Measuring the Immeasurable: Global Internet Measurement Infrastructure

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It has been said that the great question is now at issue, whether man shall henceforth start forwards with accelerated velocity towards illimitable, and hitherto unconceived improvement, or be condemned to a perpetual oscillation between happiness and misery, and after every effort remain still at an immeasurable distance from the wished-for goal.
Thomas Malthus, "An Essay on the Principle of Population." 1798 [12]

Abstract—
The cooperative anarchy of the global Internet defies easy characterization or measurement of its behavior. Fortunately, lack of global understanding has not stalled the advancement of network engineering technologies that enable and support Internet growth - for the moment. Both Internet users and providers can benefit from measurements that detect and isolate Internet problems, and identify traffic bottlenecks. Yet it is neither practical nor particularly effective to monitor and measure every single link. Common sense supports the establishment of a measurement infrastructure strategically designed to yield maximal Internet coverage at reasonable cost. However, while individual ISPs monitor their own infrastructure and quality of service, business and other practical concerns often prevent sharing of such information. We survey existing public and mission-specific Internet measurement infrastructures, comparing them using a variety of criteria. Community awareness of similar measurement activities will hopefully facilitate opportunities for collaboration, leveraging experiences and investment across groups. Cataloguing these sources of Internet measurements also provides operations researchers with places to seek topology, workload, performance, and routing data that can help them refine metrics and methodologies for effective management of the global Internet.

Keywords— **Network Measurement, Internet**

I. Global Internet Measurement Problems

In 1798, Thomas Malthus was gravely disturbed by the fact that the population of the United States had doubled itself in only 25 years. He held that there was no way for any land's resources to keep up with the needs of its population if such a trend continued unchecked. Imagine his reaction to the population growth of the Internet from an initial set of 4 hosts in 1969 [17] to more than 100 million hosts today [19]. Malthus observed an exponential population increase supported by only a linear increase in subsistence. Internet user populations grow dramatically while also increasing their demands for new services. Purported exponential growth when measured appears to be best described as doubling every year [6], though claims of much faster growth exist [14]. In any case, efforts to identify and apply meaningful metrics and measurement methodologies to assess the overall health and growth of the global Internet become increasingly challenging.

There is as yet little understanding of the impact of such dynamic, rapid growth. Internet traffic behavior has been resistant to modeling, for reasons that derive from the Internet's evolution as a composition of independently developed and deployed (and by no means synergistic) protocols, technologies, and core applications. This evolution, though punctuated by new technologies, has experienced no equilibrium thus far.

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The state of the art, or lack thereof, in high-speed measurement is neither surprising nor profound. It is a natural consequence of the economic imperatives in the industry, where empirically grounded research in wide-area Internet modeling has been an obvious casualty. Specifically, the engineering expertise required to develop advanced measurement technologies, whether in software or hardware, is essentially the same skill set required to develop advanced routing and switching capabilities. Since the latter draw far greater interest, and profit, from the marketplace, that is where the industry allocates engineering talent.

Fortunately, lack of understanding has not arrested growth in network engineering technologies. Most ISPs rely on maintaining surplus bandwidth to handle transient congestion, and upgrading hardware in advance to forestall unmeetable demand. Such pre-emptive infrastructure improvements do indeed solve many problems, but also change parameters of scale, scope, and reliability in the global Internet. While rapid growth and change will likely continue, effective management of the global Internet requires cooperation to perform useful workload and performance assessment. To date, timely identification of critical trends is still a challenge.

Internet troubleshooting and maintenance require accurate knowledge of topology at both microscopic and macroscopic levels. Discerning trends and identifying nascent problems requires models of normal and abnormal workload and performance. Historically, vital signs of network health have included throughput, latency, and packet loss rates[4]. Both active and passive methodologies to measure such metrics require substantial data reduction prior to analysis as well as management of massive data file storage. Further, while fairly benign imposition of addressing and naming standards enforce some structure to Internet topology, inter-domain routing policies defy easy coordination.

