

# Large-Scale Network Measurements

## What? Why? How? Findings? Impact?

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# Prelude

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Subject: \$EVENT - Invitation for a Keynote Presentation

Dear \$NAME,

on behalf of the Organizing Committee of \$EVENT...

\$EVENT is the premier annual conference...

[[Something nice about \$NAME and about the suggested topic.]]

We hope that you can accept this invitation. May we kindly ask that you to let us know about your decision soon, preferably by \$DATE.

We are looking forward to meeting you at \$EVENT in \$LOCATION.

[...] you could focus on [...] measurement and monitoring.

# Prelude

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## Measurements?

*Measurement* is the assignment of numbers to objects. [wikipedia]

*Network traffic measurement* is the process of measuring the amount and type of traffic on a particular network. [wikipedia]

## Monitoring?

To *monitor* or *monitoring* generally means to be aware of the state of a system. [wikipedia]

The term *network monitoring* describes the use of a system that constantly monitors a computer network for slow or failing components and that notifies the network administrator in case of outages. [wikipedia]

# Prelude

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## Network Management?

*Network management* refers to the activities, methods, procedures, and tools that pertain to the operation, administration, maintenance, and provisioning of networked systems. [wikipedia]

Network management is about control loops:

Measurements -> Monitoring -> Management -> Action

# Prelude

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## Network measurement

### Conferences:

1. Internet Measurement Conference (IMC)
2. Passive and Active Measurement (PAM)
3. (SIGCOMM, SIGMETRICS)

### Organizations:

1. ACM SIGCOMM
2. ACM SIGMETRICS
3. USENIX

### Standards:

1. IETF TSV-AREA (IPPM)

## Network management

### Conferences:

1. Integrated Management (IM)
2. Network Operations and Mgmt (NOMS)
3. Network and Service Management (CNSM)

### Organizations:

1. IEEE CNOM
2. IFIP WG 6.6

### Standards:

1. IETF OPS-AREA (SNMP, IPFIX, ...)

# Prelude

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## Network measurement

The structure of the measured system is generally unknown and measurements are used to gain insights, but not to directly influence the system.

-> black box measurements

## Network management

The structure of the system and the system states are generally known and the monitoring activity can lead to actions that influence the system's state.

-> white box measurements

## What is the network measurement community researching?

1. Detective Stories (spam, botnets, phishing, censorship, dropbox, ...)
2. Social Networks (facebook, google+, ...)
3. Mobile Network Performance
4. Services (Video on Demand, IP TV, P2P, ...)
5. Measurements Methodologies and Tools
6. Traffic Characterization (home, cloud, web, ..., schools, ...)
7. BGP Behavior / AS Topology
8. DNS Behavior and Performance
9. TCP Performance

# Large-Scale Network Measurements

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# Outline

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- Prelude
- Large-Scale Measurement Platforms
  - Example #1: SamKnows
  - Example #2: RIPE Atlas
- Standardization Efforts
- Advice to PhD Students

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- Related Work

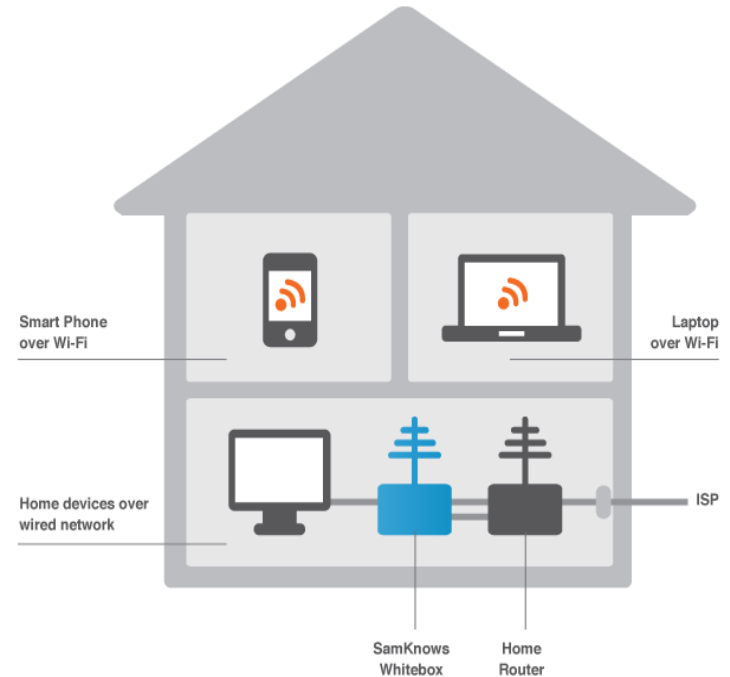
# Example #1 | SamKnows Platform

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- Measuring broadband performance (throughput, latency, jitter, loss, DNS resolution, ...)
    - 6 regulators and 12 ISP deployments:
      - Federal Communications Commission (FCC), United States
      - European Commission (EC), European Union
      - Canadian Radio-Television Commission (CRTC), Canada
      - Office of Communications (Ofcom), United Kingdom
      - Brazilian Agency of Telecommunications (Anatel), Brazil
      - Infocomm Development Authority of Singapore (IDA), Singapore
  - Around 40K measurement probes deployed
- <http://www.ietf.org/proceedings/85/slides/slides-85-iesg-opsandtech-7.pdf>

# Example #1 | SamKnows Platform

- SamKnows Whitebox functionality
  - Works as a ethernet bridge
  - The WiFi radio is only used to monitor cross-traffic
  - Does not perform any passive measurement tests
  - Active measurement tests run only in absence of cross-traffic
  - Tests catered specifically to measure broadband performance

