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University of Galway

CT 420 Real-Time Systems

Emerging Protocols-II

Dr. Jawad Manzoor
Assistant Professor
School of Computer Science

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HTTP 2.0 performance

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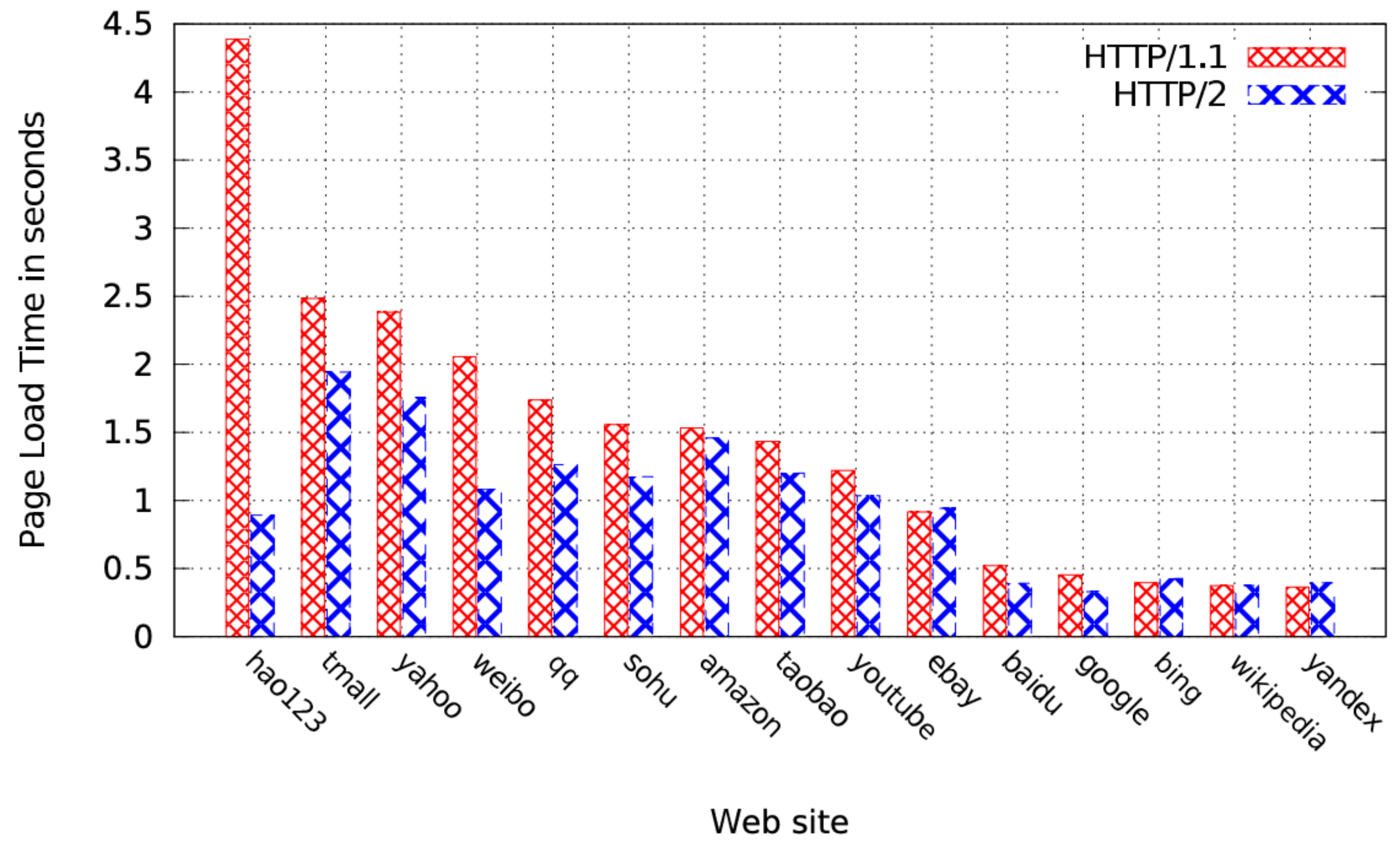
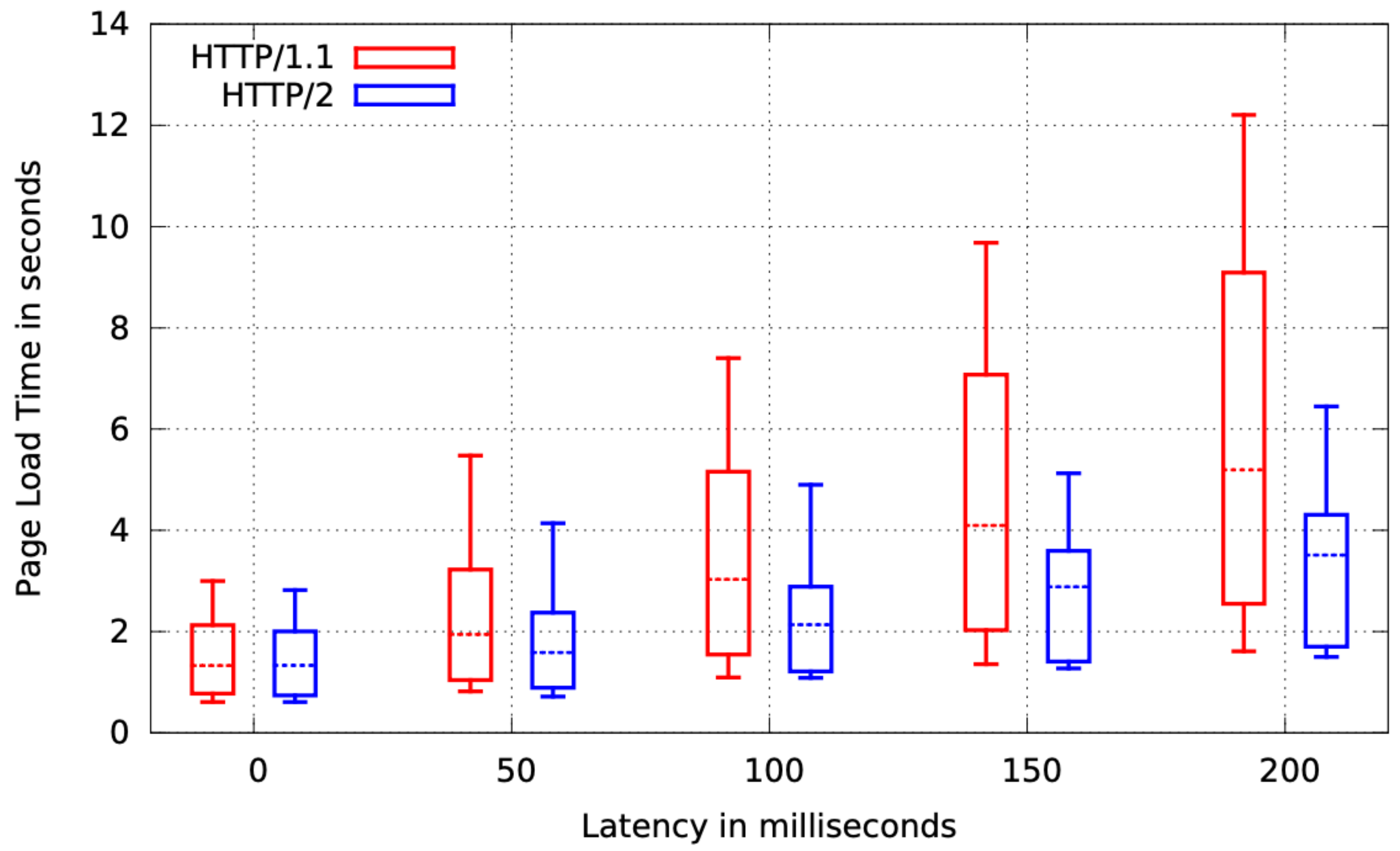