II. Differences in Internet User Populations

Performance requirements among different Internet user populations vary. For example, the scientific research community includes high-end Internet users whose tasks often involve substantial network bandwidth requirements. Another group, broadly described as financial markets and on-line businesses, require secure, reliable connectivity for a high rate of transactions, synchronized with distributed database operations. Gaming and entertainment markets stretch the limits of network technologies in support of new real-time interactions with streaming multimedia and virtual reality[18]. Finally, even individual residential users have come to expect access to email and web servers to be as reliable as the phone system and never discernably slow.

III. Measurement Infrastructure Goals for Internet Research

Notwithstanding distinctions among user populations and applications, all share a common goal: robust, reliable, secure access. Hardware and cabling failures or lack of bandwidth capacity are physical events impacting Internet access. Software or router misconfiguration can also disrupt service, sometimes catastrophically. Users are particularly vulnerable to inadvertent or malicious denial of service (DoS) attacks. A measurement infrastructure can facilitate early detection and diagnosis of many of these problems. Specifically, a measurement infrastructure addresses the following goals:

1. Establish usage logging in order to model normal versus abnormal activities.
2. Detect and localize specific Internet problems (e.g., DoS attacks, router misconfiguration, hardware and link failures).
3. Identify traffic bottlenecks as well as excess capacity.
4. Maintain an archive of data useful for long-term trend analysis.
5. Enable special-purpose data collection (e.g., run experiments).

IV. Internet Performance Metrics

Administration of measurement data and controls is arduous, attributable to both technical and political realities [5]. In the cooperative anarchy of the Internet, neighbors both share and compete with each other. Since 1995, the IP Performance Metrics (IPPM) working group of the IETF [9] has worked to standardize metrics pertaining to quality, performance, and reliability of Internet data delivery services. IPPM [15] does not judge appropriate values of metrics, but rather defines unbiased quantitative measures that allow network operators and users to coherently share information, facilitating strategic coordination of resources while still respecting business boundaries.

IPPM base metrics include delay, packet loss, and connectivity. Derived metrics [13], such as patterns and distributions of loss, can help determine whether a particular transmission service is compatible with the performance needs of a particular application's data stream.

Determination of global Internet connectivity and evaluation of traffic trends occurring over time is not possible with one particular base or derived metric. Global Internet data analysis must limit itself to the context in which measurement data is gathered. It is thus important to match appropriate research questions with collected data (or vice-versa), constrained by the need to limit the type, frequency, and locations of measurements to minimize intrusive network overhead. Accuracy in capture of traffic conditions is traded off against how much data one can generate and analyze.

Additionally, one must determine whether active or passive measurement techniques, or some combination, are appropriate. Active measurements inject test packets into the network and observe their behavior. Some active measurement tools require cooperation from both endpoints of the measurement. Indeed, some active probe signatures may appear similar to denial of service attacks and may lead uninformed destinations to block this traffic. In contrast, passive measurements observe actual traffic without perturbing the network. Passive monitors must process the full load on the link, which can be problematic on high-speed links. While passive measurement does not require cooperation or coordination from end hosts, the quality of passively gathered data critically depends on monitor placement, which does require cooperation from network operators [5] [10].

Both active and passive measurement methodologies at any useful scale involve massive amounts of data. Indeed, analysis quality depends on the granularity and integrity of the collected data. Several problems concerning collected data must be addressed: 1) Data collection is much faster than data analysis. 2) It is unclear how to achieve representative measurement coverage of the entire Internet, and 3) Identification of sufficient sampling rates remains a research problem. Furthermore, data sanitization (removing payload and user identifying information) is prerequisite both to avoid security vulnerabilities and to encourage cooperation and data sharing.

V. Survey of Measurement Activities

Table 1 compares characteristics of several public Internet measurement infrastructure projects. We summarize these publicly accessible research-oriented projects below.