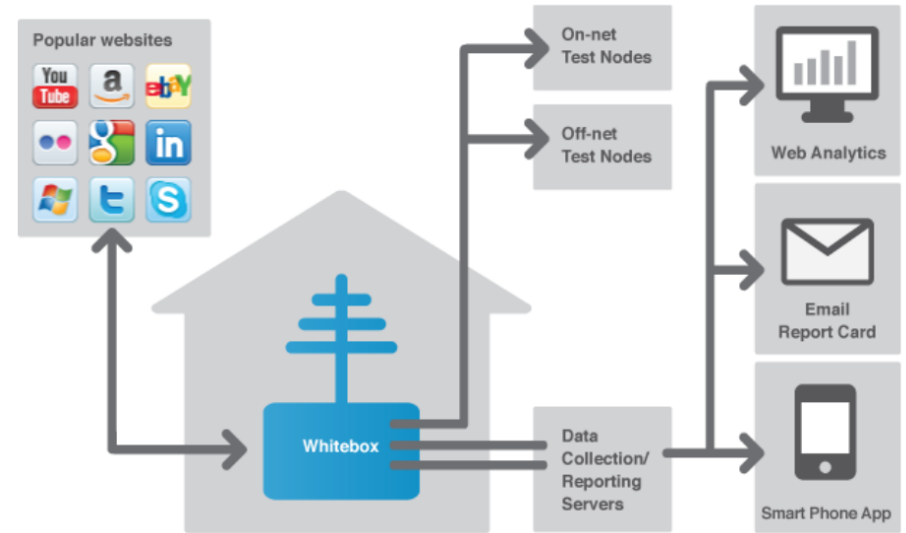


<http://www.samknows.com>

# Example #1 | SamKnows Platform

- Platform overview

- cron scripts schedule the measurement tests
- on-net nodes: measurement servers within ISP
- off-net nodes: measurement servers outside ISP
- ISPs signing code of conduct get anonymized and aggregated measurement result data

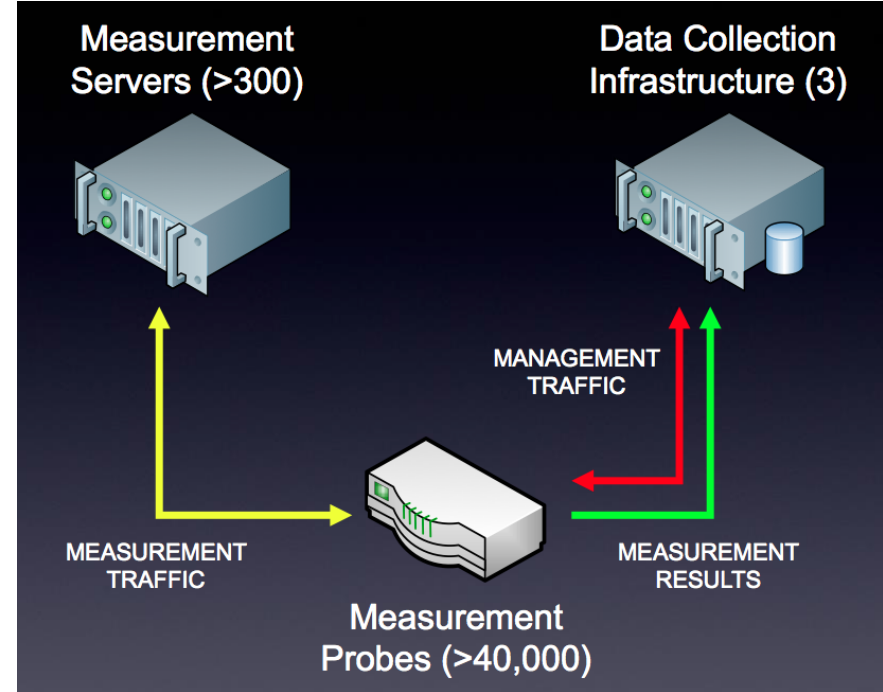


<http://www.samknows.com>

# Example #1 | SamKnows Platform

- Architecture

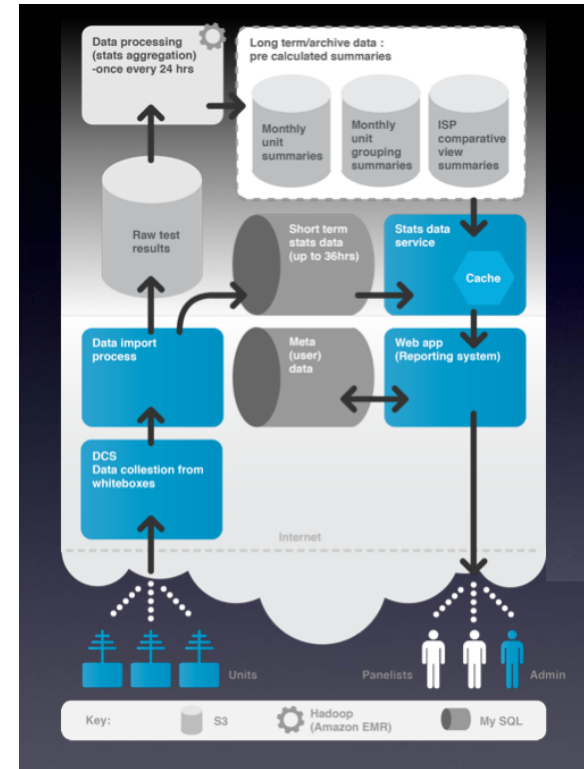
- Measurement Probes
  - runs on TP-Link router hardware
  - flashed with a custom snapshot of OpenWrt
  - tests and schedules are remotely upgradeable
- Measurement Servers
  - dumb servers to test against with
- Data Collection Servers (DCS)
  - functions both as a controller and a collector



<http://www.ietf.org/proceedings/85/slides/slides-85-iesg-opsandtech-7.pdf>

# Example #1 | SamKnows Platform

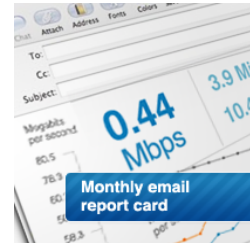
- Data Processing Backend
  - Raw measurement results are stored in Amazon S3
  - Recent stats and metadata are stored in MySQL
  - Hadoop jobs aggregate the data into monthly averages
  - Service-tier validation with the ISP
  - A web app generates a reporting web page with summary results



# Example #1 | SamKnows Platform

- Reporting Suite

- Web-based reporting system  
<http://reporting.samknows.com>
- Monthly email report card
- Smartphone app



<http://www.samknows.com>

# Example #1 | SamKnows Platform

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- Publications:

- WTF? Locating Performance Problems in Home Networks [[Sundaresan-TR-2013](#)]
- Web Performance Bottlenecks in Broadband Access Networks [[Sundaresan-SIGMETRICS-2013](#)]
- Trying Broadband Characterization at Home [[Sánchez-PAM-2013](#)]
- Revisiting Broadband Performance [[Canadi-IMC-2012](#)]
- Measuring Home Broadband Performance [[Sundaresan-CACM-2012](#)]
- Up, Down and Around the Stack: ISP characterization from Network Intensive Applications [[Bischoff-WMUST-2012](#)]
- Crowdsourcing ISP characterization to the network edge [[Bischoff-WMUST-2011](#)]
- Powerboost [[Bauer-HomeNets-2011](#)]
- Helping Users Shop for ISPs with Internet Nutrition Labels [[Sundaresan-HOMENETS-2011](#)]
- Broadband Internet Performance, A View from the Gateway [[Sundaresan-SIGCOMM-2011](#)]