Page load time for different websites using 50ms latency



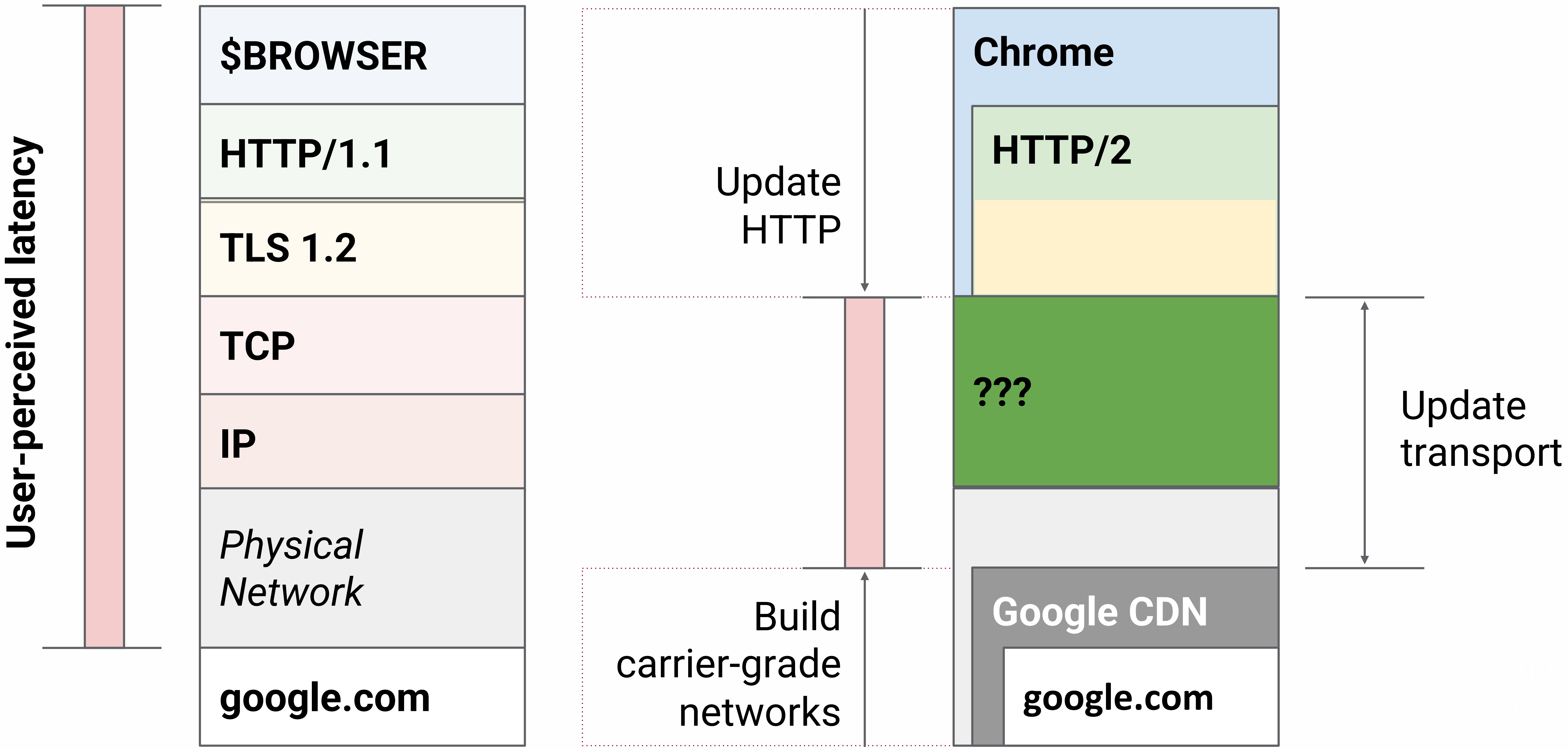
Impact of latency on page load time

"Is HTTP/2 really faster than HTTP/1.1?." *2015 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, 2015.

Can we do better?

- Improvements at the application layer have been implemented in HTTP 2.0
- To further improve the performance, fundamental changes to the underlying transport layer are required

Can we do better?



Transport Protocols

- Transmission Control Protocol (TCP)
  - Reliability and flow control
    - Ensure that data sent is delivered to the receiver application
    - Ensure that receiver buffer doesn’t overflow
  - Ordered delivery
    - Ensure bits pushed by sender arrive at receiver app in order
  - Congestion control
    - Ensure that data sent doesn’t overwhelm network resources

Transport Protocols

- User Datagram Protocol (UDP)
  - Abstraction of independent messages between endpoints
  - UDP has minimal overhead, making it the recommended transport to meet the strict latency bounds of real-time applications, but provides limited support to applications.
  - No guarantee of delivery

TCP vs UDP

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TCP

- Slower but more reliable transfers
- Typical Applications:
  - File Transfer Protocol (FTP)
  - Web Browsing
  - Email

unicast

UDP

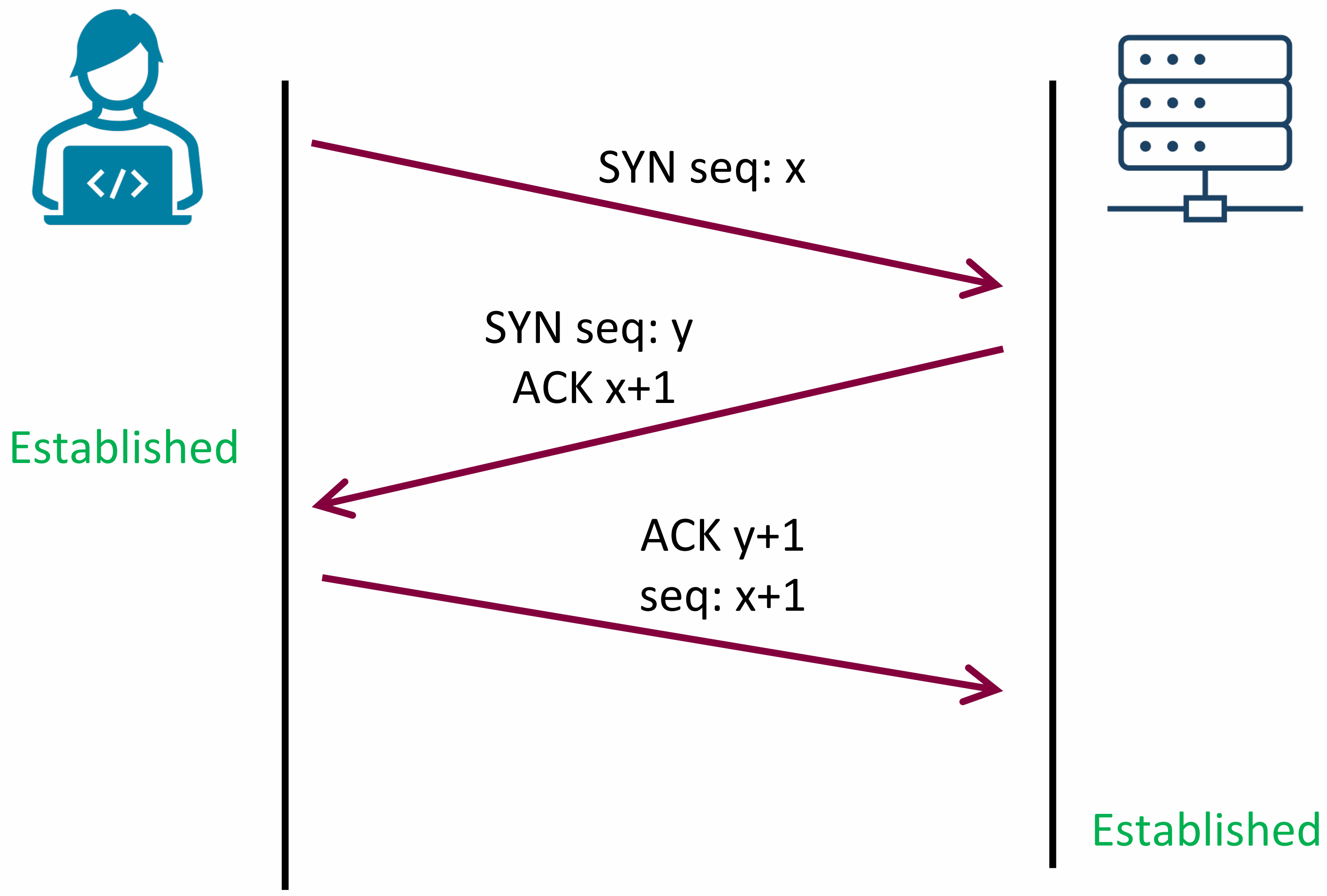
- Faster but not guaranteed transfers ("best effort")
- Typical Applications:
  - Live Streaming
  - Online Games
  - VoIP