A. CoralReef Passive Monitor (CAIDA)

https://anala.caida.org/CoralReef/Demos/cerfnet/link/

CoralReef is a comprehensive software suite developed by CAIDA to collect and analyze data from passive Internet traffic monitors, either in real time or from trace files. CoralReef[2] provides a set of drivers, libraries, utilities and analysis software for passive measurement of workload characteristics. Figure 1 shows an example visualization of CoralReef's reporting functionality, depicting relative protocol load on the measured link. The CoralReef software package includes sample data collection and reporting solutions, but is customizable to meet each user's needs. CoralReef is publicly available[10] and works with high-speed (OC3, OC12, OC48) capture hardware.

Comparison of Publicly Accessible Measurement Infrastructures						
Project	Sponsor	Target Audience	Active/ Passive	Analysis Type	*Monitors*	*Countries*
CoralReef	DARPA NSF	Traffic engineers, Internet researchers	Passive	Workload	3	1
IEPM	DOE, SLAC	Network support for HEP community	Active	Performance	38+	14
I2(Abilene)	UCAID	High-availability backbone for academic researchers	Active & Passive(SNMP)	Workload, Performance	12	14
Mantra	NSF	Internet researchers	MBGP Routing	Multicast Performance	17 routers	world-wide
MAWI(WIDE)	Japanese academic collaboration	Internet researchers	Passive(SNMP)	Workload, Performance	4	1
NIMI	DARPA, NSF	Global Internet community, Internet researchers	Active	Performance	35	6+
NLANR(MOAT) AMP	NSF	Internet researchers	Active	Workload, Performance	118	3
NLANR(MOAT) PMA	NSF	Internet researchers	Passive	Workload, Performance	32	3
NPACI NWS	NSF, DARPA, DOD	PACI high-performance application users and developers	Both	Performance	~40	1
PPNCG	JANET, UKERNA	UK particle physics community	Active	Performance	2	3+
RIPE-RIS	RIPE-NCC	European Internet community, Internet researchers	Passive(SNMP) Routing	Topology, Routing	4 collectors, ~45 peers	world-wide
skitter	DARPA, NSF	Global Internet community, Internet researchers	Active	Topology, Performance	22	world-wide
Surveyor	NSF ANS Inc.	U.S. higher education Internet community and researchers	Active	Topology Performance	51	9
TRIUMF	Canada NRC	Canadian particle physics community	Active	Topology Performance	1	N/A
U-Oregon Route Views	U-Oregon Cisco Systems	Traffic engineers, Internet researchers	Passive(SNMP) Routing	Topology, Routing	40 peers	world-wide
WAND	PGSF	Internet researchers	Passive	Workload, Performance	4	1

TABLE I

Publicly Accessible Research Measurement Infrastructures

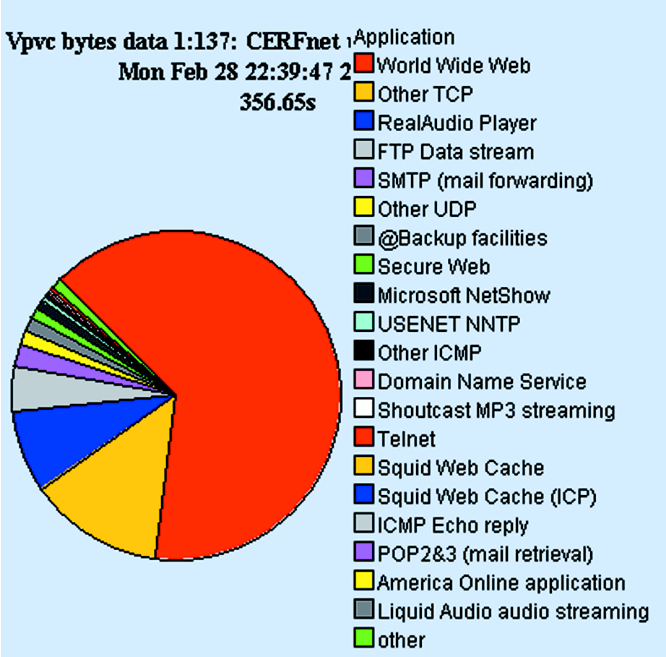

Fig. 1. CoralReef plot of protocols comprising link traffic

B. IEPM-Internet End-to-end and Process Monitoring (SLAC/DOE)

http://www-iepm.slac.stanford.edu/
http://www-iepm.slac.stanford.edu/pinger/perfmap/

