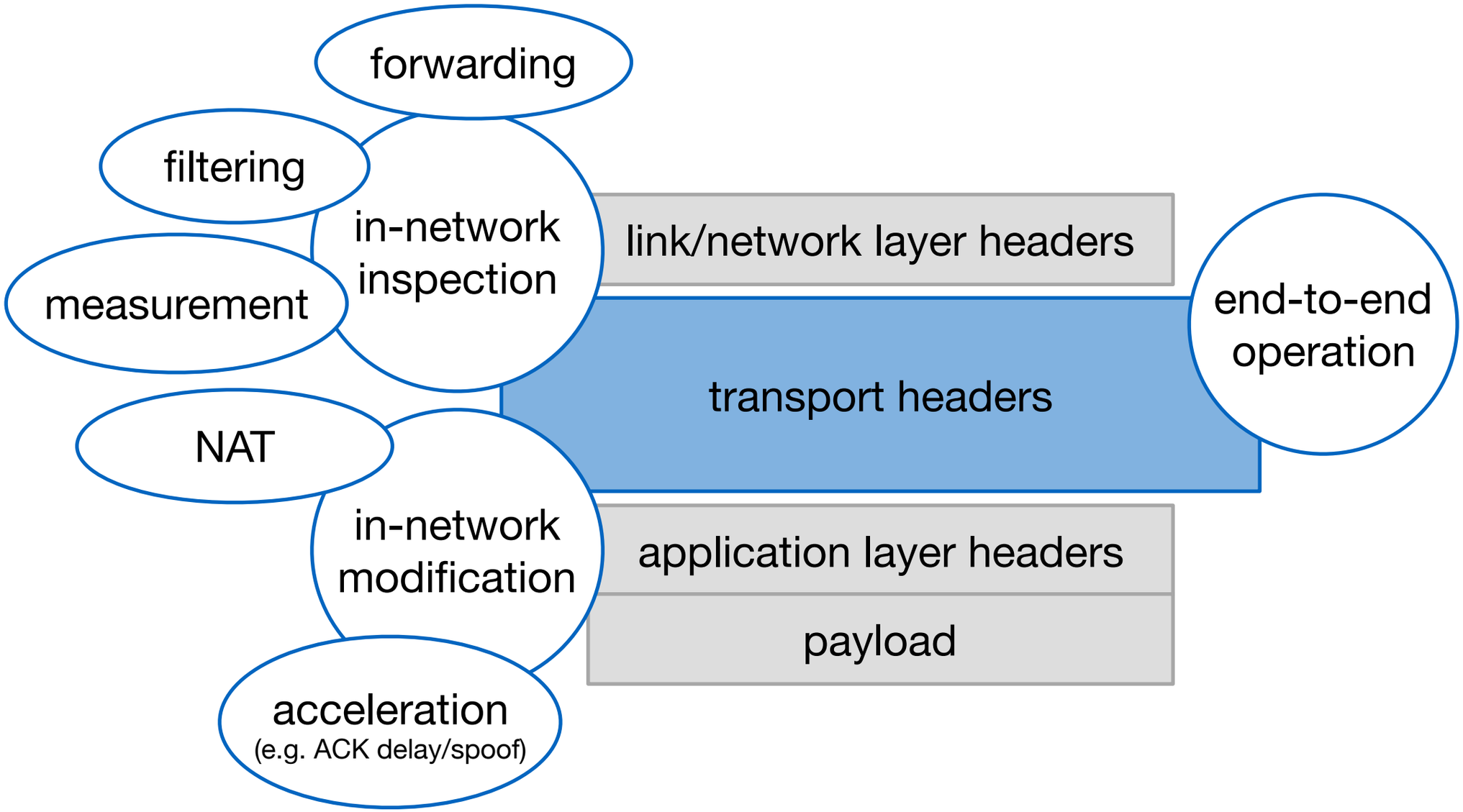

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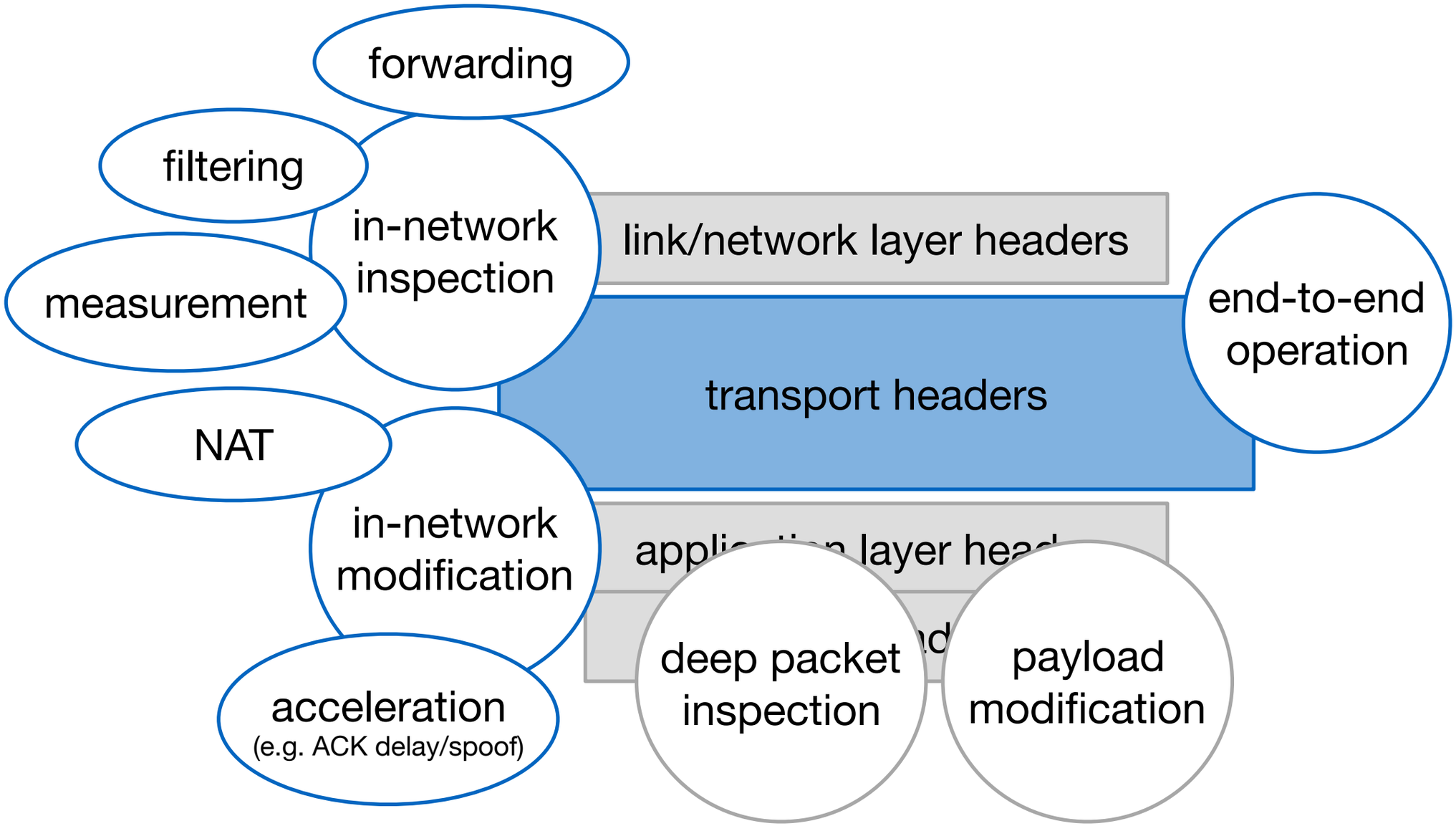
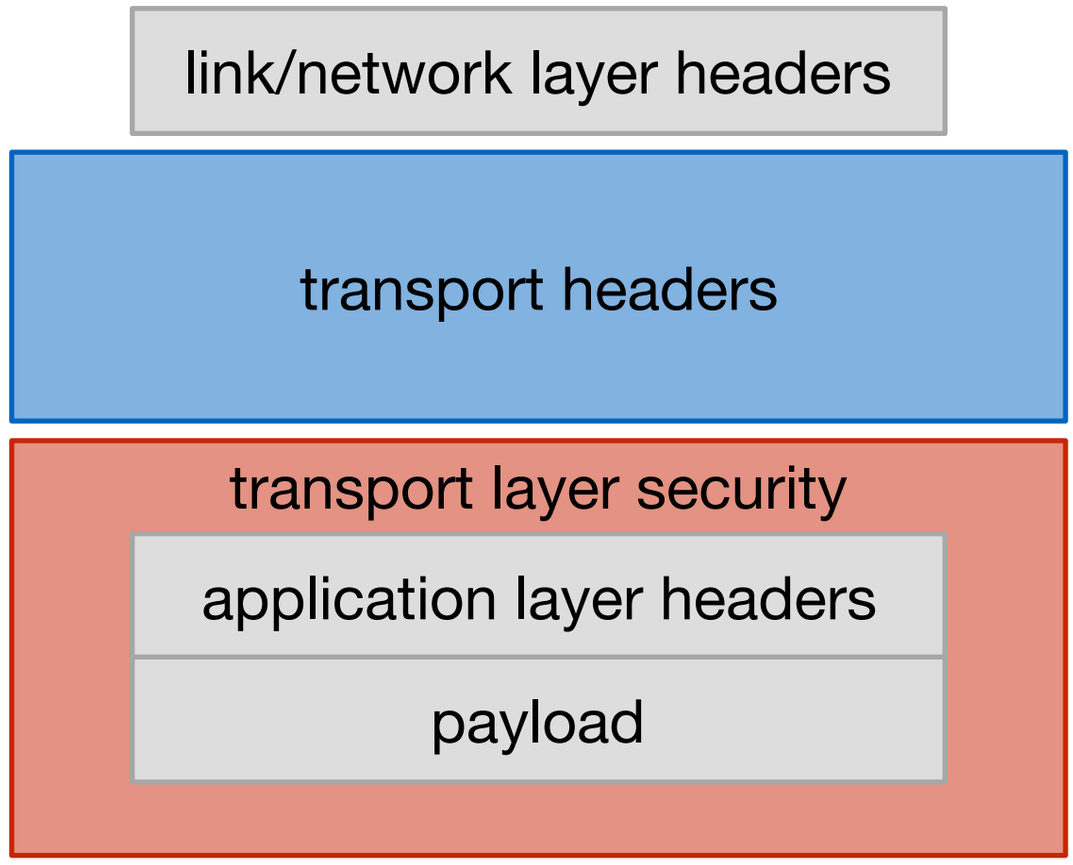


Transport protocol design, now with security!



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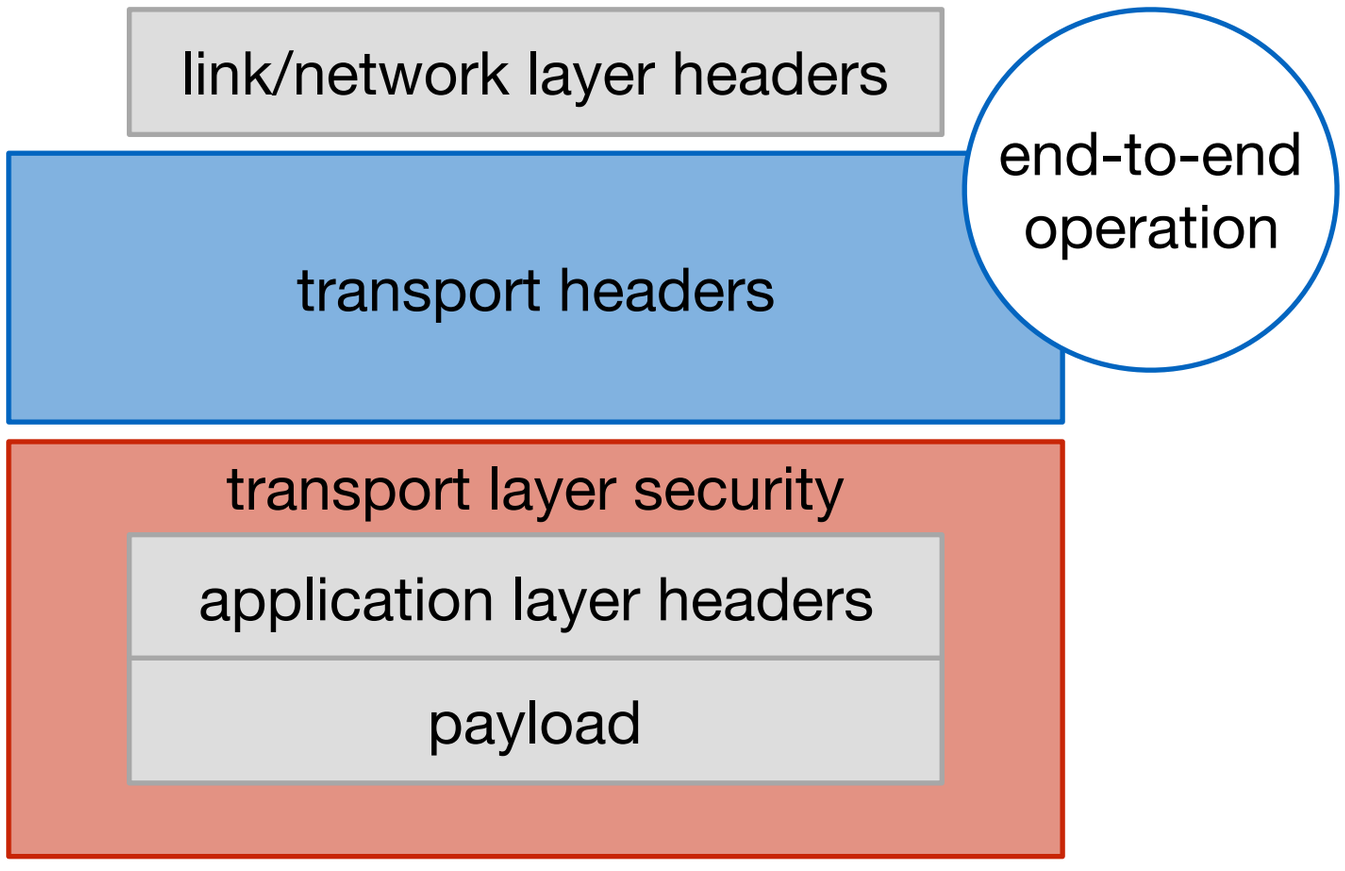

