TECHNISCHE UNIVERSITÄT DRESDEN

HAW HAMBURG

DRESDEN concept

Instant Acknowledgments in QUIC Handshakes

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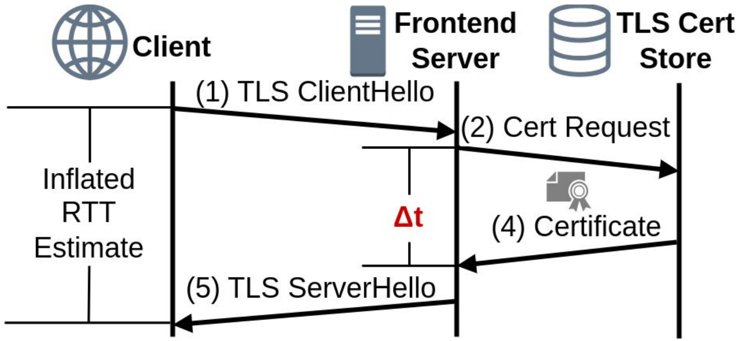
Distributed certificate stores challenge RTT estimate

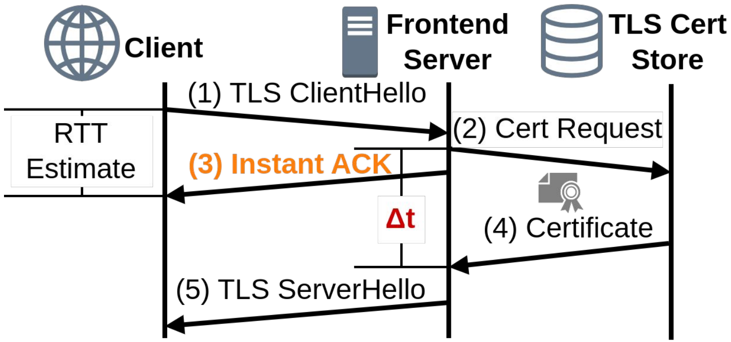
Common CDN deployments, e.g., Cloudflare, Akamai

Inflated RTT estimate



Waiting for the certificate (WFC) from a backend server inflates the client RTT estimate.

Precise RTT estimate



An instant ACK (IACK) reduces the RTT estimate of the client.

Distributed certificate stores challenge RTT estimate

Common CDN deployments, e.g., Cloudflare, Akamai

Inflated RTT estimate

Precise RTT estimate

The RTT estimate is relevant in case of packet loss and when the anti-amplification limit is reached.

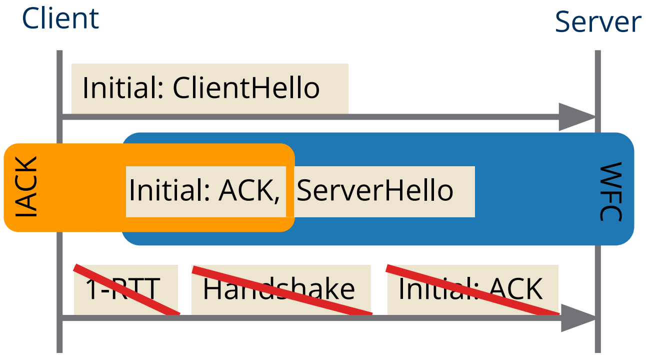
When is instant ACK beneficial? When does it harm?

We measure TTFB to analyze performance impact of instant ACK under packet loss in a controlled testbed.

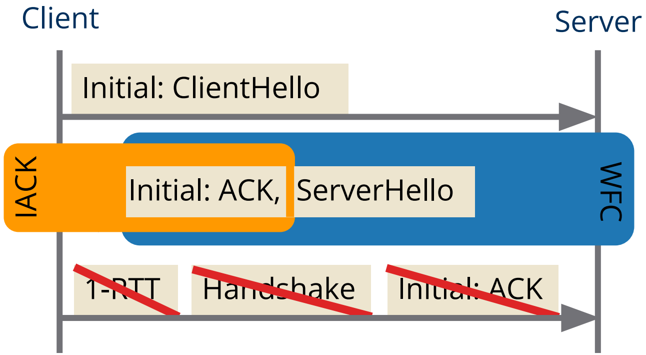
Waiting for the certificate (WFC) from a backend server inflates the client RTT estimate.

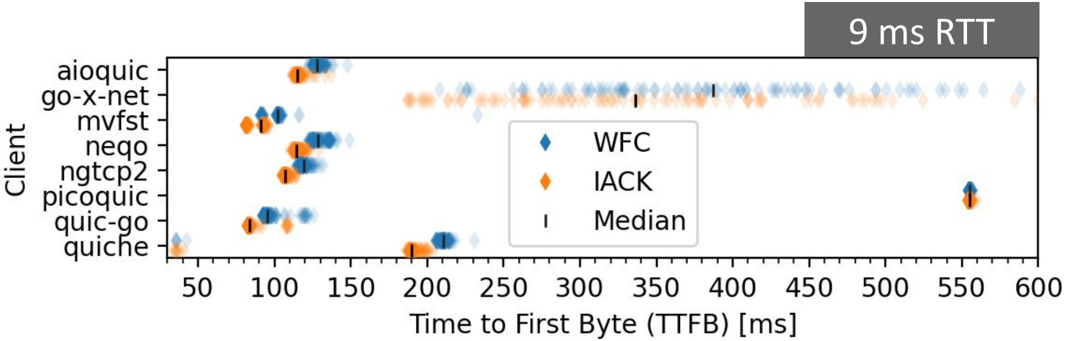
An **instant ACK (IACK)** reduces the RTT estimate of the client.

Client → server: Second client flight is lost



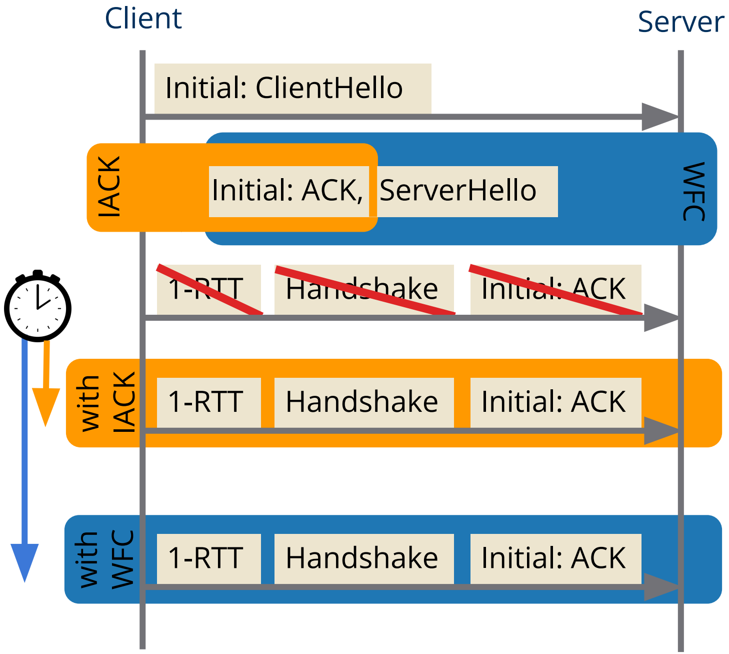
Client→server: Second client flight is lost

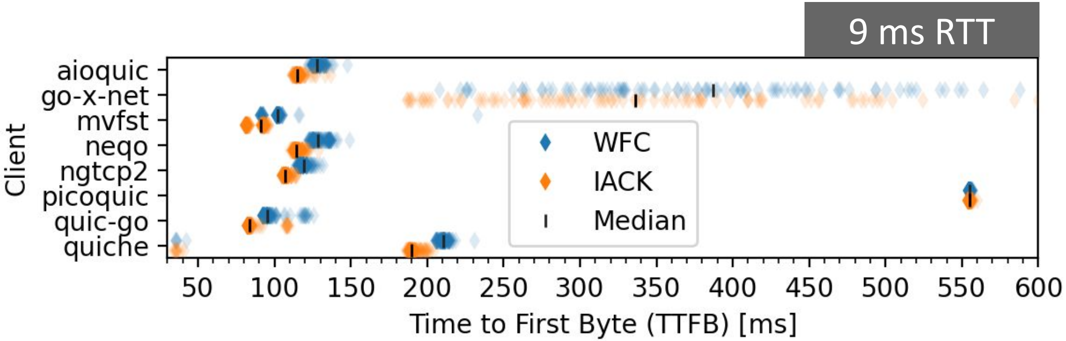




Using IACK, clients need to wait on median between 10 (mvfst) and 28 ms (go-x-net) less.

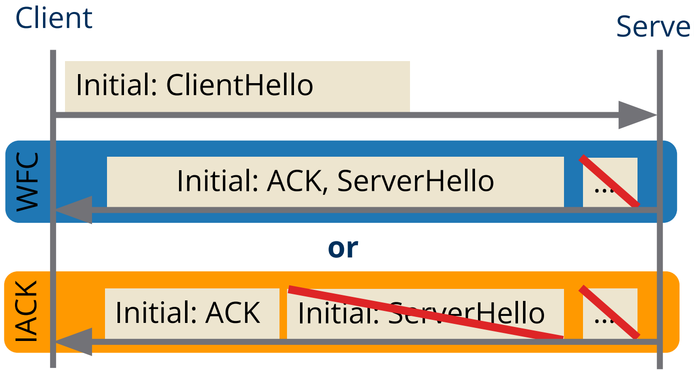
Client→server: Second client flight is lost

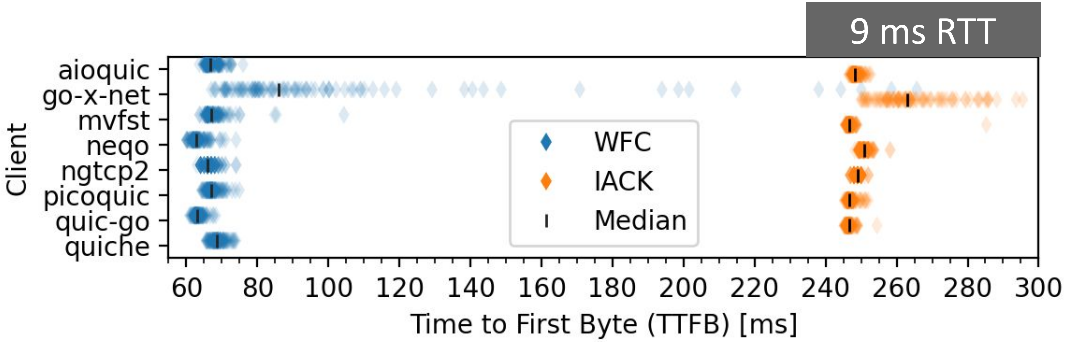




Using IACK, clients need to wait on median between 10 (mvfst) and 28 ms (go-x-net) less.

Server→client: Remaining first server flight is lost





IACK prevents RTT estimation. Server uses default PTO.

WFC allows RTT estimation. Server uses shorter PTO.

WFC outperforms IACK. WFC accelerates by the server default PTO.

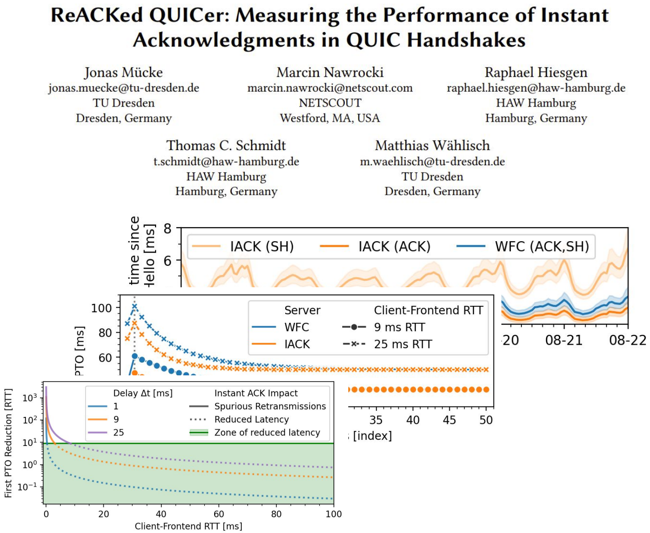
Send IACK with PING frame to ensure the server gets an RTT estimate.

Conclusion

Instant ACK is an RFC-compliant approach to more accurately set PTOs in QUIC. This **improves performance not always but often**.

Instant ACK is the only solution to provide precise RTT estimates from the first RTT sample. Neither acknowledgment delays of QUIC ACKs nor reinitialization of the PTO on the next ACK can replace it.

More results in our IMC'25 paper, and at MAPRG tomorrow.