SLAC/DOE/Esnet, HEPnet, and HENP use pingER tools to actively monitor end-to-end Internet performance among accelerator labs and collaborating universities. Animated monthly performance maps (See Figure 2) are made using NLANR's Cichlid 3-D visualization software[3].

C. Internet2 (Abilene)

http://monon.uits.iupui.edu/
http://hydra.uits.iu.edu/ abilene/traffic/

Abilene is an advanced backbone network that connects regional network aggregation points (gigapops) to support the work of Internet2 universities as they develop advanced Internet applications. Network monitoring activities include active multicast ping (mping) measurements as well as SNMP based collection of utilization data. As an example, Figure 3 depicts line utilization on the Abilene backbone.

D. Mantra-Monitor & Analysis of Traffic in Multicast Routers

http://www.caida.org/tools/measurement/mantra/

The Mantra tool is used to monitor various aspects of multicast behavior at the router level. Visualization snapshots and accompanying tables are updated every 15-30 minutes. Figure 4 shows an instance of a multicast (MBGP) topology map, showing connectivity of various components. This particular visualization was made using CAIDA's Otter tool[8].

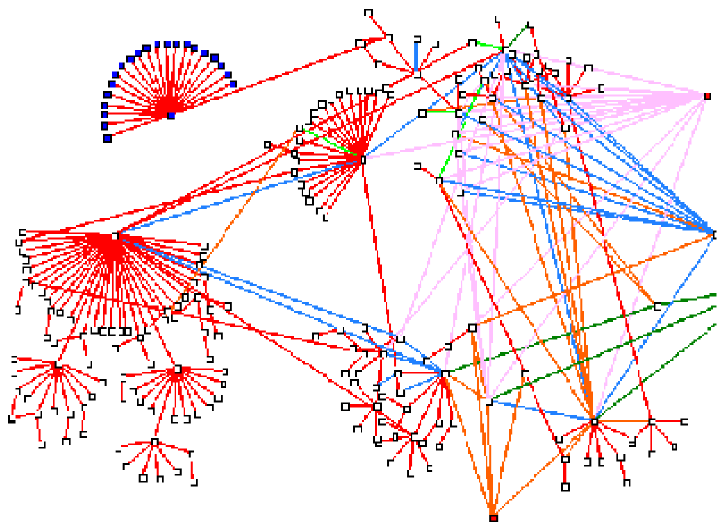

Fig. 4. A snapshot of MBGP topology as depicted by Mantra

E. MAWI-Measurement & Analysis on the WIDE Internet (WIDE-Widely Integrated Distributed Environment)

http://tracer.csl.sony.co.jp/mawi/

The MAWI Working Group maintains a data repository of traffic traces. Traces are made using tcpdump. Then, IP addresses are scrambled using a modified version of tcpdpriv. Several daily traces with visualizations and statistics from four different traffic sampling points are available. Figure 5 shows a visualization fragment showing protocol breakdown on a MAWI monitored link. Traffic data may only be used for research purposes.

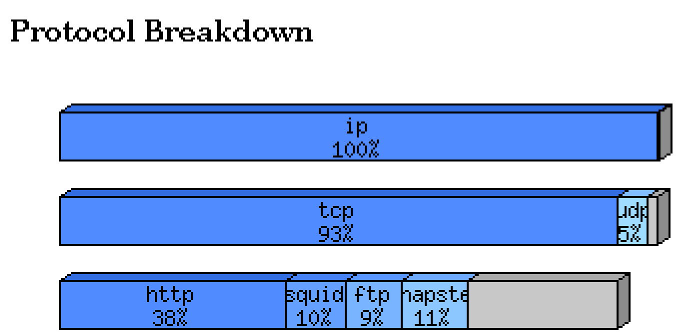

Fig. 5. Fragment of visualization of MAWI trace showing protocol breakdown for a day.