unicast **multicast** **broadcast**

https://www.freecodecamp.org/news/tcp-vs-udp/

Things we'd like to change about TCP

- Slow Connection Establishment



Things we'd like to change about TCP

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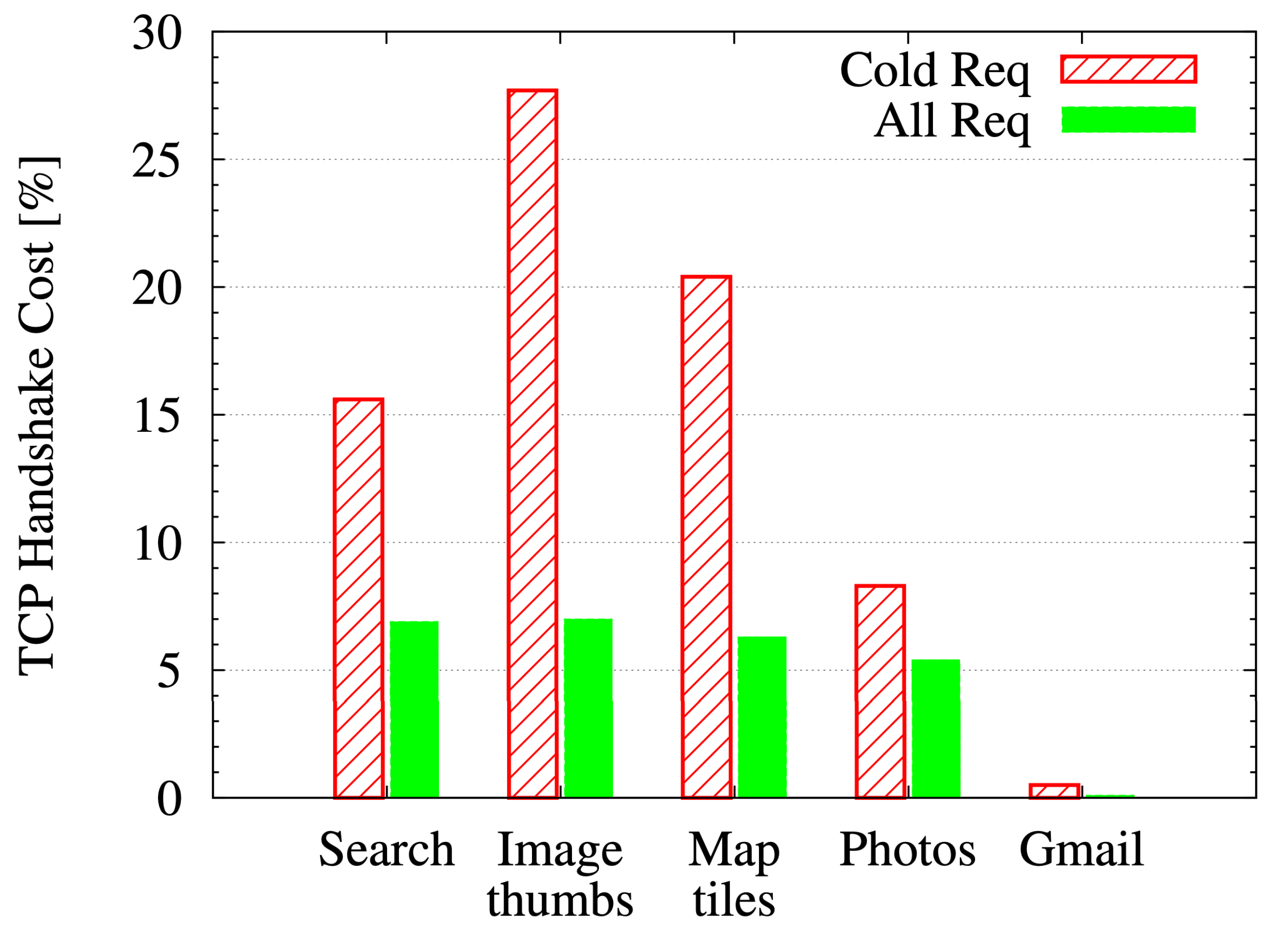
- TCP 3-way handshake has very high latency, particularly for small web requests
- Problem made worse by adding security (HTTPS / TLS) over TCP.
  - TLS handshake adds more round trips.
- Experiment: study the impact of TCP's handshake on user perceived HTTP request latency.
  - Sampled a few billion HTTP requests (on port 80) to Google servers world-wide to multiple Google services such as search, email, and photos
  - For each sampled request, we measured the latency
  - Requests sent on new TCP connections are defined as cold requests and those that reuse TCP connections as warm requests

https://static.googleusercontent.com/media/research.google.com/en//pubs/archive/37517.pdf