ReACKed QUICer: Measuring the Performance of Instant Acknowledgments in QUIC Handshakes

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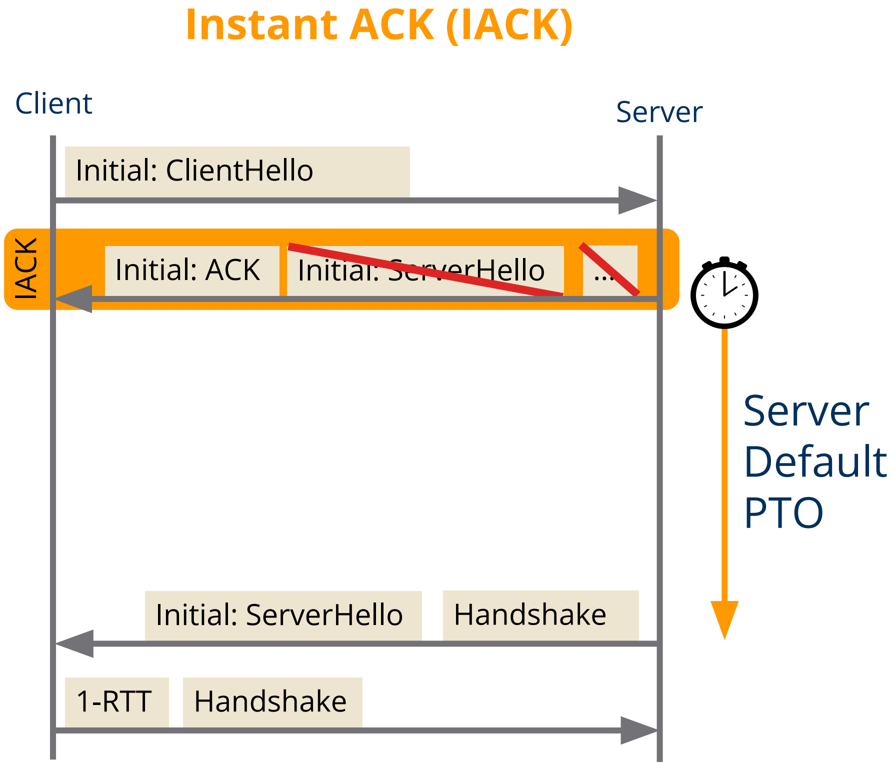
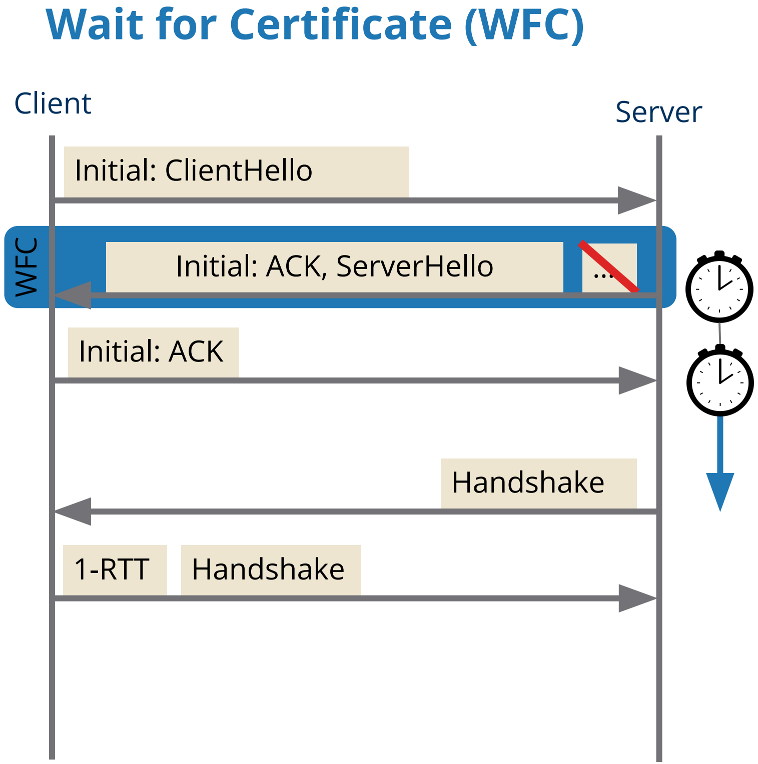
Backup

Server → client: Remaining first server flight is lost





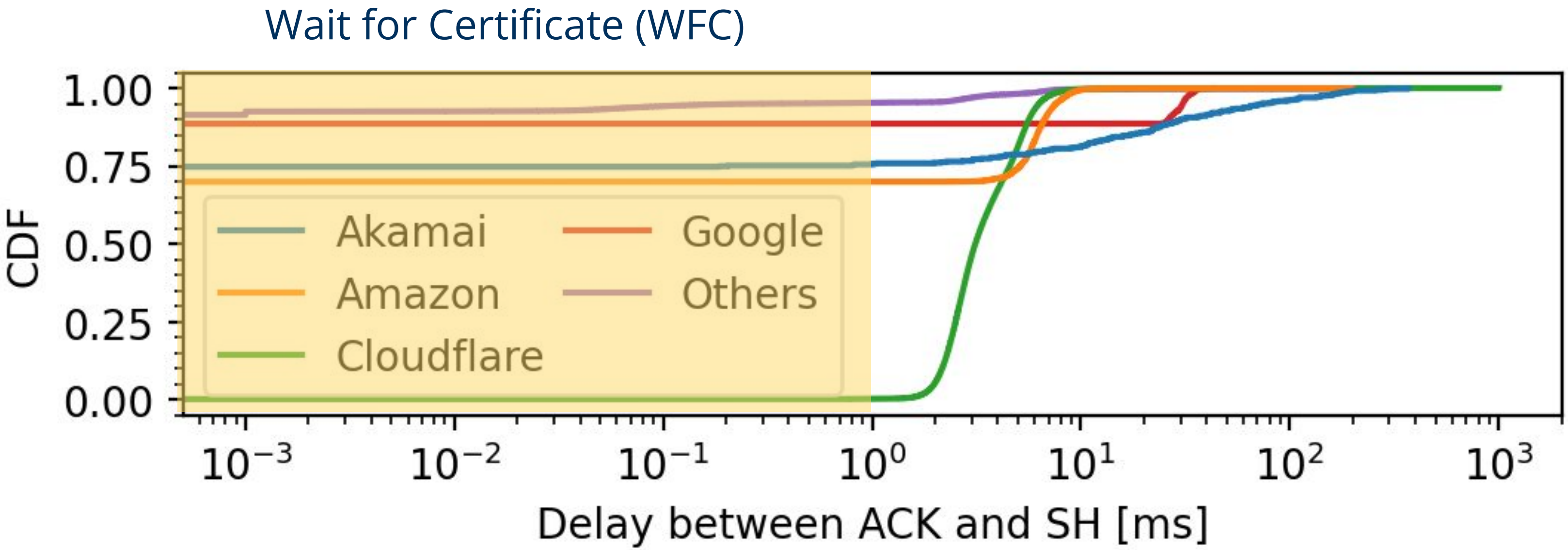
CDNs deploy instant ACK

Akamai, Amazon, Google, and Cloudflare deploy instant ACK.

Fastly, Meta, and Microsoft do not deploy instant ACK.

CDNs deploy instant ACK ... but differently

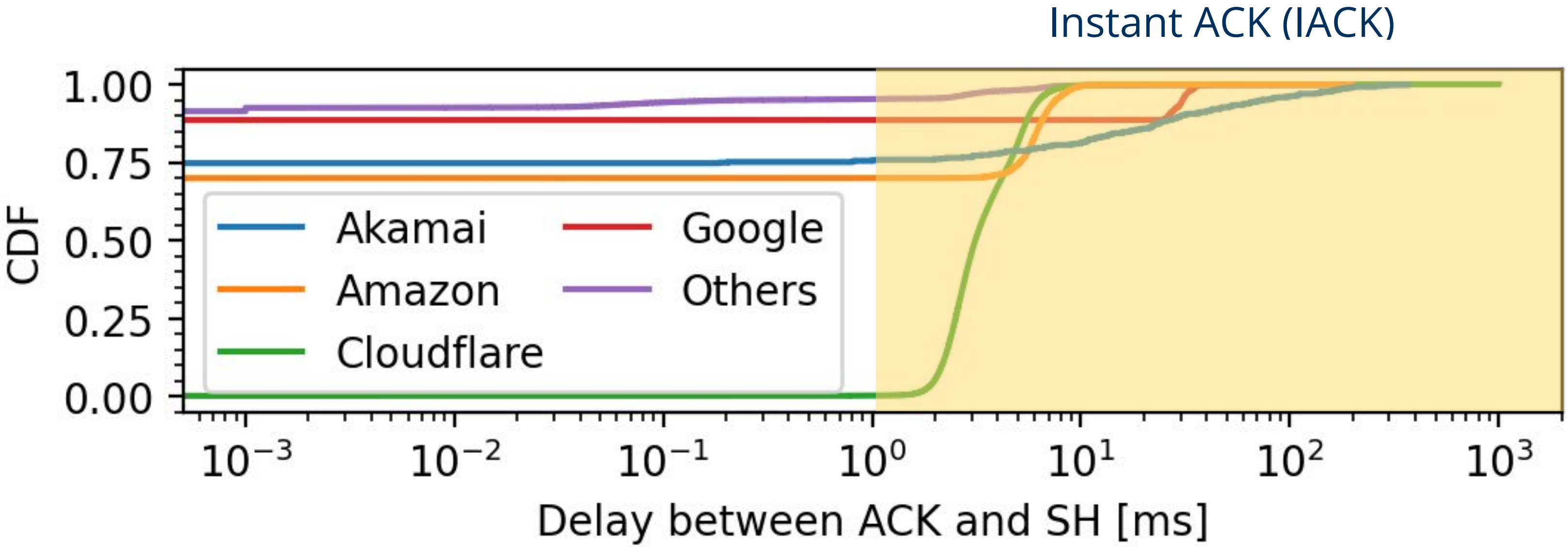
Akamai, Amazon, and Google deploy IACK relatively rarely.



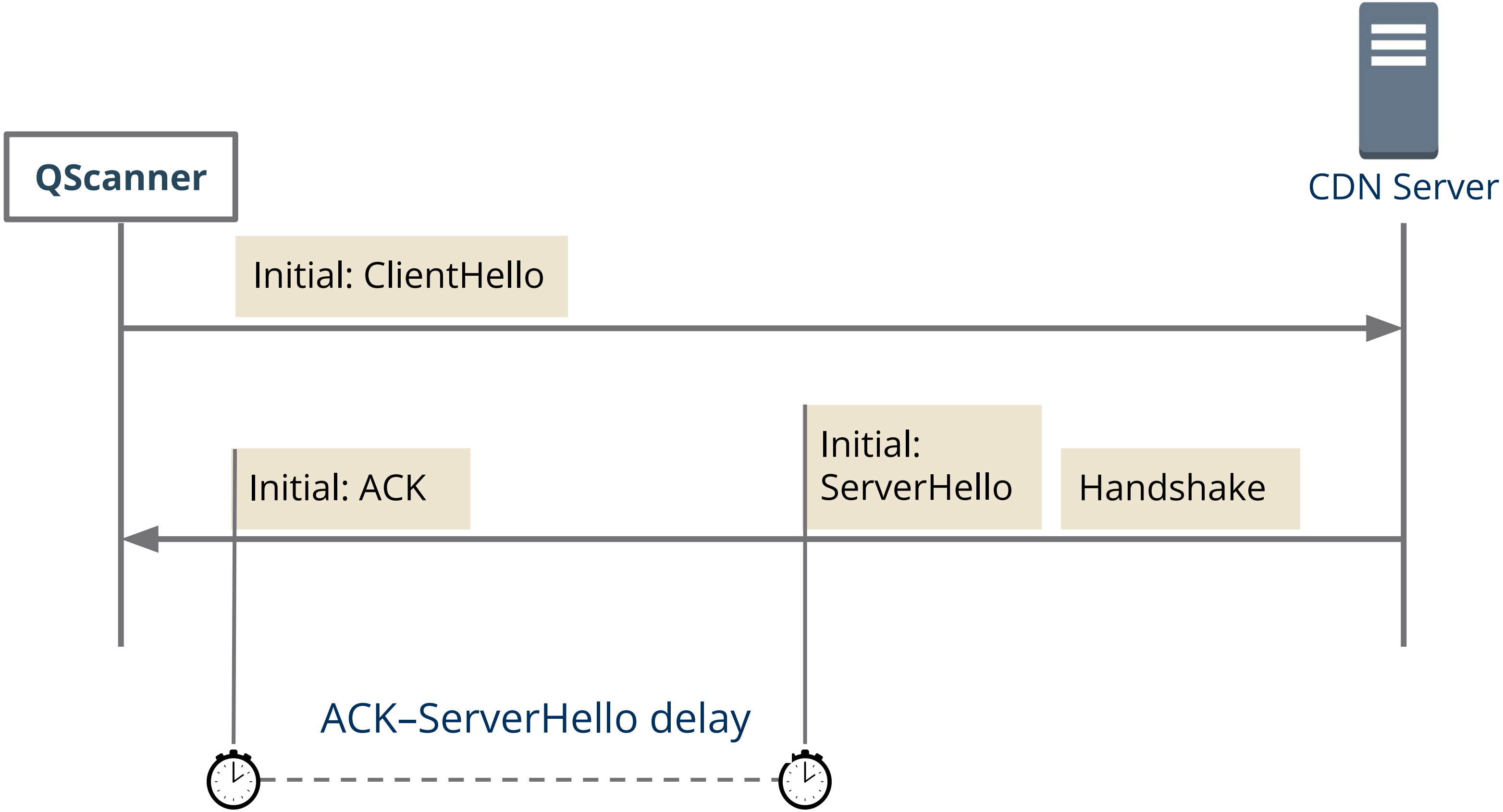
CDNs deploy instant ACK … but differently

Akamai, Amazon, and Google deploy IACK relatively rarely.

