# A Quantum of QUIC: Dissecting Cryptography with Post-Quantum Insights

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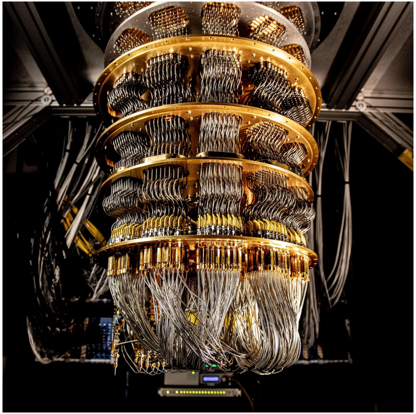
# Motivation



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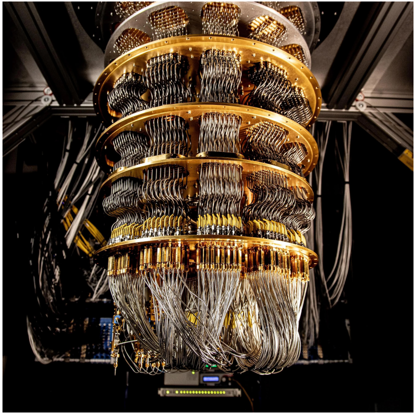
  - Post-quantum cryptography (PQC) algorithms exist
  - NIST competition: winners will be standardized



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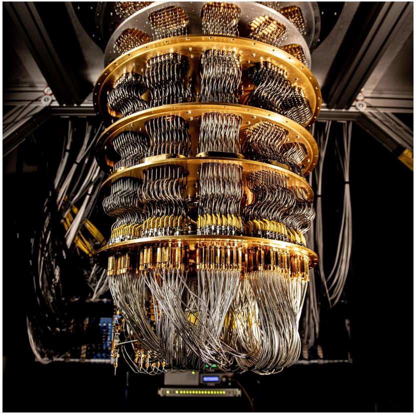
  - Significantly larger keys
  - More messages to exchange



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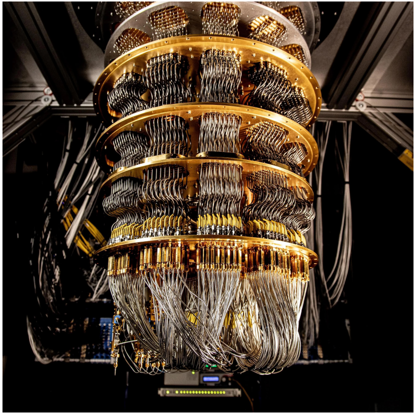
  - "Store now, decrypt later" attacks
  - Understand PQC in practice



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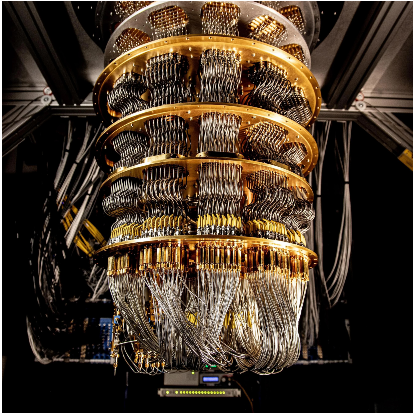
- QUIC is the new general-purpose transport protocol
  - QUIC includes TLS 1.3 and enforces encryption
  - Encryption and authentication, packet & header protection



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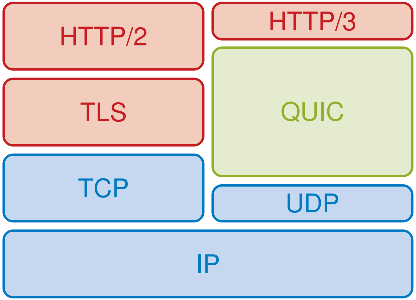
# Research Goals and Questions

- How much does QUIC's cryptography affect the performance?
- How big is the impact of the different security features?
- How does this change with PQC?
- Does the integration of PQC into QUIC lead to problems?

# Background

## What is QUIC?

- New protocol designed as replacement for TCP / TLS
- Standardized in May 2021 by the IETF as RFC 9000
- Implemented in user space on top of UDP
- Several implementations exist
- Includes multiple TCP features **and TLS 1.3**

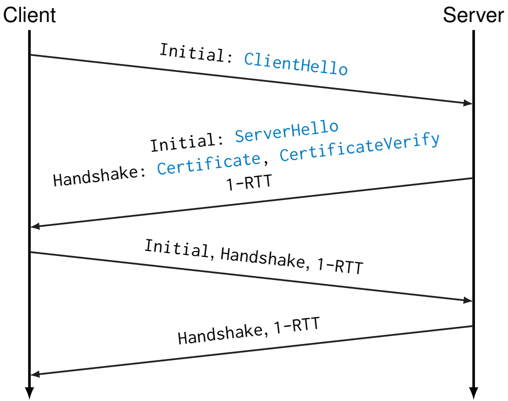



## Applications of QUIC:

- Transport protocol for HTTP/3
- MASQUE (*Apple iCloud Private Relay*, *Cloudflare WARP*)