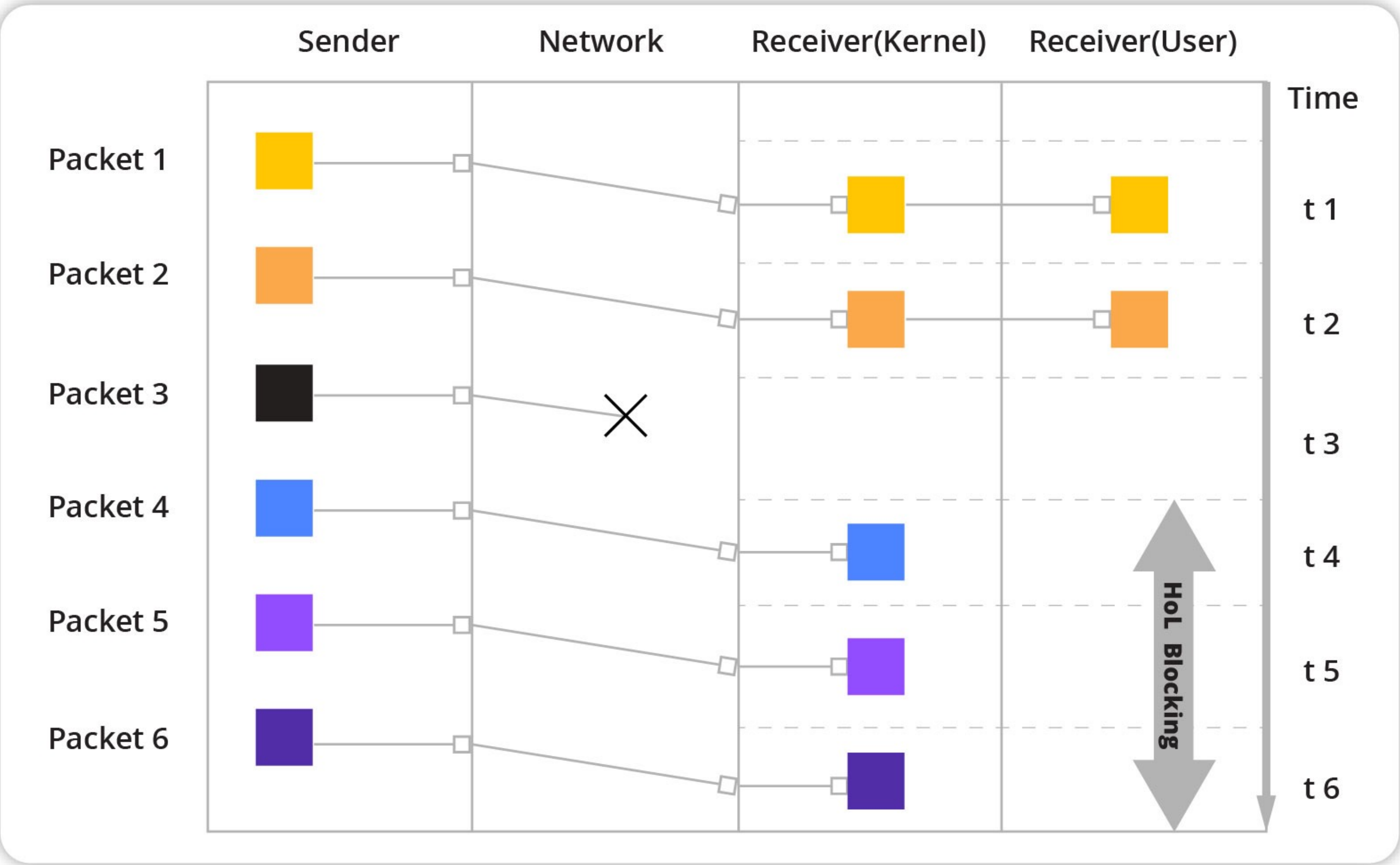


"TCP Fast Open" CoNext 2011

Things we'd like to change about TCP

- Head-of-line blocking

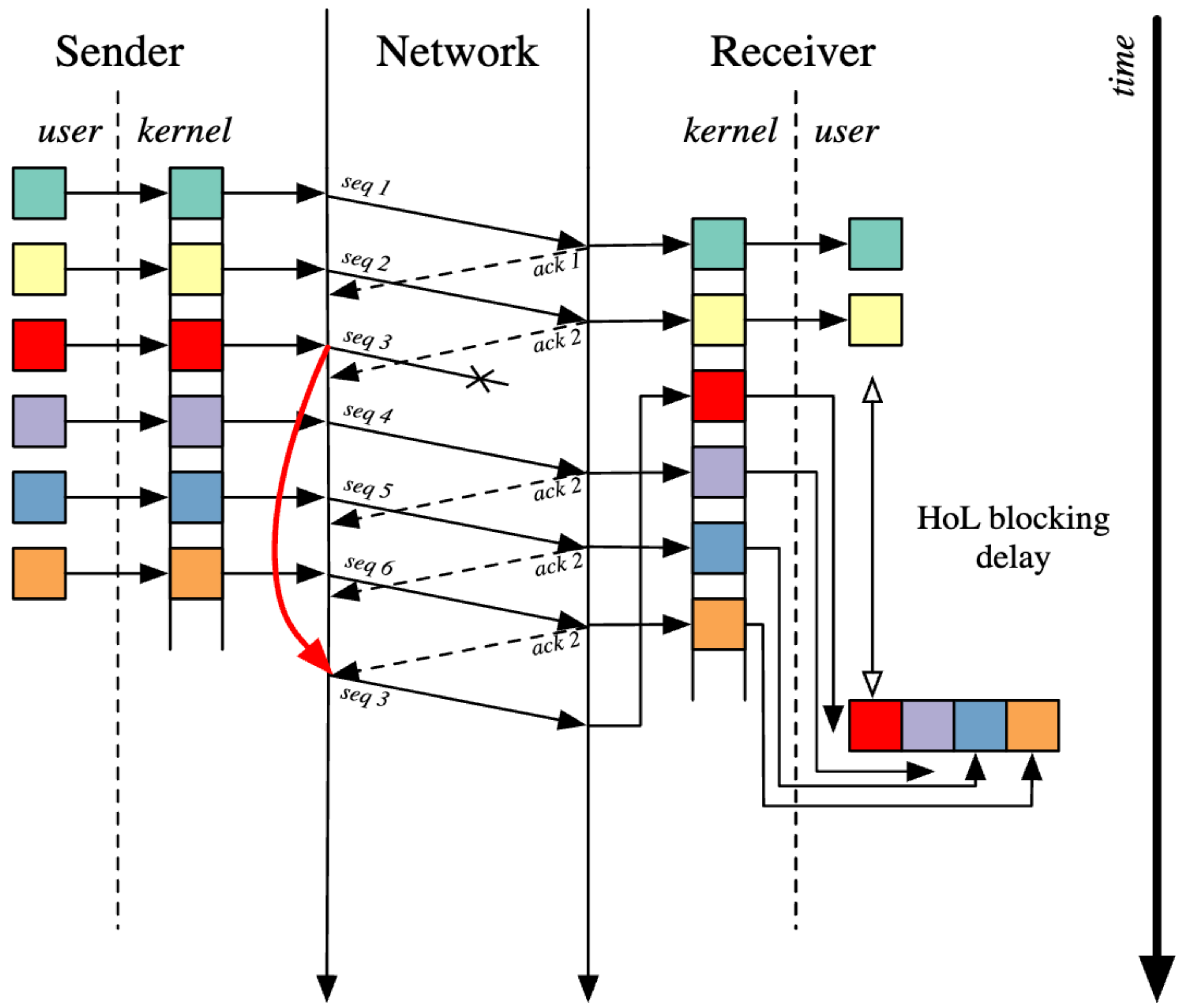
TCP Head of Line Blocking



https://www.cdnetworks.com/media-delivery-blog/what-is-quic/

Things we'd like to change about TCP

- Head-of-line blocking



"TCP Hollywood: An unordered, time-lined, TCP for networked multimedia applications." *IFIP networking conference and workshops*.

Why is it so hard to change TCP?

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- TCP is implemented in Operating System (OS) kernel
- You may need to change the OS kernel
  - On all servers and clients around the world!

- You may need to change the entire network!
  - Middleboxes may drop packets if they don’t understand something on the packet

QUIC

- QUIC protocol was developed to overcome the performance issues in TCP.
- It is a reliable transport over UDP
- Initially designed by Jim Roskind at Google, implemented, and deployed in 2012.
- In May 2021, the IETF standardized QUIC in RFC 9000
- In June 2022, IETF standardized HTTP/3 as RFC 9114 which uses QUIC by default

Browser support

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HTTP/3 protocol - OTHER

Usage | % of all users | ?
Global | 94.47% + 1.24% = 95.7%

Baseline 2024 Newly available across major browsers

Third version of the HTTP networking protocol which uses QUIC as transport protocol. Previously known as HTTP-over-QUIC, now standardized as HTTP/3.

Current aligned | Usage relative | Date relative | Filtered | All

Chrome	Edge *	Safari	Firefox	Opera	IE	Chrome for Android	Safari on iOS *	Samsung Internet	Opera Mini *	Opera Mobile *	UC Browser for Android	Android Browser *	Firefox for Android	QQ Browser	Baidu Browser	KaiOS Browser
		3.1 - 13.1					3.2 - 13.7									
4 - 78	12 - 18	[4 5] 14 - 15.6					[5] 14 - 15.8									
[2] 79 - 84	[2] 79 - 84	[5] 16.0 - 16.3	2 - 71	10 - 72			[5] 16.0 - 16.3									
[3] 85 - 86	[3] 85 - 86	[5] 16.4 - 17.6	[1] 72 - 87	[3] 73			[5] 16.4 - 17.7	4 - 13.0								
87 - 132	87 - 132	18.0 - 18.2	88 - 134	74 - 113	6 - 10		18.0 - 18.2	14.0 - 26		12 - 12.1		2.1 - 4.4.4				2.5
133	133	18.3	135	114	11	133	18.3	27	all	80	15.5	133	135	14.9	13.52	3.1
134 - 136		18.4 - TP	136 - 138				18.4									

https://caniuse.com/http3

Client support

- Google apps
  - Several mobile apps from Google support QUIC including YouTube, Gmail, Google Drive, Google Search etc.
- Social Media apps
  - Facebook, Instagram, WhatsApp, Snapchat
- Enterprise & Cloud Services
  - Microsoft 365, Uber
- Streaming
  - Netflix, Disney+, Amazon Prime, Spotify

Server support

- LiteSpeed, NGINX, Apache HTTP Server, Caddy
- Microsoft Windows Server 2022
- CDSs: Akamai Technologies, Cloudflare, CDNetworks
- As of early 2025, around 27-30% of all websites support HTTP/3

- QUIC implementations:

https://github.com/quicwg/base-drafts/wiki/Implementations

QUIC Performance

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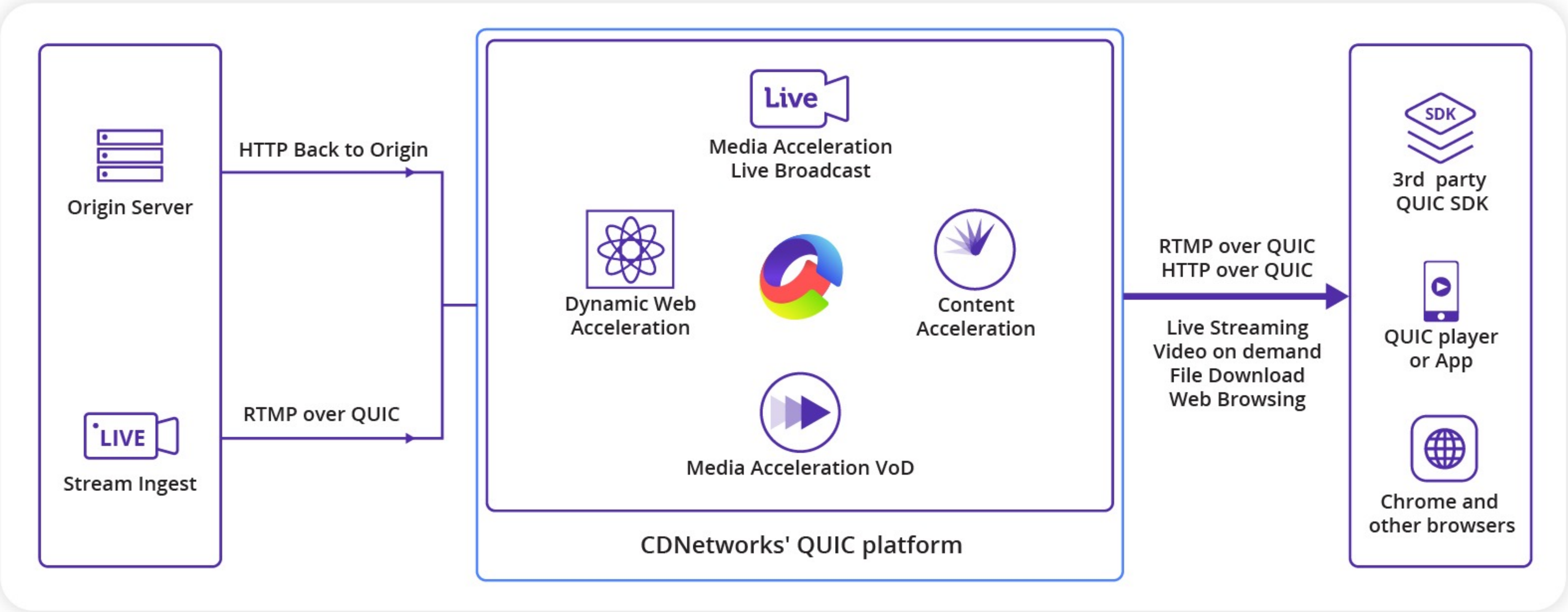
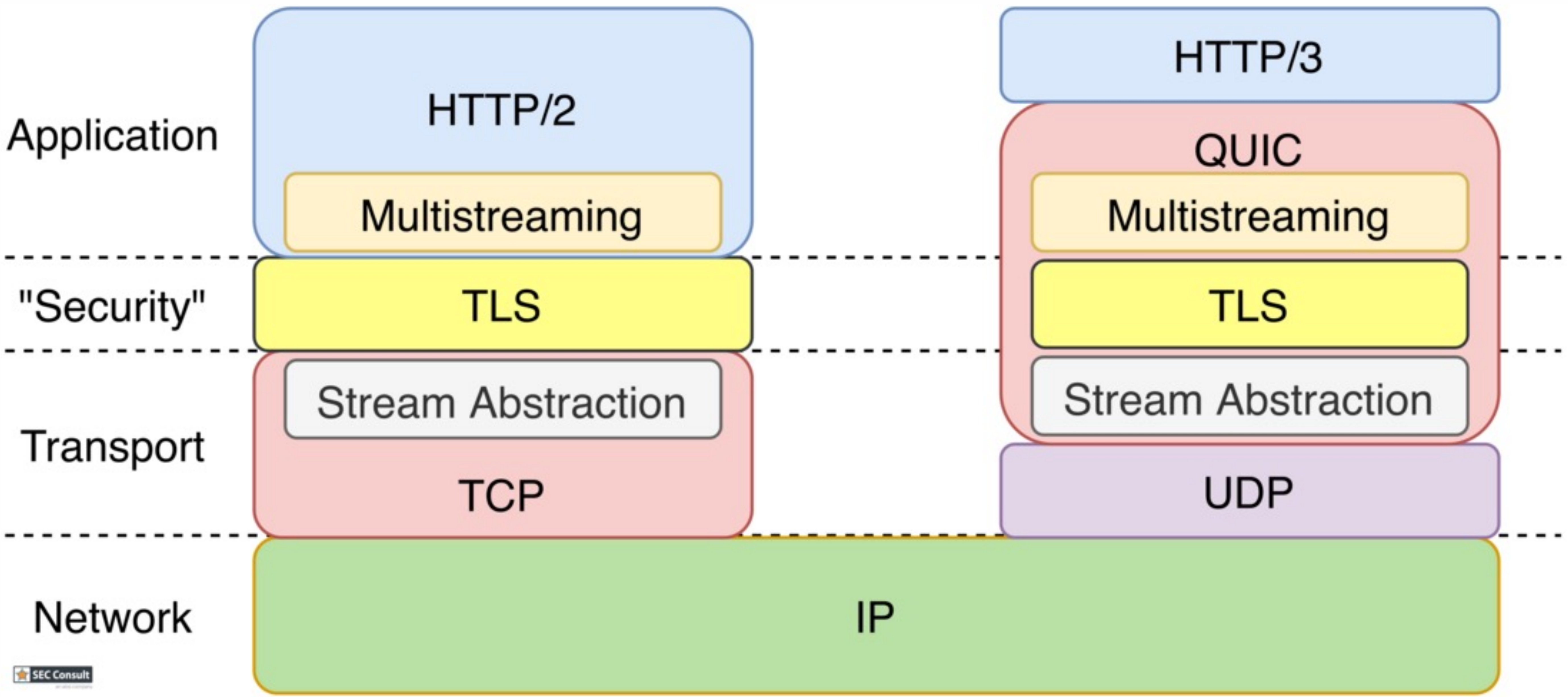
The internal testing data at CDNetworks showed that, during QUIC stream pull scenario with a 1Mbps bitrate, the new platform can improve bandwidth performance by 41% under the same business concurrency conditions

CDNetworks QUIC Overview



https://www.cdnetworks.com/media-delivery-blog/what-is-quic/

Where does QUIC fit?



https://sec-consult.com/

HTTP 3.0

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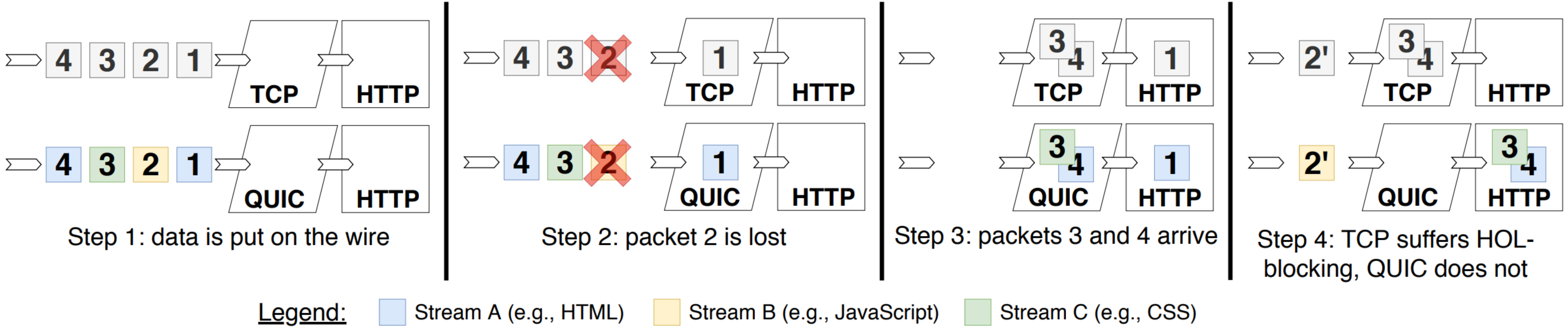
- In June 2022, IETF standardized HTTP/3 as RFC 9114
- The main difference between HTTP 2.0 and HTTP 3.0 is the underlying transport layer protocol.
  - In HTTP 2.0, we have TCP connections
  - HTTP 3.0 uses QUIC (UDP-based protocol)

QUIC Features

- Multiplexing without head-of-line blocking
- Low latency connections
- Connection Migration
- Linkability Prevention
- Encryption
- Resistance to protocol ossification
- Field compression with QPACK

No head-of-line blocking

- In QUIC each byte stream is transported independently over the network.
- QUIC ensures the in-order delivery of packets within the same byte stream.
- If a packet gets lost, only the affected stream gets blocked and waits for its re-transmission.