# Example #1 | SamKnows Platform

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- Regulator Reports:
  - FCC: <http://www.fcc.gov/measuring-broadband-america>
  - Ofcom: <http://maps.ofcom.org.uk/broadband>

# Outline

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- Prelude
  - **Large-Scale Measurement Platforms**
    - Example #1: SamKnows
    - **Example #2: RIPE Atlas**
  - Standardization Efforts
  - Advice to PhD Students
- 
- Related Work

# Example #2 | RIPE Atlas

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## The Réseaux IP Européens Network Coordination Centre (RIPE NCC)

independent

not-for-profit membership organisation

supports the Internet infrastructure through technical coordination in its service region



## RIPE Atlas

a global network of probes that measure Internet connectivity and reachability

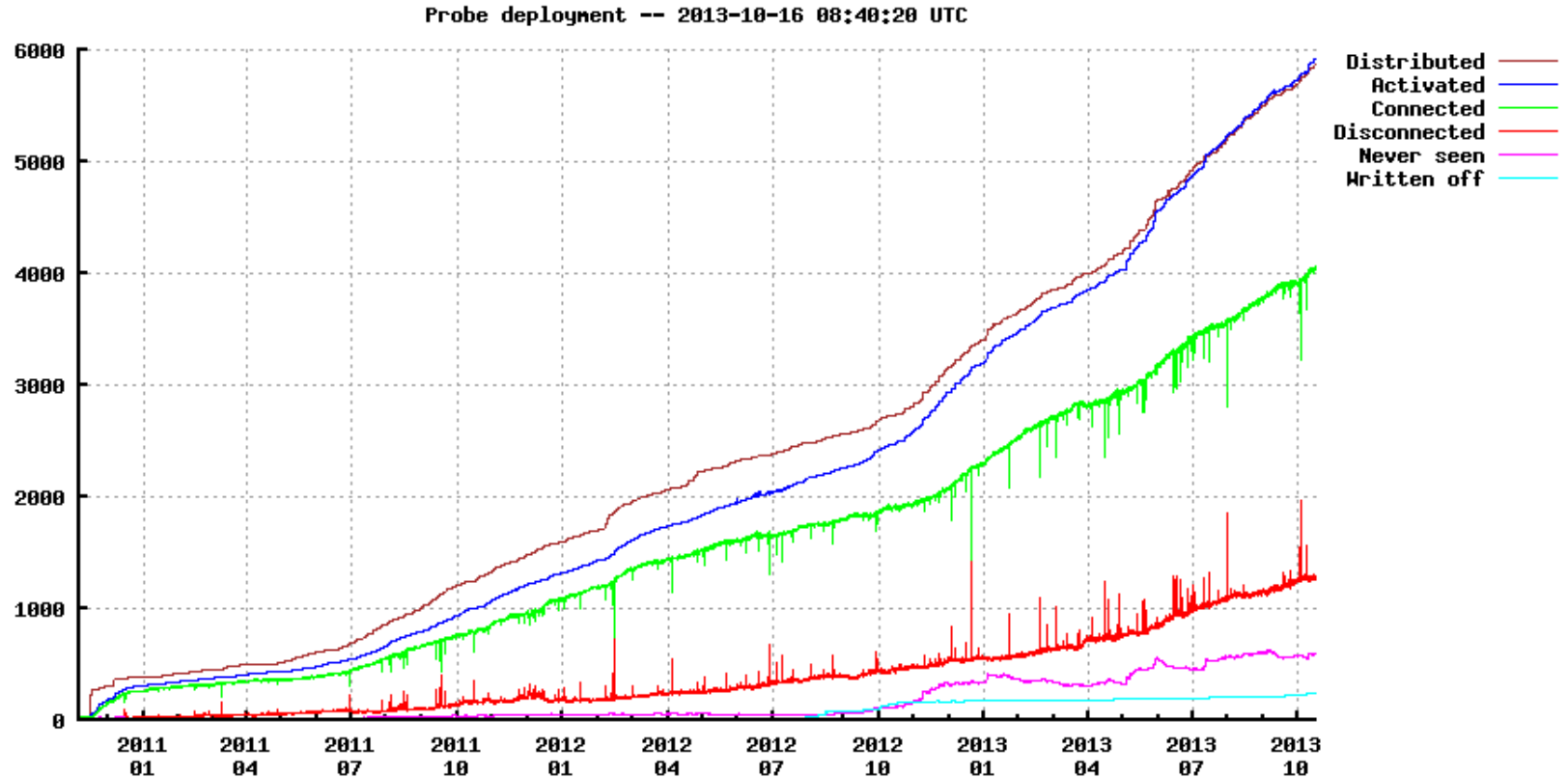
provides an unprecedented understanding of the state of the Internet in real time

