Network Measurement Research in a Complex Networked World
(在複雜網絡世界中的網絡測量研究)

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Internet Infrastructure and Security Laboratory

- Advanced Network Monitoring and Measurement Laboratory (ANEMOL)
- Internet measurement research (funded by the Innovation and Technology Commission)
  - "Design and Implementation of a Unified Box for Offering Network Path Measurement as a Service," a Tier-2 project
  - "Reliable and Accurate Bandwidth Measurement of Asymmetric Network Paths," a Tier-3 project
  - "Uncooperative Measurement and Monitoring of Internet Path Quality with Applications," a Tier-3 project
- Internet measurement services
  - “Performance Monitoring of Critical Network and Service Infrastructure in Hong Kong,” Funded by a government dept.
- Security projects
  - Android security and web security
Outline

A. The visions
B. The “old” network measurement field and new challenges
C. Recent network management initiatives
D. The (research) problems to solve
E. Our current projects
F. Conclusions
A. The visions
(1) Removing the information asymmetry between subscriber and provider

Hong Kong Broadband is the first ISP in Hong Kong that provides a “Steady Speed” guarantee, ensuring that our FibreHome 200, bb100, bb50 and bb25 broadband plans always provide upload and download speeds at least 80% of what we advertised. If we fail to live up to this guarantee, we’ll double refund you for each day you experienced slow speeds.

* Measured from user home’s wallplate to HKIX2

Take the test and see how your ISP stacks up!

- **Broadband Speed Test**
  Only a few simple steps to see your download/upload speeds! (Only Available in Chinese)

- **FibreHome 200 Speed Test**
  Dedicated FibreHome 200 user’s speed test (Only Available in Chinese)
(1) HKBN fined for deceptive representations

**FINAL DECISION OF THE COMMUNICATIONS AUTHORITY**

**ALLEGED MISLEADING OR DECEPTIVE REPRESENTATIONS BY HONG KONG BROADBAND NETWORK LIMITED IN RELATION TO THE TRANSMISSION SPEED OF ITS BROADBAND SERVICE SET OUT IN ITS ADVERTISEMENTS AND PROMOTIONAL MATERIALS**

<table>
<thead>
<tr>
<th>Licensee Concerned:</th>
<th>Hong Kong Broadband Network Limited (&quot;HKBN&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Issue:</td>
<td>The representations in relation to the transmission speed of HKBN’s broadband service set out in its advertisements and promotional materials were alleged to be misleading or deceptive</td>
</tr>
<tr>
<td>Relevant Instruments:</td>
<td>Section 7M of the Telecommunications Ordinance (&quot;TO&quot;) (Cap. 106)</td>
</tr>
</tbody>
</table>
(2) Open access to ISPs’ performance

(3) Third-party performance certification and auditing

Source: http://www.certifiedhph.com/
(4) Instantaneous Internet traffic reporting

(5) Server optimizing the data path
(5) Server optimizing the data path

Source: http://www.dialaphone.co.uk/blog/2013/05/11/best-public-transport-apps/
(6) Auto-reconfiguration to bypass faults

Source: http://techpubs.sgi.com/library/dynaweb_docs/0530/SGI_Admin/books/FDDIX_AGsgi_html/ch03.html
(7) Network measurement as a service

B. The “old” network measurement field and new challenges
Internet measurement research

• Devising sound and pragmatic methodologies for measuring different aspects (infrastructure, traffic and applications) of the Internet
  – Network traffic measurement
  – Network topology measurement
  – Network performance measurement
  – ...

