Evaluation and Optimization of the IETF QUIC Protocol for Satellite Networks

February 2, 2022

Sebastian Endres

Friedrich-Alexander-Universität Erlangen-Nürnberg
1. Introduction
2. Problem Statement
3. Architecture
4. Analysis
5. Conclusion
Geostationary Satellite Links

- Long RTT
  - $\geq 600$ ms
  - High BDP
- Asymmetric data rates
  - e.g., 20/2 Mbit/s
- Usually low PLR on Sat Link

→ Performance-Enhancing Proxies (PEPs)
IETF QUIC

- formerly gQUIC
- released in May 2021

- RFC 8999  Version-Independent Properties of QUIC
- RFC 9000  QUIC: A UDP-Based Multiplexed and Secure Transport
- RFC 9001  Using TLS to Secure QUIC
- RFC 9002  QUIC Loss Detection and Congestion Control
IETF QUIC

- formerly gQUIC
- released in May 2021

- Encrypted headers
- HoL-B eliminated
- improved & pluggable CC
- 1-RTT / 0-RTT

- RFC 8999  Version-Independent Properties of QUIC
- RFC 9000  QUIC: A UDP-Based Multiplexed and Secure Transport
- RFC 9001  Using TLS to Secure QUIC
- RFC 9002  QUIC Loss Detection and Congestion Control
IETF QUIC

- formerly gQUIC
- released in May 2021

- Encrypted headers
- HoL-B eliminated
- improved & pluggable CC
- 1-RTT / 0-RTT

Client

Server

TCP Handshake

SYN

SYN ACK

ACK, ClientHello

SrvHello, Cert, SKEx

CKEx, CCS, Fin

CCS, Fin

data

TLS1.2 Handshake

Initial, Hello

Init., Hello, Cert, Fin

Fin, data

QUIC Handshake
1. Introduction

2. Problem Statement

3. Architecture

4. Analysis

5. Conclusion
Previous Research Results

QUIC via GEO Links

VPN < QUIC < TCP+PEP

Small files (short handshake)

Weakness of QUIC:

- Losses

Plot from [3]
Research So Far

- Single implementations
- Often gQUIC instead of IETF QUIC
- Heterogeneous test environments & methodologies
- Black-box
Research So Far

QUIC via GEO Links

- Single implementations
  - Measurement of numerous implementations
- Often gQUIC instead of IETF QUIC
- Heterogeneous test environments & methodologies
- Black-box
Research So Far

QUIC via GEO Links

- Single implementations
  - Measurement of numerous implementations
- Often gQUIC instead of IETF QUIC
  - Use recent implementations
- Heterogeneous test environments & methodologies
- Black-box
Research So Far

QUIC via GEO Links

- Single implementations
  - Measurement of numerous implementations
- Often gQUIC instead of IETF QUIC
  - Use recent implementations
- Heterogeneous test environments & methodologies
  - Automated measurements with real & simulated links
- Black-box
Research So Far

- Single implementations
  - Measurement of numerous implementations

- Often gQUIC instead of IETF QUIC
  - Use recent implementations

- Heterogeneous test environments & methodologies
  - Automated measurements with real & simulated links

- Black-box
  - Automated plotting of offset plots
1. Introduction

2. Problem Statement

3. Architecture

4. Analysis

5. Conclusion
### Results Filter

<table>
<thead>
<tr>
<th>Client:</th>
<th>quic-go</th>
<th>quickly</th>
<th>ngtcp2</th>
<th>quant</th>
<th>mvfst</th>
<th>quiche</th>
<th>kwik</th>
<th>picoquic</th>
<th>aloquic</th>
<th>neqo</th>
<th>msquic</th>
<th>chrome</th>
<th>xquic</th>
<th>lsquic</th>
<th>quinn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Server:</td>
<td>quic-go</td>
<td>quickly</td>
<td>ngtcp2</td>
<td>quant</td>
<td>mvfst</td>
<td>quiche</td>
<td>kwik</td>
<td>picoquic</td>
<td>aloquic</td>
<td>neqo</td>
<td>nginx</td>
<td>msquic</td>
<td>xquic</td>
<td>lsquic</td>
<td>haproxy</td>
</tr>
<tr>
<td>Test:</td>
<td>J</td>
<td>6</td>
<td>H</td>
<td>DC</td>
<td>LR</td>
<td>C20</td>
<td>M</td>
<td>S</td>
<td>R</td>
<td>Z</td>
<td>B</td>
<td>U</td>
<td>A</td>
<td>L1</td>
<td>L2</td>
</tr>
<tr>
<td></td>
<td>344</td>
<td>11</td>
<td>136</td>
<td>118</td>
<td>88</td>
<td>128</td>
<td>116</td>
<td>116</td>
<td>163</td>
<td>190</td>
<td>86</td>
<td>125</td>
<td>94</td>
<td>130</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>184</td>
<td>116</td>
<td>144</td>
<td>117</td>
<td>55</td>
<td>35</td>
<td>56</td>
<td>56</td>
<td>107</td>
<td>146</td>
<td>89</td>
<td>114</td>
<td>132</td>
<td>124</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>117</td>
<td>89</td>
<td>144</td>
<td>119</td>
<td>55</td>
<td>35</td>
<td>56</td>
<td>56</td>
<td>107</td>
<td>146</td>
<td>89</td>
<td>114</td>
<td>132</td>
<td>124</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>9</td>
<td>13</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