# Example #2 | RIPE Atlas



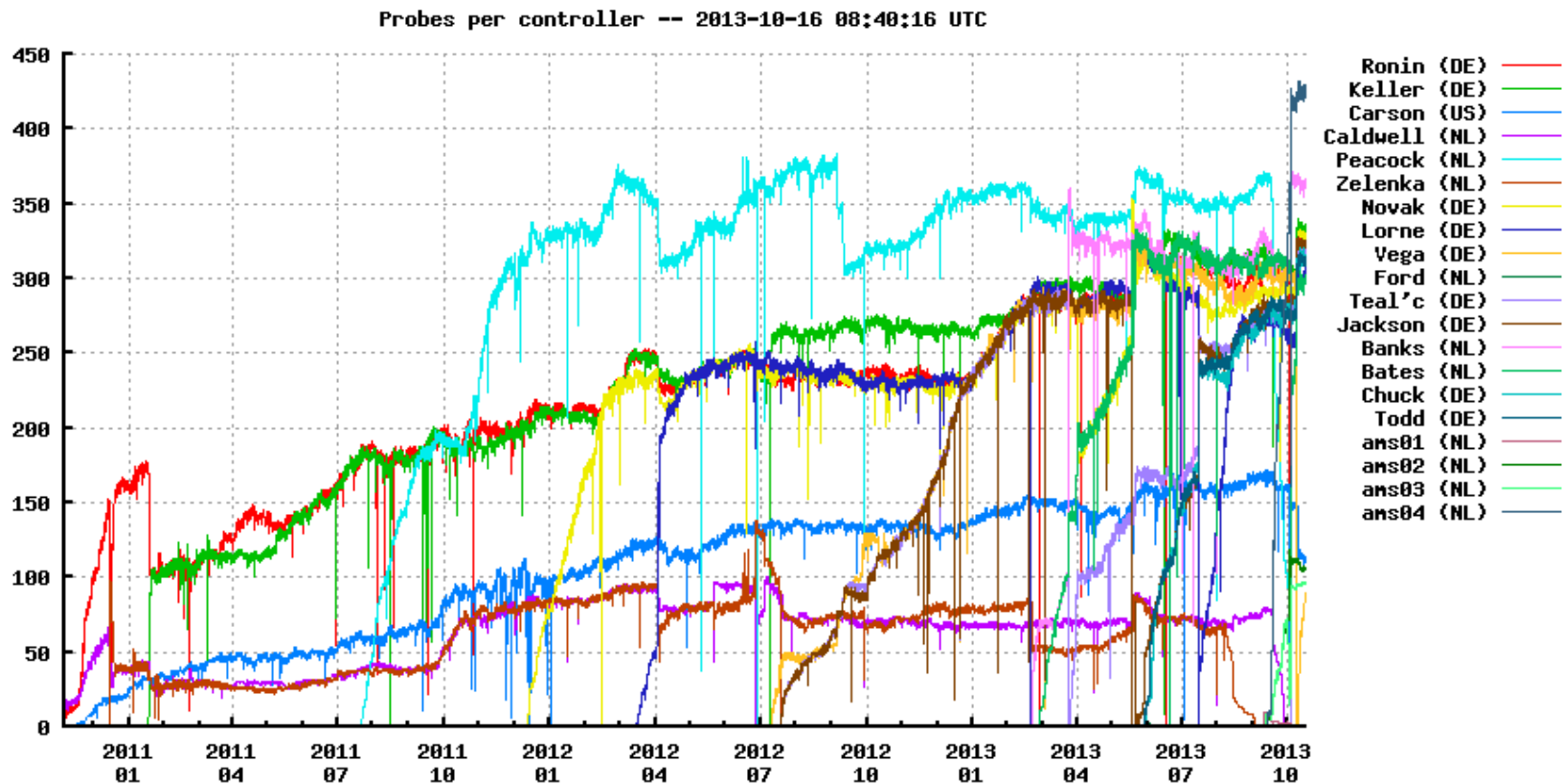
<https://atlas.ripe.net/results/maps>

# Example #2 | RIPE Atlas



<https://atlas.ripe.net/results/graphs>

# Example #2 | RIPE Atlas



<https://atlas.ripe.net/results/graphs>

# Example #2 | RIPE Atlas | Probes

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V3

TP-Link TL-MR3020 powered from USB port (500mA)

32 MB RAM, 4MB flash built-in

4GB flash on USB stick

firmware is updated remotely

runs OpenWRT, 400 MHz MIPS CPU with MMU

Cannot be used as a wireless router



V1, V2

Convenient form-factor

Production discontinued

# Example #2 | RIPE Atlas | Probes



# Example #2 | RIPE Atlas | Probes

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## Probe Capabilities:

1. Test its own network configuration
2. RTT measurements to the first and second hops
3. Current uptime, total uptime and uptime history
4. Ping and traceroute measurements to several root servers
5. Ping measurement to user-defined destinations
6. Traceroute measurement to user-defined destinations
7. DNS queries to root or user-defined DNS servers
8. SSL queries to user-defined destinations

# Example #2 | RIPE Atlas | User-defined Measurements

Active measurements defined by users

Types of measurements

DNS (v4, v6)

ping (v4, v6)

HTTP (v4, v6)

SSL Cert (v4, v6)

traceroute (v4, v6)

Public or private

Can be created only with sufficient credits (system warnings)

User-defined periodicity

User-defined number of participating probes

Scheduling

Limits: max 100 simultaneous measurements, max 500 probes/measurement, max 270,000 credits/day

Measure from

regions

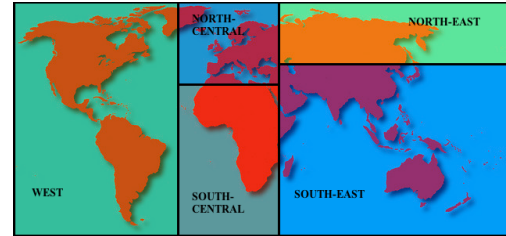
countries

AS

prefix

probes

existing UDM



Regions

# Example #2 | RIPE Atlas | User-defined Measurements

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## Credits (spend as much as you earn)

Receive for probe uptimes (more probes - more credits)

Spend to perform your own UDMs (more probes, higher frequency - more credits)

Variable costs for different measurements

Transaction history (downloadable)

Advanced warnings

Transfers to other users

One can request more (via an e-mail... and a good reason)

## Data access via

Web interface and a RESTful API: <http://atlas.ripe.net/doc/rest>

# Example #2 | RIPE Atlas | Analyses and Use-cases

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RIPE community: <https://atlas.ripe.net/results/analyses>

De-bogonising 128.0.0.0/16

Superstorm Sandy

Comparing TCP and UDP Response Times of DNS Root Servers

A Case Study of AAAA Filtering

Using RIPE Atlas: A DENIC Case Study

A Case Study of IPv6 /48 Filtering

A Use Case for IPv6 Reachability Testing with RIPE Atlas

RIPE Atlas & Anycast Instance Switches

DNS Measurements with RIPE Atlas Data

Independent research:

Traffic anomaly detection using a distributed measurement network:

<http://staff.science.uva.nl/~delaat/rp/2011-2012/p04/report.pdf>

Packet-pair technique for available bandwidth estimation in IPv6 network:

<http://arxiv.org/abs/1102.3533>

Discovering Path MTU black holes using RIPE Atlas:

[https://caldav.os3.nl/\\_media/2011-2012/students/maikel\\_de\\_boer/rp/de-boer\\_bosma-rp2\\_project\\_proposal.pdf](https://caldav.os3.nl/_media/2011-2012/students/maikel_de_boer/rp/de-boer_bosma-rp2_project_proposal.pdf)

# Outline

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- Prelude
- Large-Scale Measurement Platforms
  - Example #1: SamKnows
  - Example #2: RIPE Atlas
- **Standardization Efforts**
- Advice to PhD Students