Cloudflare uses IACK almost always.



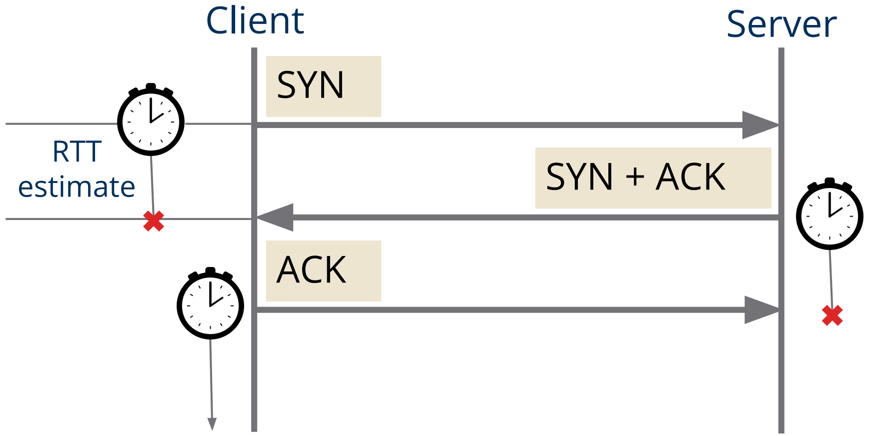
Measuring improvements by IACK in the wild



Timeouts are critical for reliable transport

They trigger retransmissions when they expire

TCP handshake



Incorrect timeouts lead to unnecessary delays or spurious retransmits.

QUIC combines the transport and TLS handshake.

This makes it even more challenging to estimate the RTT correctly.

Precise RTT estimates lead to correct timeouts.

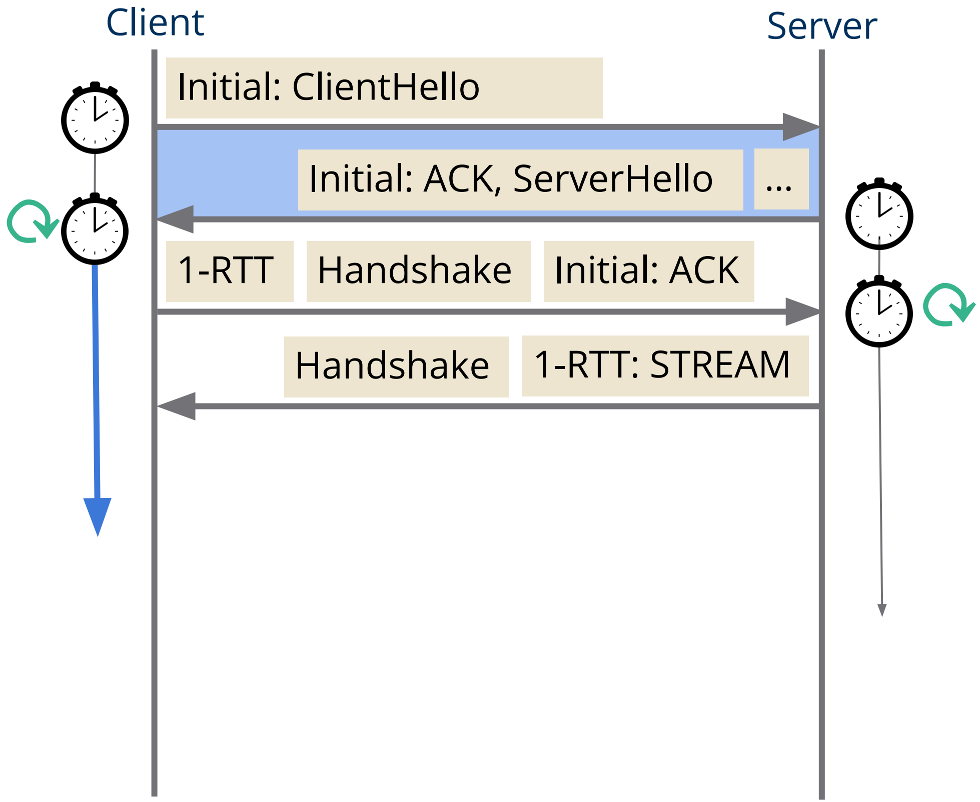
The first ACK impacts QUIC probe timeout (PTO)

Probe Timeout ⏱ determines when to resend packets in QUIC:

PTO depends on prior RTT samples

Default PTO: 1 s

Initialization: 3x FirstRTT



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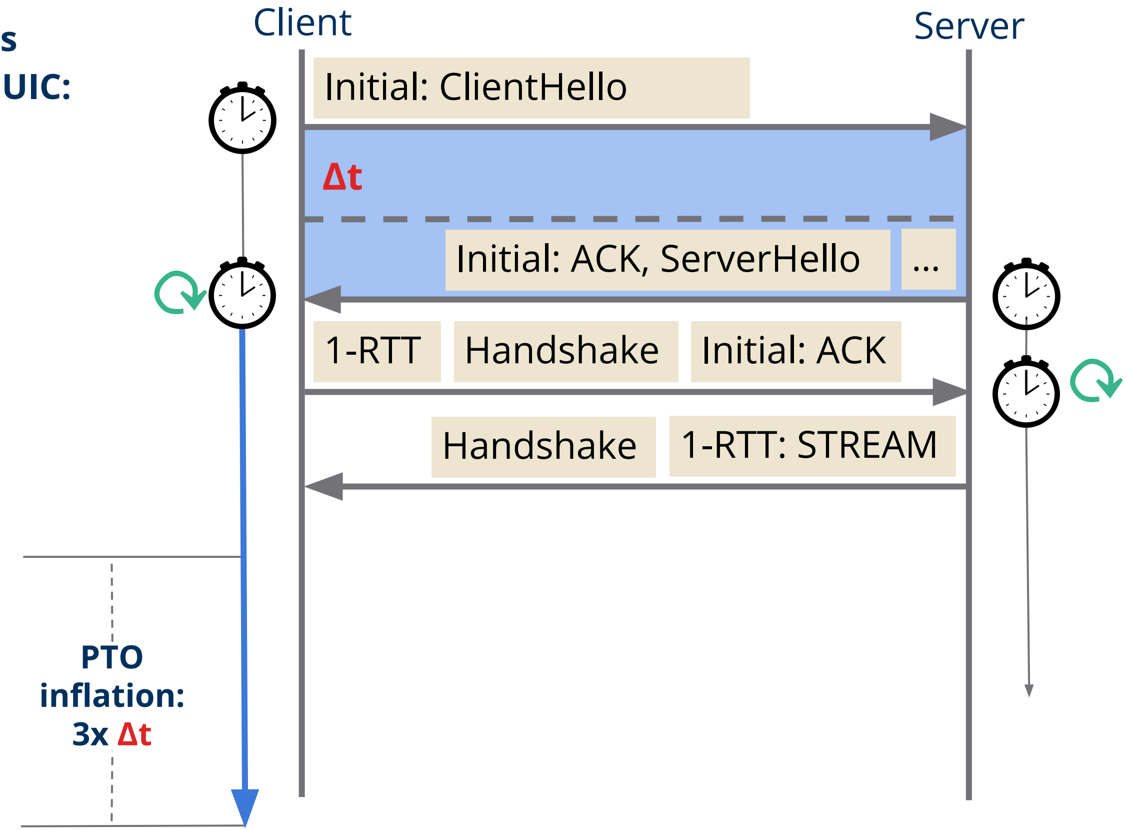

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Probe Timeout ⏱ determines when to resend packets in QUIC:

PTO depends on prior RTT samples

Default PTO:	1 s
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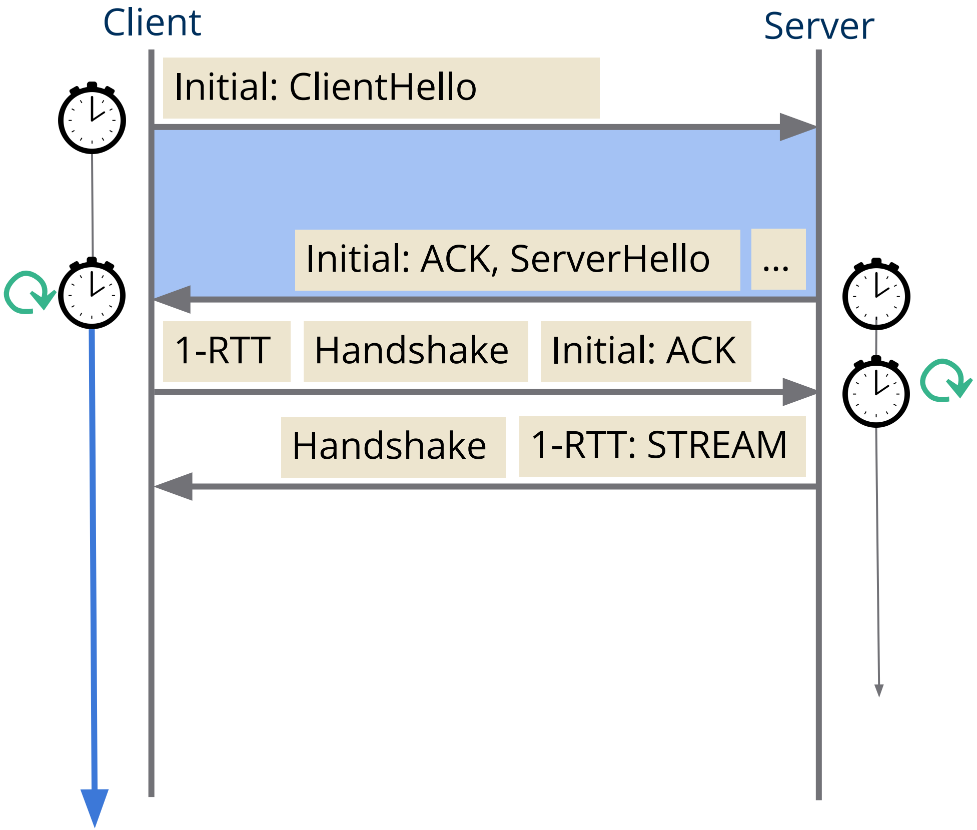
PTO is important:

… in case of packet loss

… to grant server sending budget



Research Questions

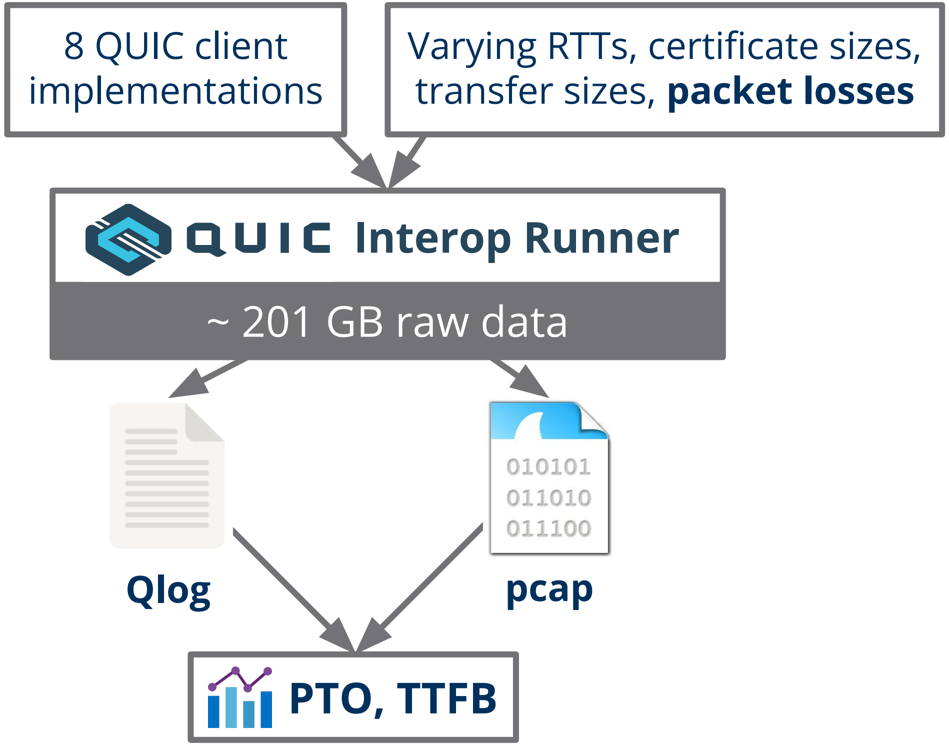
How does instant ACK influence client behavior?