### Interop Status

#### quic-go

<table>
<thead>
<tr>
<th>quic-go</th>
<th>quickly</th>
<th>ngtcp2</th>
<th>quant</th>
<th>mvfst</th>
<th>quiche</th>
<th>kwik</th>
<th>picoquic</th>
<th>aloquic</th>
<th>neqo</th>
<th>nginx</th>
<th>msquic</th>
<th>xquic</th>
<th>lsquic</th>
<th>haproxy</th>
<th>quinn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
<td>DC</td>
<td>C20</td>
<td>M</td>
<td>S</td>
<td>R</td>
<td>L1</td>
<td>L2</td>
<td>A</td>
<td>C1</td>
<td>C2</td>
<td>G</td>
<td>C</td>
<td>329</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C20</td>
<td>M</td>
<td>C20</td>
<td>M</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C20</td>
<td>M</td>
<td>C20</td>
<td>M</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C20</td>
<td>M</td>
<td>C20</td>
<td>M</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C20</td>
<td>M</td>
<td>C20</td>
<td>M</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td>C20</td>
<td></td>
</tr>
</tbody>
</table>

#### quickly

|         | H      | DC     | C20   | M     | S      | R    | L1       | L2      | A    | C1    | C2     | G    | C      | 329    |       |
|         | C20    | M     | C20   | M     | C20    | C20  | C20      | C20     | C20  | C20   | C20    | C20  | C20    | C20    |       |
|         | C20    | M     | C20   | M     | C20    | C20  | C20      | C20     | C20  | C20   | C20    | C20  | C20    | C20    |       |
|         | C20    | M     | C20   | M     | C20    | C20  | C20      | C20     | C20  | C20   | C20    | C20  | C20    | C20    |       |
|         | C20    | M     | C20   | M     | C20    | C20  | C20      | C20     | C20  | C20   | C20    | C20  | C20    | C20    |       |

#### ngtcp2

|         | H      | DC     | C20   | M     | S      | R    | L1       | L2      | A    | C1    | C2     | G    | C      | 329    |       |
|         | C20    | M     | C20   | M     | C20    | C20  | C20      | C20     | C20  | C20   | C20    | C20  | C20    | C20    |       |
|         | C20    | M     | C20   | M     | C20    | C20  | C20      | C20     | C20  | C20   | C20    | C20  | C20    | C20    |       |
|         | C20    | M     | C20   | M     | C20    | C20  | C20      | C20     | C20  | C20   | C20    | C20  | C20    | C20    |       |
|         | C20    | M     | C20   | M     | C20    | C20  | C20      | C20     | C20  | C20   | C20    | C20  | C20    | C20    |       |
# Measurement Results

| quic-go  | quickly | ngtcp2 | quant | mvfst | quiche | kwik | picoquic | aioquic | nghttp2 | msquic | xquic | isquic | haproxy | quinn |
|----------|---------|--------|-------|-------|--------|------|----------|---------|---------|--------|-------|-------|--------|--------|-------|
| C: 5757 (± 207) kbps | C: 7093 (± 335) kbps | C: 4692 (± 159) kbps | C: 7588 (± 192) kbps | C: 3588 (± 106) kbps | C: 7756 (± 192) kbps | C: 7598 (± 96) kbps | C: 7588 (± 192) kbps | C: 8738 (± 102) kbps | C: 4524 (± 46) kbps | C: 4524 (± 46) kbps | C: 4524 (± 46) kbps | C: 4524 (± 46) kbps | C: 4524 (± 46) kbps | C: 4524 (± 46) kbps |