- 
- Related Work

# Standardization Efforts | IETF

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- Large-Scale Measurement of Broadband Performance: Use Cases, Architecture and Performance Requirements  
[\[draft-schulzrinne-lmap-requirements-00\]](#)
- Internet Architecture Board (IAB) Plenary on Challenges of Network Performance Measurements, IETF 85
  - SamKnows platform by Sam Crawford:  
<http://www.ietf.org/proceedings/85/slides/slides-85-iesg-opsandtech-7.pdf>
  - Large-Scale Internet measurements for data-driven public policy by FCC :  
<http://www.ietf.org/proceedings/85/slides/slides-85-iesg-opsandtech-8.pdf>

# Standardization Efforts | IETF

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- Large-Scale Broadband Measurement Use Case [[draft-ietf-lmap-use-cases-00](#)]
  - Internet Service Provider (ISP)
    - Identify, isolate and fix problems in the access network
    - Evaluate the Quality of Experience (QoE) of the user
    - Benchmark and look into competitor insights
  - Consumers
    - Does the ISP service adhere to service level agreements (SLA)s?
    - Diagnose impaired components in the private network
  - Regulators
    - Need datasets to compare multiple broadband providers: <http://www.fcc.gov/measuring-broadband-america>
    - Frame better policies to help regulate the broadband industry: <http://maps.ofcom.org.uk/broadband>

# Standardization Efforts | IETF

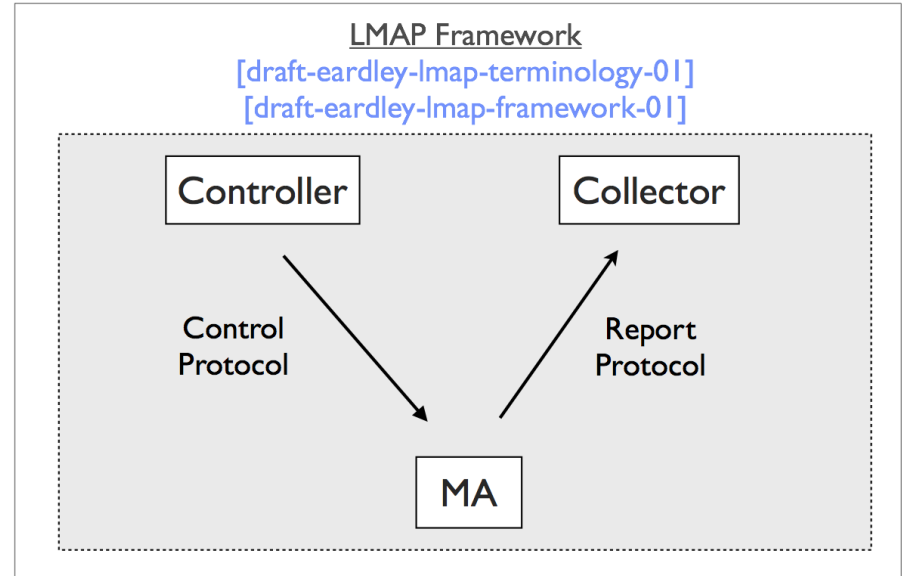
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- Large-Scale Measurement of Access Network Performance (LMAP) Bird of a Feather (BoF), IETF 86
  - LMAP scope (Network Provider Perspective) [[draft-boucadair-lmap-considerations-00](#)]
  - LMAP and IP Performance Metrics (IPPM) dependencies and coordination
  - Control and report protocol candidates, data model candidates:
    - NETCONF [[draft-schoenw-lmap-netconf-00](#)]
    - IPFIX [[draft-bagnulo-lmap-ipfix-01](#)]
    - ALTO [[draft-seedorf-lmap-alto-00](#)]
    - REST-based architectural style over HTTP
    - YANG [[draft-schoenw-lmap-yang-00](#)]
- LMAP working group approved in June 2013, first WG meeting at IETF 87

# Standardization Efforts | IETF

- IETF LMAP Working Group

- LMAP terminology and framework
- LMAP information model
  - Instructions
  - Schedules
  - Report channels
  - ...
- LMAP control protocol and data model
- LMAP report protocol and data model



# Standardization Efforts | IETF

- IETF IPPM Working Group

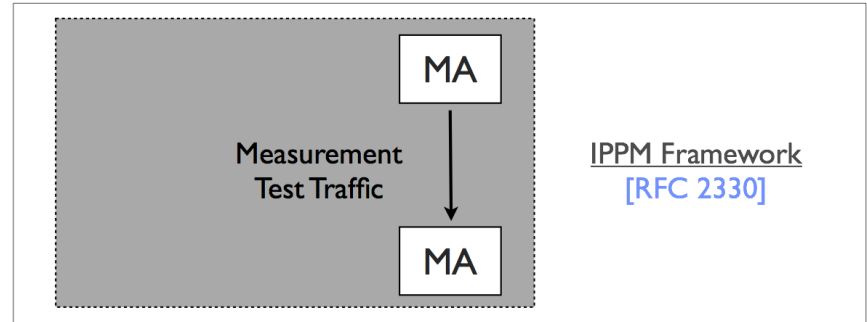
- Metrics:

- Connectivity [RFC 2678]
    - One-way delay [RFC 2679]
    - One-way packet loss [RFC 2680]
    - Round-trip delay [RFC 2681]
    - IP packet delay variation (or jitter) [RFC 3393]
    - Packet reordering [RFC 4737]
    - Round-trip packet loss [RFC 6673]

- Protocols:

- One-way active measurement protocol (OWAMP) [RFC 4656]
    - Two-way active measurement protocol (TWAMP) [RFC 5357]

