Measuring Internet Performance: Challenges and Opportunities

Rocky K. C. Chang
Internet Infrastructure and Security Group
The Hong Kong Polytechnic University
Xiamen University, 4 July 2013
Internet Infrastructure and Security Laboratory
Measuring end-to-end performance

- Source: Akamai’s network performance comparison
End-to-end network monitoring ...

End-to-End Network Monitoring, Reporting, and Analytics

Cascade Profiler Appliance

How is your IT infrastructure and network contributing to the performance of important applications? Are you overloaded with raw data but struggling to see the big picture and to communicate it? IT infrastructure exists for one reason, to deliver applications. To really understand holistic application performance, you need an end-to-end network and infrastructure view that helps you manage performance through the lens of the application. Riverbed Cascade Profiler gives you this lens to easily troubleshoot and find the root cause of network and application issues before your end users ever know there’s a problem.
Why measuring network path?

Performance metrics
- Latency
- Delay variation (jitter)
- Connectivity
- Packet loss/reordering
- Link/path capacity
- Available Bandwidth
- TCP throughput
- Router hop (count)
- Packet duplication
- ...

Applications
- Traffic engineering
  - Network tomography
  - Path fingerprinting
  - Routing optimization
  - QoS routing, admission control, channel assignment in WLAN
- User profiling
  - Network resource planning
  - SLA verification
- Application performance tuning
  - Rate adaption for VoIP/video streaming apps
  - Distance/location prediction for overlay networks, P2Ps, CDNs
- ...

Applications
- Applications
- Applications
An unfinished business

- Much had been done in late 1990 and early 2000.
- Very few measurement tools have made their way into wide deployment.
- The Internet is no longer friendly to measurement probes.
  - Many unfriendly and intelligent middleboxes
  - Measurement Lab from Google, PlanetLab, …
- Measurement results may not reflect the experience of data packets.
- Continuous monitoring for inter-domain paths is hard without receiving complaints.
Active Path-Quality Measurement
Challenges to active measurement

• Measurement scalability
  – Measure many network paths
• Measurement reliability
  – Measurement will not be interfered or interrupted
• Measurement representativeness
  – Measurement traffic representing the traffic of interest
• Measurement accuracy
  – Measurement results are accurate statistically.
• Bi-directional measurement
  – Measure both directions
• Measuring multiple metrics
Challenges to active measurement

• Measurement scalability
  – Cooperative measurement paradigm (e.g., OWAMP) not scalable

• Measurement reliability
  – Interference from various middleboxes and firewalls

• Measurement representativeness
  – Using control channel to measure data channel

• Measurement accuracy
  – Sampling rate and patterns

• Bi-directional measurement
  – Measure from both directions

• Measuring multiple metrics
  – Need multiple tools
A sampling of measurement tools

<table>
<thead>
<tr>
<th>Tools</th>
<th>Mode</th>
<th>Direction</th>
<th>Probing method</th>
<th>Probing packets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet loss:</td>
<td>Uncoop.</td>
<td>F, B</td>
<td>Induce different TCP ACKs</td>
<td>TCP data segments in a single connection</td>
</tr>
<tr>
<td>BADABING [22]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Packet reordering:</td>
<td>Uncoop.</td>
<td>F, B, D</td>
<td>Induce different ACK pairs</td>
<td>Three TCP data segments in a single connection</td>
</tr>
<tr>
<td>Single connection test [2]</td>
<td>Uncoop.</td>
<td>F, B, D</td>
<td>Induce different ACK pairs with IPIDs</td>
<td>Two TCP data segments in two connections</td>
</tr>
<tr>
<td>Dual connection test [2]</td>
<td>Un coop.</td>
<td>B</td>
<td>Request for TCP data download</td>
<td>Two TCP SYNs in two connections</td>
</tr>
<tr>
<td>TCP data transfer test [2]</td>
<td>Uncoop.</td>
<td>B</td>
<td></td>
<td>Two TCP data/ACKs in a single connection</td>
</tr>
<tr>
<td>POINTER [12]</td>
<td>Uncoop.</td>
<td>B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reordering, loss and queuing delay:</td>
<td>Un coop.</td>
<td>F, B, D</td>
<td>Induce ICMP replies with IPIDs</td>
<td>Two/three ICMP timestamp requests</td>
</tr>
<tr>
<td>tulip [13]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Available bandwidth:</td>
<td>Coop.</td>
<td>F</td>
<td>Self-loading periodic streams</td>
<td>Periodic UDP packet trains</td>
</tr>
<tr>
<td>lmTCP [23]</td>
<td>Uncoop.</td>
<td>B</td>
<td>Self-loading periodic streams</td>
<td></td>
</tr>
<tr>
<td>Capacity:</td>
<td>Uncoop.</td>
<td>F, B</td>
<td>Induce RST pairs</td>
<td>Two TCP SYN segments</td>
</tr>
<tr>
<td>SProbe [20]</td>
<td>Coop.</td>
<td>F</td>
<td>Packet pairs and trains</td>
<td>UDP packet pairs and trains</td>
</tr>
</tbody>
</table>
Our approach to active measurement