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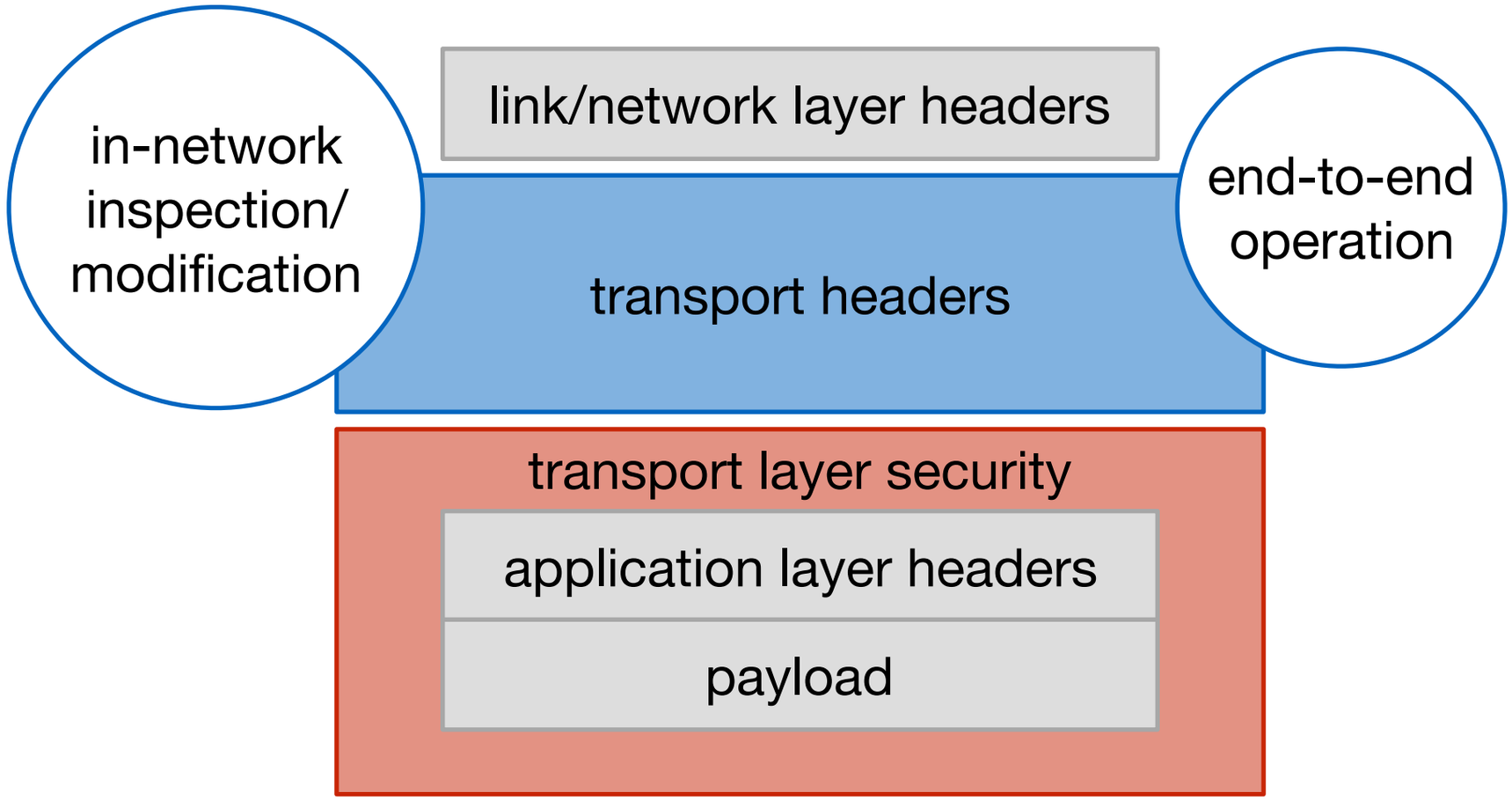

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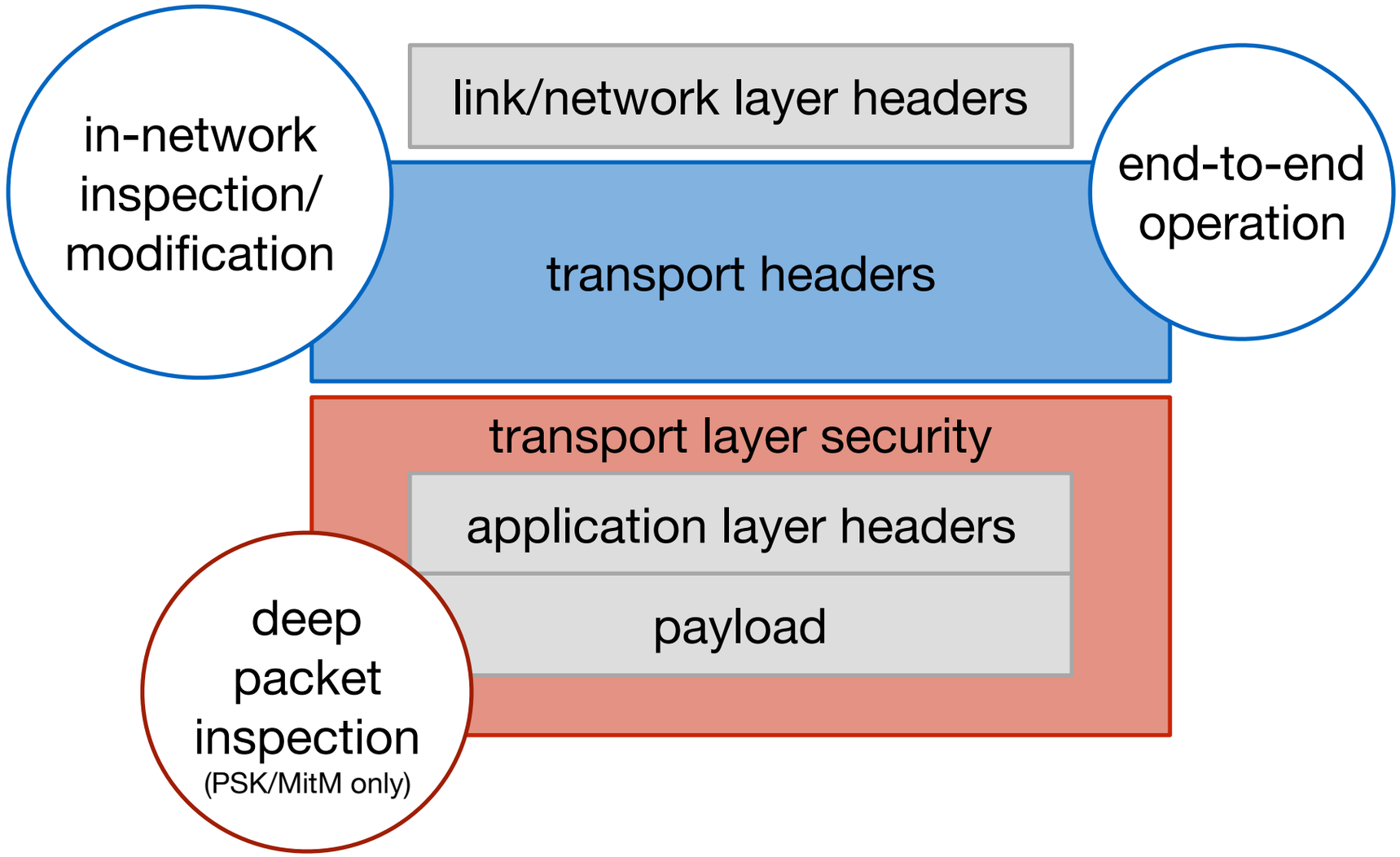
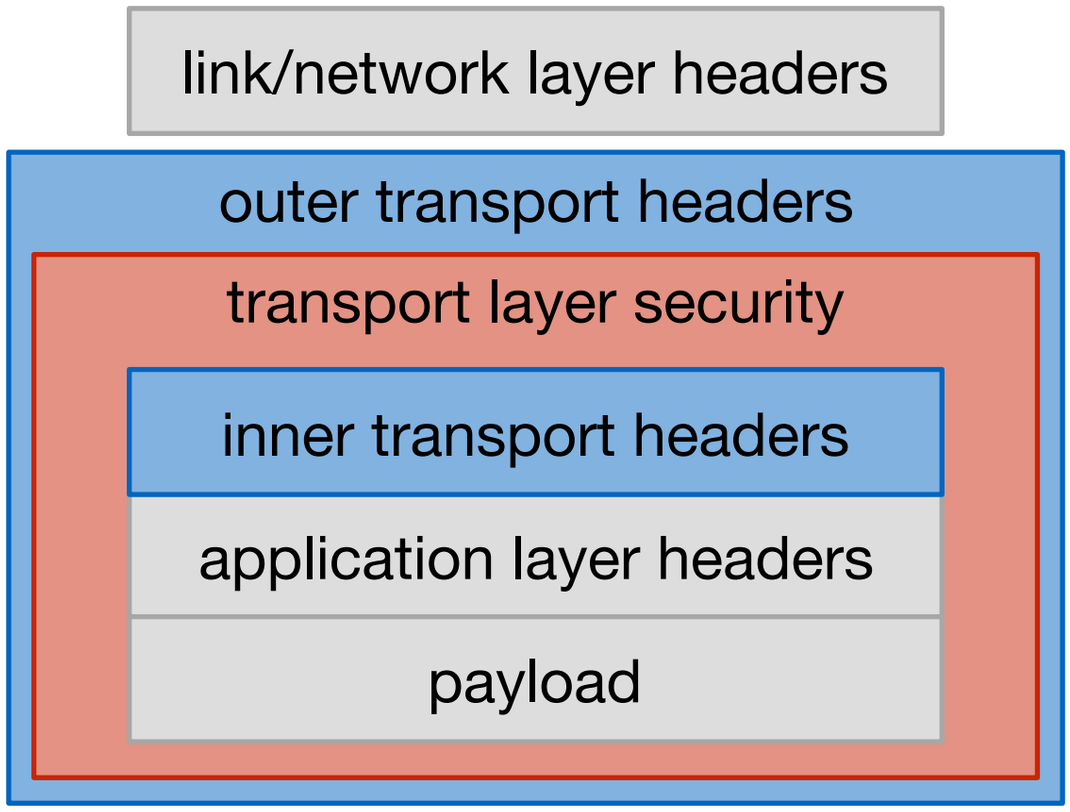


Encrypted transport protocol design: introducing the wire image



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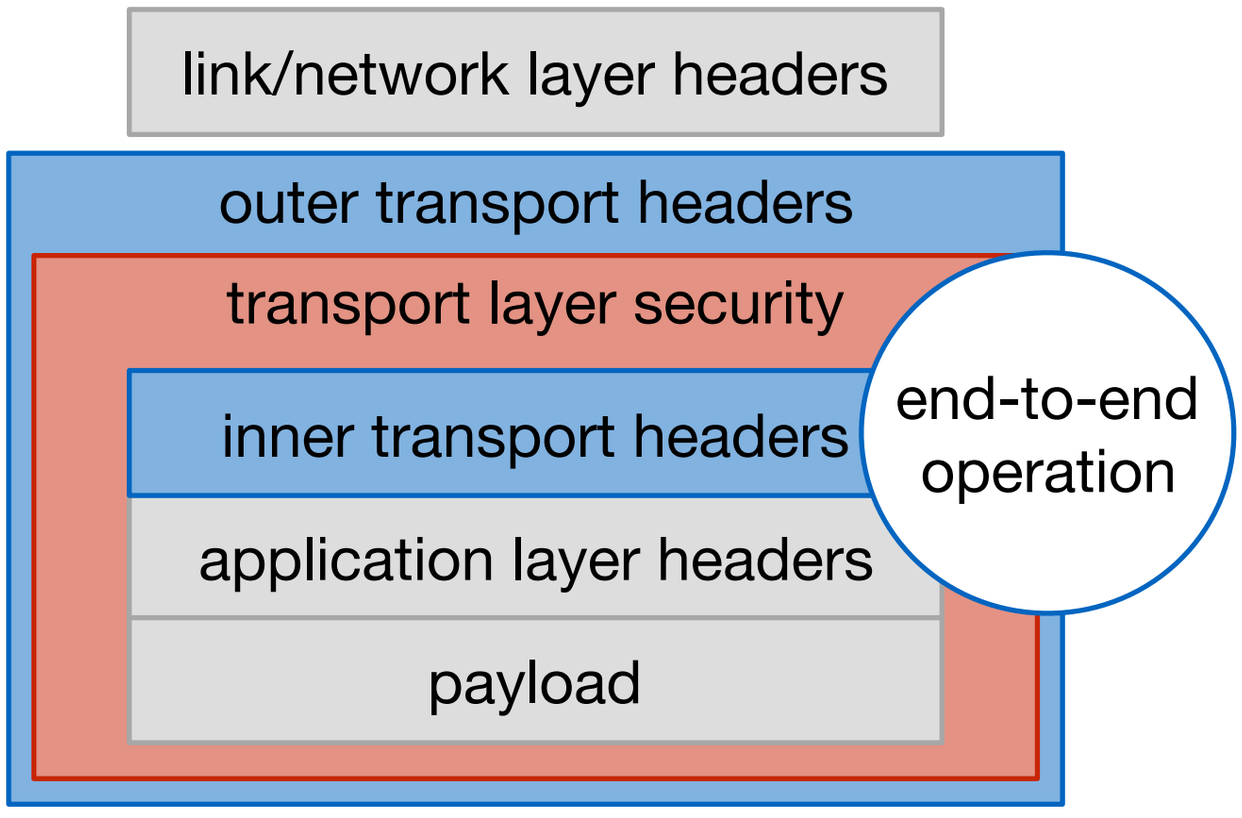

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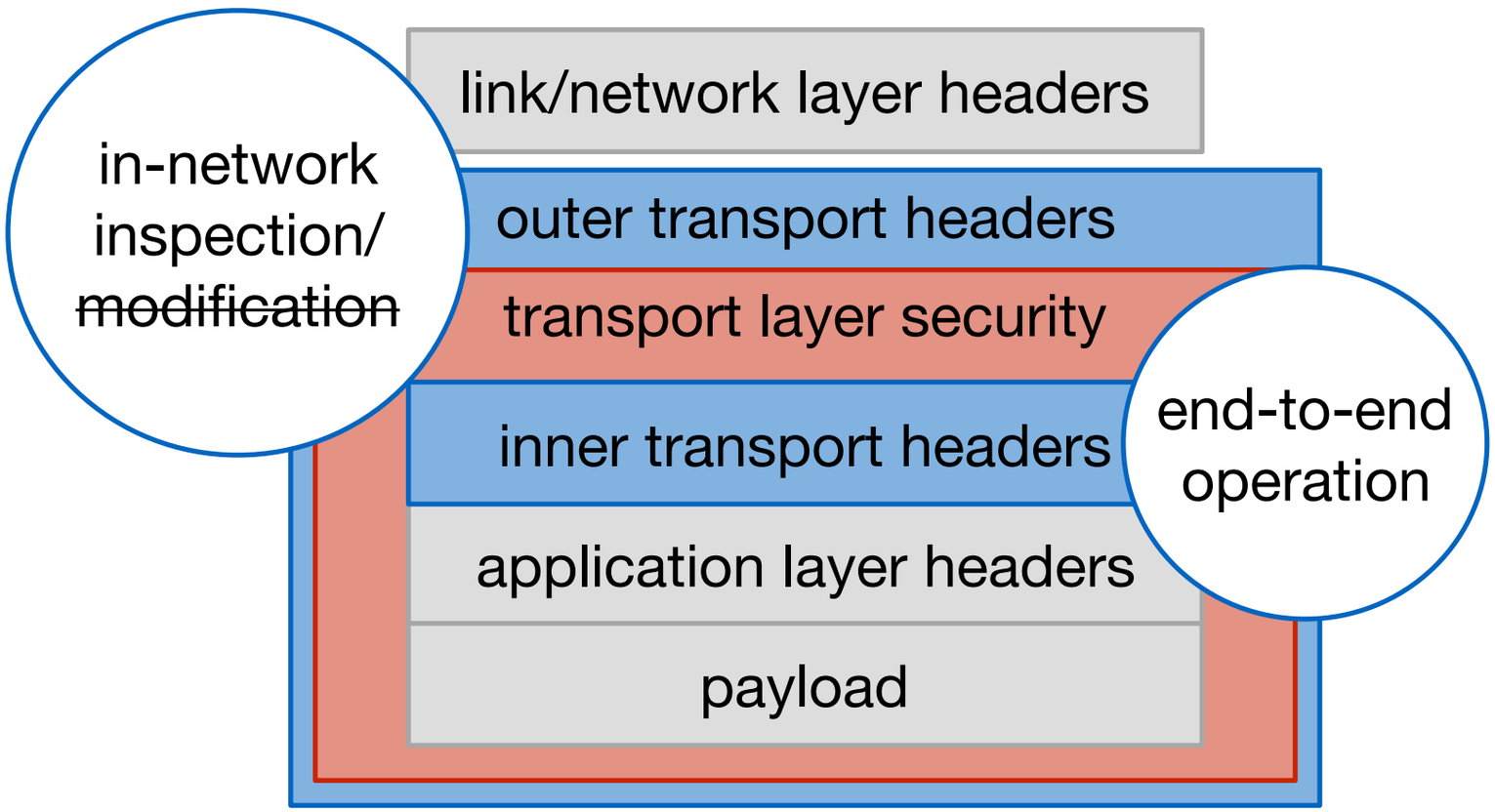

