Experience: A Three-Year Retrospective of Large-scale Multipath Deployment for Mobile Applications

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¹ ² ³
China Mobile App Industry is Booming

China mobile app market size

- **+25%/year**

<table>
<thead>
<tr>
<th>Year</th>
<th>Trillion Dollars</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>1.64</td>
</tr>
<tr>
<td>2019</td>
<td>1.85</td>
</tr>
<tr>
<td>2020</td>
<td>2.26</td>
</tr>
<tr>
<td>2021</td>
<td>3.17</td>
</tr>
</tbody>
</table>

Mobile app downloads in the Huawei app market

- **+56%/year**

<table>
<thead>
<tr>
<th>Year</th>
<th>Billion</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>120</td>
</tr>
<tr>
<td>2019</td>
<td>210</td>
</tr>
<tr>
<td>2020</td>
<td>384</td>
</tr>
<tr>
<td>2021</td>
<td>432</td>
</tr>
</tbody>
</table>

Time users spend on the mobile apps

- **+5.2%/year**

<table>
<thead>
<tr>
<th>Year</th>
<th>Hours per Month</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>138.7</td>
</tr>
<tr>
<td>2020</td>
<td>146.5</td>
</tr>
<tr>
<td>2021</td>
<td>153.9</td>
</tr>
<tr>
<td>2022</td>
<td>177.3</td>
</tr>
</tbody>
</table>

Distribution of the user session duration (%)

- **Video Streaming**
- **Instant Messaging**
- **News**
- **Others**

Source: iResearch Inc. & QuestMobile
Viewers have no patience for buffering, abandon videos after \textit{2 seconds} of waiting, with a \textit{1-second} delay increase raising the abandonment rate by 5.8%.

One of the Solutions: Multipath Transport

Multipath transport simultaneously utilizing multiple link to transfer data. Providing path robustness & aggregating more bandwidth.
# Multipath Transport in the Academia

<table>
<thead>
<tr>
<th>Layer</th>
<th>Illustrations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Application Layer</strong></td>
<td>mHTTP [SIGMETRICS’14], MSPlayer [JSAC’16], MP-DASH [CoNEXT’16], MP-H2 [MobiCom’19], …</td>
</tr>
<tr>
<td><strong>Transport Layer</strong></td>
<td>MPTCP [SIGCOMM’11], MP-RTP [MMSys’13], MP-QUIC [CoNext’17], MP-DCCP [LCN’19], …</td>
</tr>
<tr>
<td><strong>Network Layer</strong></td>
<td>MAR [MobiSys’04], BAG [TMC’06], PRISM [TMC’07], mHIP [BroadNets’09], …</td>
</tr>
<tr>
<td><strong>Link Layer</strong></td>
<td>strlPe [TOCS’99], FatVAP [NSDI’08], Switch [CellNet’12], Wi-Fi Mobility [NSDI’15], CA++ [MobiCom’23], …</td>
</tr>
</tbody>
</table>
Multipath Transport in the Industry: The Status Quo

End-to-End Deployment

Subflow 1

Subflow 2

Apple Siri (2013)

Alibaba XLINK (2021)
End-to-End Deployment

- Apple Siri (2013)
- Alibaba XLINK (2021)

Subflow 1
Subflow 2

- ISP A
- ISP B
- Wi-Fi
- App server
- Internet

Relay-Based Deployment

- GiGA (2015)
- ATSSS (2019)
- Hybrid Access (2020)

Subflow 1
Subflow 2

- App
- OS
- Wi-Fi
- ATSSS UPF / MPTCP Proxy
- Internet
- App server
Multipath Transport in the Industry: The Status Quo

End-to-End Deployment

- App
- OS
- ISP A
- ISP B
- App server
- Internet
- Wi-Fi

Subflow 1
Subflow 2

Relay-Based Deployment

- App
- OS
- ISP
- ATSSS UPF / MPTCP Proxy
- Internet
- App server
- Wi-Fi

Subflow 1
Subflow 2

1. Limited number of reports on the deployment experience.
2. Limited deployment scale: cover either a single app or a single ISP.
This Talk: A Retrospective on Multipath Deployment

• **Our mission:** Pushing forward the mobile multipath deployment.
  - Goal: To make multipath transport easy to deploy for app providers under the cross-ISP setting.