# Background

## The QUIC Handshake




Asymmetric cryptography only in blue parts:

- `Client/ServerHello` affected by PQ key encapsulation mechanisms
- `Certificate(Verify)` affected by PQ signature schemes

# Related Work

| Paper | Content |
| --- | --- |
| [Jaeger23] | • Performance analysis of QUIC implementations on physical hardware<br>• Impact of cryptographic operation broadly analyzed |
| [Yang20] | • Performance analysis of QUIC implementations<br>• NIC offloading context |
| [Sosnowski23] | • Comparison of post-quantum cipher suites<br>• Physical hardware + network emulation<br>• TCP as transport protocol |
| This paper | • Deep performance analysis of cryptography in QUIC<br>• Measurements on physical hardware & links<br>• Symmetric and asymmetric cryptography covered |


[Jaeger23] B. Jaeger et al. **"QUIC on the Highway: Evaluating Performance on High-rate Links"**, IFIP Networking 2023

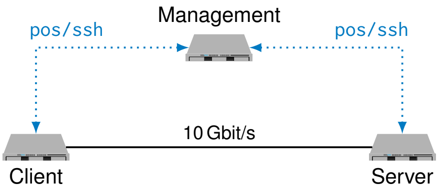
[Yang20] X. Yang et al. **"Making QUIC Quicker With NIC Offload"**, EPIQ 2020

[Sosnowski23] M. Sosnowski et al. **"The Performance of Post-Quantum TLS 1.3"**, CoNEXT 2023

# Framework for QUIC Performance Measurements

## Modified QUIC Interop Runner

- Dedicated physical hosts for client and server
- Experiment orchestration via pos [1]
- Collect CPU, OS, and NIC metrics using various tools
- Flexibility, Portability, Reproducibility




## Custom TLS Libraries

- NOOP cipher implemented into *OpenSSL* and *BoringSSL*
  - No encryption/decryption happening
  - Only `memcpy()` operation
- Fork of BoringSSL [2] for post-quantum ciphers


[1] S. Gallenmüller et al., “The pos Framework: A Methodology and Toolchain for Reproducible Network Experiments, CoNEXT 2021

[2] https://github.com/open-quantum-safe/boringssl

# Framework for QUIC Performance Measurements

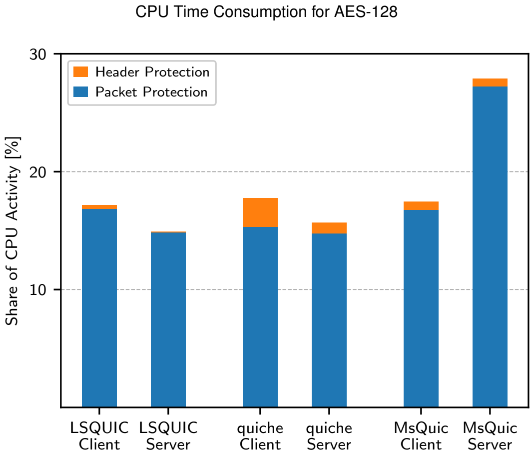
## Evaluated Implementations

| Name | Language | Developer | TLS Library | No-Crypto Mode |
|---|---|---|---|---|
| LSQUIC | C | LiteSpeed Technologies | BoringSSL | × |
| quiche | Rust | Cloudflare | BoringSSL | × |
| MsQuic | C | Microsoft | OpenSSL | ✓ |

# Evaluation

## Symmetric Cryptography in QUIC – CPU Time Consumption

- Packet protection and header protection
- CPU profiling with *perf*
- AES, ChaCha20 and NOOP cipher analyzed
  - ChaCha20: 9 % to 16 % slower than AES
  - NOOP: 10 % to 20 % faster than AES



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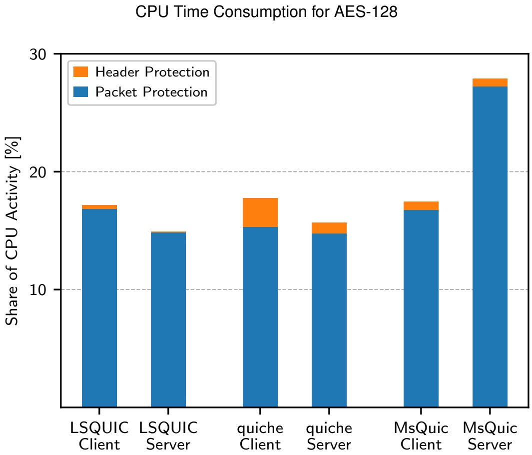
**Take-away Result:**

- QUIC's header protection is basically free, especially with AES
- Performance impact of AES key size is negligible



## PQC – Key Encapsulation Mechanisms

- Used to transmit keys for symmetric cryptography
- Kyber, BIKE and HQC analyzed
  - Kyber selected for standardization by NIST
  - Kyber was renamed to ML-KEM
- RSA-2048 certificate used for measurements
- Elliptic curve Diffie-Hellman Exchange (ECDHE) as baseline (**bold**)