• Measurement methodology, metrics, experiments, tools, data analysis, calibration, ...
Seminal works

• Walter Willinger on self-similar traffic
  – Many papers followed: http://www.informatik.uni-trier.de/~ley/pers/hd/w/Willinger:Walter.html

• Paxson on measuring IP network performance
  – “Growth Trends in Wide-Area TCP Connections” 1994
  – “Measurements and Analysis of End-to-End Internet Dynamics”, 1997
Research efforts

• The first PAM workshop in 2000, Hamilton, New Zealand
  – The 2\textsuperscript{nd} organized by RIPE NCC, ...
  – The 14\textsuperscript{th} by our research group
• The first IMC workshop in 2001, San Francisco, California, USA, organized by netVMG and Sprint
• Others: SIGCOMM, CoNEXT, SIGMETRICS, etc
• CAIDA, RIPE NCC, IETF’s IPPM WG, M-Lab (Google), Internet’s perfSONAR, MPlane

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Types of measurement

- **Active measurements**
  - Topology, configuration, routing, SNMP

- **End-to-end performance**
  - Average download time of a web page
  - TCP bulk throughput
  - End-to-end delay and loss
  - Link bit error rate
  - Link utilization
  - Traffic matrix
  - Demand matrix

- **Packet and flow measurements, SNMP/RMON**

Source: Tutorial on "Traffic Measurement for IP Operations" (Grossglauser and Rexford) at ACM SIGCOMM’01 and IEEE INFOCOM’02
Cross-domain active e2e

end-to-end performance

average download time of a web page

TCP bulk throughput

end-to-end delay and loss

link bit error rate

link utilization

active topology

active routes

traffic matrix

demand matrix

state

traffic

packet and flow measurements, SNMP/RMON

topology, configuration, routing, SNMP

active measurements

Source: Tutorial on "Traffic Measurement for IP Operations" (Grossglauser and Rexford) at ACM SIGCOMM’01 and IEEE INFOCOM’02
New challenges

• Scale of the Internet
• Many middleboxes
• Security alerts
• Different application requirements
• User’s QoE, instead of network’s QoS
Challenges to e2e 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 e2e 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
B. The recent network measurement initiatives
MPlane: a major effort in Europe

Decentralized and diverse, the Internet is resilient and universal. However, its distributed nature leads to operational brittleness and difficulty in identifying and tracking the root causes of performance and availability issues. The first step to improve this fragmentation is measurement: illuminating the currently obscure dynamics of the Internet. To address this, we advocate a measurement plane, or mPlane alongside the Internet’s data and control planes.

mPlane consists of a Distributed Measurement Infrastructure to perform active, passive and hybrid measurements; it operates at a wide variety of scales and dynamically supports new functionality. A Repository and Analysis layer collects, stores, and analyses the collected data via parallel processing and data mining. Finally, an Intelligent Reasoner iteratively drills down into the cause of an evidence, determining the conditions leading to given issues, and supporting the understanding of problem origins.

Source: http://www.ict-mplane.eu/
“The Internet is the first thing that humanity has built that humanity doesn't understand, the largest experiment in anarchy that we have ever had.”

Eric Schmidt – ex Google Exec. Chairman

Source: http://www.ict-mplane.eu/
A complicated technology...

The internet is a key infrastructure where different technologies are combined to offer a plethora of services. It’s horribly complicated and we sorely miss the technology to understand what is happening in the network and thus to optimize its performance and utilization.

Source: http://www.ict-mplane.eu/
A complicated technology... ...that no one controls and understands

- Why Skype is not working?
- Which is the best ISP in my area?
- Where is traffic coming from?
- How to optimize my LTE network for Facebook?

There are no tools to help me!

Source: http://www.ict-mplane.eu/
The mPlane architecture will allow to iteratively drill down into the measurement being collected to find the root cause of an evidence.

Source: http://www.ict-mplane.eu/
Internet2 and SamKnows in the US

Deployment Status

A listing of currently deployed perfSONAR services can be found here.