F. NIMI-National Internet Measurement Infrastructure (NSF/DARPA)

http://www.ncne.nlanr.net/nimi/

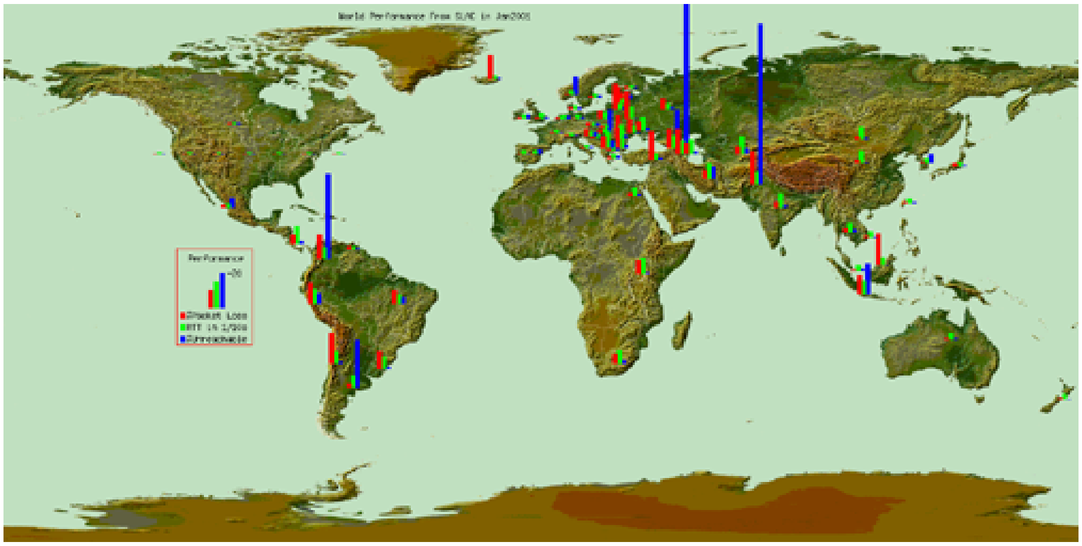

Fig. 2. IEPM animated Internet performance. (Vertical bars emphasize sites showing performance degradation.)

The NIMI architecture was designed to facilitate coordination and control of wide-area Internet measurements. Derived and expanded from Vern Paxson's Network Probe Daemon (NPD) work [15], NIMI offers a web interface for collected measurements. Measurements include bandwidth, loss and hop counts between host pairs. Figure 6 displays hopcount per day on one link for one month. NIMI was designed to be scalable and dynamic. Its scalability comes from its ability to delegate NIMI probes to administration managers for configuration and coordination of measurements and data collection. NIMI is dynamic in its architectural support for third-party measurement modules. For example, the MINC (Multicast Inference of Network Characteristics) project has used NIMI to test and calibrate the use of edge measurements to infer performance characteristics of the interior of a network.

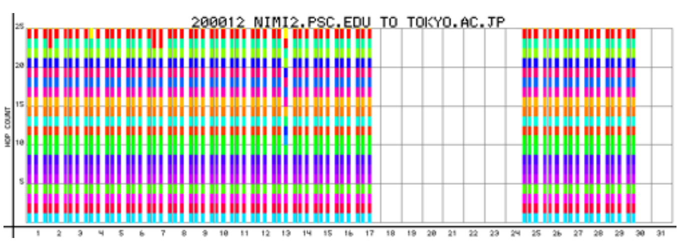

Fig. 6. NIMI traceroute display for December 2000 from PSC to Tokyo. (White regions indicate link or network monitor downtime.)