When is IACK deployment beneficial, when does it harm?

How is IACK performing in CDN deployments?

Measurement method and setups

Controlled testbed



8 QUIC client implementations

Varying RTTs, certificate sizes, transfer sizes, **packet losses**

QUIC Interop Runner

~ 201 GB raw data

Qlog

pcap

PTO, TTFB

Measurement method and setups

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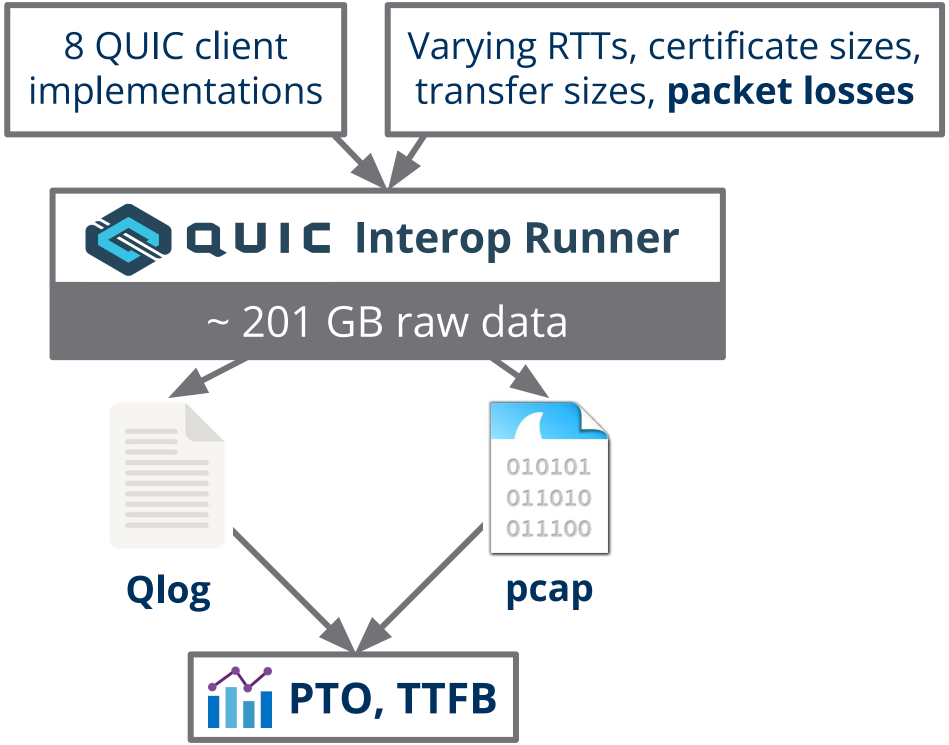

8 QUIC client implementations

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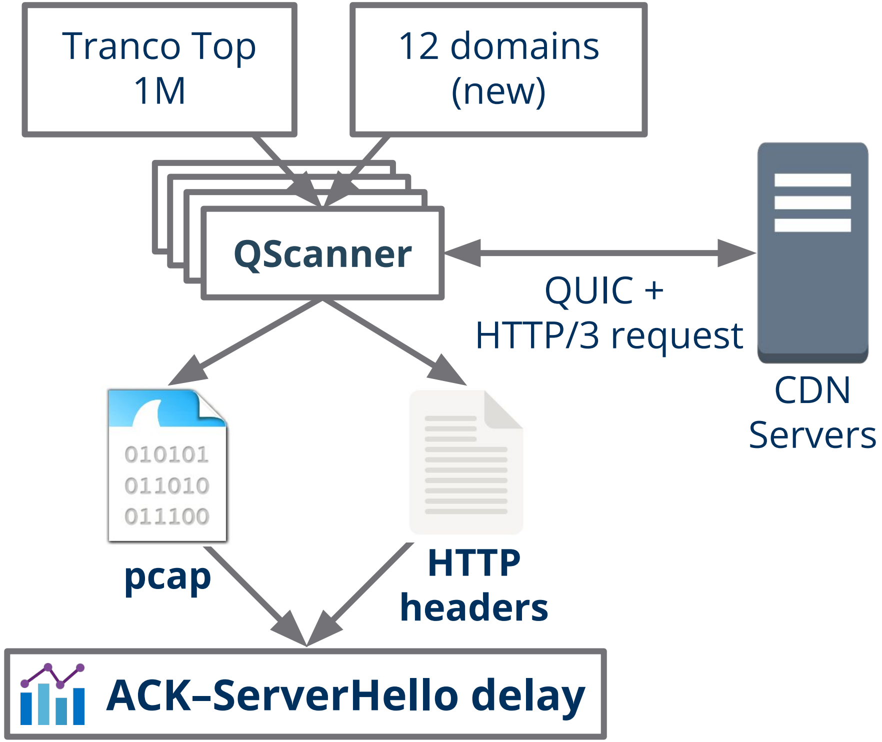
CDN deployments



Tranco Top 1M

12 domains (new)

QScanner

QUIC + HTTP/3 request

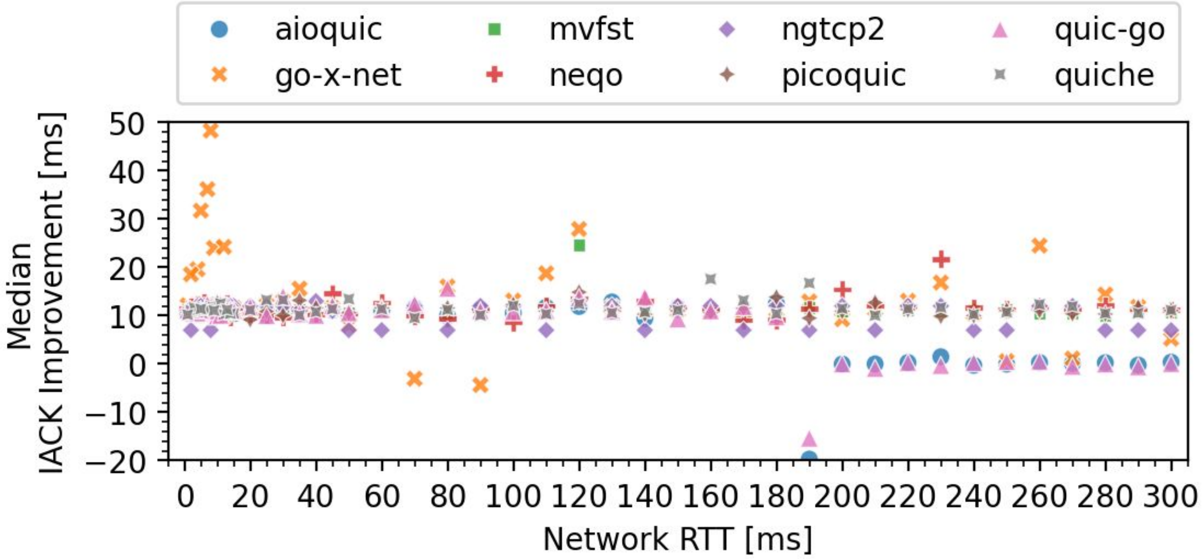
CDN Servers

pcap

HTTP headers

ACK–ServerHello delay

Median improvement of the first PTO



All clients benefit on median from ~10 ms shorter timeouts when IACK deployed.

Aioquic and quic-go use shorter default PTOs, benefiting relatively less from IACK.

Deployment guidelines

Alternatives to instant ACK

(1) Acknowledgement delay of QUIC ACKs

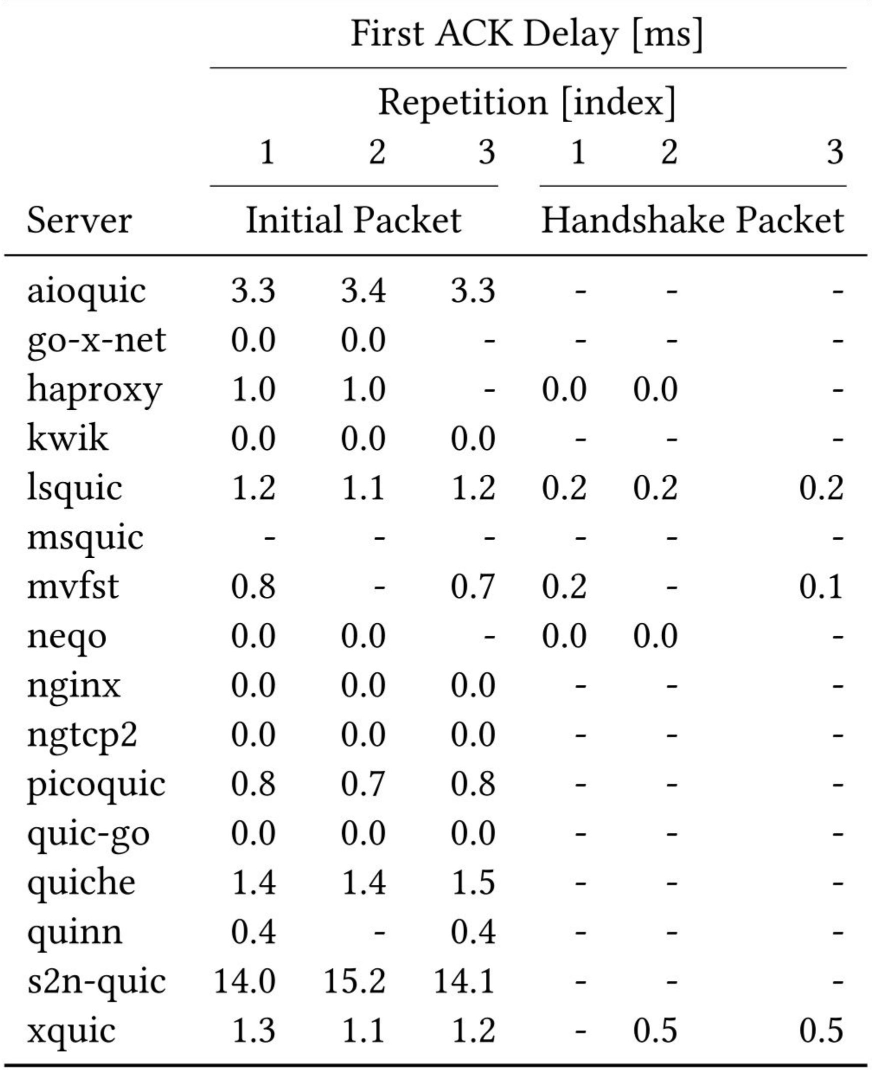
- Ignored by PTO initialization
- Not all implementations send ACK of the ClientHello
- Current deployments: ACK delay often exceeds connection RTT of coalesced ACK, SH

(2) Reinitialization after the first ACK

- Accurately represents connection RTT
- Effective only after the next ACK

The acknowledgment delay of QUIC ACKs or reinitialization strategy cannot provide precise RTT estimates from the first RTT sample.

