A Measurement Study on Multi-path TCP with Multiple Cellular Carriers on High Speed Rails

Li Li*, Ke Xu*, Tong Li†, Kai Zheng†, Chunyi Peng‡,
Dan Wang┴, Xiangxiang Wang*, Meng Shen∥, Rashid Mijumbi‡
High Speed Rails (HSRs)

Length: 38,000 km
China: 66%
Speed: 310 km/h
Passenger: 1.7 billion
Growing: 30%
2020: 30,000 km

Europe: Thalys
Japan: Shinkansen
China: High speed mobility

Increasing need for acceptable quality of network services
Single-Path Degradation on HSRs

Frequent handoff is the main cause of performance degradation [Li, INFOCOM15] [Li, TON17]
Benefit from Carrier Complementarity

Making use of the difference in handoff time between carriers

CDF of inter-carrier handoff interval

An example of two complementary carriers

To explore potential benefits of using Multi-path TCP (MPTCP)
Measurement Challenges

• Many intertwined factors
  – External: terrain, speed, handoff and network type, etc.
  – Internal: flow size and algorithms (congestion controller or scheduler), etc.

• Location and time bias
  – Same location vs high speed mobility
  – Same time vs flow interference

• Effort and time intensive
  – Many people and much money
  – Massive data traces on various HSR routes
Measurement Methodology

**Measurement setup**
USB cellular modems, USB WiFi modems accessing smartphone hotspots

**MobiNet**
Geographical location, train speed, network type and handoffs

**Footprints**
Accumulated 82,266 km: 2x Earth Equatorial Circumference
Analysis Method

Filtering data—terrain, speed, handoff and network type
- Only consider data in 4G LTE networks in areas of open plains
- Only consider two cases: static and high speed (280-310km/h)

Comparison between MPTCP and TCP
- Same flow size/duration, at the same train speed, with similar handoff frequency, in the same carrier network
- Stable MPTCP kernel implementation v0.91: www.multipath-tcp.org

Decision Making
- Robustness: If MPTCP outperforms either of the two single TCPs
- Efficiency: If MPTCP outperforms both single TCPs
Results

Mice Flows
File Completion Time (FCT)

M: Carrier M  U: Carrier U

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>MPTCP</th>
<th>TCP flow (M)</th>
<th>TCP flow (U)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sub-flow (M)</td>
<td>Sub-flow (U)</td>
<td></td>
</tr>
<tr>
<td>MS-US</td>
<td>0 handoff</td>
<td>0 handoff</td>
<td>0 handoff</td>
</tr>
<tr>
<td>M0-U0</td>
<td>280-310</td>
<td>0 handoff</td>
<td>0 handoff</td>
</tr>
<tr>
<td>M0-U1</td>
<td>280-310</td>
<td>1 handoff</td>
<td>0 handoff</td>
</tr>
<tr>
<td>M1-U0</td>
<td>280-310</td>
<td>1 handoff</td>
<td>0 handoff</td>
</tr>
</tbody>
</table>

TCP (M): single-path TCP using Carrier M
TCP (U): single-path TCP using Carrier U
MPTCP: dual-path MPTCP using Carrier M and Carrier U, simultaneously

FCT of mice flows (<1 MB)
Performance of Mice Flows

FCT of mice flows (<1 MB)

Decision Making
- Robust: If MPTCP outperforms either of the two single TCPs
- Efficient: If MPTCP outperforms both single TCPs

Robustness Efficiency
Performance of Mice Flows

FCT of mice flows (<1 MB)

Decision Making
- Robust: If MPTCP outperforms either of the two single TCPs
- Efficient: If MPTCP outperforms both single TCPs

Robustness

Efficiency

Cannot achieve advantage over TCP in efficiency
Performance of Mice Flows

**Decision Making**
- Robust: If MPTCP outperforms *either* of the two single TCPs
- Efficient: If MPTCP outperforms *both* single TCPs

**Handoff leads to efficiency reduction**

**Inefficient sub-flow establishment**

FCT of mice flows (<1 MB)
Sub-flow Establishment: Normal Case

Neither of two paths suffers a handoff

Sub-flow 1

Sub-flow 2
Sub-flow Establishment: Handoff Case

Either of two paths suffers a handoff

Lucky Case

5 handshakes

Unlucky Case

5 handshakes

3 handshakes

3 handshakes

Handoff path

Handoff path

Either of two paths suffers a handoff

Lucky Case

5 handshakes

Unlucky Case

3 handshakes

Handoff path
Sub-flow Establishment Time

CDF of total number of handshakes

CDF of Sub-flow establishment time

MPTCP's efficiency of sub-flow establishment is low on HSRs
Results

Elephant Flows
Performance of Elephant Flows

- Metric: average rate during 100 seconds

- Variable: train speed and number of handoffs suffered

\[ R_{poorer} = \frac{MPTCP_{\min(TCP_i)}}{\min(TCP_i)} > 1 \] Robustness

\[ R_{better} = \frac{MPTCP_{\max(TCP_i)}}{\max(TCP_i)} < 1 \] Efficiency

\[ R_{total} = \frac{MPTCP_{\sum(TCP_i)}}{\sum(TCP_i)} < 1 \] Aggregation

- Results remain constant, but reasons are different!

Poor adaptability of congestion control and scheduling to frequent handoffs
Congestion Control: Traffic Distribution

- Contribution rate of dominant sub-flow to quantify degree of traffic distribution balance

\[ D_{\text{balance}} = \frac{\max(TCP_i)}{\text{sum}(TCP_i)} \approx 1 \]

- Packet loss causes window drops

- Window distribution imbalance leads to traffic distribution imbalance

- **Coupled** congestion controllers
  - LIA [Raiciu et al., RFC 6356]
  - OLIA [Khalili et al., IETF draft]
  - Transfer traffic from a congested path to a less congested one

*More details please refer to the paper.*
Scheduling: Out of Order Problem

• Out-of-order queue size rises
Static Cases

- Out-of-order problem is not serious in static cases
High Speed Mobility Cases

MPTCP’s efficiency of congestion control and scheduling is low on HSRs
Key Takeaways

• **Insights:** reliability enhancement rather than bandwidth aggregation
  - Significant advantage in robustness
  - Efficiency of MPTCP is far from satisfactory

• **Cause:** poor adaptability to frequent handoffs
  - Mice: sub-flow establishment
  - Elephant: scheduling and congestion control

• **Suggestions:** handoff pattern detection and prediction
Thank You!

Email: li.tong@huawei.com
Homepage: https://leetong.weebly.com
Data traces are available at http://www.thucsnet.org/hsrmptcp.html