<table>
<thead>
<tr>
<th>ngtcp2</th>
<th>quant</th>
<th>mvfst</th>
<th>quiche</th>
<th>loxilf</th>
</tr>
</thead>
<tbody>
<tr>
<td>G: 9440 (± 10) kbps</td>
<td>G: 9436 (± 0) kbps</td>
<td>G: 9466 (± 10) kbps</td>
<td>G: 9388 (± 15) kbps</td>
<td></td>
</tr>
<tr>
<td>C: 6548 (± 142) kbps</td>
<td>C: 6579 (± 208) kbps</td>
<td>C: 6579 (± 208) kbps</td>
<td>C: 6579 (± 208) kbps</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>quant</th>
<th>mvfst</th>
<th>quiche</th>
<th>loxilf</th>
</tr>
</thead>
<tbody>
<tr>
<td>G: 9537 (± 2) kbps</td>
<td>G: 9436 (± 0) kbps</td>
<td>G: 9546 (± 10) kbps</td>
<td>G: 9356 (± 15) kbps</td>
</tr>
<tr>
<td>C: 6579 (± 208) kbps</td>
<td>C: 6579 (± 208) kbps</td>
<td>C: 6579 (± 208) kbps</td>
<td>C: 6579 (± 208) kbps</td>
</tr>
</tbody>
</table>

---

https://interop.seemann.io/
Supported Implementations by QUIC Interop Runner

**Client & Server**  
aioquic, kwik, lsquic, msquic, mvfst, neqo, ngtcp2, picoquic, quant, quic-go, quiche, quiely, xquic

**Client only**  
chrome

**Server only**  
nginx
Original QUIC Interop Runner

[Diagram showing the workflow involving Client, ns-3, and Server with interactions like deploy, log, keylog, pcap, and run]
Asymmetric ns-3 Scenario

\[ d_{fwd} = d_{ret} = \frac{RTT}{2} \]

\[ p_{loss,fwd} \quad r_{fwd} \quad l_{queue,fwd} \]

\[ l_{queue,ret} \quad r_{fwd} \quad p_{loss,ret} \]
Distributed QUIC-Interop-Runner for Real Satellite Links

- New

Client
- Tcpdump
- Docker
- SSH

Server
- Tcpdump
- Docker
- QUIC-Interop-Runner

Modem
- Internet
- Link

Protocol:
- pcap
- qlog
- keylog

Control
- call
- deploy
- logs
## Test & Measurement Scenarios

<table>
<thead>
<tr>
<th>Name</th>
<th>RTT [ms]</th>
<th>Data Rate [Mbit/s]</th>
<th>PLR [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LONGRTT</td>
<td>1500</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>GOODPUT</td>
<td>30</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>
## Test & Measurement Scenarios

<table>
<thead>
<tr>
<th>Name</th>
<th>RTT</th>
<th>Data Rate</th>
<th>PLR</th>
</tr>
</thead>
<tbody>
<tr>
<td>LONGRTT</td>
<td>1500</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>GOODPUT</td>
<td>30</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>SAT</td>
<td>600</td>
<td>20/2</td>
<td>0</td>
</tr>
<tr>
<td>SATLOSS</td>
<td>600</td>
<td>20/2</td>
<td>1</td>
</tr>
</tbody>
</table>
## Test & Measurement Scenarios

<table>
<thead>
<tr>
<th>Name</th>
<th>RTT</th>
<th>Data Rate</th>
<th>PLR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[ms]</td>
<td>[Mbit/s]</td>
<td>[%]</td>
</tr>
<tr>
<td>LongRTT</td>
<td>1500</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Goodput</td>
<td>30</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>SAT</td>
<td>600</td>
<td>20/2</td>
<td>0</td>
</tr>
<tr>
<td>SATLoss</td>
<td>600</td>
<td>20/2</td>
<td>1</td>
</tr>
<tr>
<td>Astra</td>
<td>≈600</td>
<td>20/2</td>
<td>≈0.1</td>
</tr>
<tr>
<td>Eutelsat</td>
<td>≈600</td>
<td>50/5</td>
<td>≈0.1</td>
</tr>
</tbody>
</table>
Further Modifications to the QUIC-Interop-Runner