Source: Robin Marx et al., "Resource Multiplexing and Prioritization in HTTP/2 over TCP Versus HTTP/3 over QUIC"

Connection Establishment

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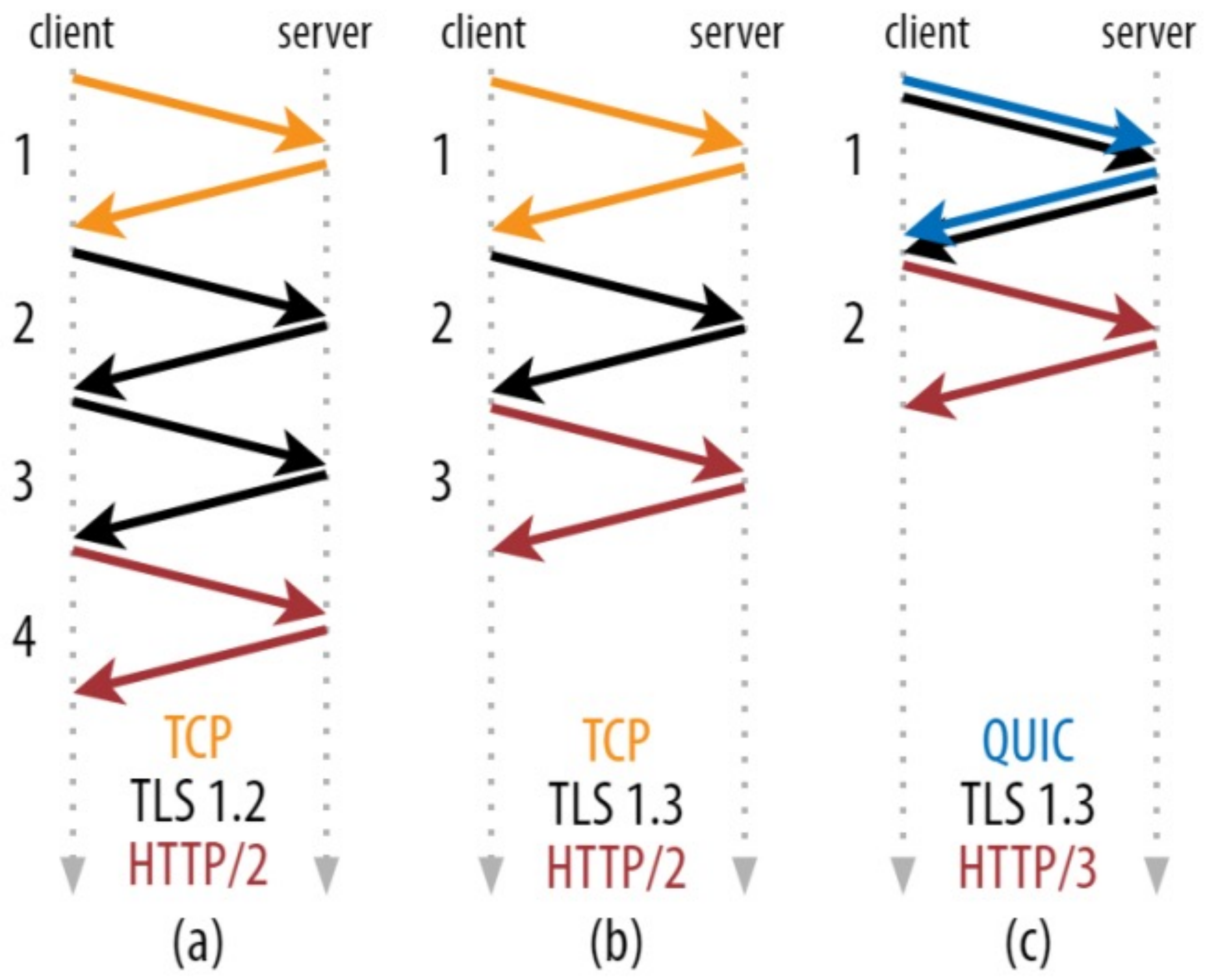
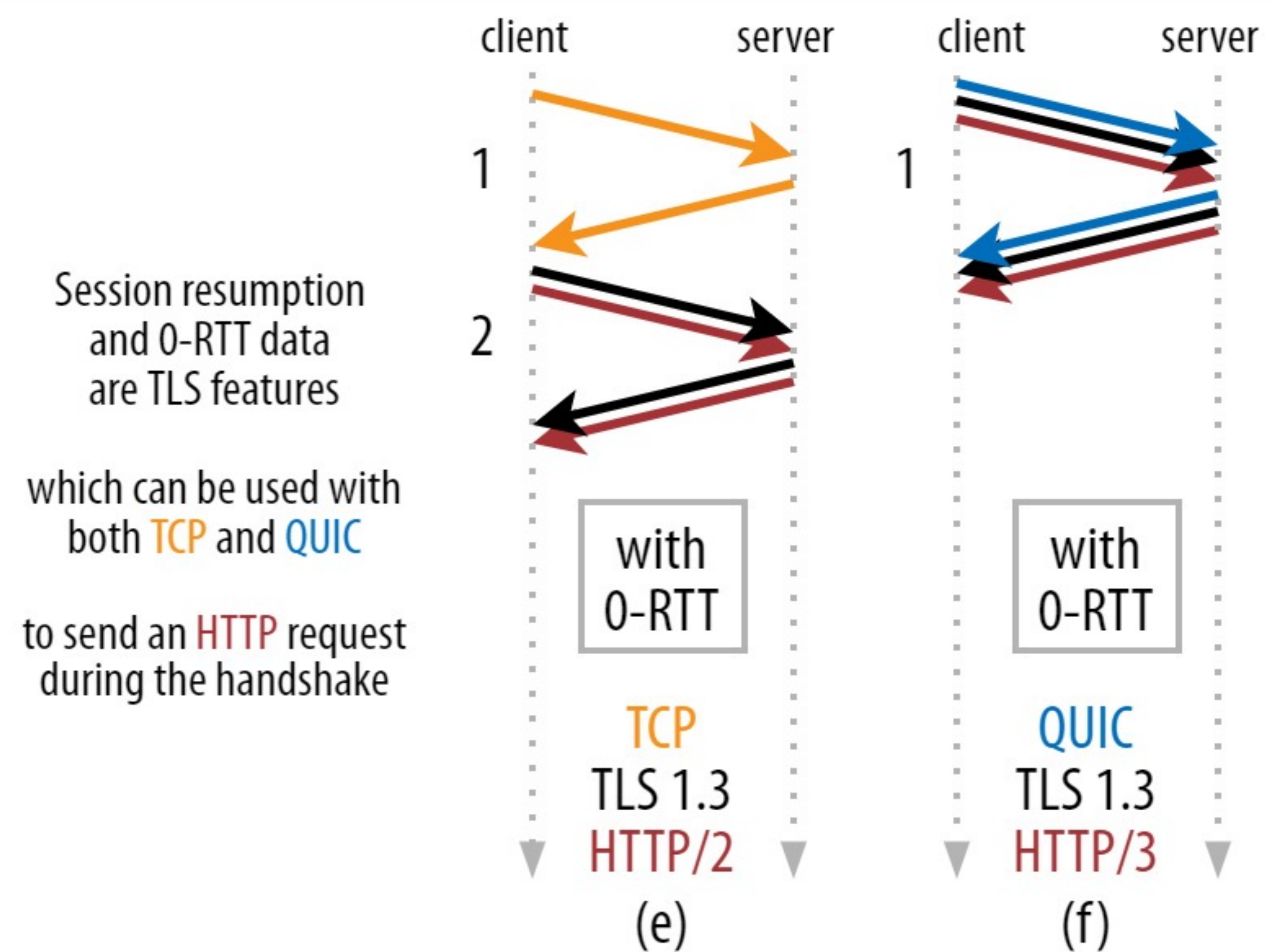
- QUIC has a faster connection setup, as it combines the 'transport' handshake with the TLS cryptographic session establishment, which in TCP+TLS are two separate processes.



0-RTT Connection

- To reduce the time required to establish a new connection, a client that has previously connected to a server may cache certain parameters from that connection and subsequently set up a 0-RTT connection with the server.
- With 0-RTT feature, an HTTP request can be sent, and a (partial) response can be received during the very first handshake!