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| | Algorithm | TTFB [ms] | |
|---|---|---|---|
| | | LSQUIC | quiche |
| I | **X25519** | 3.91 | 3.57 |
| | Kyber512 | 4.08 | 3.39 |
| | BIKE-L1 | 6.59 | 5.86 |
| | HQC-128 | 5.57 | 4.21 |
| | **P-256** | 3.90 | 3.49 |
| | P-256 + Kyber512 | 4.43 | 3.74 |
| | P-256 + BIKE-L1 | 6.95 | 6.27 |
| | P-256 + HQC-128 | 5.99 | 4.52 |
| III | Kyber768 | 4.23 | 3.78 |
| | BIKE-L3 | 11.75 | 10.49 |
| | HQC-192 | 7.57 | 4.81 |
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## Take-away Results:

- Kyber is the fastest KEM
  - Lattice-based $\rightarrow$ small key sizes
  - Even faster than ECDHE for NIST level III and V
- Hybrid approaches only marginally slower than pure post-quantum KEMs

## PQC – Problems with QUIC

- Some algorithms (especially hash-based signature schemes) have large signature sizes
- Handshake messages might spread over multiple packets
  - Amplification attack mitigation can cause an extra RTT
  - Implementation specific attack prevention might close the connection
- Some algorithms (especially code-based key encapsulation mechanisms) are computationally expensive
  - The client might need some milliseconds to process the `ServerHello`
  - The server might retransmit the `ServerHello`, assuming packet loss

# Conclusion

## Take Away Messages

- Hardware-accelerated AES is the fastest
- QUIC's header protection is basically free, especially with AES
- Integration of post-quantum cryptography is feasible
  - no major changes required thanks to *BoringSSL* fork
- PQ has promising candidates (Kyber, Dilithium) with comparable performance to traditional algorithms
- Large certificates lead to several issues in our experiments

## Framework

- Source code publicly available

Paper:

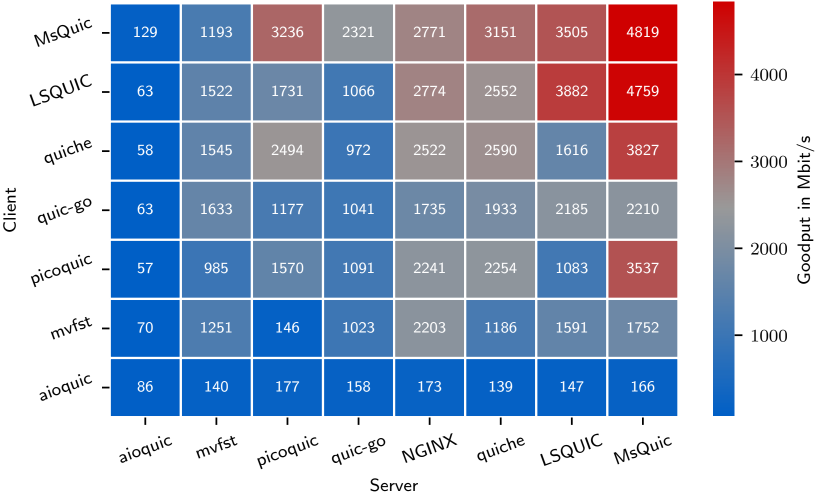
https://arxiv.org/pdf/2405.09264

Source Code:

https://github.com/tumi8/quic-crypto-paper

# Backup Slides

# QUIC Implementations - Performance Comparison

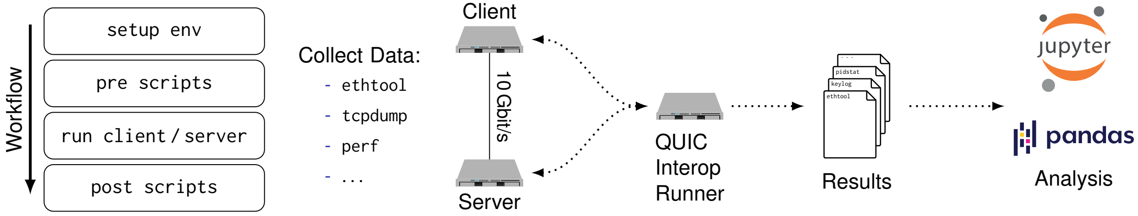


# NIST Levels

NIST's quantum security strength categories

| NIST Level | At least as hard to break as | Type of attack |
|---|---|---|
| I | AES-128 | Exhaustive key search |
| II | SHA-256 | Collision search |
| III | AES-192 | Exhaustive key search |
| IV | SHA-384 | Collision search |
| V | AES-256 | Exhaustive key search |

# Measurement and Analysis Workflow




## Measurement Workflow

1. Setup client and server host
2. Configure OS parameters
3. Start QUIC server and client
4. Reset OS parameters
5. Collect results

## Analysis Pipeline

- Tools have various output formats
- Collect and parse available result files
- Export via Pandas as CSV
- Results contain meta data like version hashes for reproducibility