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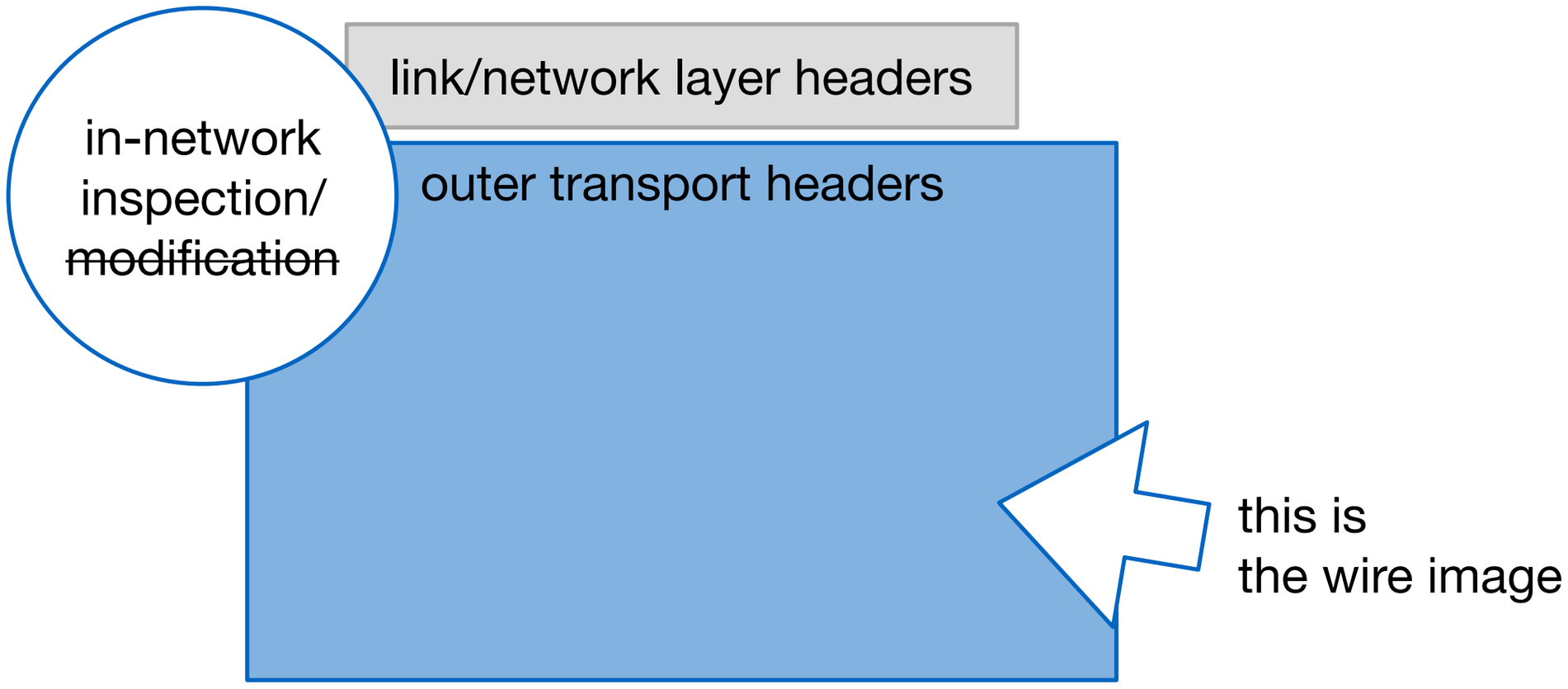


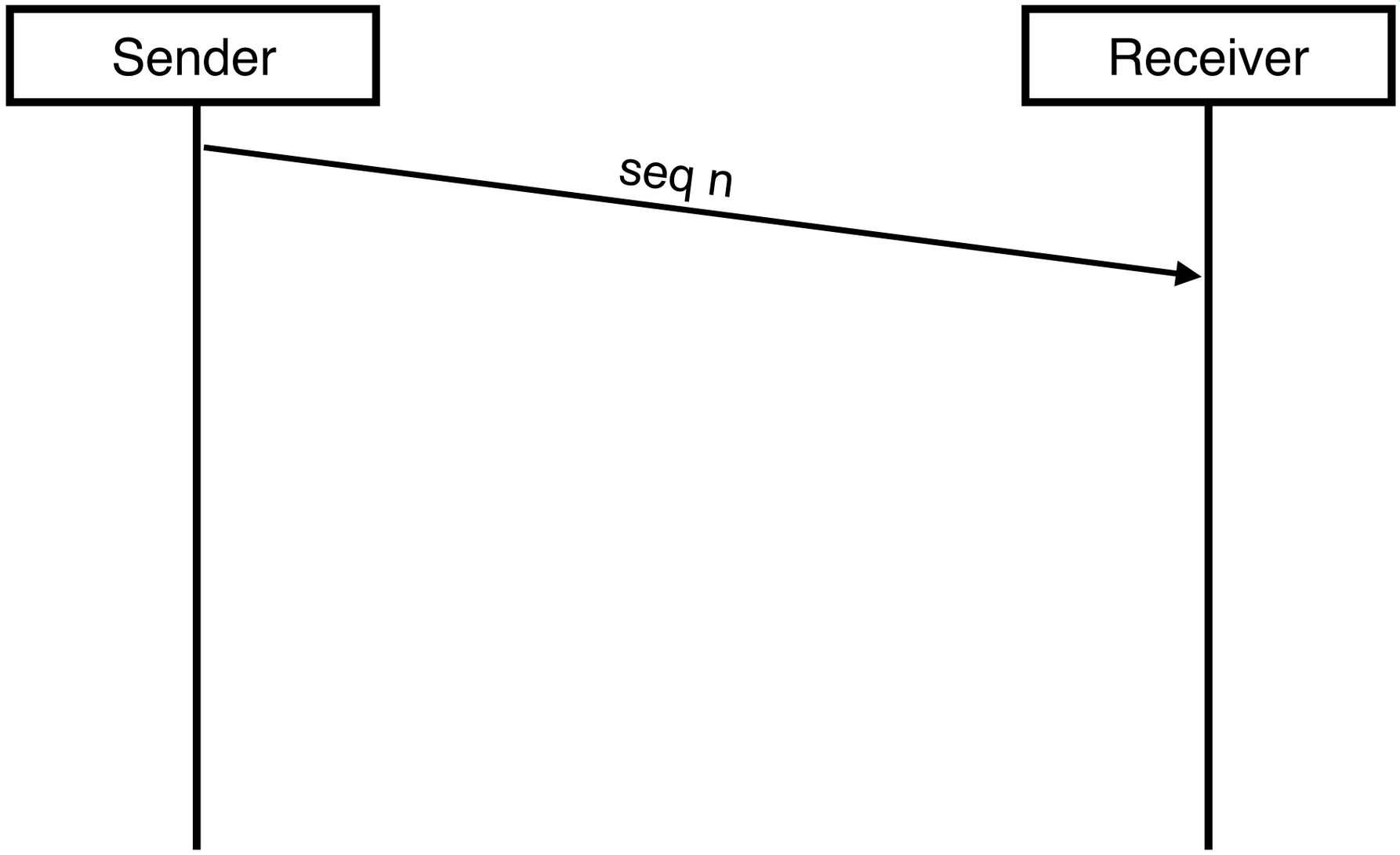
The Wire Image: Three levels of accessibility

- Unprotected (as TCP today): all bits can be seen at all points along the path, and can be modified without endpoint knowledge.
  - Supports manipulation of transport internals.
- Integrity-protected (e.g. QUIC outer header): all bits can be seen at all points along the path, but modification is endpoint detectable (and leads to packet rejection).
- Encrypted (e.g. QUIC frame headers): no bits can be interpreted, modification leads to corruption and rejection.

RTT estimation with TCP

- Use of SEQ# and ACK# and/or TCP Timestamp Option

RTT estimation with TCP



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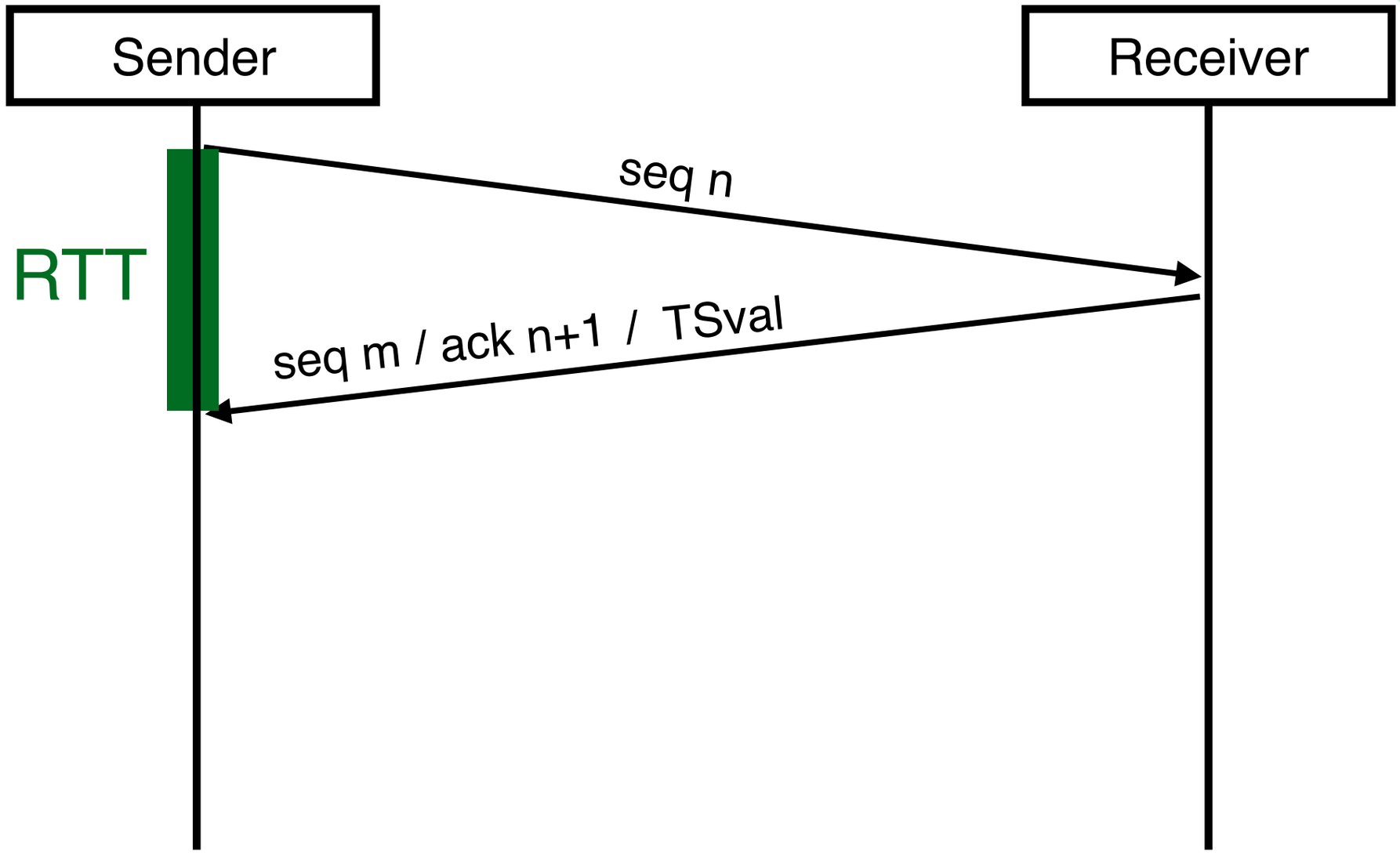

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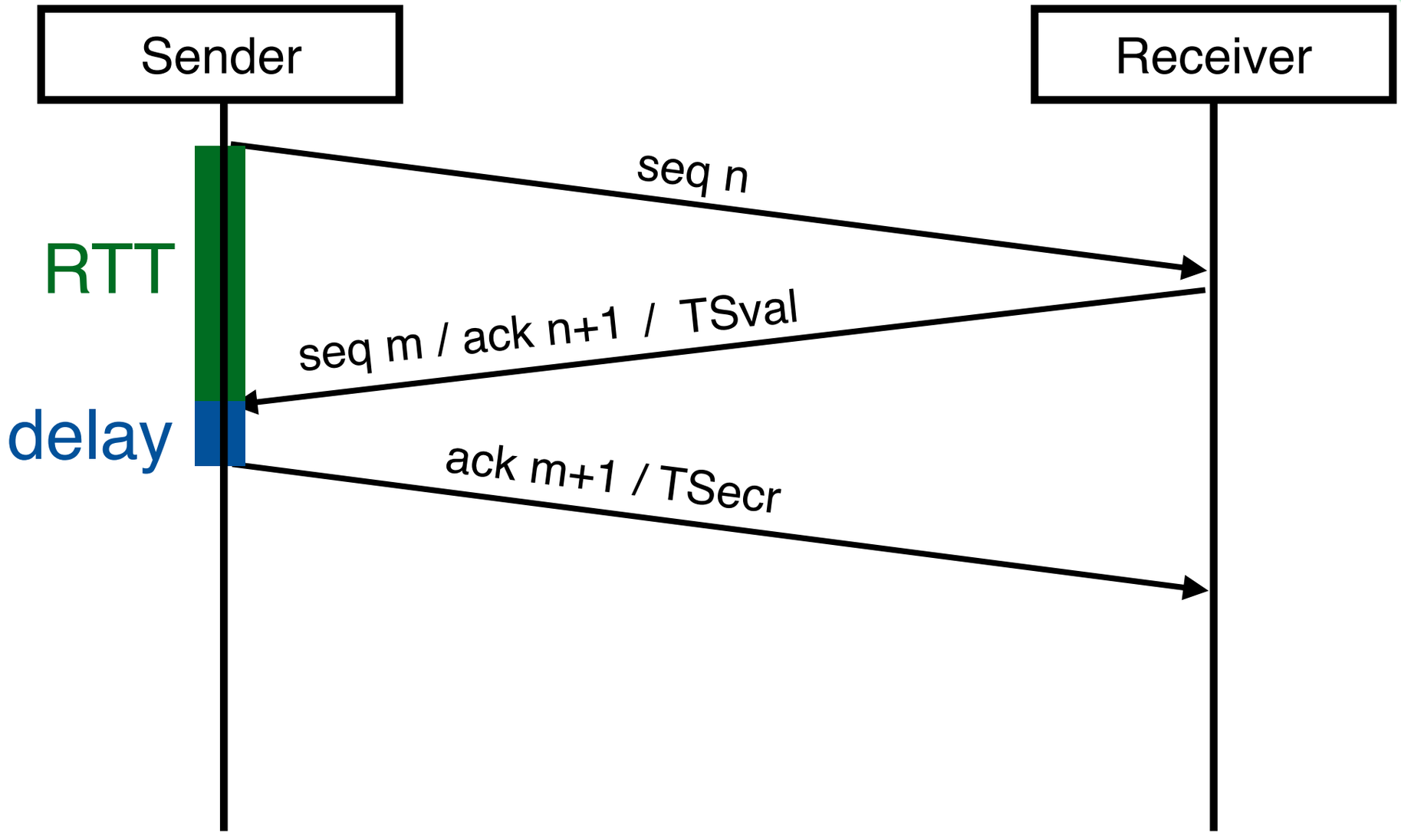