- pause during prime time (18:00 – 23:00)
- shuffle experiments
- automatic plots for individual experiments
<table>
<thead>
<tr>
<th></th>
<th>aioquic</th>
<th>kwik</th>
<th>lsquic</th>
<th>msquic</th>
<th>mvfst</th>
<th>quiche</th>
<th>quicy</th>
<th>xquic</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SAT: 1058 (± 0) kbps</td>
<td>SAT: 10093 (± 430) kbps</td>
<td>SAT: 8082 (± 466) kbps</td>
<td>SAT: 8481 (± 680) kbps</td>
<td>SAT: 7858 (± 369) kbps</td>
<td>SAT: 4963 (± 231) kbps</td>
<td>SAT: 7486 (± 618) kbps</td>
<td>SAT: 6668 (± 369) kbps</td>
<td>SAT: 34 %</td>
</tr>
<tr>
<td></td>
<td>SATL</td>
<td>SATL</td>
<td>SATL</td>
<td>SATL</td>
<td>SATL</td>
<td>SATL</td>
<td>SATL</td>
<td>SATL</td>
<td>SATL: 22 %</td>
</tr>
<tr>
<td></td>
<td>SAT</td>
<td>SAT</td>
<td>SAT</td>
<td>SAT</td>
<td>SAT</td>
<td>SAT</td>
<td>SAT</td>
<td>SAT</td>
<td>SAT: -</td>
</tr>
<tr>
<td></td>
<td>SATL</td>
<td>SATL</td>
<td>SATL</td>
<td>SATL</td>
<td>SATL</td>
<td>SATL</td>
<td>SATL</td>
<td>SATL</td>
<td>SATL: -</td>
</tr>
<tr>
<td></td>
<td>G: 5674 (± 43) kbps</td>
<td>G: 2802 (± 6) kbps</td>
<td>G: 2873 (± 6) kbps</td>
<td>G: 444 (± 30) kbps</td>
<td>G: 2804 (± 30) kbps</td>
<td>G: 2767 (± 0) kbps</td>
<td>G: 2767 (± 0) kbps</td>
<td>G: 91 %</td>
<td>G: -</td>
</tr>
</tbody>
</table>
### Figure 1: Screenshot for GOODPUT

<table>
<thead>
<tr>
<th>Server</th>
<th>aioquic</th>
<th>kwik</th>
<th>lsquic</th>
<th>msquic</th>
<th>mvfst</th>
<th>ngtcp2</th>
<th>picoquic</th>
<th>quant</th>
<th>quic-go</th>
<th>quiche</th>
<th>quickly</th>
<th>xquic</th>
</tr>
</thead>
<tbody>
<tr>
<td>chrome</td>
<td><img src="image" alt="chrome" /></td>
<td><img src="image" alt="kwik" /></td>
<td><img src="image" alt="lsquic" /></td>
<td><img src="image" alt="msquic" /></td>
<td><img src="image" alt="mvfst" /></td>
<td><img src="image" alt="ngtcp2" /></td>
<td><img src="image" alt="picoquic" /></td>
<td><img src="image" alt="quant" /></td>
<td><img src="image" alt="quic-go" /></td>
<td><img src="image" alt="quiche" /></td>
<td><img src="image" alt="quickly" /></td>
<td><img src="image" alt="xquic" /></td>
</tr>
</tbody>
</table>

### Figure 2: GOODPUT (RTT: 30 ms, 10 Mbit/s)

![Diagram showing Goodput with RTT: 30 ms, 10 Mbit/s]
<table>
<thead>
<tr>
<th>Client</th>
<th>aioquic</th>
<th>kwik</th>
<th>lsquic</th>
<th>msquic</th>
<th>mvfst</th>
<th>neqo</th>
<th>ngtcp2</th>
<th>picoquic</th>
<th>quant</th>
<th>quic-go</th>
<th>quiche</th>
<th>xquic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goodput</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5 Mbit/s</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
</tr>
<tr>
<td>5.0 Mbit/s</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
</tr>
</tbody>
</table>

**Figure 3:** SAT (RTT: 600 ms, 20/2 Mbit/s)

<table>
<thead>
<tr>
<th>Client</th>
<th>aioquic</th>
<th>kwik</th>
<th>lsquic</th>
<th>msquic</th>
<th>mvfst</th>
<th>neqo</th>
<th>ngtcp2</th>
<th>picoquic</th>
<th>quant</th>
<th>quic-go</th>
<th>quiche</th>
<th>xquic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goodput</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5 Mbit/s</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
</tr>
<tr>
<td>5.0 Mbit/s</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
<td>[●]</td>
</tr>
</tbody>
</table>