- Measurement scalability
  - Non-cooperative measurement paradigm
- Measurement reliability
  - Use standard protocol and legitimate application data
- Measurement representativeness
  - Using data channel to measure data channel
- Measurement accuracy
  - Supporting different sampling rate and patterns
- Bi-directional measurement
  - Measure from only one direction
- Measuring multiple metrics
  - Obtain multiple metrics from one side
HTTP/OneProbe

- Use normal **TCP** data packet to measure data-path quality.
- Use normal and basic **TCP** data transmission mechanisms specified in **RFC 793**.
- Integrated into normal **HTTP** application sessions.

Data clocking
Path measurement
What does HTTP/OneProbe offer?

- Continuous path monitoring in an HTTP session (stateful measurement)
- All in one:
  - Round-trip time
  - Loss rate (uni-directional)
  - Reordering rate (uni-directional)
  - Capacity (uni-directional)
  - Loss-pair analysis
  - ...

The probe design

• Send two back-to-back probe data packets.
  – Capacity measurement based on packet-pair dispersion
  – At least two packets for packet reordering
  – Determine which packet is lost.
The probe design (cont’d)

• Similarly for the response packets

• Each probe packet elicits a response packet.
  – Adv. Window = 2 and acknowledge only 1 packet.
Bootstrapping and continuous monitoring
Loss and reordering measurement via response diversity

(a) FR×R0
(b) F1×R0
(c) F2×R0
(d) F3
### 18 possible path events

<table>
<thead>
<tr>
<th></th>
<th>R0</th>
<th>RR</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>FR</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>F1</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>F2</td>
<td>✓</td>
<td>–</td>
<td>✓</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>F3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
Based on their response packets