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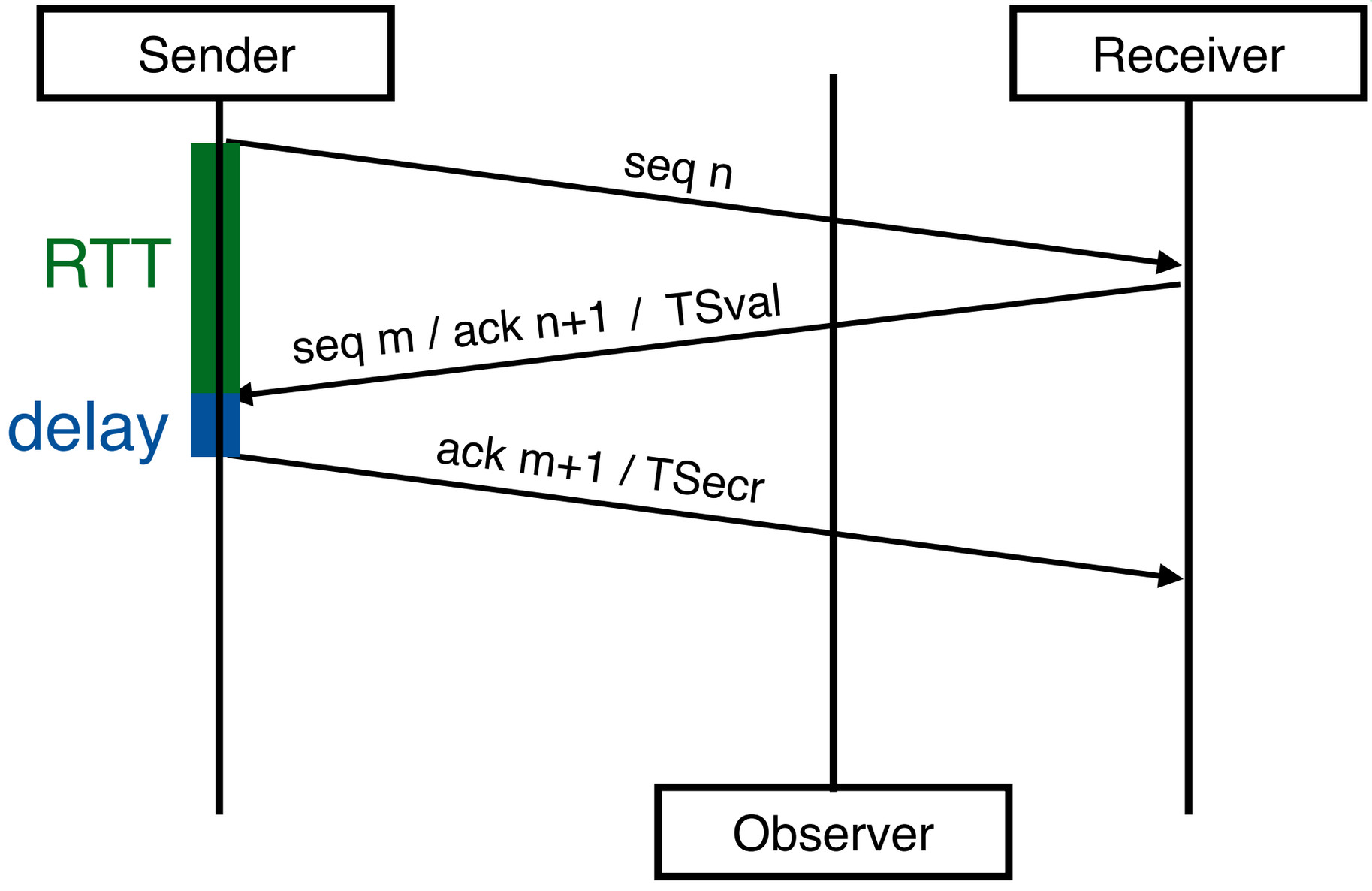

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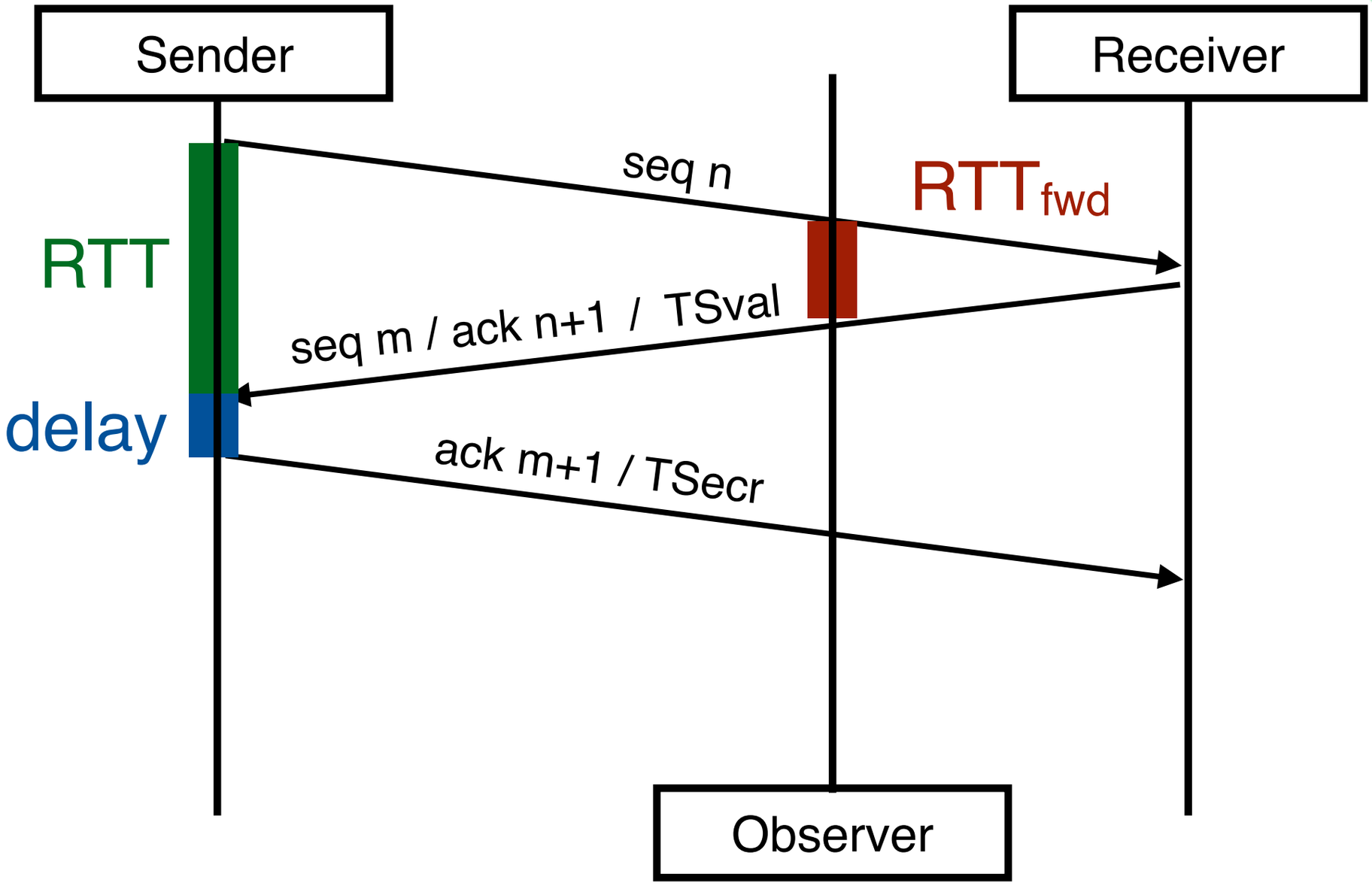
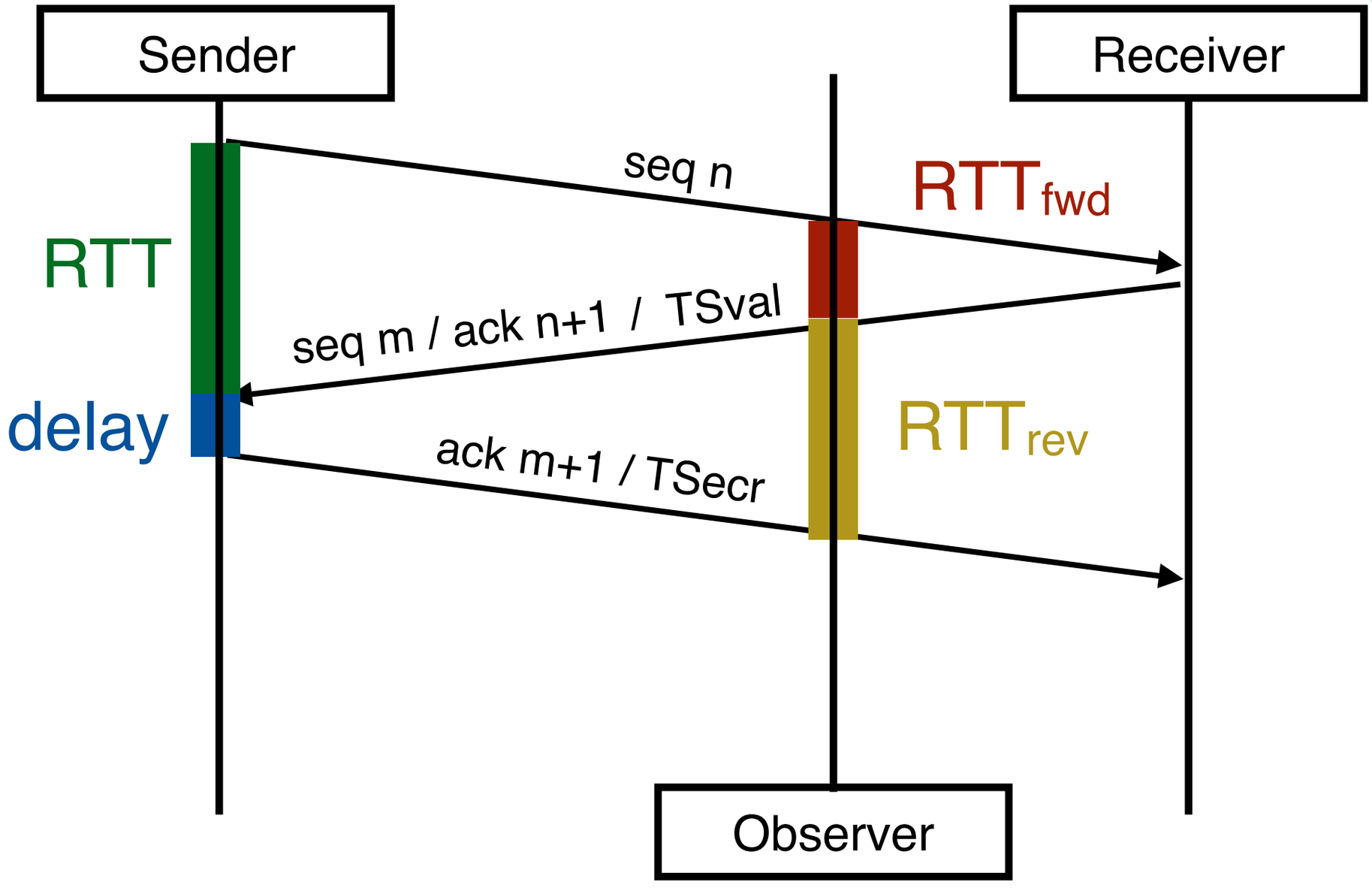
RTT estimation with TCP



- Use of SEQ# and ACK# and/or TCP Timestamp Option

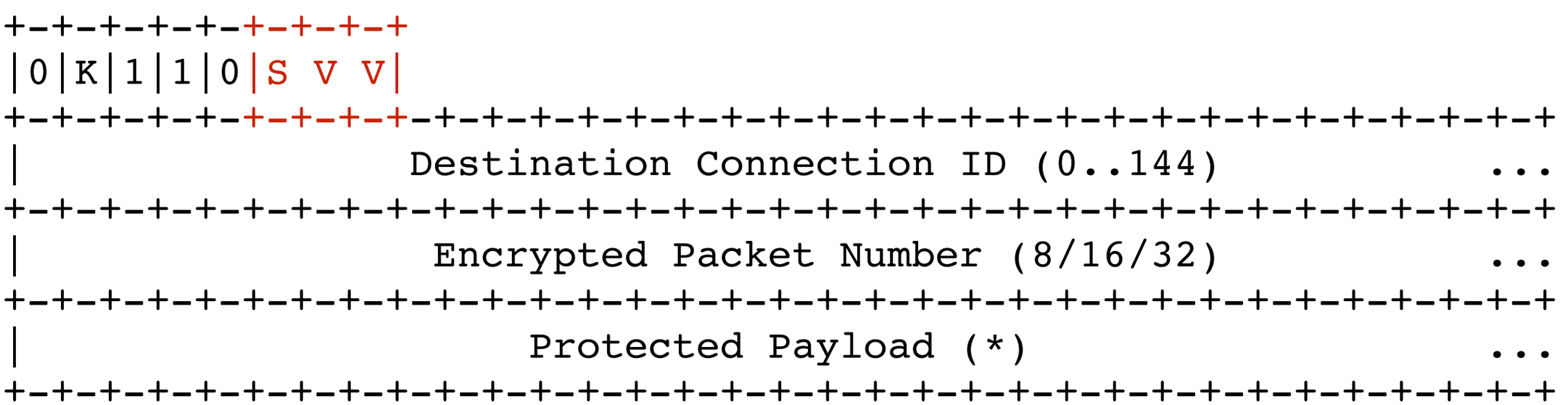
RTT estimation with TCP



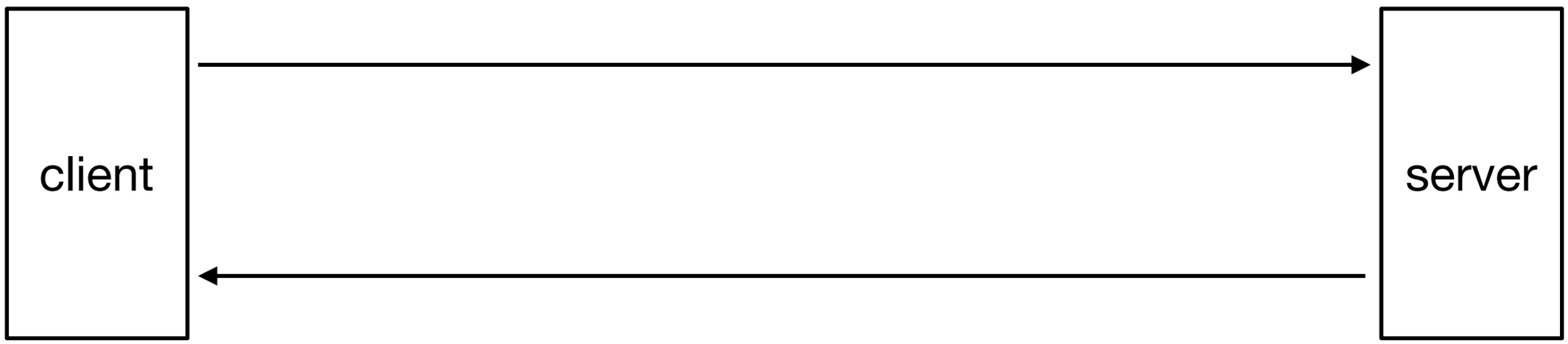
- Use of SEQ# and ACK# and/or TCP Timestamp Option