**Figure 4:** SATLOSS (RTT: 600 ms, 20/2 Mbit/s)
Figure 5: ASTRA (20/2 Mbit/s)

Figure 6: EUTELSAT (50/5 Mbit/s)
Goodput

- 0 bit/s
- 2.5 Mbit/s
- 5.0 Mbit/s
- 7.5 Mbit/s
- 10.0 Mbit/s
- 12.5 Mbit/s
- 15.0 Mbit/s
- 17.5 Mbit/s
- 20.0 Mbit/s

Efficiency

- 0%
- 20%
- 40%
- 60%
- 80%
- 100%
## Influence of CCA

<table>
<thead>
<tr>
<th>Name</th>
<th>CCA</th>
<th>HyStart</th>
</tr>
</thead>
<tbody>
<tr>
<td>aioquic</td>
<td>NewReno</td>
<td>×</td>
</tr>
<tr>
<td>chrome</td>
<td>BBRv2, CUBIC</td>
<td>✔️</td>
</tr>
<tr>
<td>kwik</td>
<td>NewReno</td>
<td>×</td>
</tr>
<tr>
<td>lsquic</td>
<td>BBR, CUBIC</td>
<td>×</td>
</tr>
<tr>
<td>msquic</td>
<td>CUBIC</td>
<td>×</td>
</tr>
<tr>
<td>mvfst</td>
<td>BBR, CUBIC, NewReno,</td>
<td>✔️</td>
</tr>
<tr>
<td>neqo</td>
<td>CUBIC, NewReno</td>
<td>×</td>
</tr>
<tr>
<td>nginx</td>
<td>?</td>
<td>×</td>
</tr>
<tr>
<td>ngtcp2</td>
<td>BBRv2, BBR, CUBIC,</td>
<td>×</td>
</tr>
<tr>
<td>picoquic</td>
<td>BBR, CUBIC</td>
<td>✔️</td>
</tr>
<tr>
<td>quant</td>
<td>NewReno</td>
<td>×</td>
</tr>
<tr>
<td>quic-go</td>
<td>CUBIC ?, Reno ?</td>
<td>×</td>
</tr>
<tr>
<td>quiche</td>
<td>CUBIC</td>
<td>✔️</td>
</tr>
<tr>
<td>quicly</td>
<td>CUBIC, Reno, pico</td>
<td>×</td>
</tr>
<tr>
<td>xquic</td>
<td>BBR, CUBIC, Reno</td>
<td>×</td>
</tr>
</tbody>
</table>

![Graph](image-url)
Clean Trace

aioquic – aioquic – SAT

Offset vs. Time (SAT, server: aioquic, client: mvfst)

Offset

Time (s)

0 Bytes
0 10 20 30 40 50 60 70 80

0 1.0 MiB 2.0 MiB 3.0 MiB 4.0 MiB 5.0 MiB 6.0 MiB 7.0 MiB 8.0 MiB 9.0 MiB 10.0 MiB

622 ms

303 ms

TTLB = 83.225 s

Last Resp. TX = 82.923 s

TTLB = 5.435 s

ideal TTLB

1st Resp. TX = 0.635 s

Start 0.16 s

Resp.
Offset vs. Time (SATL, server: picoquic, client: picoquic)
Drop in Data Rate & Bad Pacing

Offset vs. Time (SAT, server: kwik, client: msquic)

- TTFB = 1.619 s
- Last Resp. TX = 22.596 s
- TTIB = 22.898 s

1st Resp. TX = 1.316 s
Not In-Order

Offset vs. Time (SAT, server: Isquic, client: xquic)

- TTFB = 0.930 s
- 1st Resp. TX = 0.627 s
- Last Resp. TX = 18.654 s
- TTLLB = 18.957 s

= Isquic – xquic – SAT
Severe Influence of Packet Losses

Offset vs. Time (SATL, server: msquic, client: xquic)
Early Retransmission

Offset vs. Time (AST, server: picoquic, client: ngtcp2)

1st Resp. TX = 0.661 s

Last Resp. TX = 41.186 s
1. Introduction

2. Problem Statement

3. Architecture

4. Analysis

5. Conclusion
Automated measurement & evaluation framework

Measurement results of numerous QUIC implementations

Most currently relevant implementations included
Automated measurement & evaluation framework

- Measurement results of numerous QUIC implementations
- Most currently relevant implementations included
Automated measurement & evaluation framework

Measurement results of numerous QUIC implementations

Most currently relevant implementations included
Automated measurement & evaluation framework

Measurement results of numerous QUIC implementations

Most currently relevant implementations included
Results

- low link utilization on satellite links
- many fails
- large difference between implementations
- increasing data rate $\rightarrow$ increased goodput
- client and server contributes to efficiency