• **Stage 1 (Starts from 2018):** Understanding the cost of multipath transport.
  - What are the challenges during the development, deployment, and operation?
Understanding the Cost of Multipath Transport

- Use the de-facto solution **MPTCP** to create two subflows.
- Collaborate with the phone vendor and use the **end-to-end deployment** solution.
- Collaborate with a major **video streaming platform** in China.
## Development Phase

### Issues

<table>
<thead>
<tr>
<th>Heterogeneous paths adversely affect performances.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default scheduler is unaware of path cost.</td>
</tr>
<tr>
<td>The default initial path can break.</td>
</tr>
</tbody>
</table>

### Related work

<table>
<thead>
<tr>
<th>STMS [ATC’18]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECF [CoNEX’17]</td>
</tr>
<tr>
<td>MP-DASH [CoNEX’16]</td>
</tr>
<tr>
<td>Greenbag [RTSS’13]</td>
</tr>
<tr>
<td>RobE [ANRW’18]</td>
</tr>
<tr>
<td>RobE [IETF proposal]</td>
</tr>
</tbody>
</table>

### Limitations of the related work

- Require server-side modifications.
- Server operators refuse to merge the out-of-tree kernel patch:
  - Cannot guarantee no-worse performance than single path.
  - High upgrade capital.
  - Hard to locate the incidence.
Development Phase: Our Development Efforts

Develop client-side middleware to solve the above problem, while avoiding server modifications and hiding the implementation from the app.
Deployment Phase

• In December 2018, we launched an incremental deployment for MPTCP in Beijing, Shanghai, and Shenzhen. We enable MPTCP only for video chunks.

• Required Modifications:
  - The phone vendor needs to merge the MPTCP project into the vendor-specific OS.
  - The app uses the SDK provided by us to enable the multipath capability.
  - The app servers need to be upgraded to support MPTCP, and the video manifest files must be modified to specify the MPTCP servers used.
Deployment Phase Issue: Slow Start Time

Expectation: Low Video Start Time

Reality: Still Slow Loading
The app needs access to a number of different servers

- **Danmaku subtitling** from data.iqiyi.com
- **Video ads** from ads.edge.com
- **Video** from a.edge.com
- **User comments** from u-data.iqiyi.com
- **Playlist** from user.iqiyi.com
- **Ads** from data.ads.com
- **Video thumbnail** from static.iqiyi.com
The app needs access to a number of different servers

- **Danmaku subtitling** from `data.iqiyi.com`
- **Video ads** from `ads.edge.com`
- **Video** from `a.edge.com`
- **User comments** from `u-data.iqiyi.com`
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- **Ads** from `data.ads.com`

Accelerating only video traffic can still stall video playback and page loading
Operation Phase Issue #1: Cross-ISP Access

Cross-ISP access leads to performance degradation.

A prolonged network path could increase the latency.

The peering agreement could cap the throughput.
## Operation Phase Issue #1: Cross-ISP Access

Cross-ISP access leads to performance degradation.

### Delay increase

<table>
<thead>
<tr>
<th>Server ISP</th>
<th>User ISP</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>A</td>
<td>82.5%</td>
<td>42.5%</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>95.9%</td>
<td>N/A</td>
<td>42.2%</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td>N/A</td>
<td>26.4%</td>
<td>11.6%</td>
</tr>
</tbody>
</table>

### Throughput decrease

<table>
<thead>
<tr>
<th>Server ISP</th>
<th>User ISP</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>A</td>
<td>-25.9%</td>
<td>-3.1%</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>-44.4%</td>
<td>N/A</td>
<td>-43.6%</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td>N/A</td>
<td>-4.0%</td>
<td>-37.2%</td>
</tr>
</tbody>
</table>

MPTCP requires multi-homed servers to provide good performance.
Operation Phase Issue #1: Cross-ISP Access

The servers require a special geographic location (e.g. close to IXP) so that it can be connected to multiple ISPs.