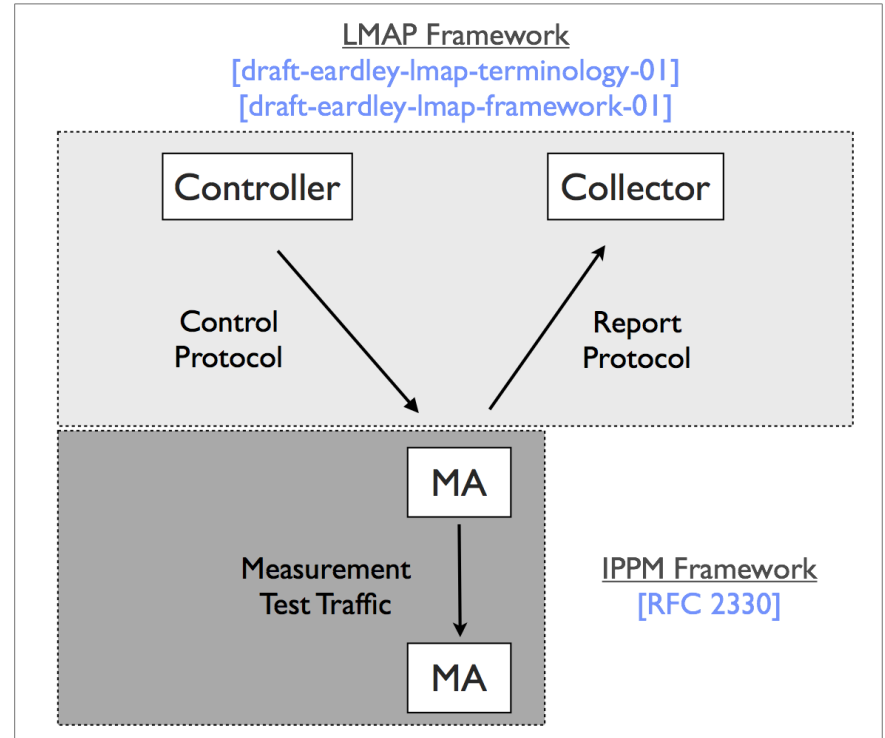
- Information model and XML data model for traceroute measurements [RFC 5388]



# Standardization Efforts | IETF

- IETF LMAP and IPPM Glue

- A reference path and measurement points for LMAP:  
[\[draft-ietf-ippm-lmap-path-01\]](#)
- Registry for commonly-used metrics:  
[\[draft-bagnulo-ippm-new-registry-00\]](#)  
[\[draft-bagnulo-ippm-new-registry-independent-00\]](#)



# Standardization Efforts | IETF

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- IETF Metric Blocks for use with RTCP's Extended Report Framework (Xrblock) Working Group:
  - RTP Control Protocol (RTCP) provides feedback on the quality of the Real Time Protocol (RTP) data distribution [\[RFC 3550\]](#)
  - RTCP Extended Reports (RTCP XR) convey information beyond the defined reception report blocks [\[RFC 3611\]](#)
    - Packet-by-packet block types
    - Reference time block types
    - Metrics block types
  - Xrblock evaluates proposals for new metric block type definitions
    - Measurement identity reporting [\[RFC 6776\]](#)
    - Packet delay [\[RFC 6843\]](#)
    - Packet delay variation [\[RFC 6798\]](#)
    - Burst/Gap loss [\[RFC 6958\]](#)

# Standardization Efforts | IEEE and ITU-T

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- Institute of Electrical and Electronics Engineers (IEEE)
  - Mobile Broadband Network Performance Measurements [[P802.16.3](#)]
    - End-to-end performance measurements
    - Characterize mobile broadband networks from the user's vantage point
- International Telecommunication Union - Telecommunication Standardization Sector (ITU-T)
  - Meet demands for a standardized methodology for measuring Internet access speeds
  - ITU-T Joint Coordination Activity on Conformance and Interoperability Testing (JCA-CIT) [2013 - 2016]

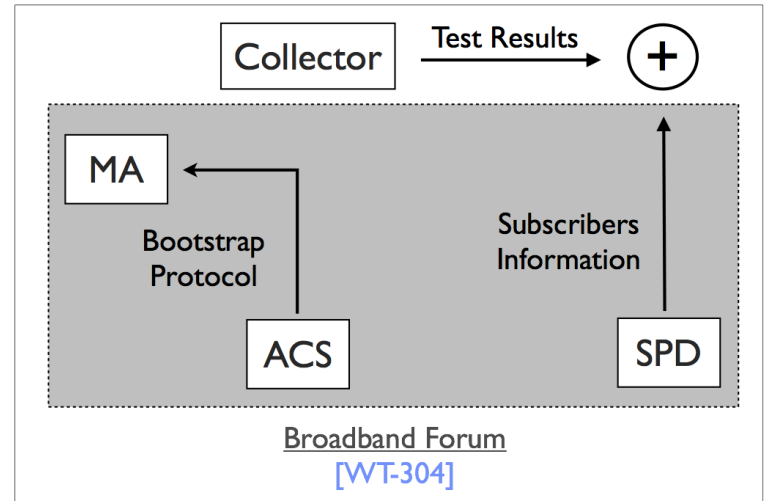
# Standardization Efforts | BBF

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- Enabling Network Throughput Performance Tests and Statistical Monitoring [\[TR-143\]](#)
  - Data-models to initiate performance, throughput and latency tests
  - Data-models to monitor the Customer Premises Equipment (CPE) using defined diagnostic mechanisms [\[TR-069\]](#)
- Broadband Access Service Attributes and Performance Metrics [\[WT-304\]](#)
  - Additional performance tests: loss, jitter, emulated streaming, browsing etc.
  - Additional capabilities:
    - Measure particular segments of the network
    - Measure across multiple networks
    - Scheduling tests
    - Initiate on-demand triggering of tests