Acknowledgment delay of the first ACK received from QUIC servers

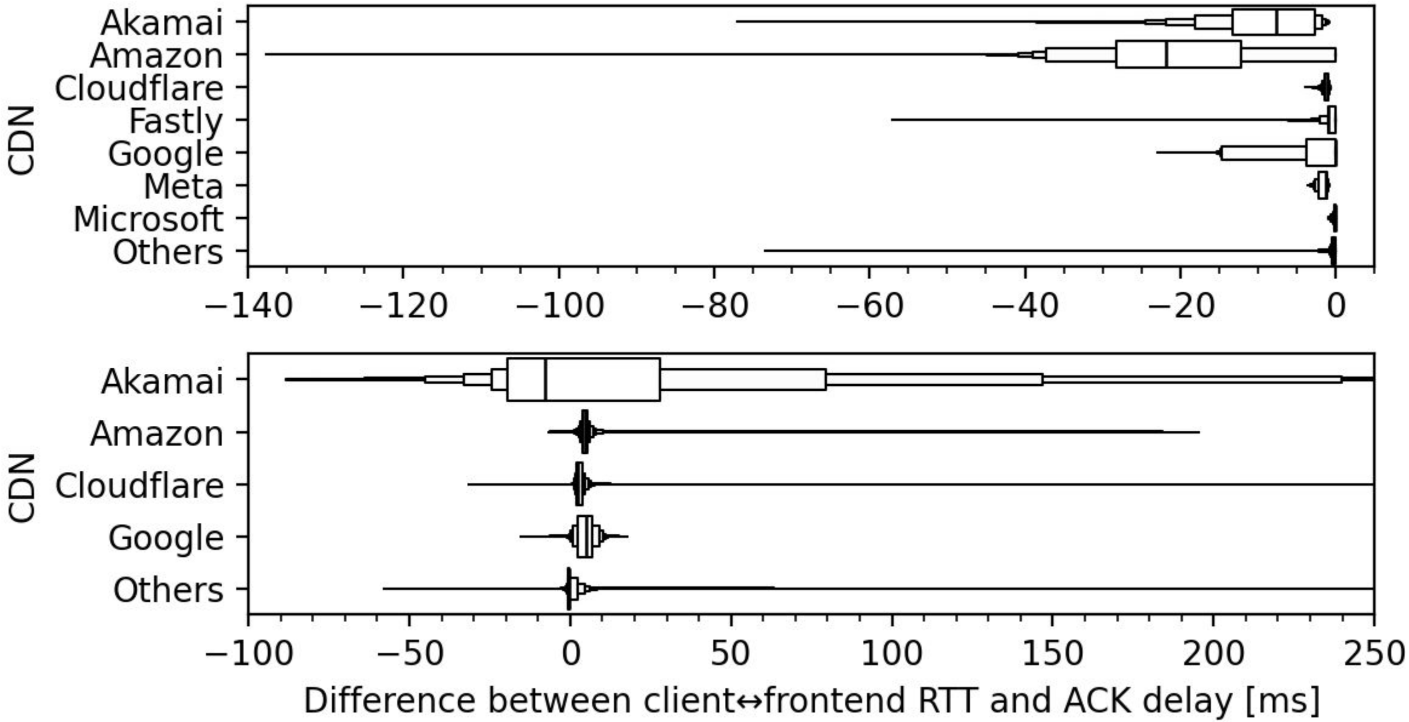


	First ACK Delay [ms]					
	Repetition [index]					
	1	2	3	1	2	3
Server	Initial Packet			Handshake Packet		
aioquic	3.3	3.4	3.3	-	-	-
go-x-net	0.0	0.0	-	-	-	-
haproxy	1.0	1.0	-	0.0	0.0	-
kwik	0.0	0.0	0.0	-	-	-
lsquic	1.2	1.1	1.2	0.2	0.2	0.2
msquic	-	-	-	-	-	-
mvfst	0.8	-	0.7	0.2	-	0.1
neqo	0.0	0.0	-	0.0	0.0	-
nginx	0.0	0.0	0.0	-	-	-
ngtcp2	0.0	0.0	0.0	-	-	-
picoquic	0.8	0.7	0.8	-	-	-
quic-go	0.0	0.0	0.0	-	-	-
quiche	1.4	1.4	1.5	-	-	-
quinn	0.4	-	0.4	-	-	-
s2n-quic	14.0	15.2	14.1	-	-	-
xquic	1.3	1.1	1.2	-	0.5	0.5

QUIC ACK delay vs. client-frontend RTT

Coalesced ACK,SH

Instant ACK



Which deployments benefit from instant ACK?

Which deployments benefits from instant ACK?

Improvements are not limited to CDN setups with separate certificate servers. All servers with delays in sending ACKs to the client profit from instant ACK.

Do alternatives to instant ACK exist?

There is no alternative to provide the client with precise RTT information from the beginning of the connection. The acknowledgment delay is ignored by the PTO initialization and often set incorrectly by server implementations.

The source of QUIC stack delays

Waiting for the certificate (WFC)

- Calculate Initial keys
- Calculate Handshake keys
- Construct and send TLS ServerHello
- Load and send certificate
- Calculate and send signature

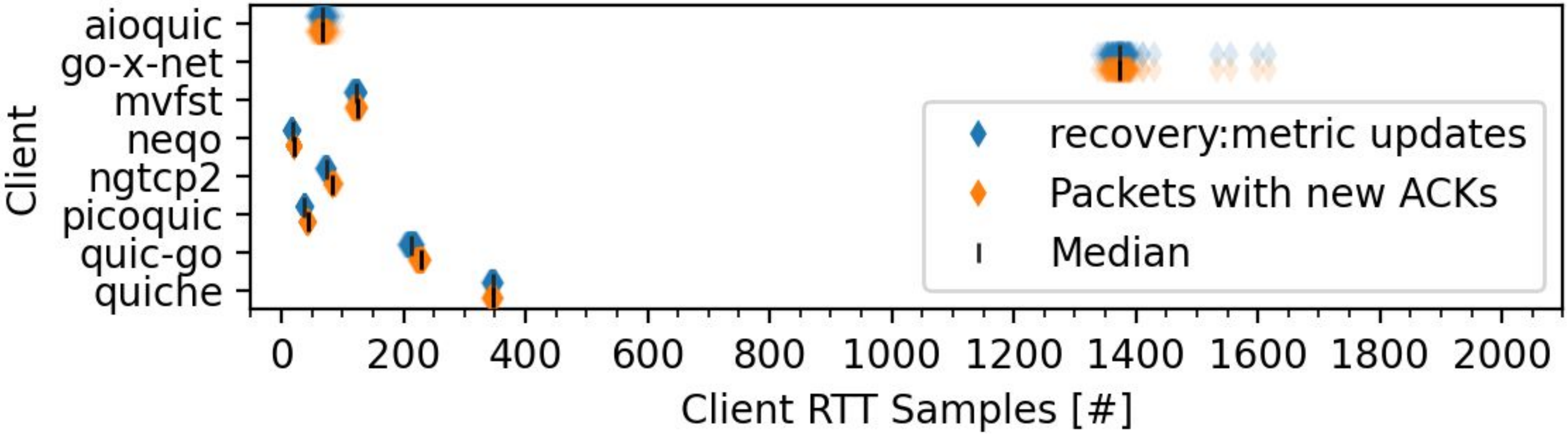
Profiling our server implementation quic-go, signature calculation was the single most CPU consuming function.

Instant ACK (IACK)

- Calculate Initial keys

Without additional delay, client RTT estimates differ on median between 3 and 8 ms.

Number of exposed RTT samples and newly acknowledging ACKs for 10 MB file transfer at 100 ms RTT, WFC



Does instant ACK generalize to 0-RTT and Retry handshakes?

0-RTT connections perform a 1-RTT QUIC handshake along with the 0-RTT exchange.

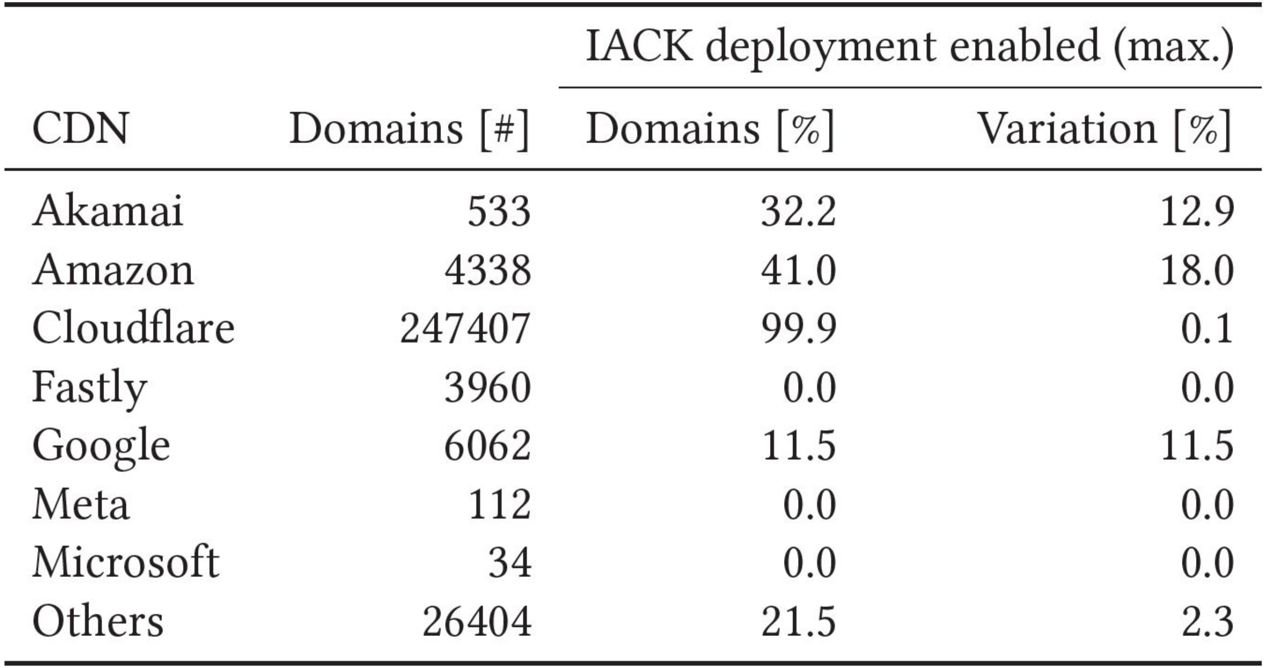
Retry packets cause the client to resend the ServerHello with a token.

In 0-RTT and Retry handshakes, instant ACK helps to set a more precise RTT estimate at the client.