Replacing TCP RTT Measurement in the QUIC Wire Image: the Spin Bit

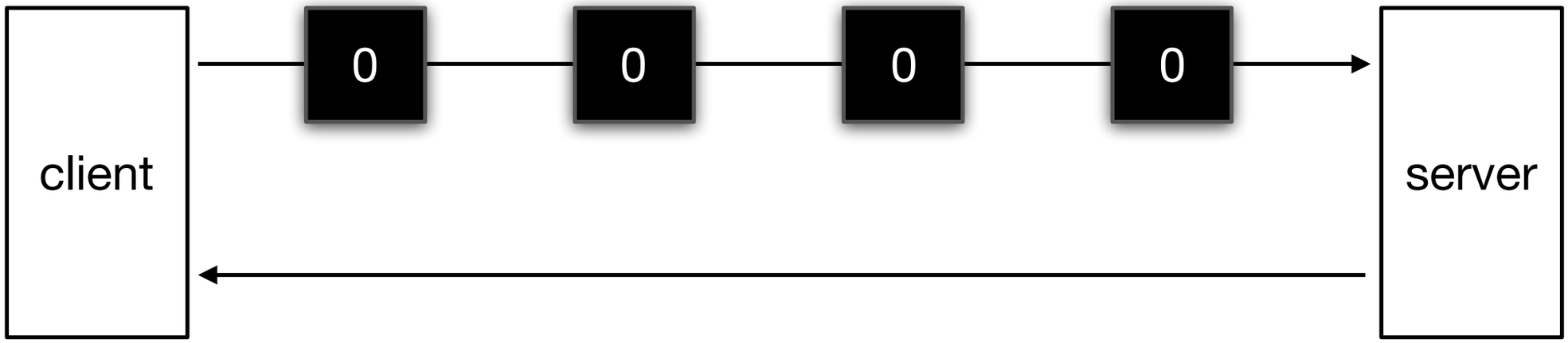
- Proposal: take a bit from QUIC short header type field and make it spin
- Server sets last spin it saw on each packet it sends
- Client sets ~(last spin it saw) on each packet it sends
- Creates a square-wave with period == RTT (when sender not app-limited)



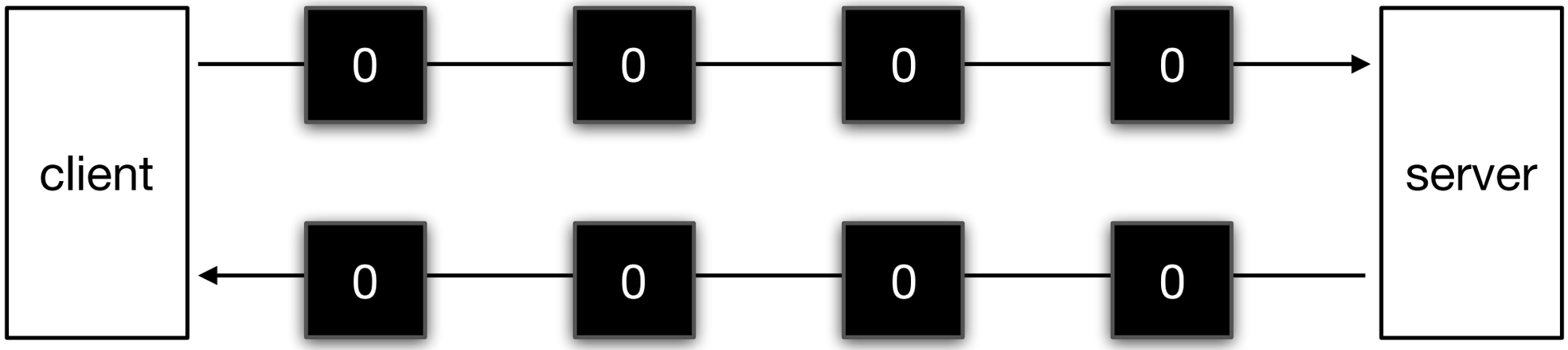
How does it work?



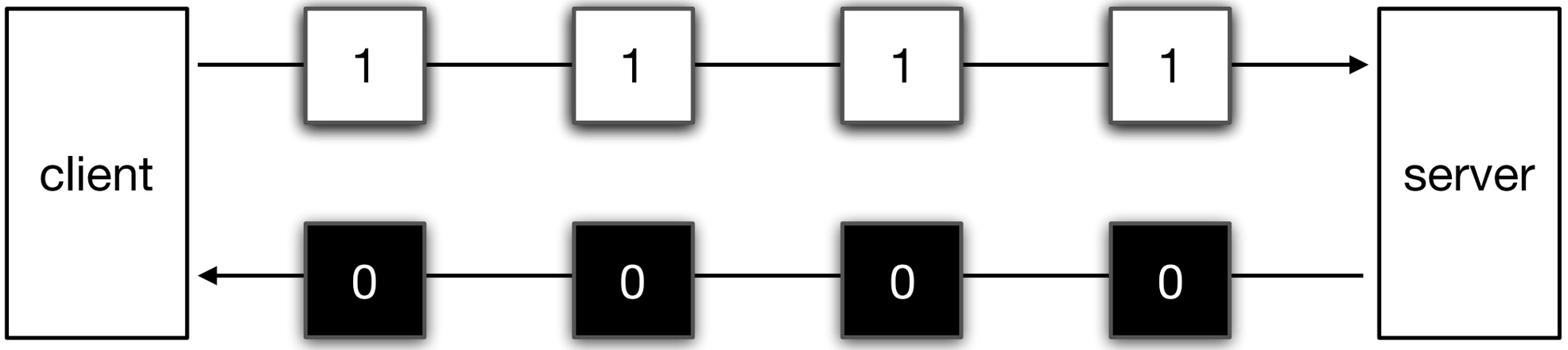
How does it work?



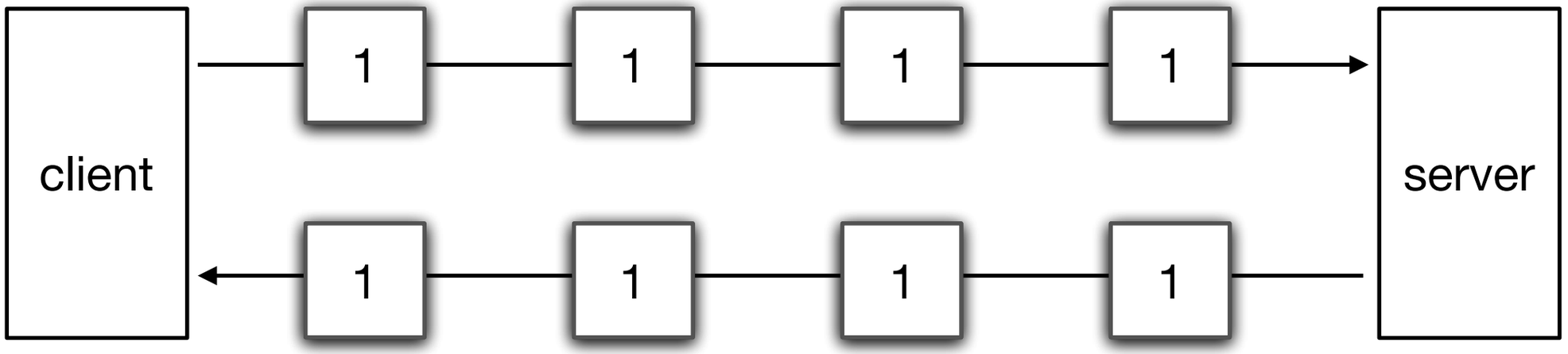
How does it work?



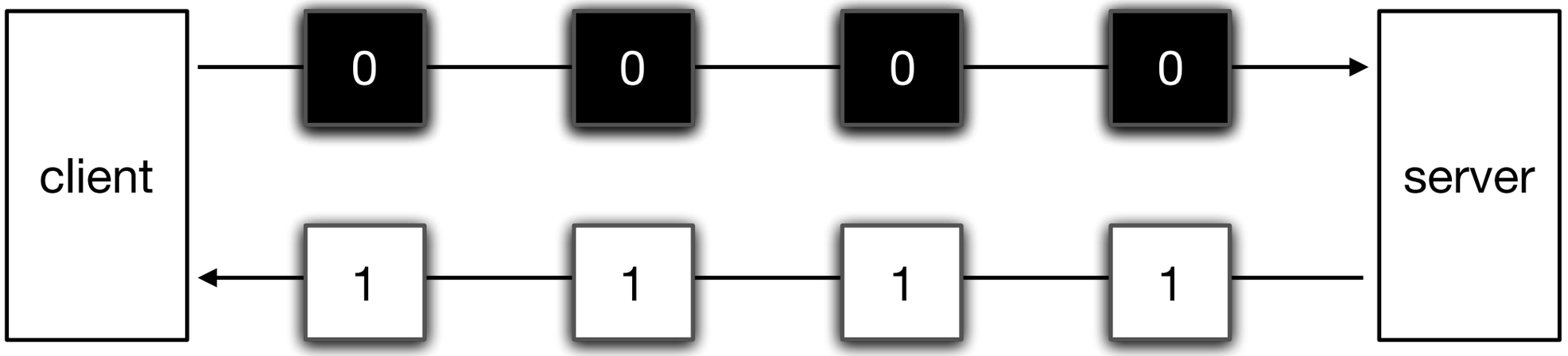
How does it work?



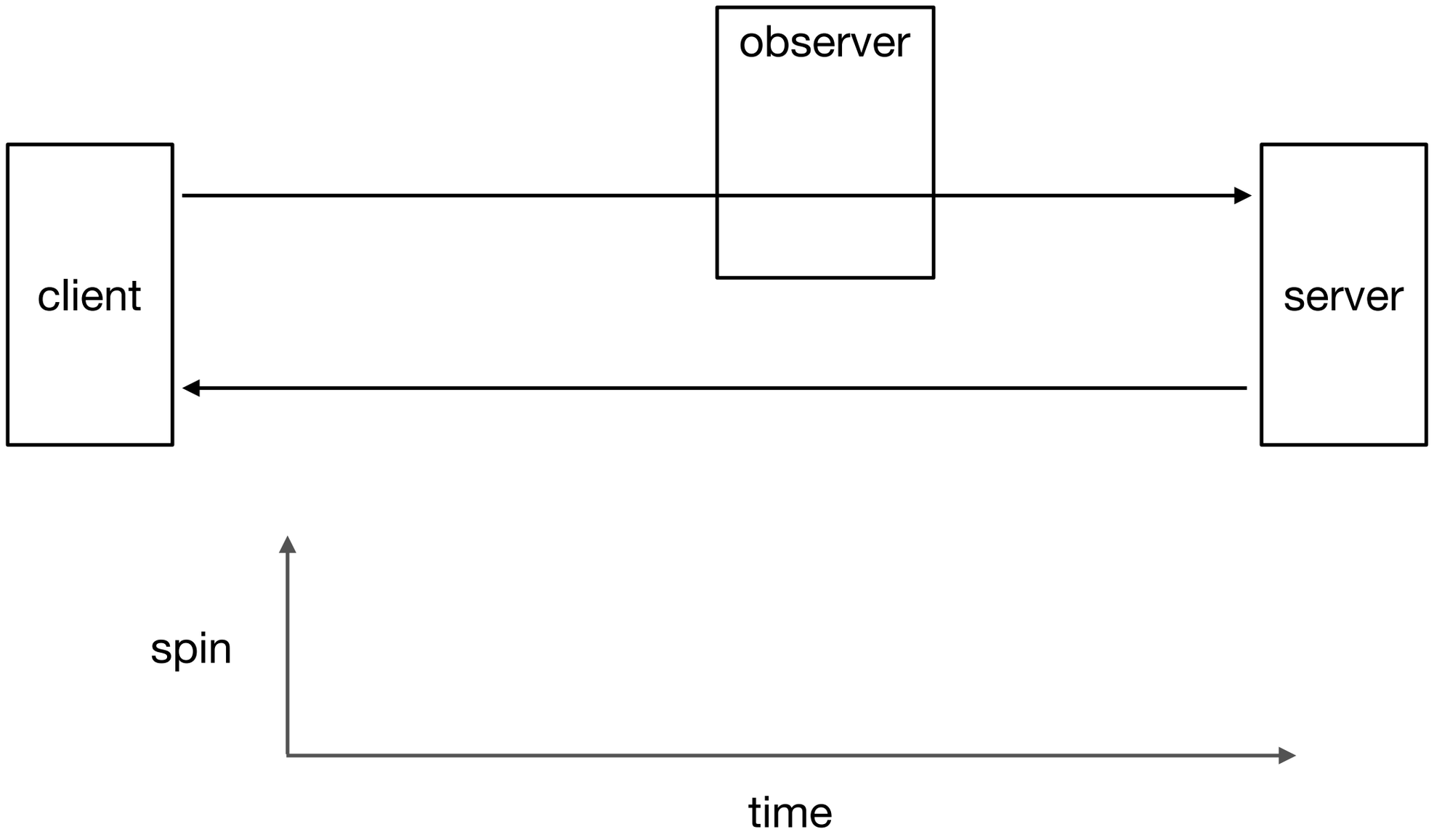
How does it work?