G. NLANR(MOAT)-Measurement & Operations Analysis Team NLANR(MOAT)-AMP Active Measurement Program NLANR(MOAT)-PMA Passive Measurement and Analysis

http://moat.nlanr.net/

http://moat.nlanr.net/AMP/

http://moat.nlanr.net/PMA/

The NLANR Measurement and Operations Analysis Team (MOAT) maintains a Network Analysis Infrastructure (NAI) to support operations research into Internet service models and metrics. MOAT's PMA project archives IP packet header trace files and SNMP RMON data from dozens of participating sites. The AMP project archives active measurement data from over a hundred campuses.

H. NWS-Network Weather Service (NPACI)

http://nws.npaci.edu/NWS/

The Network Weather Service is a distributed system that provides NPACI users a way to select high performance computing resources on which to run their applications. NWS periodically monitors and dynamically forecasts performance to various NPACI network and computational resources over a given time interval (e.g., seconds, minutes, hours). NWS uses a distributed set of performance sensors from which it gathers readings of instantaneous conditions. Numerical models and statistical methods are then used to generate 24 candidate forecasts of conditions; the forecast with lowest statistical error is then presented to the user. NWS aims to forecast TCP/IP end-to-end throughput and latency from a user application perspective[21]. Figure 7 shows a sample NWS plot of TCP bandwidth measurements, forecasts, and errors on a link between the San Diego Supercomputer Center (SDSC) and University of Texas.

I. PPNCG-Particle Physics Network Coordinating Group

http://ppncg.rl.ac.uk/ppncg/main.html

The PPNCG runs several traceping [11] monitors throughout Europe and America to gather end-to-end performance data for links of interest to UK particle physics researchers. Collected data can both identify problems and

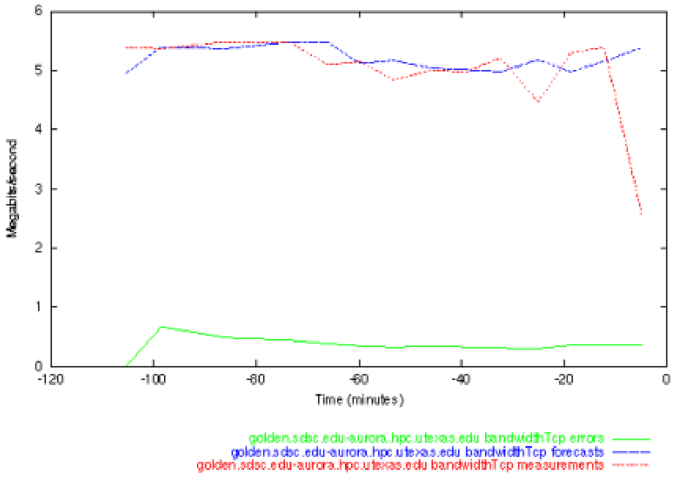

Fig. 7. NWS TCP bandwidth measurements, forecasts, and errors

suggest recommendations for optimizing network resources available via JANET and UKERNA. Figure 8 shows sample PPNCG graphs of packet loss and round trip time.