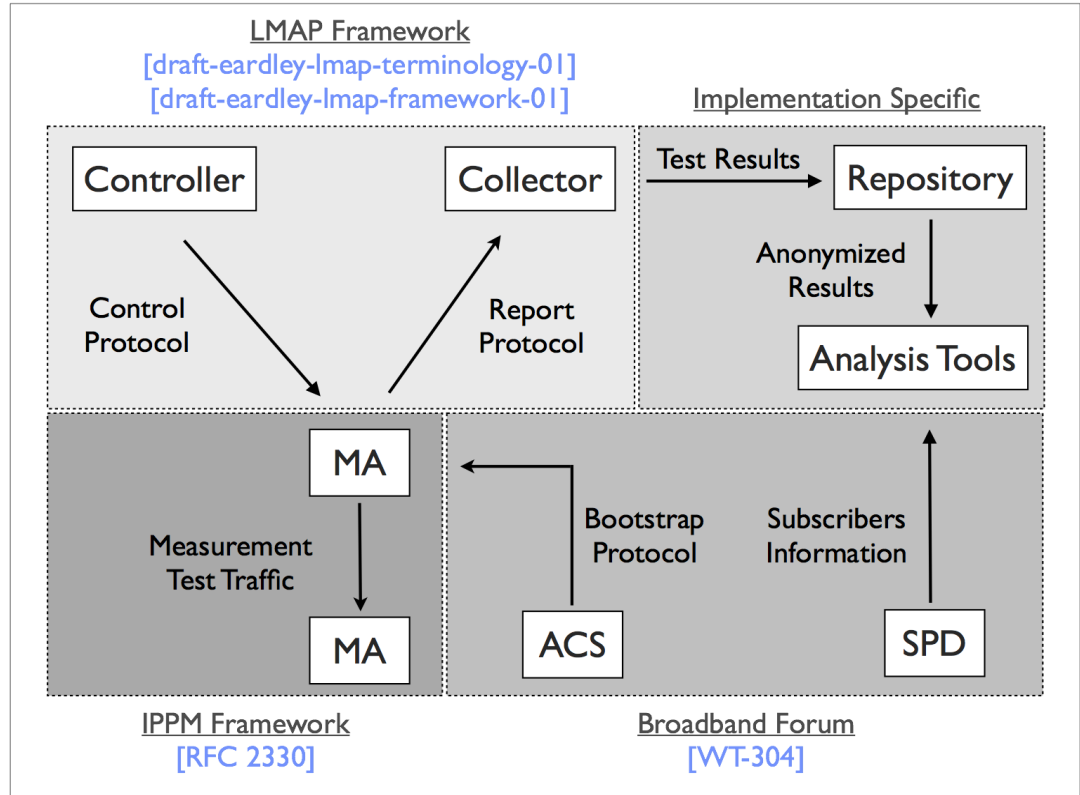
# Standardization Efforts | BBF

- Bootstrap the Measurement Agent (MA)
  - Using TR-069 (or DOCSIS)
- Capability exchange between Controller and MA
- On-demand tests
- Splicing Subscriber Parameter Database (SPD) into results
  - Collector splices the parameters into results (or)
  - MA reports the parameters to the Operational Support System (OSS) using TR-069



# Standardization Efforts | Big Picture

- IETF LMAP
  - Framework and terminology
  - Use cases
  - Information model
  - Data model
  - Control protocol
  - Report protocol
- IPPM Framework
  - Measurement metrics
- Broadband Forum
  - Bootstrap protocol
  - Splicing SPD



# Outline

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- Prelude
- Large-Scale Measurement Platform
  - Example #1: SamKnows
  - Example #2: RIPE Atlas
- Standardization Efforts
- **Advice to PhD Students**

- 
- Related Work

# Advice | Measurements need to be repeatable

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- Everything impacting the measurement must be clearly documented
- It is good practice to make the data set openly available
- Ideally, data sets can be used that have already been obtained by others in related work since this enabled comparisons
- Making the implementation of data analysis scripts available is a great idea since this allows others to follow up on your work

# Advice | Measurements require proper data analysis

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- It is not sufficient to throw a coin once to derive any conclusions about its behavior
- It is insufficient to state that a measurement has been repeated  $N$  times (or it did run for  $N$  days): you need to explain why  $N$  is a reasonable number
- Averages hide properties (e.g., variation), leading to wrong conclusions
- It is necessary to do some basic data analysis (like calculating percentiles or confidence intervals), some basic knowledge of statistics is needed

# Advice | Measurements produce data not graphs

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- While plots are nice, it is often more useful to provide numeric results in tables
- Have you ever tried to read numbers out of a 3D-plot in a paper to compare them with your results?
- Impressive colorful plots often have close to zero value
- Think about numbers as the main result of your measurement and graphs just as an *additional* representation to visualize certain interesting aspects

# Advice | Measurements results need an interpretation

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- It is not sufficient to produce a number of tables and plots
- It is crucial to interpret data - in particular, any unexpected results need an explanation
- Yes, this can often be difficult and usually requires further measurements in order to understand what is going on
- But gaining further insight into the system is crucial for understanding it
- Substantial research often starts after the initial data has been collected and you observe something unexpected that you cannot explain

# Advice | Measurements need to be designed

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- You need to design the measurements you perform
- You need to think upfront about the research question you want to answer with the measurement and which data you need
- Start from a rather simple question; but once the obtained results show surprising (unexpected) behavior, it is crucial to iterate by designing new measurements to find answers explaining the surprising behavior
- Use models and the literature to derive a sound understanding of what you measure and what expected results are before measuring

**Thanks for your attention!**

**Questions?**

# Related Work | One-off measurements

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- Early studies:
  - Inject packet trains to infer broadband link characteristics [Dischinger-IMC-2007].
- Software-based:
  - Speedtest.net, A flash tool to measure broadband throughput: <http://www.speedtest.net>.
  - Glasnost, A Java-based applet that detects ISP-enforced traffic shaping [Dischinger-NSDI-2010].
  - Netalyzr, A Java-based applet that performs DNS, NAT, HTTP, IPv6-based tests [Kreibich-IMC-2010].
  - Fathom, A Firefox-extension to Netalyzr [Dhawan-IMC-2012].

# Related Work | Topology Discovery

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- Traceroute-based
  - Cooperative Association for Internet Data Analysis (CAIDA) Archipelago (Ark) (or skitter): <http://www.caida.org/projects/ark>
  - Ripe Test Traffic Measurement (TTM): <http://www.ripe.net/data-tools/stats/ttm/test-traffic-measurement-service>
  - Dimes, A software agent that performs ping and traceroute measurements [Shavitt-CCR-2005].
  - National Laboratory for Applied Network Research (NLNR) Active Measurement Project (AMP): [Mcgregor-Commag-2000].
  - Rocketfuel, An ISP topology mapping engine [Spring-SIGCOMM-2002].
  - Scriptroute, remote measurement execution on Planetlab nodes [Spring-USITS-2003].
  - Network Cartographer (nec), uses traceroute web servers as proxies [Magoni-COMCOM-2005].

# Related Work | Topology Discovery

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- **Source-Routing-based**
  - Atlas Project, source-routing IPv6 traceroute: [[Waddington-CCR-2003](#)]
  - Mercator, source-routing IPv4 traceroute and alias resolution: [[Govindan-Infocom-2000](#)].
  
- **Backward-Probing-based**
  - Doubletree, cooperative network topology discovery: [[Donnet-SIGMETRICS-2005](#)].

# Related Work | Topology Discovery

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- **Routing Registry Information**

- Regional Internet Registry (RIR) IP address blocks and AS number allocations are available via WHOIS [RFC 3912].
- Internet Routing Registry (IRR) policies are also available via WHOIS.