CDN deployment

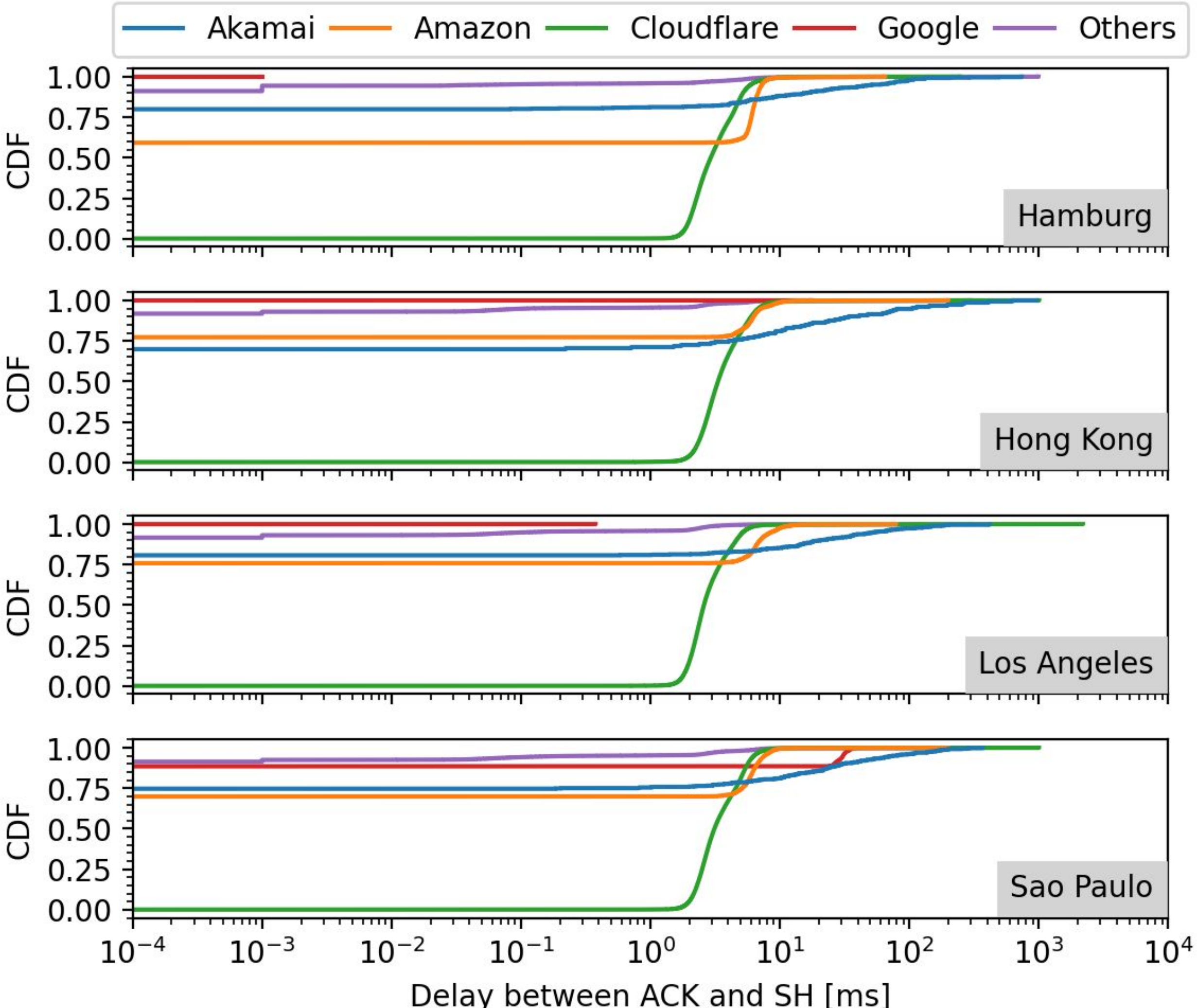
Instant ACK support of CDNs

Domains from the Tranco Top 1M, Aug 06, 2024



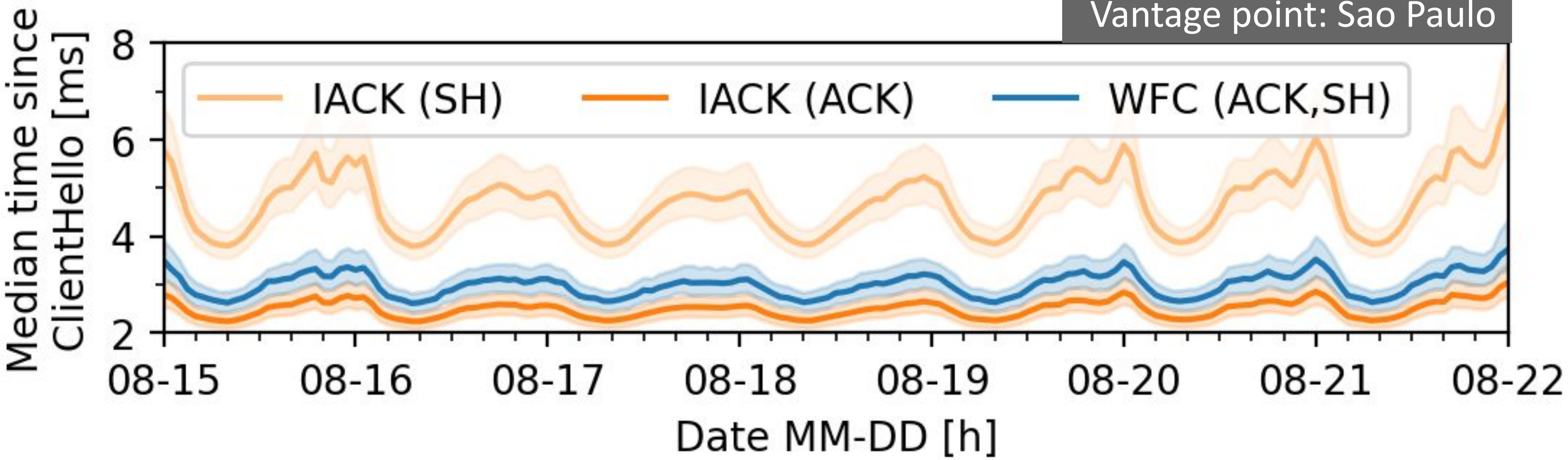
		IACK deployment enabled (max.)	
CDN	Domains [#]	Domains [%]	Variation [%]
Akamai	533	32.2	12.9
Amazon	4338	41.0	18.0
Cloudflare	247407	99.9	0.1
Fastly	3960	0.0	0.0
Google	6062	11.5	11.5
Meta	112	0.0	0.0
Microsoft	34	0.0	0.0
Others	26404	21.5	2.3

Tranco Top 1M: Delay between ACK and SH [ms]



Cloudflare: Reception latency and 50% percentile interval of ACK and SH

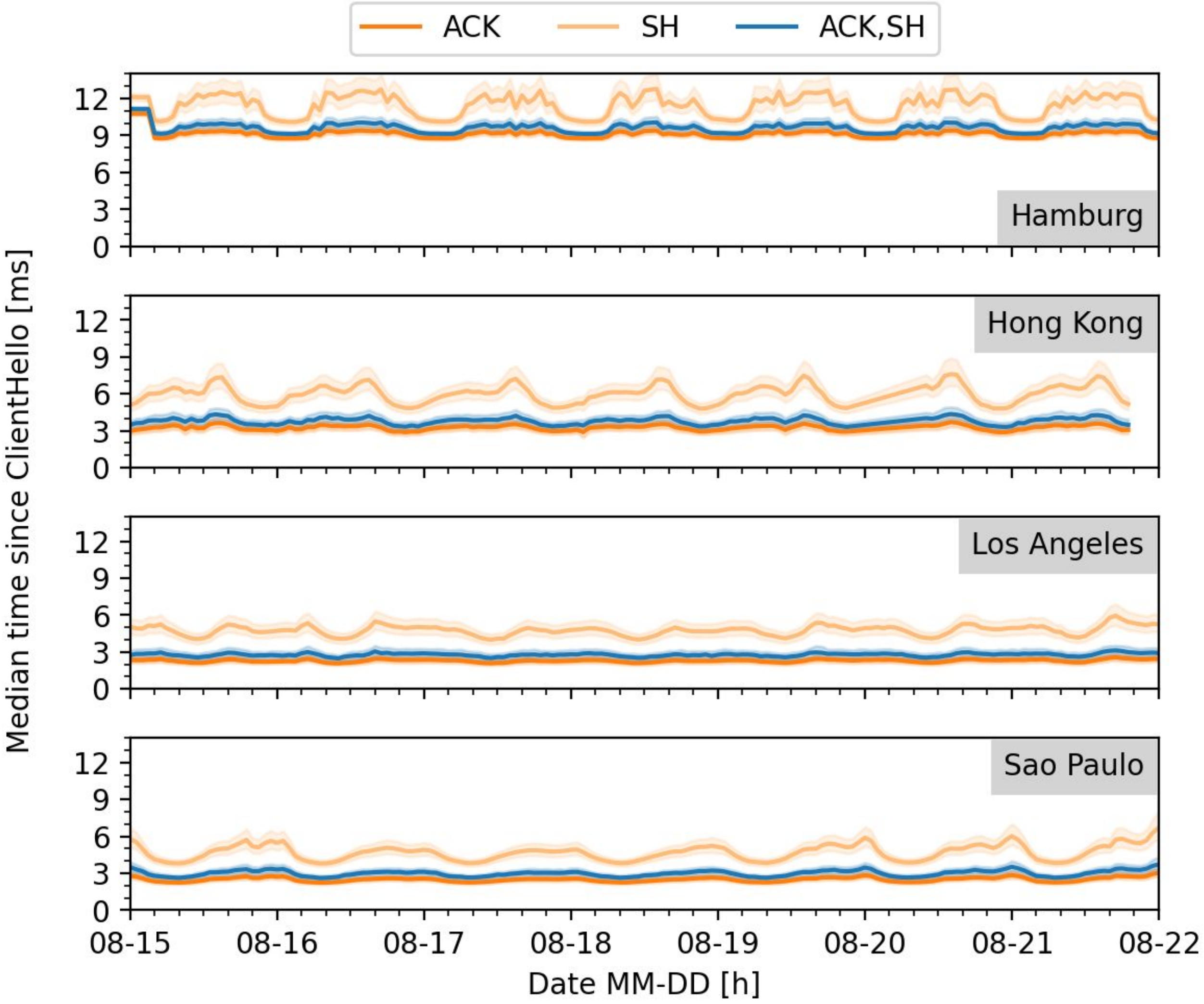
Vantage point: Sao Paulo



WFC is significantly more common for frequently requested domains.

WFC shows similar performance to IACK (□ likely cached certificate).

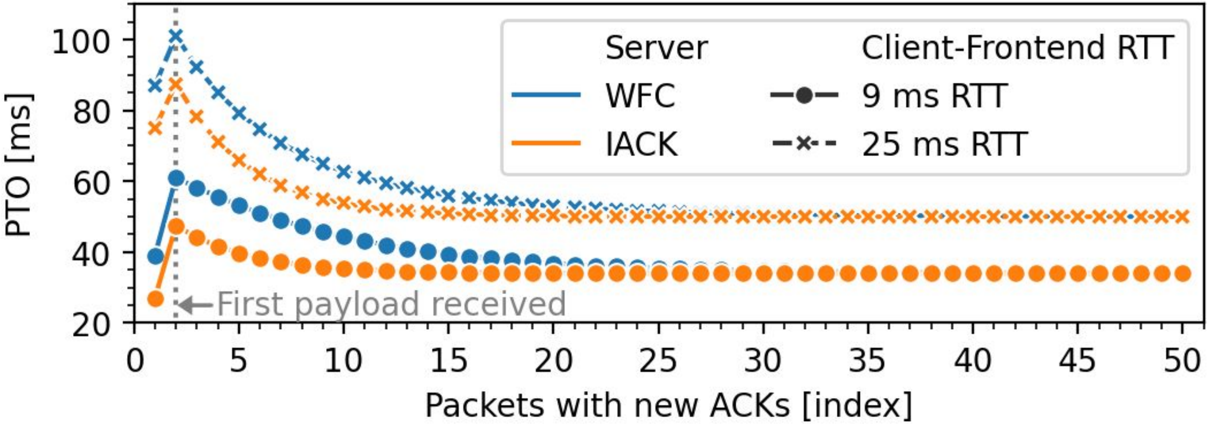
Cloudflare: Median time since ClientHello [ms]