Connection Migration

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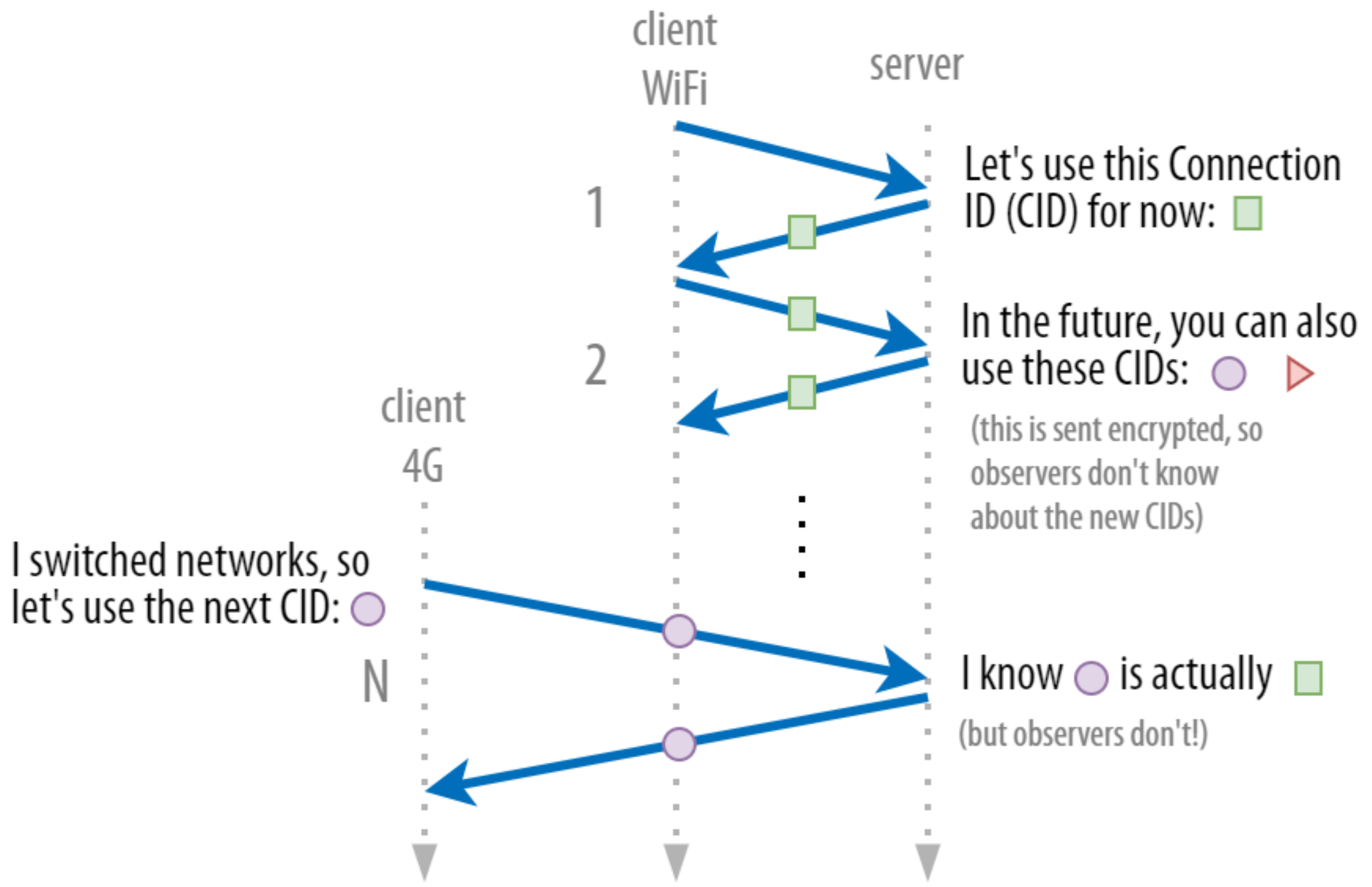
- QUIC improves performance during network-switching events, like what happens when a user of a mobile device moves from a local WiFi hotspot to a mobile network.
- When this occurs on TCP, a lengthy process starts where every existing connection times out one-by-one and is then re-established on demand.
- QUIC includes a connection identifier to uniquely identify the connection to the server regardless of source.
- This allows the connection to be re-established simply by sending a packet, which always contains this ID, as the original connection ID will still be valid even if the user's IP address changes.

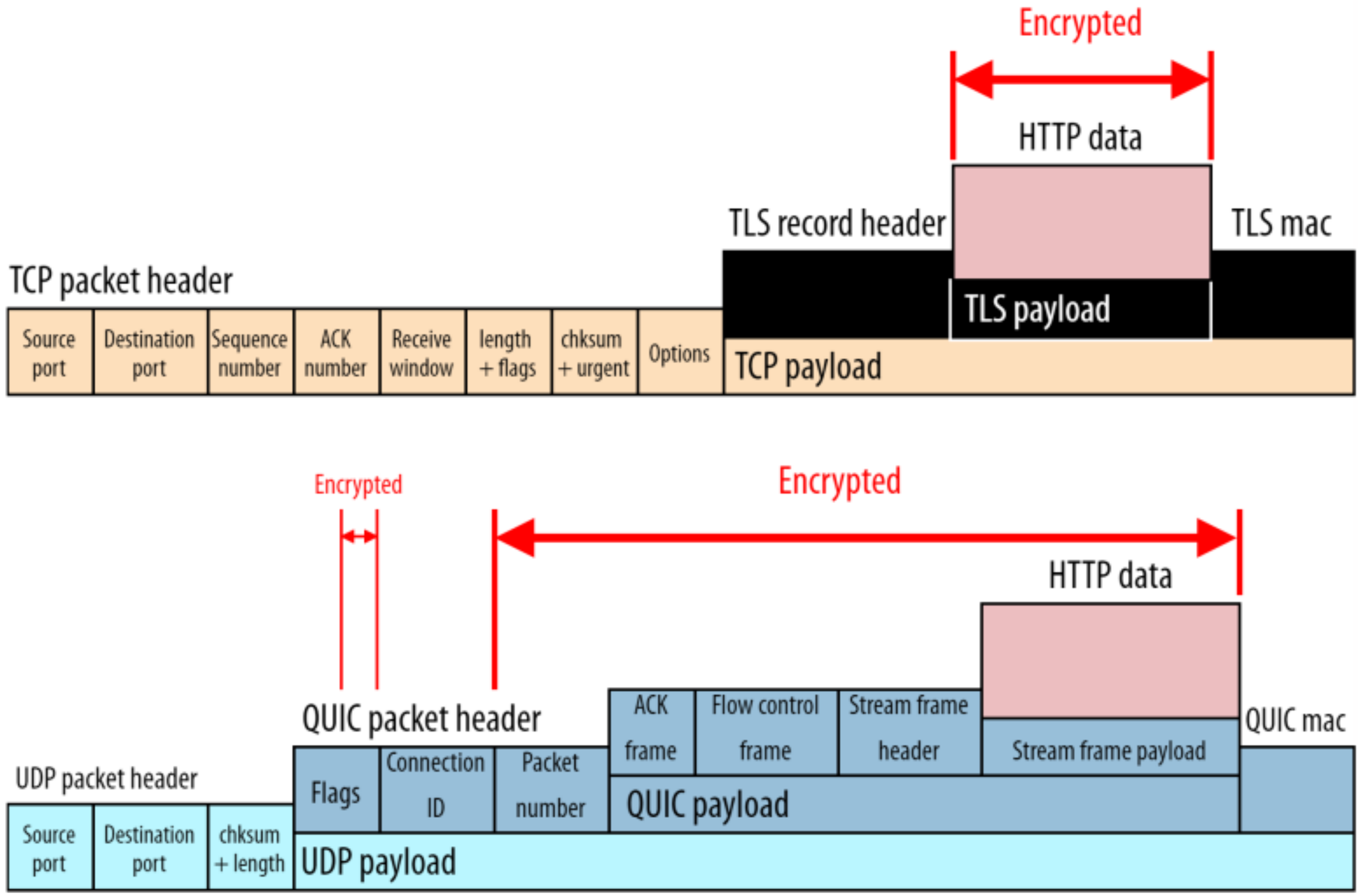
Linkability prevention

- To avoid privacy issues, e.g. to prevent hackers from following the physical movement of a smartphone user by tracking the unencrypted CID across networks, QUIC uses a list of connection identifiers instead of just one.



Encryption

- TCP + TLS only encrypts the actual HTTP data.
- QUIC also encrypts large parts of the protocol header.
  - Metadata, such as packet numbers and connection-close signals, which were visible to all middleboxes (and attackers) in TCP, are now only available to the client and server in QUIC.



Source: https://pulse.internetsociety.org/

Resistance to protocol ossification

- Protocol ossification, is an inherent characteristic of protocols implemented in the operating system (OS) kernel, such as TCP.
  - OSs are rarely updated, which applies even more to the operating systems of middleboxes, such as firewalls and load balancers.
  - It is a problem because it makes it hard to introduce new features, as middleboxes with an older version of the protocol don't recognize the new feature and drop the packets.
- QUIC aims to solve this issue.
  - QUIC runs in the user space instead of the kernel, so it's easier to deploy new implementations.
  - QUIC is heavily encrypted. If middlebox can't read a piece of info, it can't make any decisions based on that info.