- **BGP Routing Information**

- Looking Glass and Route Servers: <http://www.traceroute.org>
- University of Oregon's Route Views Project: <http://www.routeviews.org>
- RIPE Routing Information Service (RIS): <http://www.ripe.net/ris>

# Related Work | Large-Scale Measurement Platforms

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- Project BISmark: <http://projectbismark.net>
  - Led by Georgia Institute of Technology,
  - Study specific issues (e.g. bufferbloat) on a wider scale
- SamKnows: <http://www.samknows.com>
  - Over 40K probes deployed all over the world
  - Working in conjunction with Federal Communications Commission (FCC), European Commission (EC), Ofcom, *et al.*
- RIPE Atlas: <http://atlas.ripe.net>
  - Over 4000 probes deployed all over the world, over 1800 active measurements running concurrently

# Related Work | Large-Scale Measurement Facilitators

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- Google's Measurement Lab (M-Lab): <http://www.measurementlab.net>
  - Open platform to deploy measurement tools. Tests measure against M-lab hosted servers.
  - Limited to active broadband measurements, open-source tools and open data mandate.
  - Avoid resource contention between experiments to avoid impact on accuracy.
  - Measurement data stored in Google Storage, retrievable via Google Query.
  
- PlanetLab: <http://www.planet-lab.org>
  - A global overlay testbed initiated by Princeton University, *et al.*
  - Provides access to real Internet path characteristics.
  - It's not a controlled environment. Results from experiments may not be repeatable.
  - Allocated slices are not isolated but shared amongst experiments.
  - Experiments on new network architectures, content distribution, measurements and monitoring.

# Related Work | Large-Scale Measurement Facilitators

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- **Emulab:** <http://www.emulab.net>
  - A network testbed initiated by the University of Utah.
  - It's a controlled environment. Results from experiments are repeatable.
  - Flexibility to create network characteristics suited for the experiment.
  - Clear separation between the control plane and measurement plane.
  - Isolates experiments from one another.
  
- **Federated Testbeds:**
  - EmanicsLab: <http://www.emanicslab.org>
  - PlanetLab Japan: <http://www.planet-lab.jp>
  - Private PlanetLab Korea: <http://www.planet-lab.kr>
  - German Lab: <http://www.german-lab.de>

# References

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[Dischinger-IMC-2007] M.Dischinger, et al., Characterizing Residential Broadband Networks, ACM Conference on Internet Measurement Conference (IMC), 2007.

[Shavitt-CCR-2005] Y. Shavitt, et al., DIMES: Let the Internet Measure Itself, ACM Computer Communications Review (CCR), 2005.

[Dischinger-NSDI-2010] M.Dischinger, et al., Glasnost: Enabling End Users to Detect Traffic Differentiation, USENIX Symposium on Networked Systems Design and Implementation (NSDI), 2010.

[Kreibich-IMC-2010] C.Kreibich, et al., Netalyzer: Illuminating the Edge Network, ACM Conference on Internet Measurement Conference (IMC), 2010.

# References

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[[Dhawan-IMC-2012](#)] M.Dhawan, et al., Fathom: A Browser-based Network Measurement Platform, ACM Conference on Internet Measurement Conference (IMC), 2012.

[[Mcgregor-Commag-2000](#)] T.McGregor, et al., The NLANR Network Analysis Infrastructure, IEEE Communications Magazine, May 2000.

[[Spring-SIGCOMM-2002](#)] N.Spring, et al., Measuring ISP Topologies with Rocketfuel, ACM SIGCOMM, 2002.

[[Spring-USITS-2003](#)] N.Spring, et al., Scriptroute: A Public Internet Measurement Facility, 4th USENIX Symposium on Internet Technologies and Systems (USITS), 2003.

# References

---

[Magoni-COMCOM-2005] D.Magoni, et al., Internet Core Topology Mapping and Analysis, Elsevier Computer Communications (COMCOM), 2005.

[Waddington-CCR-2003] D.Waddington, et al., Topology Discovery for Public IPv6 Networks, ACM Computer Communications Review (CCR), 2003.

[Govindan-Infocom-2000] R.Govindan, et al., Heuristics for Internet Map Discovery, IEEE International Conference on Computer Communications (Infocom), 2000.

[Donnet-SIGMETRICS-2005] B.Donnet, et al., Efficient Algorithms for Large-Scale Topology Discovery, International Conference on Measurement and Modeling of Computer Systems (ACM SIGMETRICS), 2005

# References

---

[Sundaresan-TR-2013] S.Sundaresan, et al., WTF? Locating Performance Problems in Home Networks, School of Electrical and Computer Science Technical Report (SCS TR), 2013.

[Sundaresan-SIGMETRICS-2013] S.Sundaresan, et al., Web Performance Bottlenecks in Broadband Access Networks, International Conference on Measurement and Modeling of Computer Systems (ACM SIGMETRICS), 2013.

[Sánchez-PAM-2013] M.Sánchez, et al., Trying Broadband Characterization at Home, Passive and Active Measurement Conference (PAM), 2013.

[Canadi-IMC-2012] I.Canadi, et al., Revisiting Broadband Performance, ACM Conference on Internet Measurement Conference (IMC), 2012.

# References

---

[Bischof-WMUST-2012] Z.Bischof, et al., Up, Down, and around the Stack: ISP Characterization from Network Intensive Applications, ACM SIGCOMM Workshop on Measurements up the Stack (W-MUST), 2012.

[Bischof-WMUST-2012] Z.Bischof, et al., Crowdsourcing ISP Characterization to the Network Edge, ACM SIGCOMM Workshop on Measurements up the Stack (W-MUST), 2011.

[Bauer-HomeNets-2011] S.Bauer, et al., Powerboost, ACM SIGCOMM Workshop on Home Networks (HomeNets), 2011.

[Sundaresan-HomeNets-2011] S.Sundaresan, et al., Helping users shop for ISPs with Internet Nutrition Labels, ACM SIGCOMM Workshop on Home Networks (HomeNets), 2011.

# References

---

[Sundaresan-SIGCOMM-2011] S.Sundaresan, et al., Broadband Internet Performance: A View from the Gateway, ACM SIGCOMM, 2011.

[Bagnulo-FNMS-2013] M.Bagnulo, et al., A Framework for Large-Scale Measurements, Future Network and Mobile Summit (FNMS), 2013.

[Bagnulo-CCR-2013] M.Bagnulo, et al., Standardizing Large-Scale Measurement Platforms, ACM Computer Communications Review (CCR), 2013.