Testbed emulation

PTO evolution in a setting with constant RTTs

Numerical analysis

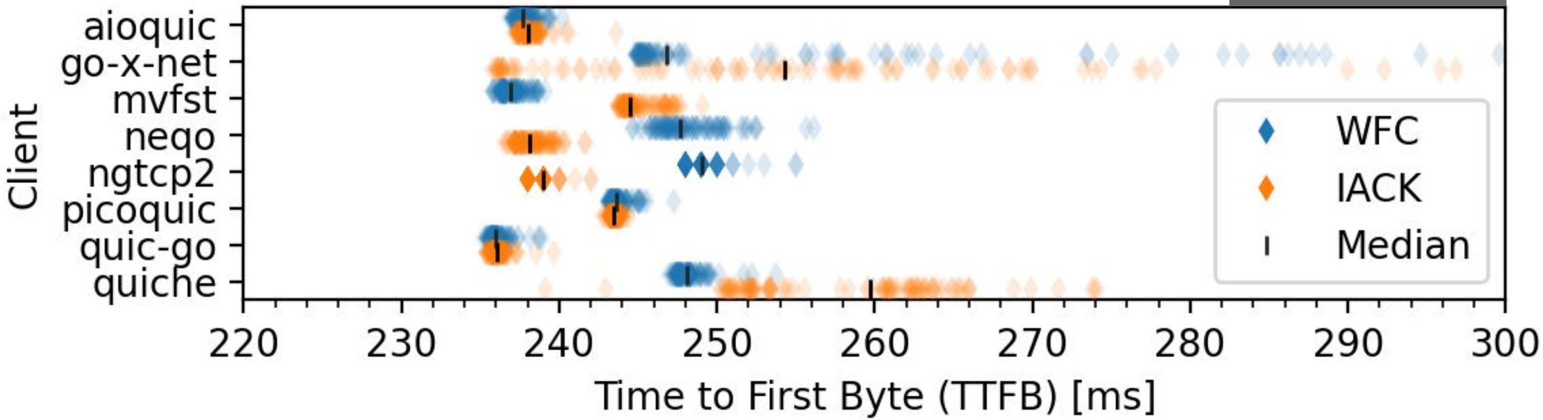


Emulation: IACK reception 4 ms earlier than WFC

Initial PTO improvement IACK: 12 ms

Scenario: No loss, server blocked by anti-amplification limit

9 ms RTT

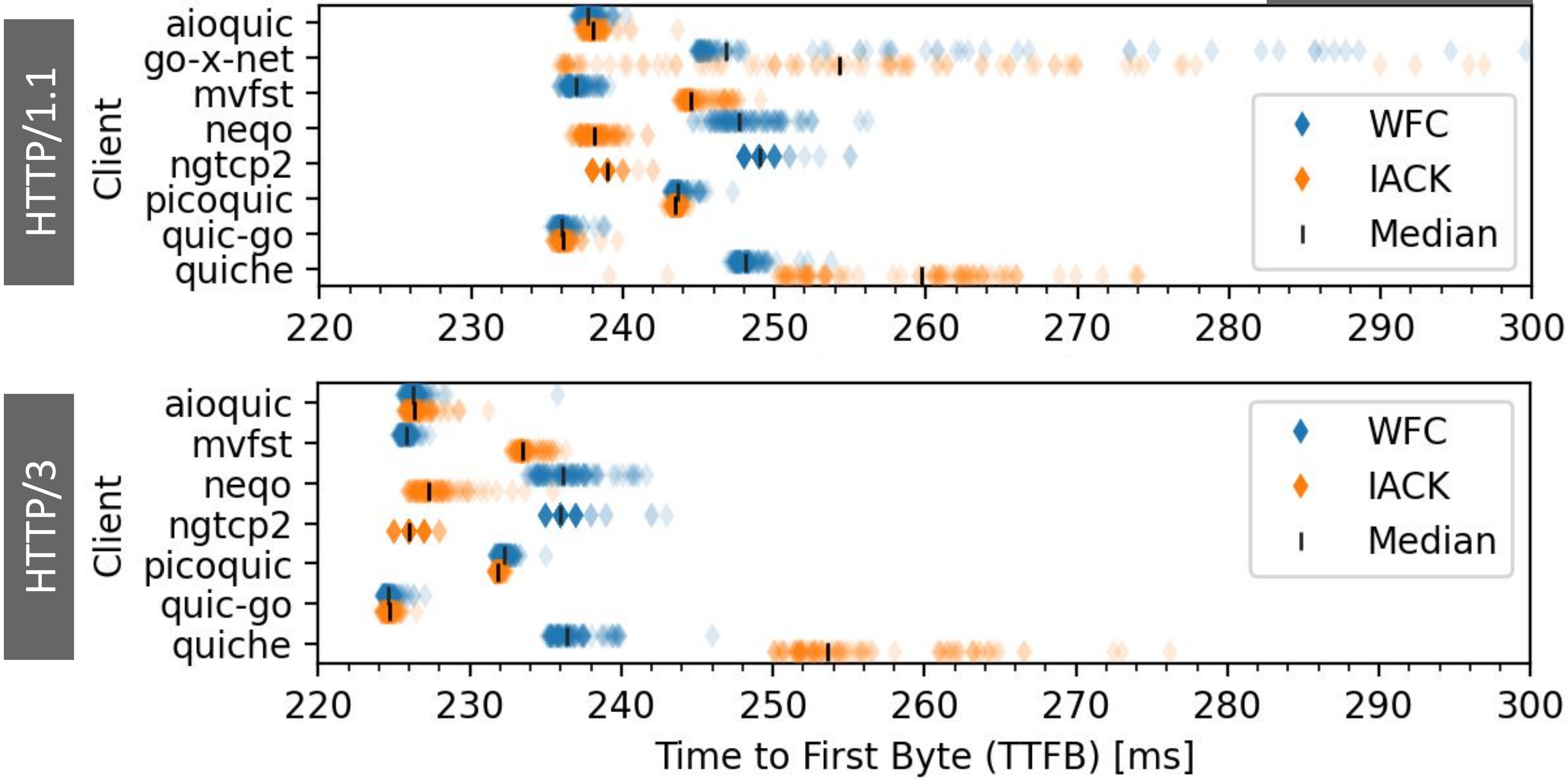


TTFB reduced by 9.6 ms (*neqo*) and 10 ms (*ngtcp2*).

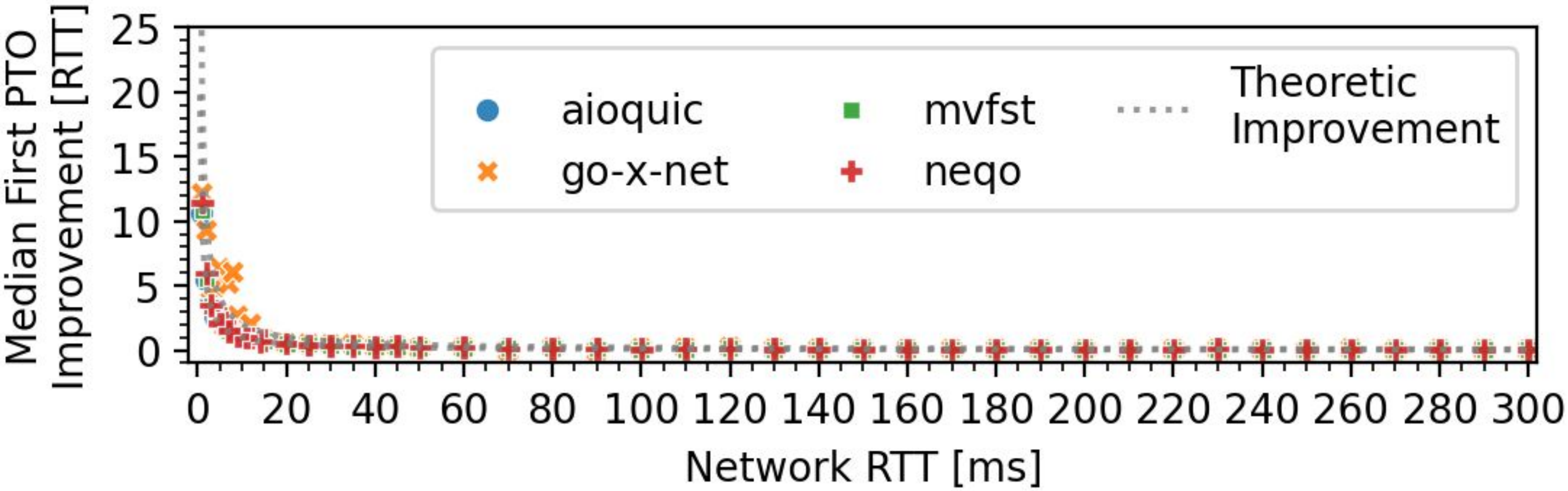
quiche drops replies to PING frames as invalid together with coalesced packets, which costs additional resends.

Scenario: No loss, server blocked by anti-amplification limit

9 ms RTT

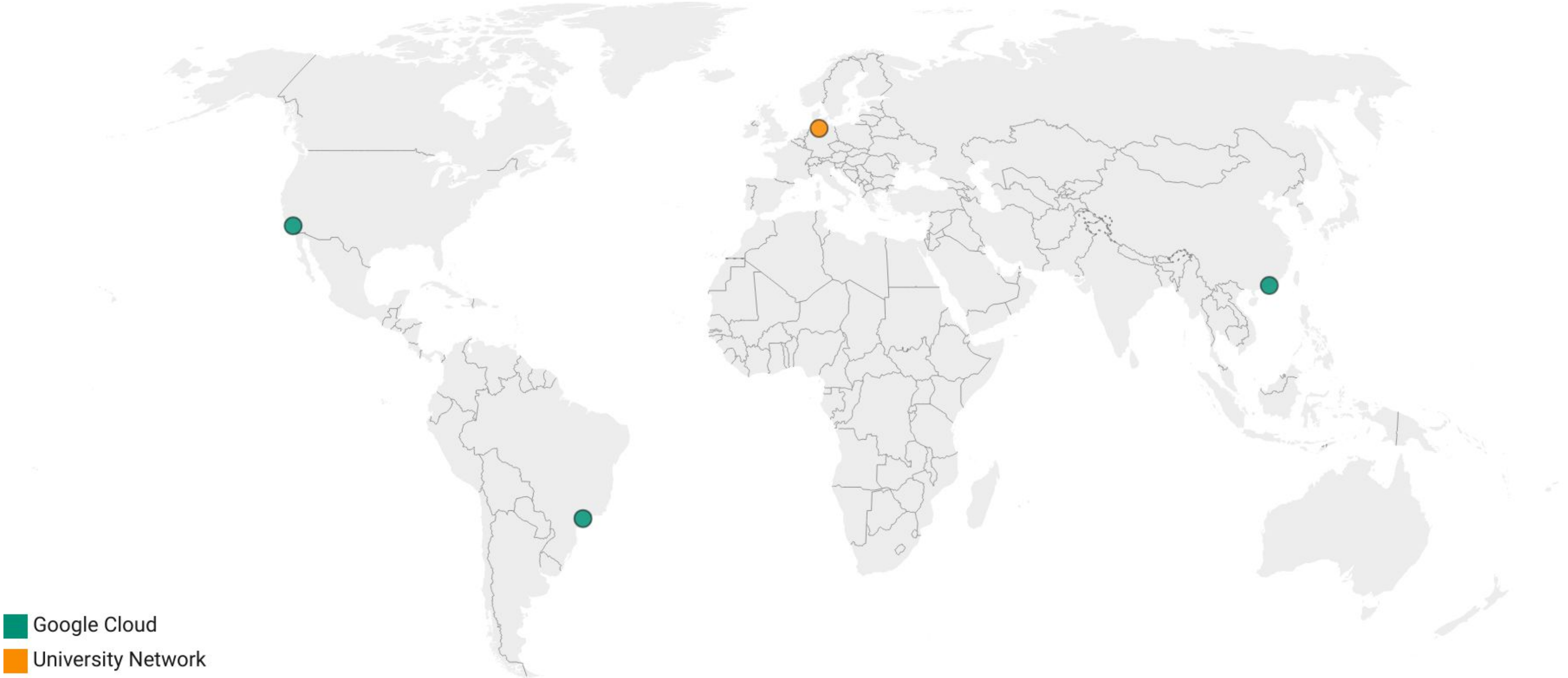


Median improvement of the first PTO



Measurement setup (extended)

Vantage points locations



Why use Qlog over packet captures?

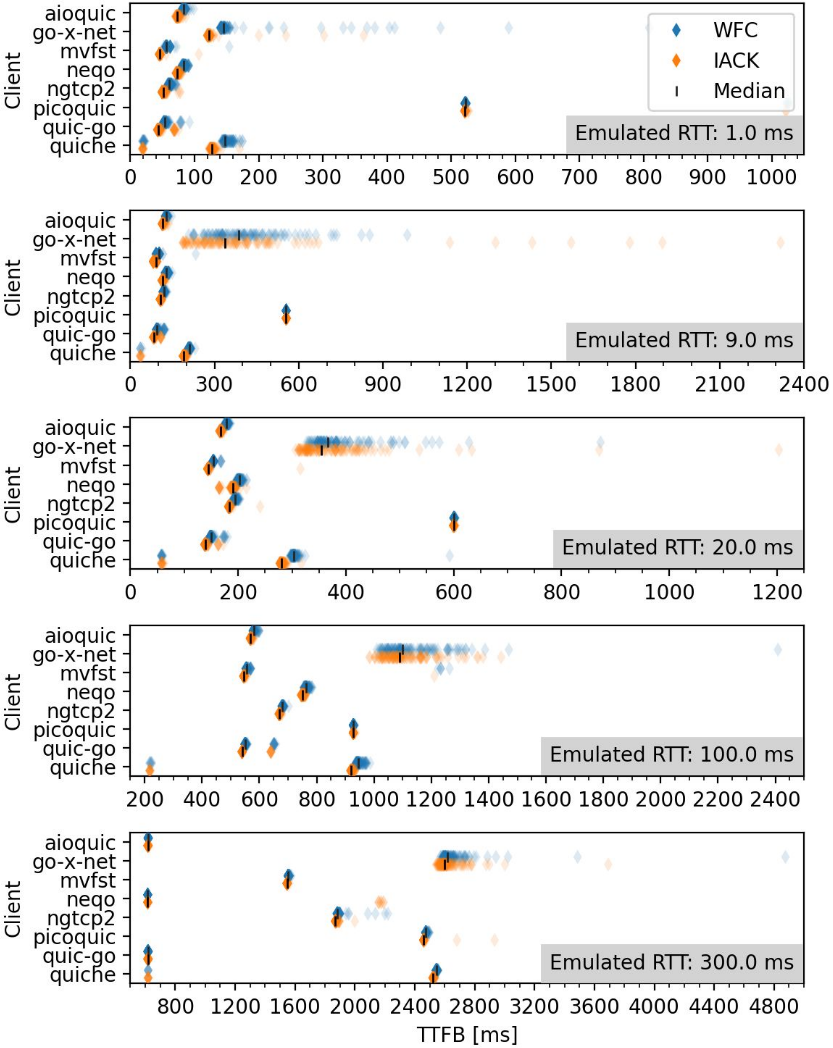
Qlog represents the view the implementation has on the connection. This includes all kind of system stack delays.