QPACK Field Compression

- QPACK is a field compression format for HTTP/3.
- Field compression eliminates redundant metadata by assigning indexes to fields that are used multiple times during the connection.
- The goal of QPACK is to reduce the space taken up by HTTP headers.
  - Smaller size translates to higher throughput and better user experience.
  - Effectiveness of data compression is expressed as compression ratio.
- For example, if you compare a string “LiteSpeed” to “ls”, the compression ratio is 2/9, or about 0.22. The smaller the number, the better the compression performance.

QUIC Packet Structure

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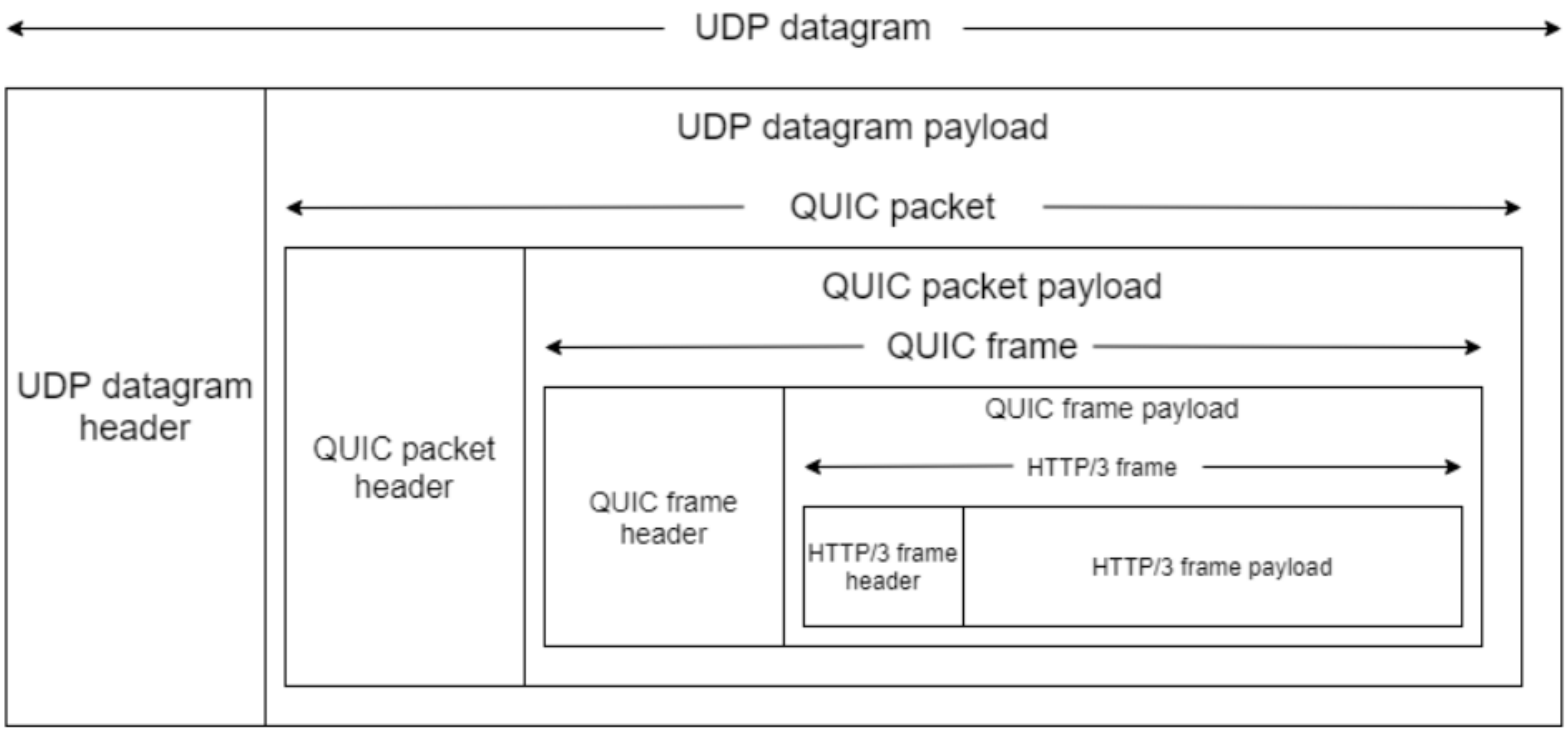
- A QUIC packet is composed of a common header followed by one or more frames.



QUIC packets

- QUIC endpoints communicate by exchanging packets.
- QUIC packet consists of header and payload.
- QUIC has two different types of headers.
  - The long header is used prior to the connection establishment.
  - The short header is used after the first connection established.
- Packets are carried in UDP datagram.

QUIC packets

- QUIC provides different packet types:
  - Initial packet - It transports the first CRYPTO frames transmitted by the client and server during the key exchange and the ACK frames in both directions.
  - Handshake packet - It is used for sending and receiving encrypted handshake messages and acknowledgments between the server and the client.
  - 0-RTT packet – It sends "early" data from the client to the server before the handshake is completed.
  - 1-RTT packet – It is used to exchange data between client and server after the handshake is completed.

QUIC packets

- QUIC initial packet example

```
QUIC IETF
    QUIC Connection information
    [Packet Length: 1350]
    1... .... = Header Form: Long Header (1)
    .1.. .... = Fixed Bit: True
    ..00 .... = Packet Type: Initial (0)
    .... 00.. = Reserved: 0
    .... ..00 = Packet Number Length: 1 bytes (0)
    Version: draft-29 (0xff00001d)
    Destination Connection ID Length: 8
    Destination Connection ID: 45fb5955dfaa8914
    Source Connection ID Length: 0
    Token Length: 0
    Length: 1332
    Packet Number: 1
    Payload:
5a99e5b29413627619ca3b5add4cf8b6ce348355b1c1a2be9874c7961e7996a24aeec
860…
    TLSv1.3 Record Layer: Handshake Protocol: Client Hello
    PADDING Length: 997
```

QUIC frames

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- A QUIC packet is composed of a common header followed by one or more frames.
- There are various types of frames:
  - ACK frame - Receivers send ACK frames to inform senders of packets they have received and processed. The ACK frame contains one or more ACK Ranges.
  - CRYPTO frame - It is used to transmit cryptographic handshake messages.
  - STREAM frame – It implicitly create a stream and carry stream data. It contains a Stream ID, Offset, Length and Stream Data.
  - MAX_DATA frame - Used in flow control to inform the peer of the maximum amount of data that can be sent on the connection as a whole.
  - MAX_STREAM_DATA frame - Used in flow control to inform a peer of the maximum amount of data that can be sent on a stream.
  - MAX_STREAMS frame - Informs the peer of the cumulative number of streams of a given type it is permitted to open.

QUIC frames

- QUIC CRYPTO frame examples

```
TLSv1.3 Record Layer: Handshake Protocol: Client Hello
    Frame Type: CRYPTO (0x0000000000000006)
    Offset: 0
    Length: 314
    Crypto Data
    Handshake Protocol: Client Hello
```

```
TLSv1.3 Record Layer: Handshake Protocol: Server Hello
  Frame Type: CRYPTO (0x0000000000000006)
  Offset: 0
  Length: 90
  Crypto Data
  Handshake Protocol: Server Hello
    Handshake Type: Server Hello (2)
    Length: 86
    Version: TLS 1.2 (0x0303)
    Random:
0f58bdbd934450c7aa98242121447bef2fe0733aa5fc3beffab6513c7177f9a4
    Session ID Length: 0
    Cipher Suite: TLS_AES_128_GCM_SHA256 (0x1301)
    Compression Method: null (0)
    Extensions Length: 46
    Extension: key_share (len=36)
    Extension: supported_versions (len=2)
```

QUIC streams

- Streams in QUIC provide a lightweight, ordered byte-stream abstraction to an application.
- Streams can be created by either endpoint, can concurrently send data interleaved with other streams.
- Streams are identified within a connection by a numeric value, referred to as the stream ID (a 62-bit integer) that is unique for all streams on a connection.
- Client-initiated streams have even-numbered stream IDs and server-initiated streams have odd-numbered stream IDs

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Thank you for your attention!