Release Information

- Internet2-coordinated
  - 20 April 2012: pS-Performance Toolkit 3.2.2
  - 17 October 2011: pS-Performance Toolkit 3.2.1
  - 21 October 2010: pS-Performance Toolkit 3.2
  - 23 April 2010: pS-Performance Toolkit 3.1.3
  - 18 February 2010: pS-Performance Toolkit 3.1.2
  - 06 November 2010: pS-Performance Toolkit 3.1.1
  - 26 September 2009: pS-Performance Toolkit 3.1
  - 08 April 2009: perfSONAR-PS 3.1
- GEANT-coordinated
  - 15 April 2008: perfSONAR-PS (Perl)
  - 18 January 2008: perfSONAR-PS (Perl)
<table>
<thead>
<tr>
<th>Services Offered</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth Test Controller (BWCTL)</td>
<td>Running</td>
</tr>
<tr>
<td>• tcp://perfonar.ucar.edu:4823</td>
<td></td>
</tr>
<tr>
<td>Lookup Service</td>
<td>Running</td>
</tr>
<tr>
<td>• <a href="http://perfonar.ucar.edu:9995/perfSONAR_PS/services/hLS">http://perfonar.ucar.edu:9995/perfSONAR_PS/services/hLS</a></td>
<td></td>
</tr>
<tr>
<td>Network Diagnostic Tester (NDT)</td>
<td>Running</td>
</tr>
<tr>
<td>• tcp://perfonar.ucar.edu:3001</td>
<td></td>
</tr>
<tr>
<td>• <a href="http://perfonar.ucar.edu:7123">http://perfonar.ucar.edu:7123</a></td>
<td></td>
</tr>
<tr>
<td>Network Path and Application Diagnosis (NPAD)</td>
<td>Running</td>
</tr>
<tr>
<td>• tcp://perfonar.ucar.edu:8001</td>
<td></td>
</tr>
<tr>
<td>• <a href="http://perfonar.ucar.edu:8000">http://perfonar.ucar.edu:8000</a></td>
<td></td>
</tr>
<tr>
<td>One-Way Ping Service (OWAMP)</td>
<td>Running</td>
</tr>
<tr>
<td>• tcp://perfonar.ucar.edu:861</td>
<td></td>
</tr>
<tr>
<td>perfSONAR-BOUY Regular Testing (Throughput)</td>
<td>Running</td>
</tr>
<tr>
<td>perfSONAR-BOUY Measurement Archive</td>
<td>Running</td>
</tr>
<tr>
<td>• <a href="http://perfonar.ucar.edu:8085/perfSONAR_PS/services/pS8">http://perfonar.ucar.edu:8085/perfSONAR_PS/services/pS8</a></td>
<td></td>
</tr>
<tr>
<td>perfSONAR-BOUY Regular Testing (One-Way Latency)</td>
<td>Not Running</td>
</tr>
<tr>
<td>PingER Measurement Archive and Regular Tester</td>
<td>Running</td>
</tr>
<tr>
<td>• <a href="http://perfonar.ucar.edu:8075/perfSONAR_PS/services/pinger/ma">http://perfonar.ucar.edu:8075/perfSONAR_PS/services/pinger/ma</a></td>
<td></td>
</tr>
<tr>
<td>SNMP Measurement Archive</td>
<td>Running</td>
</tr>
<tr>
<td>• <a href="http://perfonar.ucar.edu:9990/perfSONAR_PS/services/SNMPMA">http://perfonar.ucar.edu:9990/perfSONAR_PS/services/SNMPMA</a></td>
<td></td>
</tr>
<tr>
<td>Traceroute Measurement Archive</td>
<td>Running</td>
</tr>
<tr>
<td>• <a href="http://perfonar.ucar.edu:8086/perfSONAR_PS/services/tracerouteMA">http://perfonar.ucar.edu:8086/perfSONAR_PS/services/tracerouteMA</a></td>
<td></td>
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<tr>
<td>Traceroute Regular Testing</td>
<td>Running</td>
</tr>
</tbody>
</table>

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SamKnows and Bismark

Global Leaders in Broadband Measurement
Sign up with us today to accurately measure your broadband performance.

Sign up here to measure...