<table>
<thead>
<tr>
<th>Path events</th>
<th>1st response packets</th>
<th>2nd response packets</th>
<th>3rd response packets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. F0 × R0</td>
<td>S3</td>
<td>3’</td>
<td>S4</td>
</tr>
<tr>
<td>2. F0 × RR</td>
<td>S4</td>
<td>4’</td>
<td>S3</td>
</tr>
<tr>
<td>3. F0 × R1</td>
<td>S4</td>
<td>4’</td>
<td>S3</td>
</tr>
<tr>
<td>4. F0 × R2</td>
<td>S3</td>
<td>3’</td>
<td>S3</td>
</tr>
<tr>
<td>5. F0 × R3</td>
<td>S3</td>
<td>4’</td>
<td>–</td>
</tr>
<tr>
<td>6. FR × R0</td>
<td>S3</td>
<td>2’</td>
<td>S4</td>
</tr>
<tr>
<td>7. FR × RR</td>
<td>S4</td>
<td>2’</td>
<td>S3</td>
</tr>
<tr>
<td>8. FR × R1</td>
<td>S4</td>
<td>2’</td>
<td>S3</td>
</tr>
<tr>
<td>9. FR × R2</td>
<td>S3</td>
<td>2’</td>
<td>S3</td>
</tr>
<tr>
<td>10. FR × R3</td>
<td>S3</td>
<td>4’</td>
<td>–</td>
</tr>
<tr>
<td>11. F1 × R0</td>
<td>S3</td>
<td>2’</td>
<td>S4</td>
</tr>
<tr>
<td>12. F1 × RR</td>
<td>S4</td>
<td>2’</td>
<td>S3</td>
</tr>
<tr>
<td>13. F1 × R1</td>
<td>S4</td>
<td>2’</td>
<td>S3</td>
</tr>
<tr>
<td>14. F1 × R2</td>
<td>S3</td>
<td>2’</td>
<td>S3</td>
</tr>
<tr>
<td>15. F1 × R3</td>
<td>S3</td>
<td>2’</td>
<td>–</td>
</tr>
<tr>
<td>16. F2 × R0</td>
<td>S3</td>
<td>3’</td>
<td>S2</td>
</tr>
<tr>
<td>17. F2 × R1</td>
<td>S2</td>
<td>3’</td>
<td>–</td>
</tr>
<tr>
<td>18. F3</td>
<td>S1</td>
<td>2’</td>
<td>–</td>
</tr>
</tbody>
</table>
Path event distinguishability

• All 18 cases can be distinguished except for
  – A1. F1×R2 and F1×R3
  – A2. F1×RR and F1×R1
  – A3. F0×R3 and FR×R3

• Resolving the ambiguities
  – A1 and A2: use RTT.
  – A3: use TCP timestamping.
Our measurement methods

- Round-trip delay, asymmetric packet loss and packet reordering measurement

- Capacity measurement

- Loss-pair measurement

- Available bandwidth measurement
The capacity measurement and loss-pair measurement

Design and analyze three packet-pair methods for sound network measurements

- MDDIF [CoNEXT 09], TRIO [CoNEXT 11], Loss pair [IMC 10]
- Fundamentals: decompose + recompose + recycle

Non-cooperative destination

Source

Incorporate all the methods into a non-cooperative measurement tool – HTTP/OneProbe [USENIX 08]
Network capacity

Source

<table>
<thead>
<tr>
<th>Link</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20 Mbits/s</td>
</tr>
<tr>
<td>2</td>
<td>8 Mbits/s</td>
</tr>
<tr>
<td>3</td>
<td>100 Mbits/s</td>
</tr>
<tr>
<td>4</td>
<td>10 Mbits/s</td>
</tr>
<tr>
<td>5</td>
<td>15 Mbits/s</td>
</tr>
<tr>
<td>6</td>
<td>50 Mbits/s</td>
</tr>
</tbody>
</table>

**Sub-path**

**Forward path**

**Reverse path**

One-way link capacity

Asymmetric capacity

A router hop
Cross-traffic impact on packet pairs

- Existing techniques: Identify the unaffected packet pair/train
Delay difference = PPD

- The MDDIF method: Difference between first and second packets’ minimum delays (minDelays)

Source: 20 Mbits/s
Round-trip capacity
B

Destination: 50 Mbits/s

Round-trip capacity

Compressed PPD
Expanded PPD
Correct PPD = S/C_b
TRIO: measuring asymmetric capacity with three minRTTs

- Exploit 1-RTP and (1,1)-TWP with $S_f = S_r = S$

- $d_{j-1}^T - d_{j-1}^R = S/C_f$
- $d_j^T - d_{j-1}^T = S/C_r$
- Reuse $d_{j-1}^T$
- Avoid probe interference!

For self-diagnosis
Taxonomy of capacity measurement techniques

Available tools: Nettimer (tailgating), Envelope, MultiQ, Bprobe, Pathrate, Paśtor’s method, PBM, MDDIF, TRIO, DSLprobe, SProbe.
Loss-pair measurement

- Packet pair with exactly one lost packet (defined by Liu & Crovella [liu01imw])
- Path queueing delay $\Theta$
  - $LP_{01}: \Theta_{j-1} = d_{j-1} - \text{minRTT}$.
  - $LP_{10}: \Theta_j = d_j - \text{minRTT}$.
- Buffer size of congested hop $h'$ [liu01imw]: $B = \Theta_j \times C^{(h')}$. 