→ presented on 2nd QUIC & SAT Stakeholder Meeting
Results

- low link utilization on satellite links
- many fails
- large difference between implementations
- increasing data rate $\rightarrow$ increased goodput
- client and server contributes to efficiency

→ presented on 2\textsuperscript{nd} QUIC & SAT Stakeholder Meeting
Results

- low link utilization on satellite links
- many fails
- large difference between implementations
- increasing data rate $\rightarrow$ increased goodput
- client and server contributes to efficiency

$\rightarrow$ presented on 2\textsuperscript{nd} QUIC & SAT Stakeholder Meeting
Results

- low link utilization on satellite links
- many fails
- large difference between implementations
- increasing data rate $\rightarrow$ increased goodput
- client and server contributes to efficiency

→ presented on 2\textsuperscript{nd} QUIC & SAT Stakeholder Meeting
Results

- low link utilization on satellite links
- many fails
- large difference between implementations
- increasing data rate → increased goodput
- client and server contributes to efficiency

→ presented on 2nd QUIC & SAT Stakeholder Meeting
Results

- Low link utilization on satellite links
- Many fails
- Large difference between implementations
- Increasing data rate → increased goodput
- Client and server contributes to efficiency

→ Presented on 2\textsuperscript{nd} QUIC & SAT Stakeholder Meeting
Suggested Improvements to make QUIC performing better on sat links

Congestion Control
- More aggressive (buffer & windows sizes)
- BBR
- Pacing

Extensions
- o-RTT(-BDP)
- Reduce ACK ratio
- FEC
Future Work

- Improve failure handling
- Long-term evaluation
- More detailed analysis of combinations
- Add Starlink
- Measure impact of QUIC features
Evaluation and Optimization of the IETF QUIC Protocol for Satellite Networks

Sebastian Endres

Thanks! — Questions?

Image: https://eutelsat.com/
Key Results

TODO
SATL
CDF Using Efficiency Without Failed Experiments

Proportion vs Efficiency

Measurement:
- GOODPUT
- SAT
- SATLOSS
- ASTRA
- EUTELSAT
CDF Using Goodput Without Failed Experiments

Goodput:
- 0 bit/s
- 2.5 Mbit/s
- 5 Mbit/s
- 7.5 Mbit/s
- 10 Mbit/s
- 12.5 Mbit/s
- 15 Mbit/s
- 17.5 Mbit/s
- 20 Mbit/s

Proportion:
- 0 %
- 20 %
- 40 %
- 60 %
- 80 %
- 100 %

Proportion vs. Goodput

Measurement:
- GOODPUT
- SAT
- SATLOSS
- ASTRA
- EUTELSAT
aioquic with larger IW

Offset vs. Time (SAT, server: aioquic, client: aioquic)

Offset vs. Time (SAT, server: aioquic-larger-iw, client: aioquic-larger-iw)
Long Term Evaluation of GOODPUT of Official Runner

Values of Measurement Goodput over Time

Average Goodput of each Implementation

Server
- aioquic
- kwik
- lsquic
- msquic
- neqo
- nginx
- ngtcp2
- picoquic
- quant
- quic-go
- quiche
- xquic

Run

- 2021-08
- 2021-09
- 2021-10
- 2021-11
- 2021-12
Measurement Results of ASTRA & EUTELSAT over Time

Time

ASTRA
EUTELSAT

Time of Day

0 bit/s
2.5 Mbit/s
5.0 Mbit/s
7.5 Mbit/s
10.0 Mbit/s
12.5 Mbit/s
15.0 Mbit/s
17.5 Mbit/s

00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00
Weather During Measurements