The bandwidth cost is $\sim 3x$ higher for multi-homed servers.
Operation Phase Issue #2: Redirection by Sub-Tier ISP

Some sub-tier ISPs use DNS hijacking to redirect the connection to their local cache server, for bandwidth saving.
Summary of Our Experience with MPTCP

**Development**
- Vanilla MPTCP has suboptimal performance for mobile scenarios.
- Hard to fix them by letting other parties merge the out-of-tree patch.

**Deployment**
- Covering a fraction of the app traffic results in a limited improvement.
- Outreach need to be massive and involve upgrading multiple sites simultaneously.

**Operation**
- Cross-ISP server access requires high bandwidth budget.
- Middlebox may not be compatible with MPTCP.

We need a solution that reduces the outreach expense.
The solution should be transparent to app providers, ISPs, and server operators.
This Talk: A Retrospective on Multipath Deployment

- **Our mission:** Pushing forward the mobile multipath deployment.
  - Goal: To make multipath transport easy to deploy for app providers under the cross-ISP setting.

- **Stage 1 (2018-2019):** Understanding the cost of multipath transport.
  - What are the challenges during the development, deployment, and operation?

- **Stage 2 (2019-Now):** Deploying multipath transport at scale.
  - How to design and implement a easy-to-deploy multipath transport system?
Our Observation

Video traffic in China is primarily delivered over unencrypted HTTP.

HTTP is highly compatible with existing middleboxes and servers.
Multipath HTTP (MPHTTP)

MPHTTP uses HTTP \texttt{byte-range-request} to fetch different portions of a video chunk.
Fleety: A Mobile System Service for Multipath Transport

- Implemented as a transparent shim layer in the vendor-specific OS, with four building blocks.
Fleety: A Mobile System Service for Multipath Transport

• Flow classifier
  - Identify HTTP flows from the app by looking at the first few bytes of the flow.
  - Only select requests for medium-to-large files due to performance considerations.

Diagram:
- App
  - Standard Socket API
    - Flow Classifier
      - HTTP Traffic
      - Others
- Fleet
- Wi-Fi
- Cellular
Fleety: A Mobile System Service for Multipath Transport

- Flow classifier
- MPHTTP proxy
  - Splits the HTTP request, assigns sub-requests to different network paths, and reassembles the responses.
Fleety: A Mobile System Service for Multipath Transport

- Flow classifier
- MPHTTP proxy
- Consistency verifier
  - Ensures data fetched from different paths corresponds to the original content.
  - Sampling a small byte range as a “fingerprint”. Compare the fingerprints.
Fleety: A Mobile System Service for Multipath Transport

- Flow classifier
- MPHTTP proxy
- Consistency verifier
- Path Selector
  - The application QoE can be affected by both non-HTTP and HTTPS traffic.
  - The path selector provides link reliability for non-HTTP traffic.
An Example for MPHTTP Proxy & Consistency Verifier

The **MPHTTP proxy** splits and reassemble the request.

The **consistency verifier** extends the end bytes of former sub-request and compares the overlap.
Multipath Transport in the Industry

**End-to-End Deployment**

**Relay-Based Deployment**

**Client-Only Deployment**

Advantage: Maintain transparency to all other network parties.
Deployment of Fleety

• In September 2019, the phone vendor deployed Fleety in China.
  - Support 142 device models including smartphones and tablets,
  - Support 156 popular apps (video streaming, instant messaging, etc.)

• In January 2022, there were 9.96 million opted-in users that used multipath transport for one or more applications. The opt-in rate is 20.63%.
Evaluation

Additional bandwidth of 4.4 Mbps on average and 6.1 Mbps at the 80th percentile.

No significant impact on the latency and effectively reduces latency spikes.
Conclusions

• Understanding the cost of multipath transport.
  - The deployment of end-to-end solution and relay-based solution has been slow over the past decade due to the high industry outreach cost.

• Deploying multipath transport at scale.
  - The MPHTTP-based system, that only requires client-side modification, can lower the deployment bar and immediately benefit the applications at scale.

Thank you! Open questions?