Drawbacks:

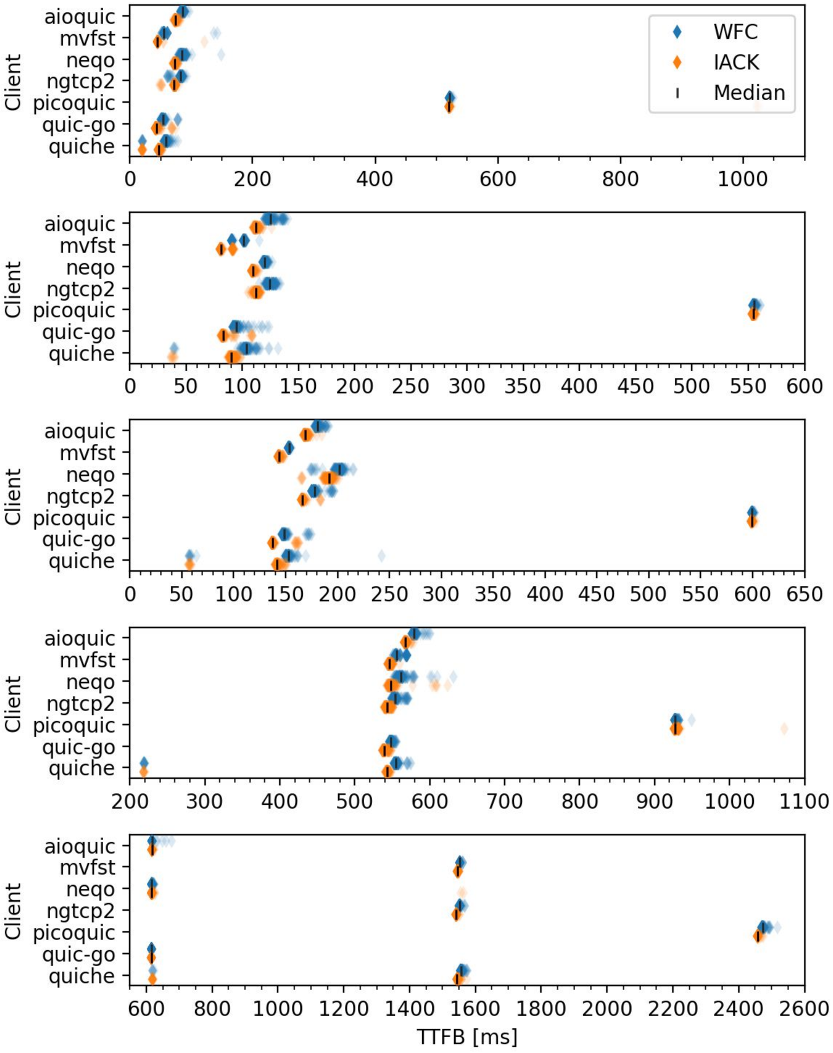
- Not all implementations expose all information in Qlog.
  - Missing RTT variance

Emulation of packet loss at different RTTs

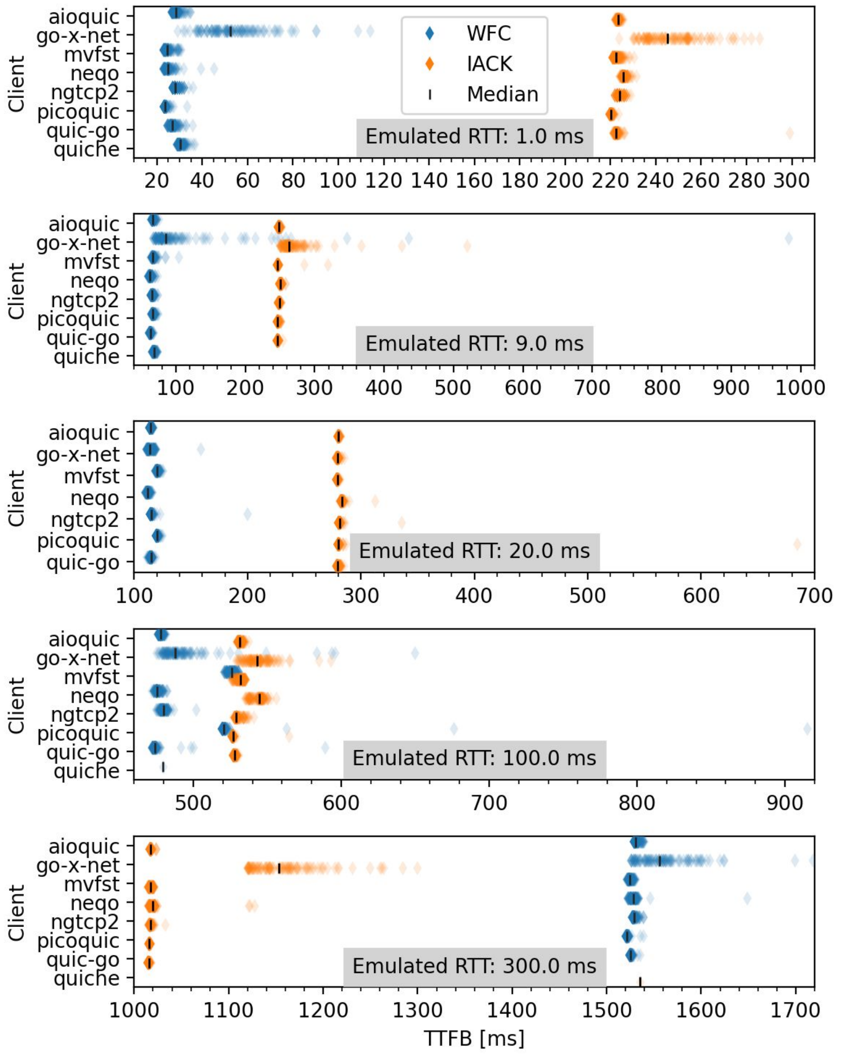
Loss of second client flight: HTTP/1.1



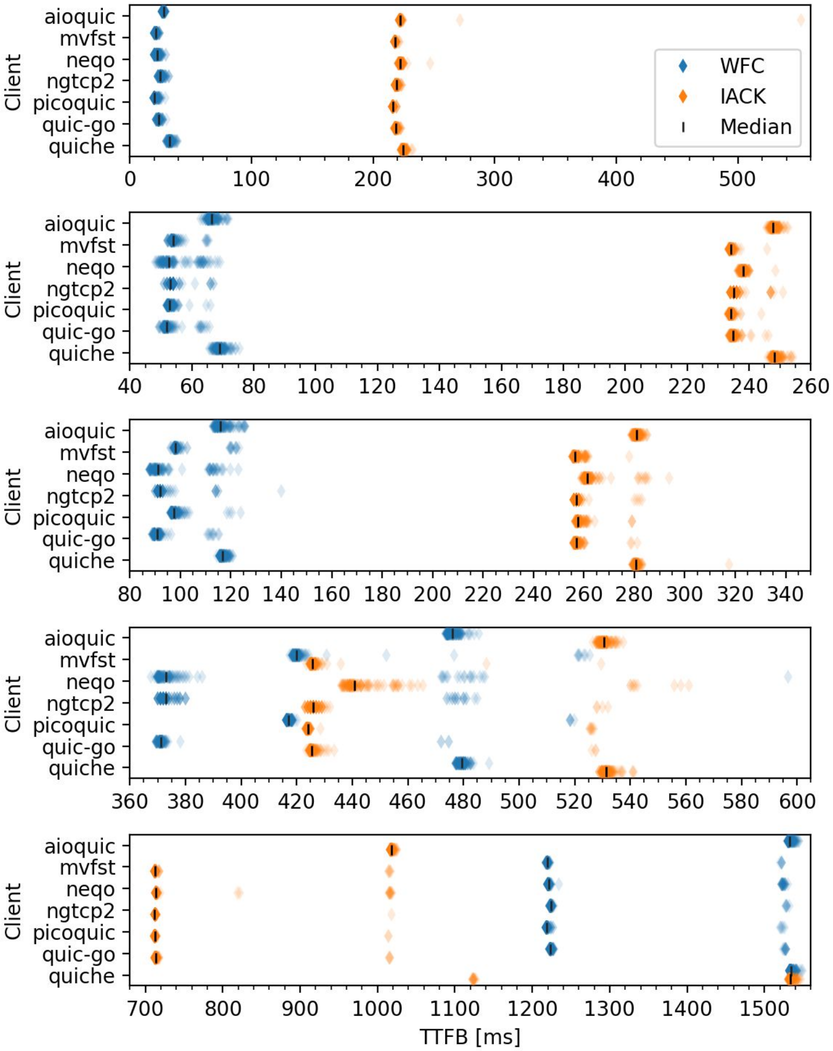
Loss of second client flight: HTTP/3



Loss of remaining first server flight: HTTP/1.1



Loss of remaining first server flight: HTTP/3



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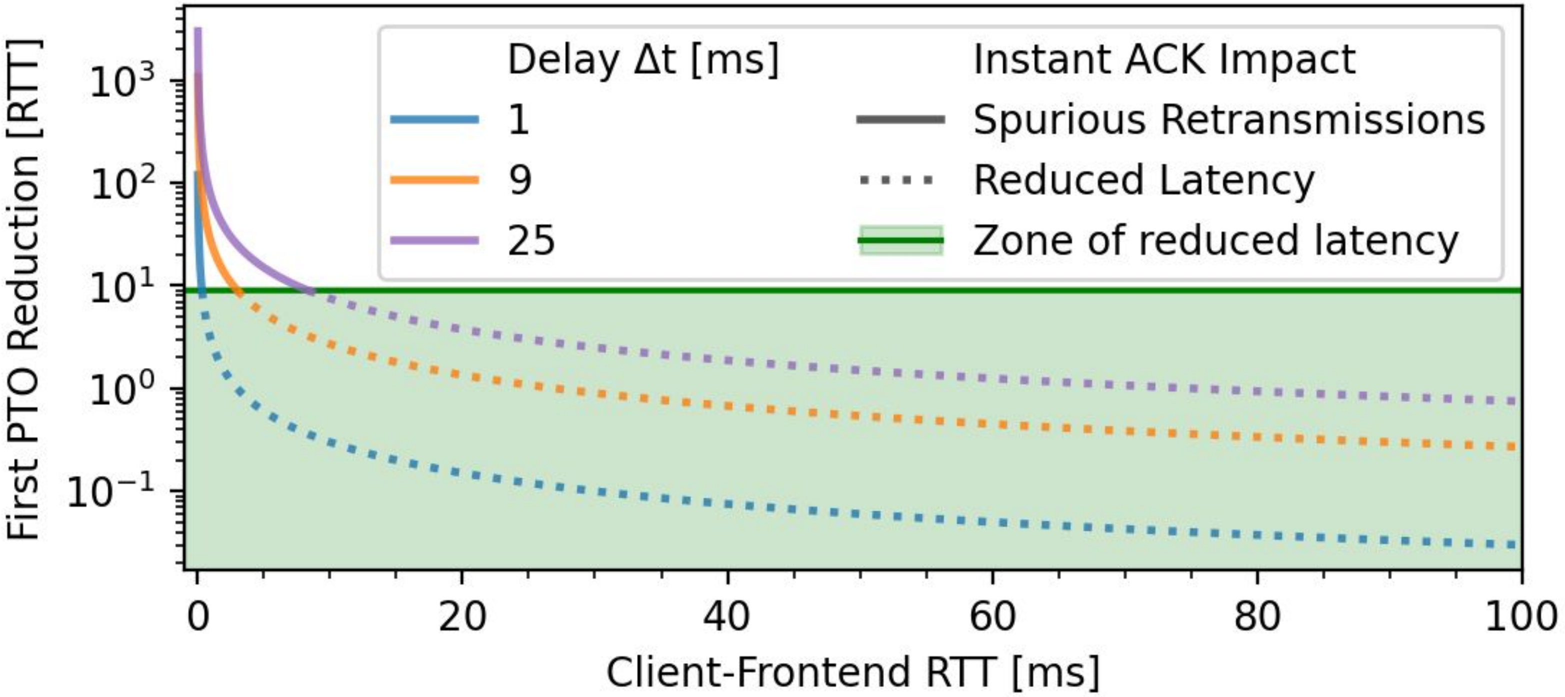
DRESDEN concept

Numerical analysis

First PTO improvement according to RFC9002 [6]



Probe Timeout (PTO)

```
    RTTVar = 3/4 * RTTVar + 1/4 * abs(SmoothedRTT -
             adjusted_rtt)

SmoothedRTT = 7/8 * SmoothedRTT + 1/8 * adjusted_rtt


      PTO = SmoothedRTT + max(4*RTTVar, kGranularity) +
             max_ack_delay
```