Date | Precipitation per 6 hours in mm | Temperature in °C
--- | --- | ---
2021-11-16 | 0.0 | -8
2021-11-17 | 0.6 | -7
2021-11-18 | 0.4 | -6
2021-11-19 | 0.2 | -5
2021-11-20 | 0.1 | -4
2021-11-21 | 0.0 | -4
2021-11-22 | 0.0 | -4
<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
<th>Repository on GitHub / URL</th>
<th>Version</th>
</tr>
</thead>
<tbody>
<tr>
<td>aioquic</td>
<td>both</td>
<td>aiortc/aioquic</td>
<td>0.9.17</td>
</tr>
<tr>
<td>chrome</td>
<td>client</td>
<td>marten-seemann/chrome-quic-interop-runner</td>
<td>ChromeDriver 89.0.4389.23</td>
</tr>
<tr>
<td>kwik</td>
<td>both</td>
<td>ptrd/kwik</td>
<td>@a9e478c (Nov 2021, 03)</td>
</tr>
<tr>
<td>lsquic</td>
<td>both</td>
<td>litespeedtech/lsquic</td>
<td>？</td>
</tr>
<tr>
<td>msquic</td>
<td>both</td>
<td>microsoft/msquic</td>
<td>？</td>
</tr>
<tr>
<td>mvfst</td>
<td>both</td>
<td>facebookincubator/mvfst</td>
<td>？</td>
</tr>
<tr>
<td>neqo</td>
<td>both</td>
<td>mozilla/neqo</td>
<td>0.4.21</td>
</tr>
<tr>
<td>nginx</td>
<td>server</td>
<td><a href="https://quic.nginx.org/">https://quic.nginx.org/</a></td>
<td>1.21.4</td>
</tr>
<tr>
<td>ngtcp2</td>
<td>both</td>
<td>ngtcp2/ngtcp2</td>
<td>0.1.0-DEV ？</td>
</tr>
<tr>
<td>picoquic</td>
<td>both</td>
<td>private-octopus/picoquic</td>
<td>@8dfc4776 (Oct 2021, 23)</td>
</tr>
<tr>
<td>quant</td>
<td>both</td>
<td>NTAP/quant</td>
<td>0.0.34 ？</td>
</tr>
<tr>
<td>quic-go</td>
<td>both</td>
<td>lucas-clemente/quic-go</td>
<td>0.23.0</td>
</tr>
<tr>
<td>quiche</td>
<td>both</td>
<td>cloudflare/quiche</td>
<td>？</td>
</tr>
<tr>
<td>quicly</td>
<td>both</td>
<td>h2o/quicly</td>
<td>@699e2564 (Nov 2021, 10)</td>
</tr>
<tr>
<td>xquic</td>
<td>both</td>
<td>Kulsk/xquic</td>
<td>？</td>
</tr>
</tbody>
</table>
### Implementations

<table>
<thead>
<tr>
<th>Name</th>
<th>CCA</th>
<th>HyStart</th>
</tr>
</thead>
<tbody>
<tr>
<td>aioquic</td>
<td>NewReno</td>
<td>x</td>
</tr>
<tr>
<td>chrome</td>
<td>BBRv2, CUBIC</td>
<td>✓</td>
</tr>
<tr>
<td>kwik</td>
<td>NewReno</td>
<td>x</td>
</tr>
<tr>
<td>lsquic</td>
<td>BBR, CUBIC</td>
<td>x</td>
</tr>
<tr>
<td>msquic</td>
<td>CUBIC</td>
<td>x</td>
</tr>
<tr>
<td>mvfst</td>
<td>BBR, CUBIC, NewReno, ...</td>
<td>✓</td>
</tr>
<tr>
<td>neqo</td>
<td>CUBIC, NewReno</td>
<td>x</td>
</tr>
<tr>
<td>nginx</td>
<td></td>
<td>⬤</td>
</tr>
<tr>
<td>ngtcp2</td>
<td>BBRv2, BBR, CUBIC, Reno</td>
<td>x</td>
</tr>
<tr>
<td>picoquic</td>
<td>BBR, CUBIC</td>
<td>✓</td>
</tr>
<tr>
<td>quant</td>
<td>NewReno</td>
<td>x</td>
</tr>
<tr>
<td>quic-go</td>
<td>CUBIC, Reno</td>
<td>⬤</td>
</tr>
<tr>
<td>quiche</td>
<td>CUBIC</td>
<td>✓</td>
</tr>
<tr>
<td>quicly</td>
<td>CUBIC, Reno, pico</td>
<td>x</td>
</tr>
<tr>
<td>xquic</td>
<td>BBR, CUBIC, Reno</td>
<td>x</td>
</tr>
</tbody>
</table>
## Related Work