American Broadband
European Broadband
Singaporean Broadband
Brazilian Broadband
UK Broadband
Active measurement in Bismark

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type</th>
<th>Prot.</th>
<th>Freq.</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BISMark: 17 devices, 3 ISPs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latency</td>
<td>End-to-end</td>
<td>ICMP</td>
<td>5 min</td>
<td>Host</td>
</tr>
<tr>
<td></td>
<td>Last-mile</td>
<td>ICMP</td>
<td>5 min</td>
<td>First IP hop</td>
</tr>
<tr>
<td></td>
<td>Upstream load</td>
<td>ICMP</td>
<td>30 min</td>
<td>During upload</td>
</tr>
<tr>
<td></td>
<td>Downstream load</td>
<td>ICMP</td>
<td>30 min</td>
<td>During download</td>
</tr>
<tr>
<td>Packet loss</td>
<td>End-to-end</td>
<td>UDP</td>
<td>15 min</td>
<td>D-ITG</td>
</tr>
<tr>
<td>Jitter</td>
<td>End-to-end</td>
<td>UDP</td>
<td>15 min</td>
<td>D-ITG</td>
</tr>
<tr>
<td>Downstream Throughput</td>
<td>Single-thread HTTP</td>
<td>TCP</td>
<td>30 min</td>
<td>curlget to Host</td>
</tr>
<tr>
<td></td>
<td>Passive throughput</td>
<td>N/A</td>
<td>30 min</td>
<td>/proc/net/dev</td>
</tr>
<tr>
<td></td>
<td>Capacity</td>
<td>UDP</td>
<td>12 hrs</td>
<td>ShaperProbe</td>
</tr>
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<td>Upstream Throughput</td>
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</tr>
</tbody>
</table>
Bismark deployment
C. The (research) problems to solve
(1) Measuring network path properties

- Cooperative vs uncooperative
- Forward-path, reverse-path, both
- Data channel vs control channel

<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></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sting [21]</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>Coop.</td>
<td>F</td>
<td>Improved probing algorithm</td>
<td>Packet trains</td>
</tr>
<tr>
<td>Packet reordering:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dual connection test [2]</td>
<td>Uncoop.</td>
<td>F, B, D</td>
<td>Induce ACK pairs with IPIDs</td>
<td>Two TCP data segments in two connections</td>
</tr>
<tr>
<td>SYN test [2]</td>
<td>Uncoop.</td>
<td>F, B, D</td>
<td>Induce different SYN-RST pairs</td>
<td>Two TCP SYNs in two connections</td>
</tr>
<tr>
<td>POINTER [12]</td>
<td>Uncoop.</td>
<td>F, B, D</td>
<td>Induce different TCP data and ACKs</td>
<td>Two TCP data/ACKs in a single connection</td>
</tr>
<tr>
<td>Reordering, loss and queuing delay:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>tulip [13]</td>
<td>Uncoop.</td>
<td>F, B, D</td>
<td>Induce ICMP replies with IPIDs</td>
<td>Two/three ICMP timestamp requests</td>
</tr>
<tr>
<td>Available bandwidth:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ImTCP [23]</td>
<td>Uncoop.</td>
<td>F</td>
<td>Self-loading periodic streams</td>
<td>TCP data packet trains</td>
</tr>
<tr>
<td>Capacity:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SProbe [20]</td>
<td>Uncoop.</td>
<td>F, B</td>
<td>Induce RST pairs</td>
<td>Two TCP SYN segments</td>
</tr>
</tbody>
</table>
(1) Measuring network path properties (cont’d)

• How to measure capacity without flooding?
  – Packet-pair measurement, machine learning?
• How stable is the available bandwidth for an e2e path?
• How to sample packet losses without self-inducing losses?
• How to sample the path performance per application flow?
  – Inband vs out-of-band, existing protocol vs new protocol
• How to mitigate the influence of middleboxes?
• Our works: HTTP/OneProbe (USENIX ATC’09), MDDIF (CoNEXT’09), Loss-pair analysis (IMC’10), TRIO (CoNEXT’11), Irate (NSDI’13 poster/demo)
(2) Fault diagnosis

• Network tomography: Inferring link-level characteristics (e.g., loss, delay) from a set of e2e path measurement
• Active vs passive tomography
• Unicast vs multicast probes