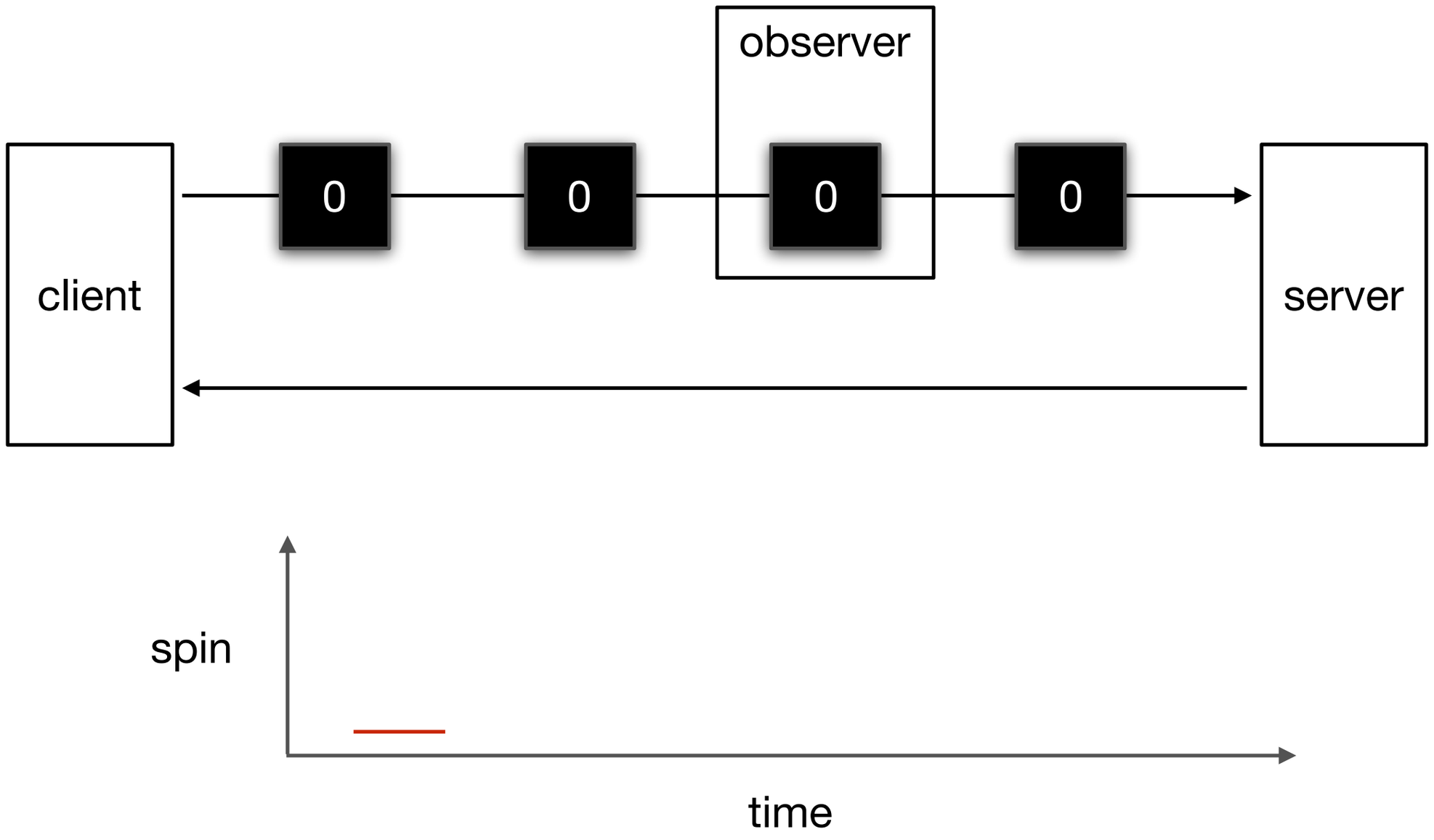
How does it work?