Three questions:
1. $\Theta_{j-1} = \Theta_j$?
2. Is $B$ accurate?
3. Any additional info from $\Theta_{j-1}$ and $\Theta_j$?
Loss pairs
Collaborative path-quality measurement
HARNET measurement (since 1 Jan 2009)

- “Four-Year Experience of Monitoring and Troubleshooting Multi-domain Networks from a Local Federation” under review for a SI in the *IEEE Commun. Mag.*
Running OneProbe at the 8 Us

- 24x365 probing of the paths to 40+ websites
40+ web servers selected by the JUCC

Measurement side

OneProbe @HKU
OneProbe @CUHK
OneProbe @PolyU
OneProbe @CityU
OneProbe @BU
OneProbe @HKUST
OneProbe @LU
OneProbe @HKIED

Planetopus, database, etc

User side

HKU
CUHK
PolyU
CityU
BU
HKUST
LU
HKIED
<table>
<thead>
<tr>
<th>Name</th>
<th>URL</th>
<th>UB</th>
<th>UF</th>
<th>UC</th>
<th>UA</th>
<th>UH</th>
<th>UE</th>
<th>UD</th>
<th>UG</th>
</tr>
</thead>
<tbody>
<tr>
<td>HKIX(HK)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>minguo</td>
<td><a href="http://www.minguna.org">www.minguna.org</a></td>
<td>2.4</td>
<td>1.6</td>
<td>2.6</td>
<td>2.9</td>
<td>3.1</td>
<td>2.1</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>atnext</td>
<td><a href="http://www.atnext.com">www.atnext.com</a></td>
<td>3.2</td>
<td>2</td>
<td>3.4</td>
<td>3.3</td>
<td>3.5</td>
<td>2.5</td>
<td>3.7</td>
<td>2.4</td>
</tr>
<tr>
<td>pccw</td>
<td><a href="http://www.pccw.com">www.pccw.com</a></td>
<td>4</td>
<td>3.1</td>
<td>4.1</td>
<td>4.4</td>
<td>5.3</td>
<td>3.6</td>
<td>4.3</td>
<td>3.5</td>
</tr>
<tr>
<td>wifi.juice</td>
<td>wifi.juice.edu.hk</td>
<td>1.3</td>
<td>1.3</td>
<td>1.6</td>
<td>3</td>
<td>4.2</td>
<td>1.3</td>
<td>2.3</td>
<td>1.6</td>
</tr>
<tr>
<td>HKIX(ASGCNET)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>twgrid</td>
<td><a href="http://www.twgrid.org">www.twgrid.org</a></td>
<td>50.3</td>
<td>19.2</td>
<td>20.1</td>
<td>20.5</td>
<td>20.7</td>
<td>19.6</td>
<td>20</td>
<td>19.5</td>
</tr>
<tr>
<td>HKIX(KREONET)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ktc</td>
<td>ktc.gist.ac.kr</td>
<td>43.1</td>
<td>43.6</td>
<td>44.7</td>
<td>45</td>
<td>45.2</td>
<td>44</td>
<td>44.5</td>
<td>44</td>
</tr>
<tr>
<td>kreonet</td>
<td><a href="http://www.kreonet.net">www.kreonet.net</a></td>
<td>39.2</td>
<td>39.7</td>
<td>40.6</td>
<td>40.9</td>
<td>41.2</td>
<td>40.1</td>
<td>40.5</td>
<td>40</td>
</tr>
<tr>
<td>Internet(China)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>taobao</td>
<td><a href="http://www.taobao.com">www.taobao.com</a></td>
<td>35.2</td>
<td>35</td>
<td>34.8</td>
<td>34.9</td>
<td>202</td>
<td>33.6</td>
<td>36.1</td>
<td>34.1</td>
</tr>
<tr>
<td>lenovo</td>
<td>appserver,lenovo.com.cn</td>
<td>74.9</td>
<td>55.2</td>
<td>55.5</td>
<td>57.8</td>
<td>293</td>
<td>329.3</td>
<td>51.6</td>
<td>52.4</td>
</tr>
<tr>
<td>Internet(England)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>eng2</td>
<td><a href="http://www.itraveluk.co.uk">www.itraveluk.co.uk</a></td>
<td>243</td>
<td>242.9</td>
<td>243.4</td>
<td>233.4</td>
<td>259.1</td>
<td>241.5</td>
<td>238</td>
<td>242.7</td>
</tr>
<tr>
<td>eng4</td>
<td><a href="http://www.oldmap.co.uk">www.oldmap.co.uk</a></td>
<td>228.1</td>
<td>222.3</td>
<td>226.6</td>
<td>258.7</td>
<td>272.3</td>
<td>226</td>
<td>222.5</td>
<td>222</td>
</tr>
<tr>
<td>eng3</td>
<td><a href="http://www.maps-of-britain.co.uk">www.maps-of-britain.co.uk</a></td>
<td>227.2</td>
<td>227.2</td>
<td>227.6</td>
<td>261.9</td>
<td>318.1</td>
<td>227</td>
<td>229.2</td>
<td>227</td>
</tr>
<tr>
<td>bbc</td>
<td><a href="http://www.bbc.co.uk">www.bbc.co.uk</a></td>
<td>225.3</td>
<td>227.8</td>
<td>225.4</td>
<td>262.1</td>
<td>270.8</td>
<td>228.9</td>
<td>228.2</td>
<td>227.6</td>
</tr>
<tr>
<td>Internet(Finland)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>nokia</td>
<td><a href="http://www.nokia.com">www.nokia.com</a></td>
<td>273.7</td>
<td>272.2</td>
<td>272.3</td>
<td>273.9</td>
<td>319.1</td>
<td>273.4</td>
<td>272.4</td>
<td>271.8</td>
</tr>
<tr>
<td>Internet(USA)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><a href="http://www.cnn.com">www.cnn.com</a></td>
<td>247.7</td>
<td>245.6</td>
<td>247.4</td>
<td>235.8</td>
<td>244.1</td>
<td>242.5</td>
<td>242.5</td>
<td>241.9</td>
</tr>
</tbody>
</table>
**Major performance problems diagnosed**