Source: “Network Radar: Tomography from Round Trip Time Measurements”
(2) Problems with network tomography

- The knowledge of an IP-level network topology
- Multicast probes are not widely supported
- Exponential increase in e2e path measurement if unicast is used.
- **Our works**: using coordinated measurement to diagnose faults (HotDep’10 poster, PAM’11, Networking’12, IM’13)
(3) Cross-domain network diagnosis

Call for Papers
IEEE Communications Magazine

Monitoring and Troubleshooting Multi-domain Networks using Measurement Federations

Aims and Scope
In both the scientific and corporate worlds, users, resources, and data are often physically distributed, making networks increasingly important for all operations. Enormous progress has been made in increasing the capacity and accessibility of networking infrastructures, which in turn has fostered wider adoption of Cloud and Grid environments. Unfortunately, these advances have not directly translated into improved performance for all applications and users. Instead, network performance problems become even more subtle and detrimental as the number of the network increases, and troubleshooting them on multi-domain network paths is highly challenging. These problems may be as benign as congestion from other network users, or as serious as packet loss caused by one or more intermediate-domain infrastructure and architectural flaws.

Troubleshooting performance problems on multi-domain networks requires great deal of effort and expertise, as well as measurement policy agreements that mutually benefit domains within measurement federations. Novel approaches are needed to foster wider adoption of explicit measurement federations such as perfSONAR, SumKnows, Grenouille and M-Lab involving co-operating agents in collaborating vendor organizations as well as user communities. These approaches may also be suitable for implicit measurement federations soon in content-delivery networks involving multiple service providers that co-operate to reduce operating costs, while providing satisfactory end-user experience. Building upon current end-to-end measurement federation related standards-development efforts - at Open Grid Forum (OGF), IETF IP Performance Metrics (IPPM), IEEE 802.1 arg, ITU-T Y.1731, and Metro Ethernet Forum (MEF) - can benefit the interoperability and sustainability of explicit and implicit measurement federations.

In addition, sophisticated tools are required to monitor multi-domain networks and to detect, localize and diagnose performance problems in real-time. As networks increase in capacity, and new paradigms such as Software Defined Networking emerge to aid in traffic management, performance monitoring tools must be scalable and capable of detecting performance issues in a timely manner. The monitoring and diagnosing tools must comply with measurement federation policies, and aid network operators when troubleshooting perceived abnormalities, as well as help network middleware and intelligent applications to work around problems, ultimately minimizing the impact to end users.

This special issue will cover novel techniques and standardization efforts in the area of monitoring and troubleshooting of multi-domain networks using measurement federations. Topics to be covered include, but are not limited to:

- Algorithms and Techniques for Automated Network Troubleshooting
- Architectures for Federated Measurement Collection and Sharing
- Intra and Inter Domain Monitoring Strategies
- Measurement Federation related Standards-development Efforts
- Monitoring of Software Defined, Content-delivery and Overlay Networks
-Troubleshooting of Hybrid Packet and Circuit Networks
- Network-aware Middleware for High Speed Networks
- Measurements from Cloud and Grid Environments
- Security and Policy Considerations for Federated Measurements
- New Policy-based Network Monitoring/Analysis Tools and Paradigms
- End-to-End ("Disk-to-Disk") Performance Problem Troubleshooting
- Scalability of Measurement Methods and Infrastructures
- Embedded Active Monitoring based Collaborative Management
- Case Studies of End-to-End or Network Performance Troubleshooting
- Federations to jointly troubleshoot Home-area and Wide-area Networks
(3) Cross-domain network diagnosis (cont’d)

- Network tomography without fixed topology
- A “sufficient” number of probes “strategically” distributed
- Coordinated and adaptive probing
- E2e measurement with traceroute facility
- Federated network measurement
(3) Cross-domain cont’d: Existing platforms