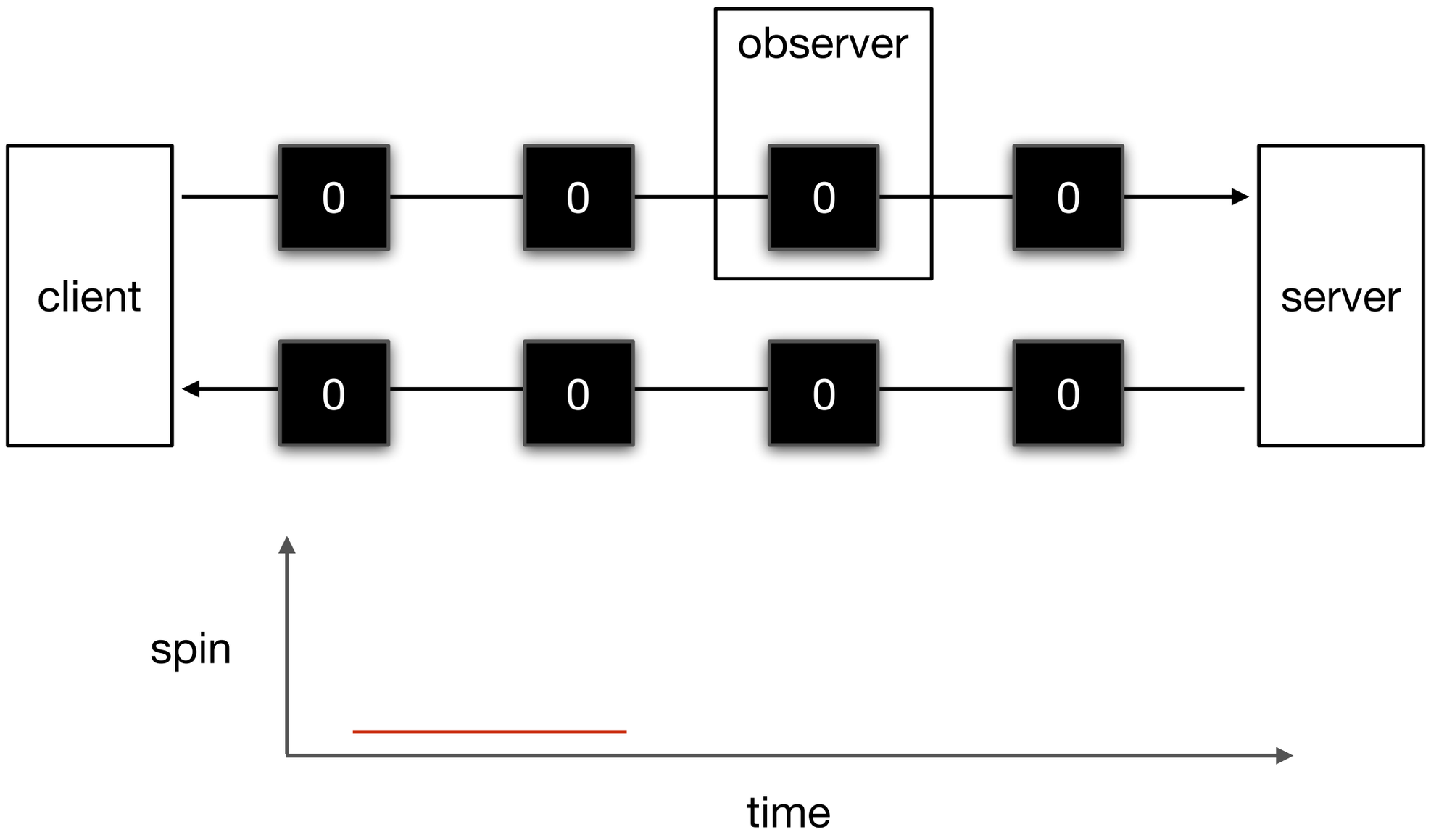
Unidirectional one-point measurement



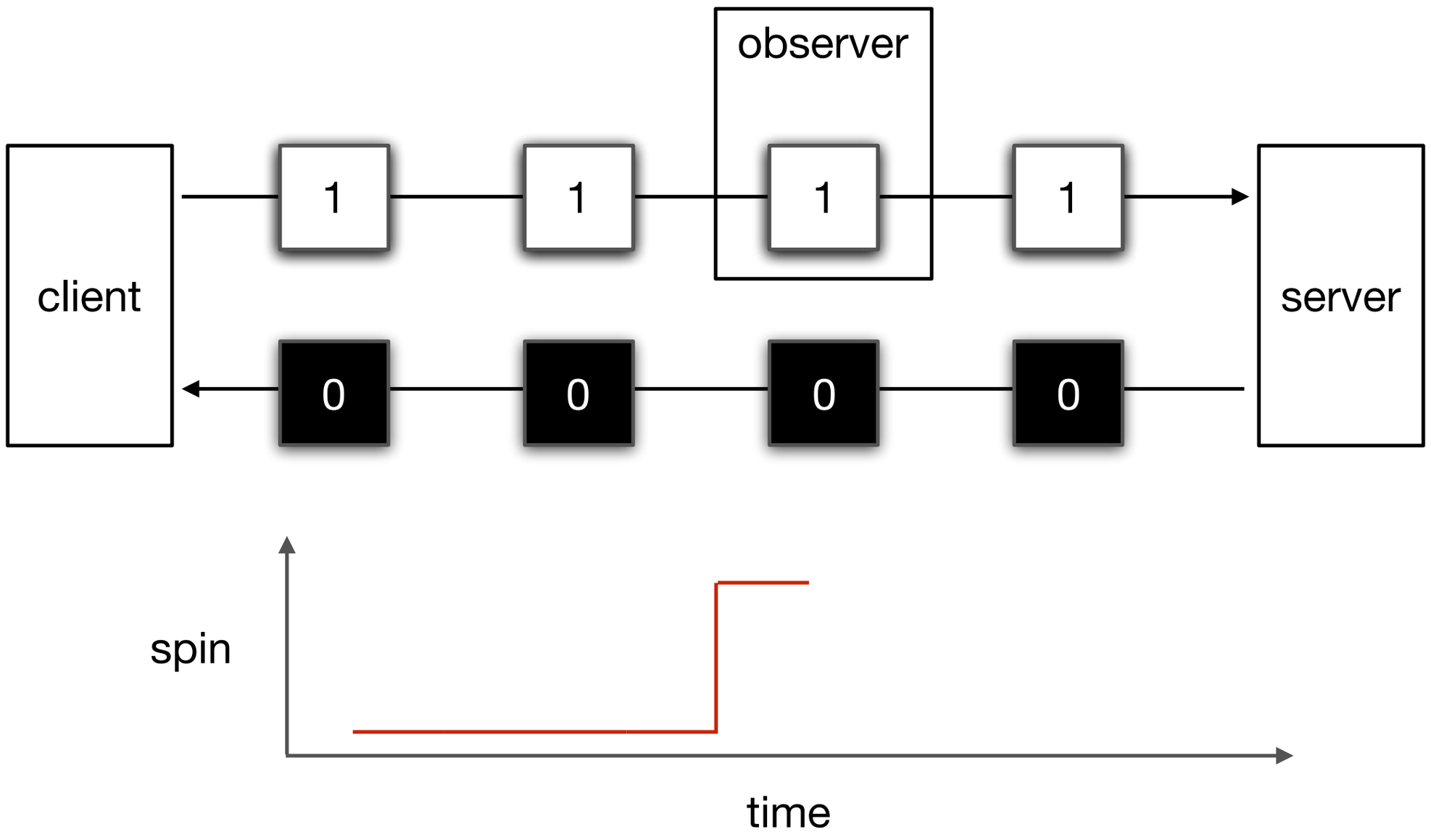
Unidirectional one-point measurement



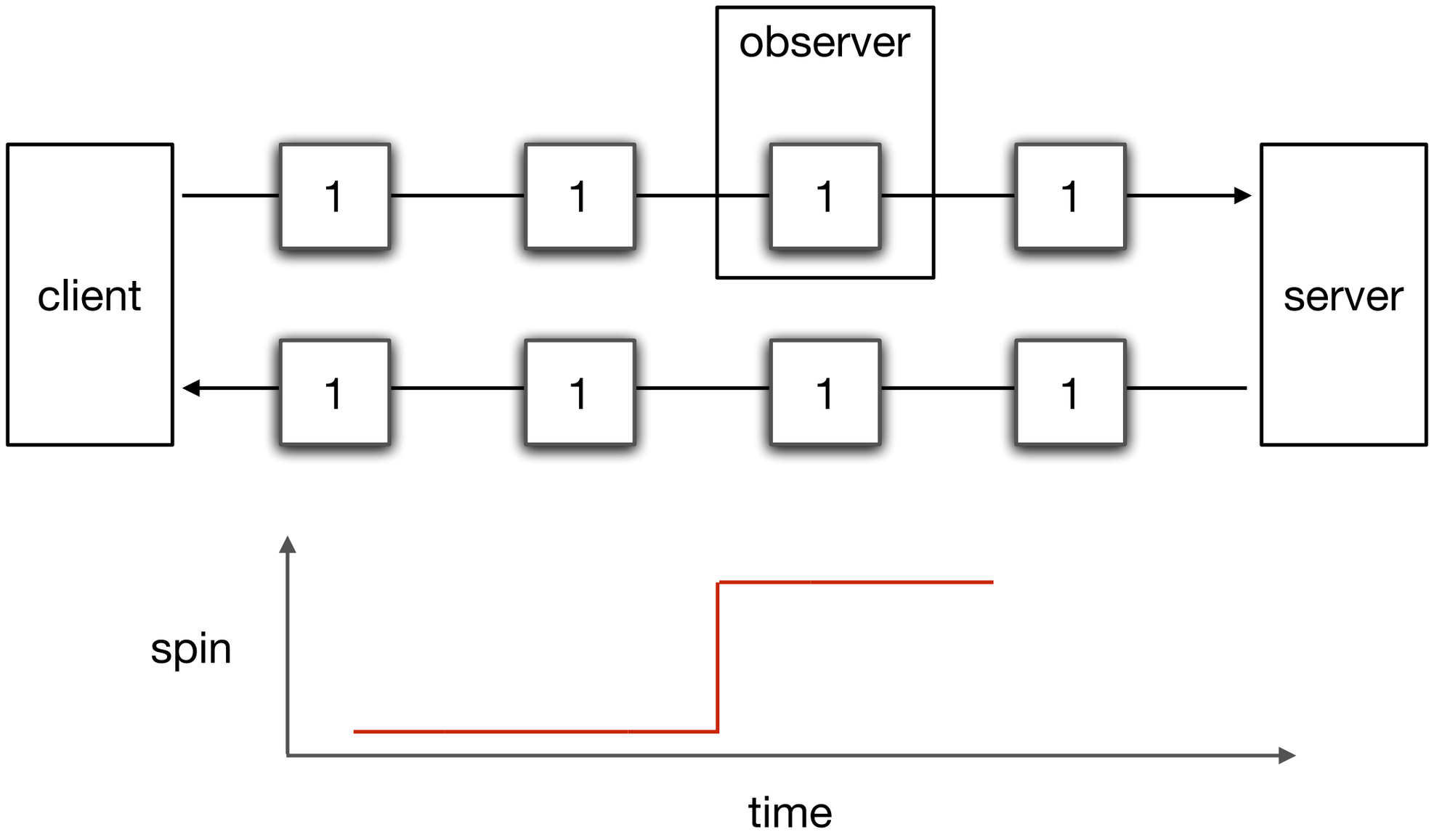
Unidirectional one-point measurement



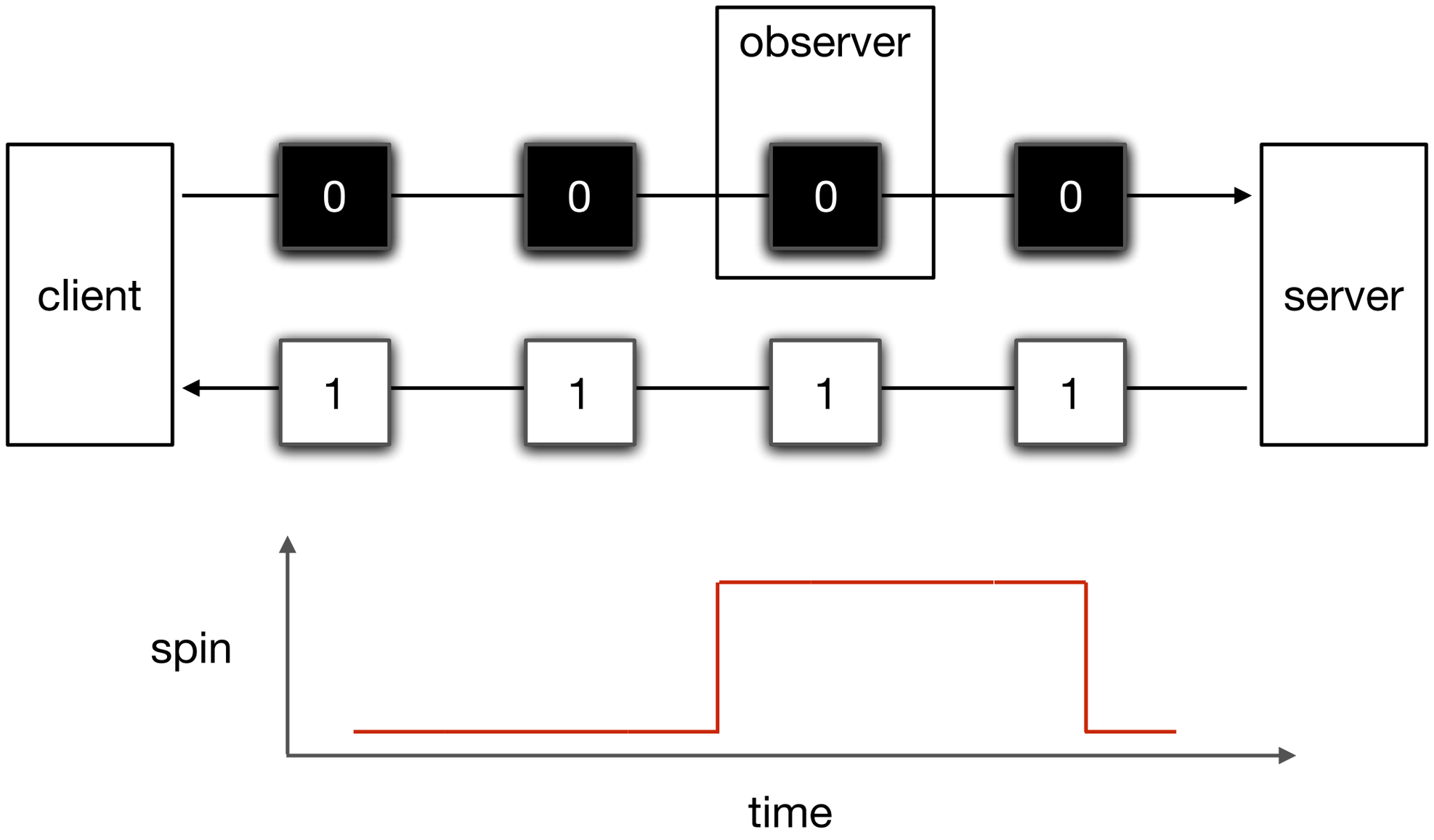
Unidirectional one-point measurement



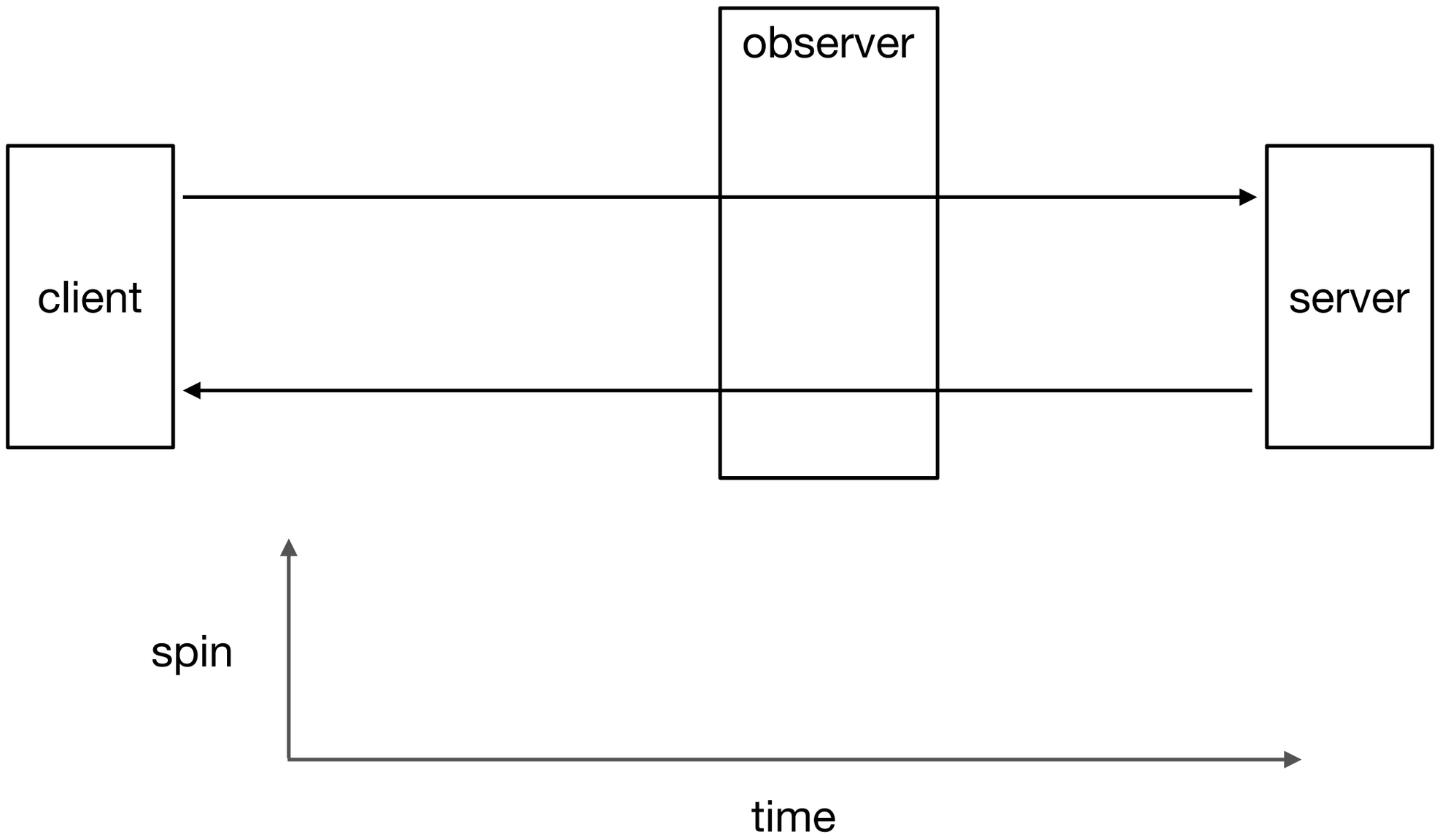
Unidirectional one-point measurement



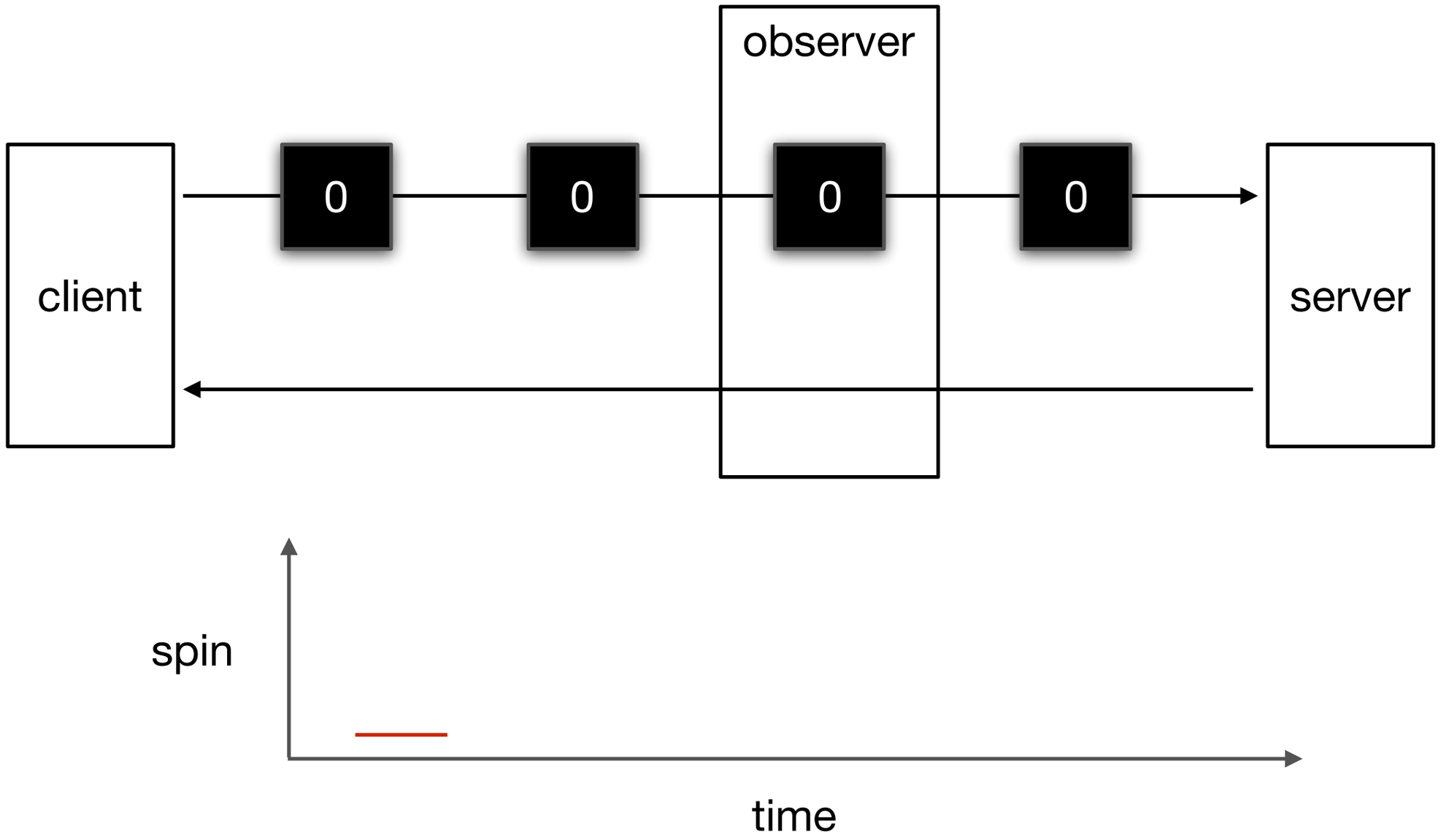
Unidirectional one-point measurement



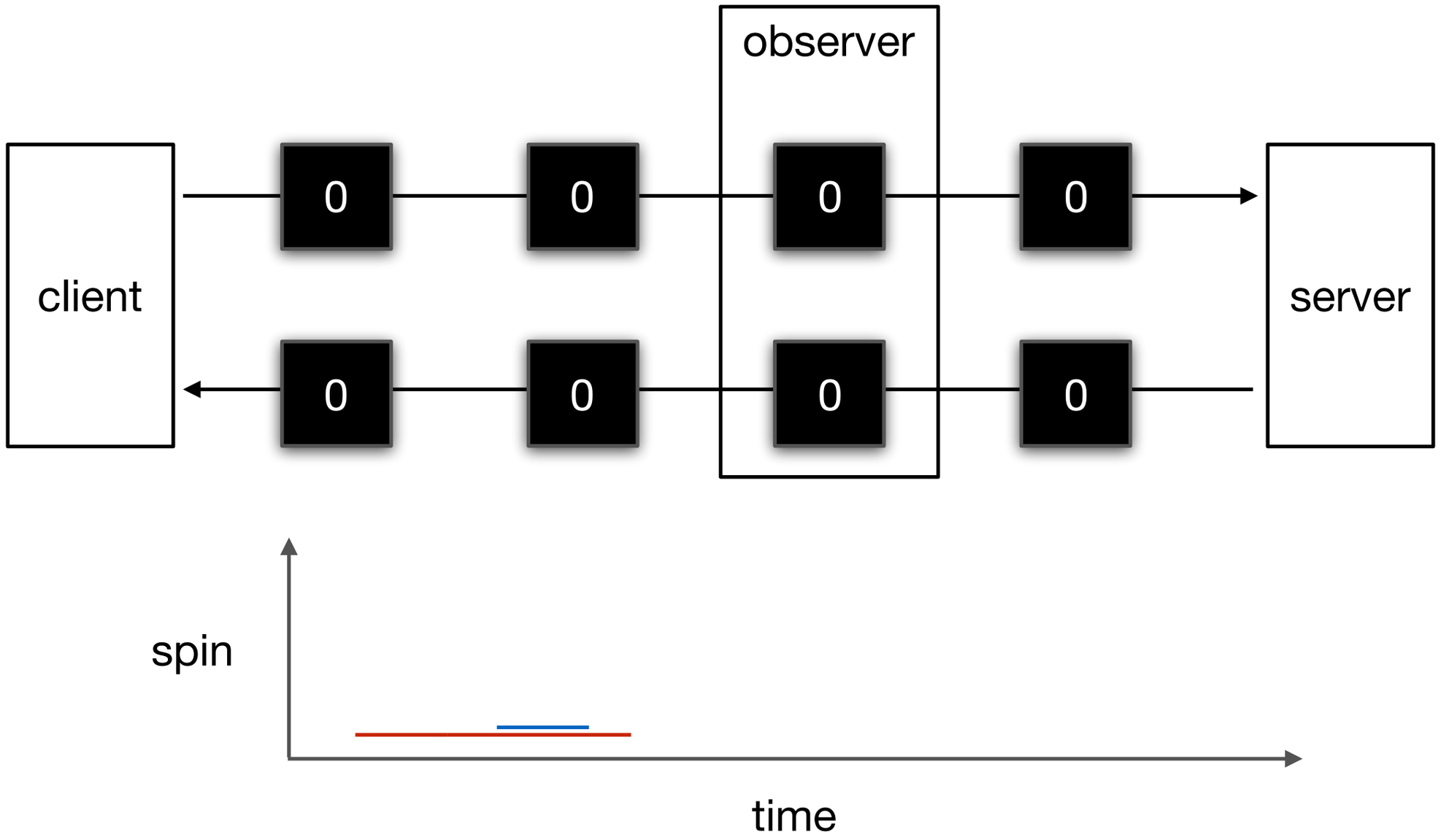
Bidirectional one-point measurement



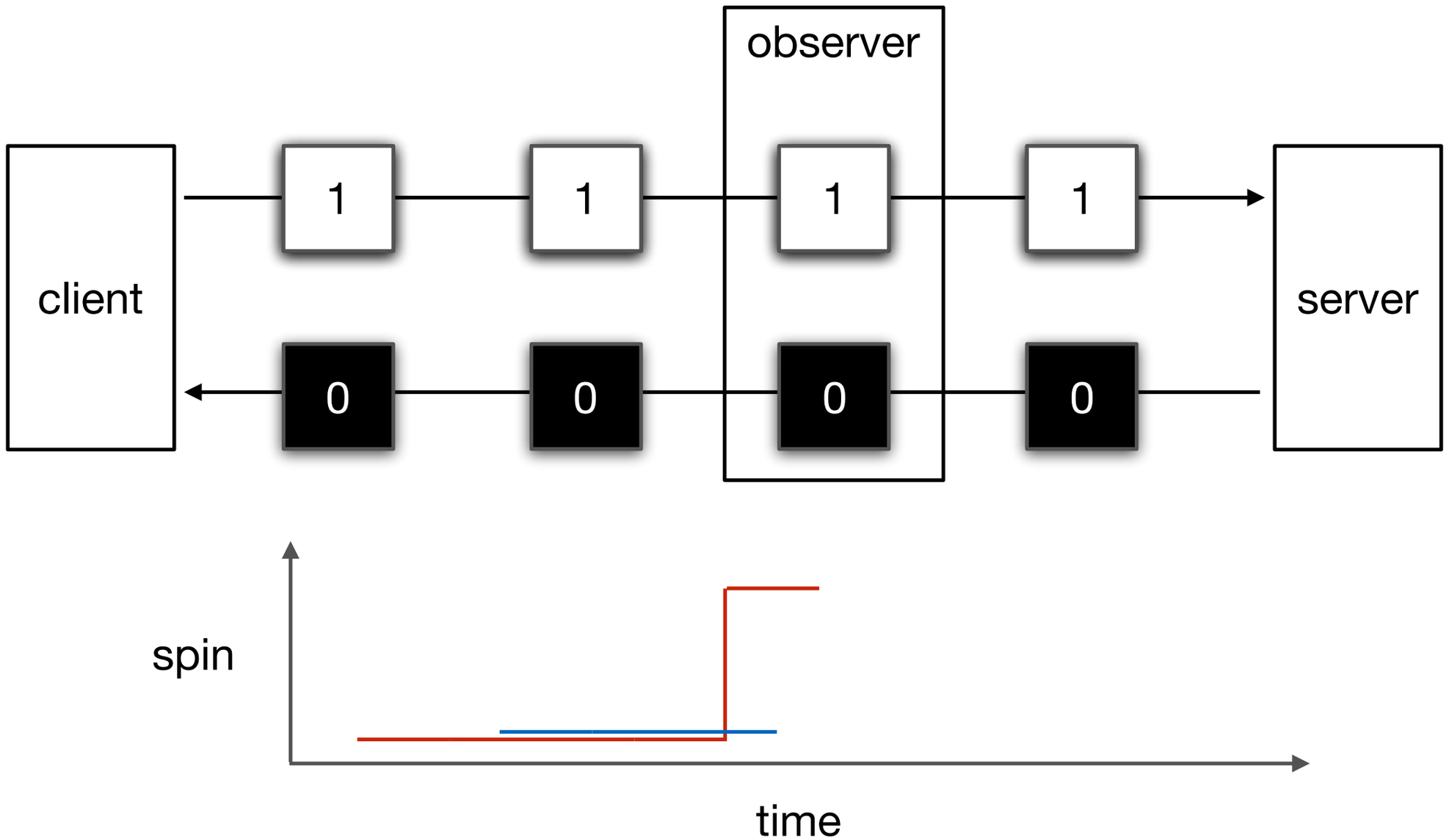
Bidirectional one-point measurement



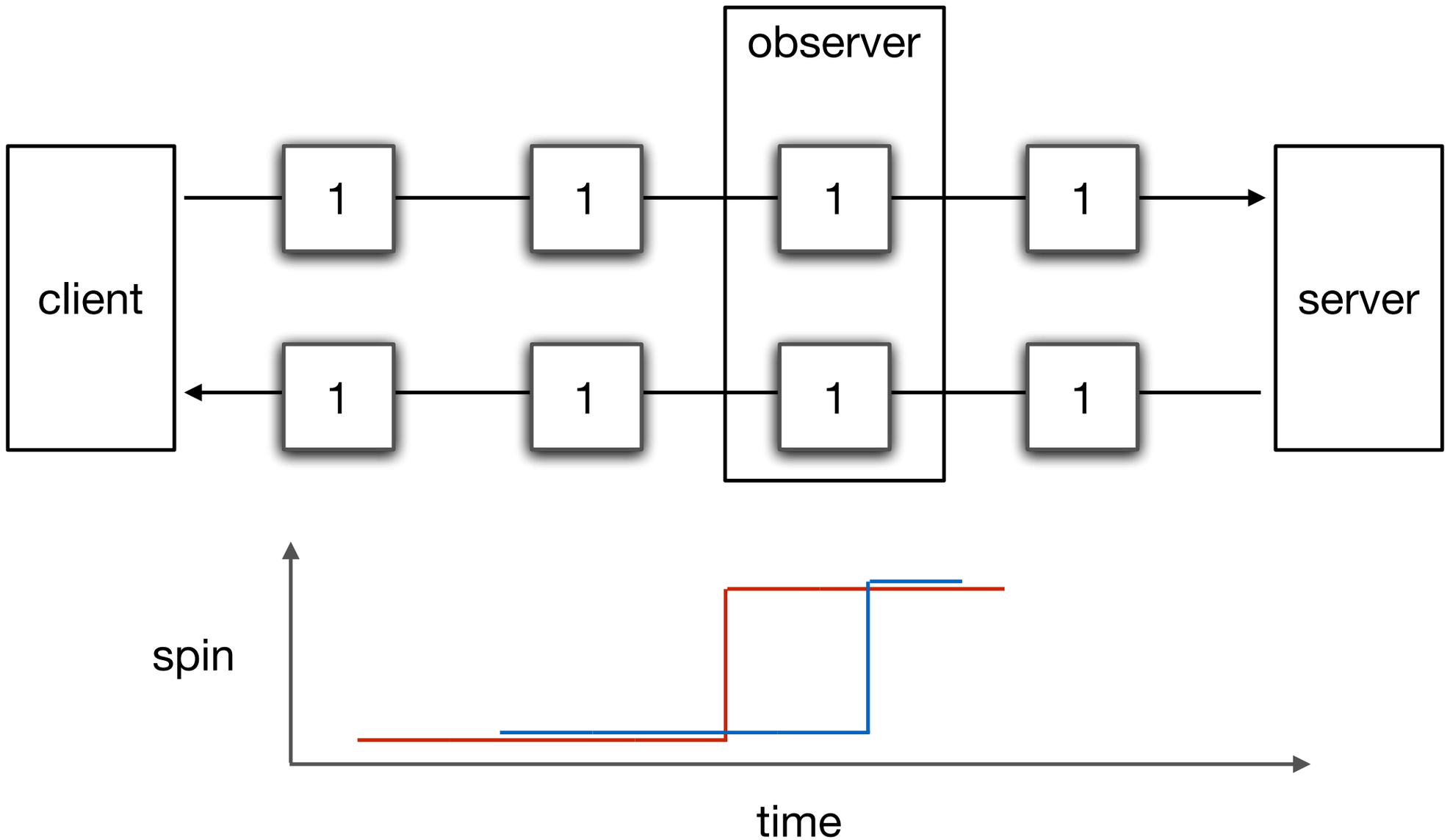
Bidirectional one-point measurement



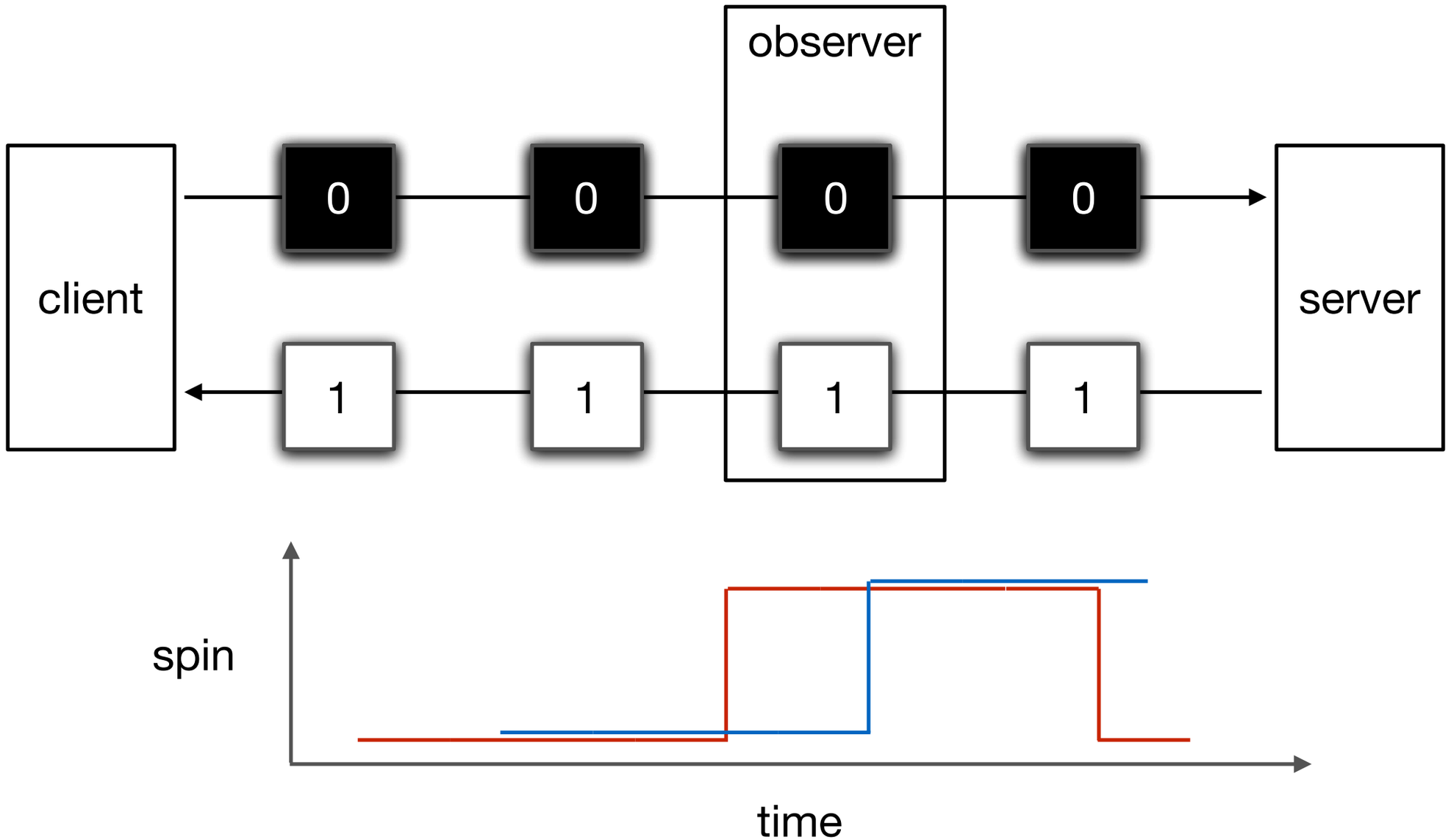
Bidirectional one-point measurement



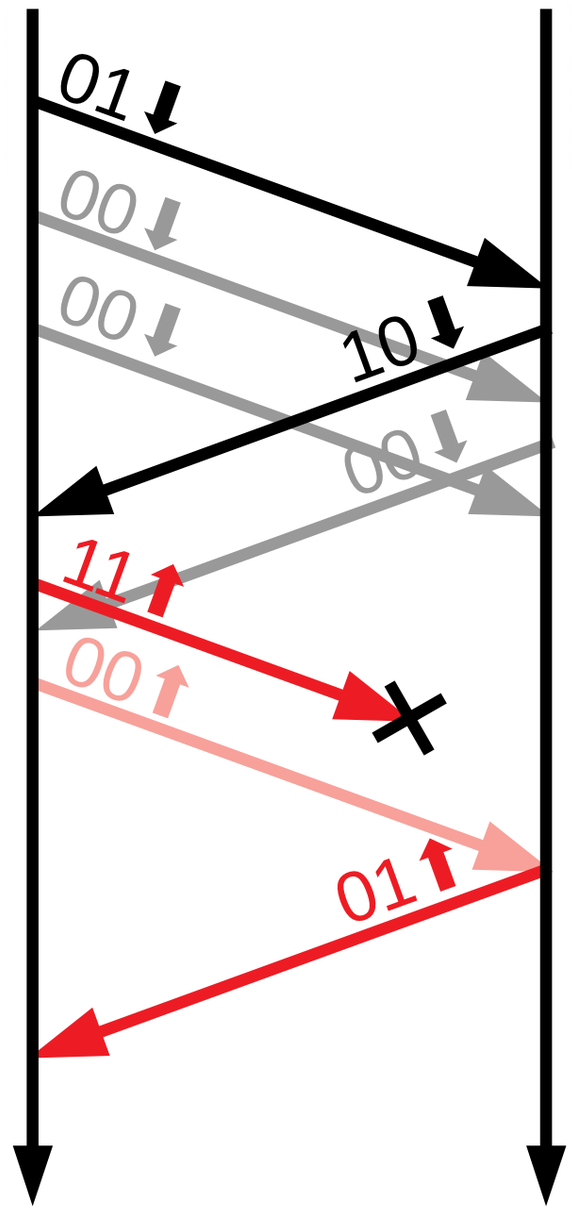
Bidirectional one-point measurement



Bidirectional one-point measurement



Dealing with Loss and Reordering: The Valid Edge Counter



- Bursty traffic can lead to wild overestimates of RTT: adds delay between bursts to actual measured RTT.
  - A damping filter can reduce overestimate samples
- Addition of a two-bit *valid edge counter* eliminates overestimation as well as fixing issues with packet loss and reordering:
  - On non-edge, delayed edge, edge on reordered packet: valid ← 00
  - On all other edges: valid ← last received valid + 1
  - Produces a 11 signal ("good edge") 1.5RTT after last reorder/ delay, requires both sides to be reordering/delay-free, resets after an edge is lost.
- Rejects invalid samples due to bursty traffic, deals with reordering as well as two-bit spin, and adds tolerance to heavy burst losses, without PN visibility

Summary

- New protocol suite for web traffic is optimized for latency and provides increased security
  - *Mutlistreaming* to avoid Head-of-line Blocking in **HTTP2** and **QUIC**
  - *0-RTT support* and *Perfect Forward Secrecy* in **TLS1.3**
  - Encryption integrated in the transport layer with **QUIC**

- Limited information available in the network visible **wire image**
  - *Explicit measurability* to replace implicit assumptions about the internal protocol machinery