<table>
<thead>
<tr>
<th>Root Causes</th>
<th>Anomalies Observed by the HARNET Measurement Platform</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Network Outage</strong></td>
<td></td>
</tr>
<tr>
<td>HARNET backbone disruption</td>
<td>Total blackout and traffic rerouting through backup links</td>
</tr>
<tr>
<td><strong>Hardware and Software Faults</strong></td>
<td></td>
</tr>
<tr>
<td>Web server’s faulty NIC</td>
<td>A very high (30%) forward-path packet loss rate for all measurement nodes to UF’s test server.</td>
</tr>
<tr>
<td>HKIX fault</td>
<td>A high forward-path packet loss rate for overseas academic networks through the HKIX peering</td>
</tr>
<tr>
<td>An anomalous router in HARNET</td>
<td>A high diurnal reverse-path reordering rate for non-academic destinations</td>
</tr>
<tr>
<td><strong>Congestion</strong></td>
<td></td>
</tr>
<tr>
<td>HARNET’s ISP changeover</td>
<td>High packet losses during the switching to a temporary network</td>
</tr>
<tr>
<td>PL node congestion</td>
<td>Persistent high packet losses for paths destined to the PL node</td>
</tr>
<tr>
<td><strong>Path and Performance Discrepancy</strong></td>
<td></td>
</tr>
<tr>
<td>Different reverse paths from a US website</td>
<td>A 70-ms higher RTT observed for the paths from two measurement nodes to a US website</td>
</tr>
<tr>
<td>Different forwarding paths to KREONET, CERNET, and TANET</td>
<td>Different RTT performance for the measurement nodes to KREONET, CERNET, and TANET</td>
</tr>
<tr>
<td><strong>Submarine Cable Disruption</strong></td>
<td></td>
</tr>
<tr>
<td>Traffic rerouting due to a SeaMeWe-4 outage</td>
<td>Abrupt RTT increase for paths to websites in Europe and the UK</td>
</tr>
<tr>
<td>Traffic rerouting due to a SEACOM outage during World Cup 2010</td>
<td>Abrupt increase in RTT and forward-path loss rates for some websites in South Africa.</td>
</tr>
<tr>
<td>Traffic rerouting due to multiple submarine cable outages caused by the Sendai earthquake in 2012</td>
<td>High reverse-path packet losses observed for some paths</td>
</tr>
</tbody>
</table>
Application: Impact analysis of submarine cable faults
Eyjafjallajökull volcano eruption