<table>
<thead>
<tr>
<th>Reference</th>
<th>QUIC Version</th>
<th>Client</th>
<th>Server</th>
<th>Type of Benchmark</th>
<th>Type of Link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhang 2018 [16]</td>
<td>gQUIC Q039</td>
<td>chrome</td>
<td>Google QUIC test server</td>
<td>Websites</td>
<td>emul.</td>
</tr>
<tr>
<td>Thomas 2019 [12]</td>
<td>gQUIC Q039</td>
<td>chrome 67</td>
<td>Google Server</td>
<td>File</td>
<td>real</td>
</tr>
<tr>
<td>Deutschmann 2019 [4]</td>
<td>gQUIC Q043</td>
<td>chrome 69</td>
<td>chrome quic-go</td>
<td>File</td>
<td>real</td>
</tr>
<tr>
<td>Fairhurst 2019 [5]</td>
<td>draft-20</td>
<td></td>
<td>quickly v20</td>
<td>Files</td>
<td>real</td>
</tr>
<tr>
<td>Border 2020 [1]</td>
<td>gQUIC Q046</td>
<td>chrome 77</td>
<td>Google Drive</td>
<td>File</td>
<td>real, emul.</td>
</tr>
<tr>
<td>Kuhn 2020 [8]</td>
<td>gQUIC ✭</td>
<td>chrome 67</td>
<td>Google Server</td>
<td>Websites</td>
<td>real</td>
</tr>
</tbody>
</table>
## Measurement Results

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Mean</th>
<th>Maximum</th>
<th>Failed</th>
<th>Timeout</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[Mbit/s]</td>
<td>[%]</td>
<td>[Mbit/s]</td>
<td>[%]</td>
</tr>
<tr>
<td>GOODPUT</td>
<td>8.54</td>
<td>85</td>
<td>9.6</td>
<td>96</td>
</tr>
<tr>
<td>SAT</td>
<td>4.88</td>
<td>24</td>
<td>12.0</td>
<td>60</td>
</tr>
<tr>
<td>SATLOSS</td>
<td>2.86</td>
<td>14</td>
<td>11.5</td>
<td>57</td>
</tr>
<tr>
<td>Astra</td>
<td>3.98</td>
<td>20</td>
<td>13.5</td>
<td>68</td>
</tr>
<tr>
<td>EUTELSAT</td>
<td>6.01</td>
<td>12</td>
<td>17.5</td>
<td>35</td>
</tr>
<tr>
<td>Source</td>
<td>Implementation</td>
<td>Link Rate</td>
<td>RTT</td>
<td>PLR</td>
</tr>
<tr>
<td>---------------------</td>
<td>----------------</td>
<td>-----------</td>
<td>------</td>
<td>-----</td>
</tr>
<tr>
<td>Jones 2021 [6]</td>
<td>chrome</td>
<td>20/2</td>
<td>real Link</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>chrome</td>
<td>30/2</td>
<td>real Link</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>chrome</td>
<td>15/3</td>
<td>real Link</td>
<td>10</td>
</tr>
<tr>
<td>Deutschmann 2019 [4]</td>
<td>ngtcp2</td>
<td>20/2</td>
<td>real Link</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>ngtcp2</td>
<td>20/2</td>
<td>600 0%</td>
<td>1</td>
</tr>
<tr>
<td>Name</td>
<td>RTT</td>
<td>Data Rate</td>
<td>PLR</td>
<td>Time-out</td>
</tr>
<tr>
<td>-----------</td>
<td>-----</td>
<td>-----------</td>
<td>-----</td>
<td>----------</td>
</tr>
<tr>
<td>LONGRTT</td>
<td>1500</td>
<td>10</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>GOODPUT</td>
<td>30</td>
<td>10</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>SAT</td>
<td>600</td>
<td>20/2</td>
<td>0</td>
<td>120</td>
</tr>
<tr>
<td>SatLoss</td>
<td>600</td>
<td>20/2</td>
<td>1</td>
<td>360</td>
</tr>
<tr>
<td>ASTRA</td>
<td>≳600</td>
<td>20/2</td>
<td>≳0.1</td>
<td>120</td>
</tr>
<tr>
<td>EUTELSAT</td>
<td>≳600</td>
<td>50/5</td>
<td>≳0.1</td>
<td>120</td>
</tr>
</tbody>
</table>
J. Border, B. Shah, C.-J. Su, and R. Torres. 
**Evaluating QUIC’s Performance Against Performance Enhancing Proxy over Satellite Link.**

A. Custura, T. Jones, and G. Fairhurst. 
**Impact of Acknowledgements using IETF QUIC on Satellite Performance.**


Work in Progress.

N. Kuhn.  
**Feedback from using QUIC’s 0-RTT-BDP extension over SATCOM public access, July 2021.**

N. Kuhn, F. Michel, L. Thomas, E. Dubois, and E. Lochin.  
**QUIC: Opportunities and threats in SATCOM.**  


Y. Wang, K. Zhao, W. Li, J. Fraire, Z. Sun, and Y. Fang. 
**Performance Evaluation of QUIC with BBR in Satellite Internet.**

**A Performance Perspective on Web Optimized Protocol Stacks: TCP+TLS+HTTP/2 vs. QUIC.**