- iPlane (providing accurate predictions of Internet path performance for emerging overlay services)
- Scriptroute (allowing any user to connect to any server and execute any safe network measurement)
- Dipzoom (using P2P concepts to bring together experimenters in need of measurements with external measurement providers)
- Crowdsourcing (e.g., Portolan, a crowdsourcing-based system that uses smartphones as mobile measuring elements)
- Edge measurement (e.g., Dasu, a measurement experimentation platform for the Internet's edge)
- Etomic (closed?)
- **Our work: Open Measurement Platform**
(4) Measuring user’s QoE

- Network QoS, application QoS and user’s QoS (QoE)
- MOS vs network QoS for HTTP streaming

- Our works: IM’11 (pre-conf), W-MUST’11, MMSys’12, NSDI’13 poster/demo
(5) Scientific study of network properties

• Power-law relationship in the Internet topology discovered around 15 years ago

• Route asymmetry in the Internet discovered around 10 years ago

• Delay asymmetry in the Internet

• “Network science”

• Our work: “Characterizing Inter-domain Rerouting by Betweenness Centrality after Disruptive Events” (JSAC 2013)
D. Our current projects
(1) Residential broadband measurement platform

- Enabling users with network diagnosis capability
- Performing cooperative network measurement
- HTTP/OneProbe in OpenWrt routers
- “OMware: An Open Measurement Ware for Stable Residential Broadband Measurement" SIGCOMM'13 poster/demo
(2) High-performance measurement box

- Implementing measurement functions in kernel and NetMagic
- Supporting client-side and server-side measurement
- Unified APIs for POSIX raw socket, OpenWrt and NetMagic
(3) Network measurement as a service

- Providing measurement service to a content service provider
- Providing measurement service to clients
(4) HTTP streaming

- IRate: determining the best initial bit rate

- QDASH: adjust bit rate during the playback
(5) Appraising the accuracy of browser-based measurement

- Inaccuracy introduced by browsers
- Inaccuracy introduced by the measurement methods

<table>
<thead>
<tr>
<th>Approaches</th>
<th>Technology</th>
<th>Availability</th>
<th>Methods</th>
<th>Subject to the same-origin policy by default?</th>
<th>Measured path quality</th>
<th>Tools / Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>XHR</td>
<td>Native</td>
<td>GET, POST</td>
<td>Yes, Yes</td>
<td>RTT, Tput</td>
<td></td>
<td>Speedof.me [2], BandwidthPlace [14]</td>
</tr>
<tr>
<td>DOM</td>
<td>Native</td>
<td>GET</td>
<td>No</td>
<td>RTT, Tput</td>
<td></td>
<td>[9], [14], Wang’s method [22]</td>
</tr>
<tr>
<td>Flash</td>
<td>Plug-in</td>
<td>GET, POST</td>
<td>Yes*, Yes*</td>
<td>RTT, Tput</td>
<td>Speedtest [17], AuditMyPC [3], Speedchecker [20]</td>
<td></td>
</tr>
<tr>
<td>Java applet</td>
<td>Plug-in</td>
<td>GET, POST</td>
<td>Yes*, Yes*</td>
<td>RTT, Tput</td>
<td>Bandwidth Meter [5], InternetFrog [8]</td>
<td></td>
</tr>
<tr>
<td>WebSocket</td>
<td>Native</td>
<td>TCP</td>
<td>No</td>
<td>RTT, Tput</td>
<td></td>
<td>Netlyzer [12], HMN [18], JavaNws [13], Pingtest [16], NDT [15], AuditMyPC [4]</td>
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<td>Yes*</td>
<td>RTT, Tput</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: * The same-origin policy can be bypassed.
(6) Open measurement platform

- HARNET measurement (since 1 Jan 2009)
(5) Open measurement platform

- OMP for CERNET-2: Tsinghua U., Xiamen U., ...
- OMP for residential broadband
- OMP for IPv4 networks
E. Conclusions
Conclusions

• “IP networks are hard to measure by design.” (Grossglauser and Rexford)
  – Best-effort network measurement
  – The deployed e2e methods much less than best effort.

• The role of network measurement in the increasingly network-dependent and usage-based applications
  – A lack of science in the network measurement practices
  – Not enough skepticism on the measurement accuracy

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