- “Could Ash Cloud or Deep-Sea Current Overwhelm the Internet?” Poster in HotDep 2010.
Path-quality degradation for NOK (Finland) and ENG (in UK)
(a) UB→NOK’s RTT and loss rates.

(b) UB→BBC’s RTT and loss rates.
Network congestion caused by the volcano ashes?

• The surges on packet loss and RTT occurred on 14 April 2010.

• But
  – The onsets of the path congestion and air traffic disruption do not entirely match.
  – Some of the peak loss rate and RTT occurred on weekends.
  – Path congestion can still be observed at the end of the measurement period.
A SEA-ME-WE 4 cable fault

• The SEA-ME-WE 4 cable encountered a shunt fault on the segment between Alexandria and Marseille on 14 April 2010.
• The repair was started on 25 April 2010, and it took four days to complete.
• During the repair, the service for the westbound traffic to Europe was not available.
The SEA-ME-WE 4 cable
A plausible explanation for the network congestion

- The congestion in the FLAG network was caused by taking on rerouted traffic from the faulty SEA-ME-WE 4 cable.
  - FLAG does not use the SEA-ME-WE 4 cable for Hong Kong → NOKIA, ENG3, and BBC.
  - FLAG uses FEA for Hong Kong → NOKIA, ENG3, and BBC
  - TATA uses different cables between Mumbai and London.

![Network diagram](chart.png)
Currently

- Server-side measurement methods
  - Induce data from clients for measurement.
  - Quality measurement without user intervention
- NetMagic/OpenWrt kernel implementation of measurement boxes
  - Supporting client-side and server-side measurement
  - “OMware: An Open Measurement Ware for Stable Residential Broadband Measurement,” ACM SIGCOMM’13 poster/demo
- CERNET-2 measurement platform
  - Deploy a measurement platform on CERNET-2
  - IPv6 measurement
- Residential broadband measurement platform
  - SLA measurement
  - Facilitate a social network for network diagnosis and monitoring
- Open measurement platform
More research projects

• Network performance data analytics
  – What and when to induce for measurement?
  – What can we say from the measurement data with high confidence?
  – “Appraising the Delay Accuracy in Browser-based Network Measurement,” under review for *ACM/USENIX IMC’13*

• Automating diagnosis and patch-up of network performance problems
  – Network tomography
  – Multiple-time-series analysis for anomaly detection

• Adapting video bitrate for HTTP streaming
  – Using network measurement to estimate the available bandwidth
  – “IRate: Initial Video Bitrate Selection System for HTTP Streaming” under review for *ACM CoNEXT’13*

• Adaptive network monitoring
• QoE measurement
• ...

Conclusions

• Develop a suite of atomic path-quality measurement methods.
  – Atomic => application specific, e.g., video, cloud services
  – Path quality => QoE
  – Client side => server side

• Network data research
  – Mining network data
  – Designing measurement “experiments” to facilitate network data mining
  – Towards a science of network research

• Operational experience informs research; research underpins network operations
  – Unearthing important problems and questions from operations
  – Putting research output into practice.
Thanks