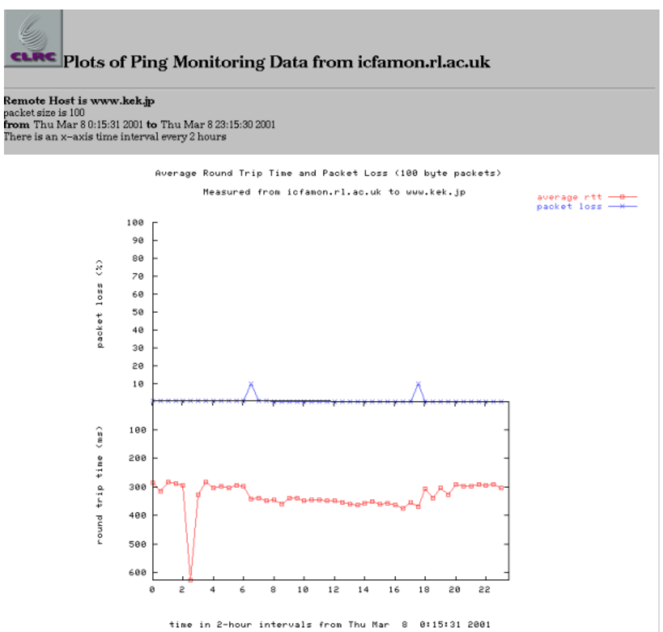

Fig. 8. PPNCG Performance Measurements for one day on a link between UK and JP. (Upper graph shows percent packet loss, bottom graph shows round trip time (ms). Data points occur every two hours.)

J. RIPE-NCC (Reseaux IP Europeens Network Coordination Center) RIS-Routing Information Service Project

http://www.ripe.net/ripencc/pub-services/np/ris-index.html

RIPE is a collaborative organization open to groups and individuals operating wide area IP networks in Europe and beyond. The objective of the RIPE Routing Information Service (RIS) Project is to collect default free inter-domain BGP routing information. RIS uses multiple route collectors to integrate multiple views, and archives routing updates to support longer term trend analysis. A prototype web interface enables data archive queries by domain prefix, AS number, or timeframe.

RIPE also offers a Test Traffic Measurement (TTM) service for members wishing to host a RIPE NCC Test-box. Test-boxes actively measure Internet delays and losses by sending time-stamped packets to each other. More information on this RIPE-NCC project can be found at: http://www.ripe.net/ripencc/mem-services/ttm/

K. skitter Project (CAIDA)

http://www.caida.org/cgi-bin/skitter_summary/main.pl

CAIDA's skitter tool actively collects topology and performance data from approximately 22 sources (as of April 2001) around the world to hundreds of thousands of destinations in IPv4 address space. CAIDA analyzes the data to visualize macroscopic topology and performance attributes of a large cross-section of the Internet. Figure 9 shows a topology visualization derived from skitter data, where AS nodes are plotted by longitude and degree of connectivity. Other visualizations of daily hop counts and performance derived from skitter data are at the URL above[7].

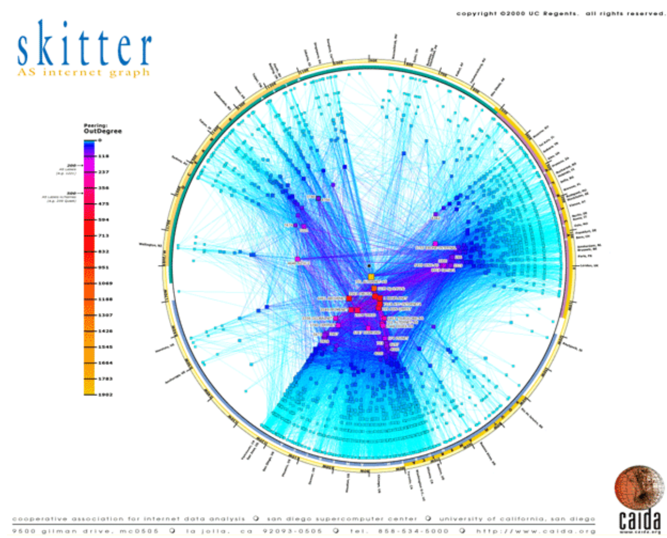

Fig. 9. Visualization of AS topology derived from skitter data. (AS nodes are plotted in polar coordinates, with angle corresponding to longitude of AS headquarters and radius corresponding to connectivity degree. Large white sections of the circle roughly correspond to oceans.)

L. Surveyor (Advanced Network & Services / Common Solutions Group R&E Network Measurements)

http://www.advanced.org/csg-ippm/

Based on standards from the IETF's IPPM working group, Surveyor measures performance of Internet paths among participating organizations world-wide. The project is also developing methodologies and tools to analyze the gathered performance data. Data per site, per path, and per calendar day are available from the URL above. Figure 10 shows a sample graph.

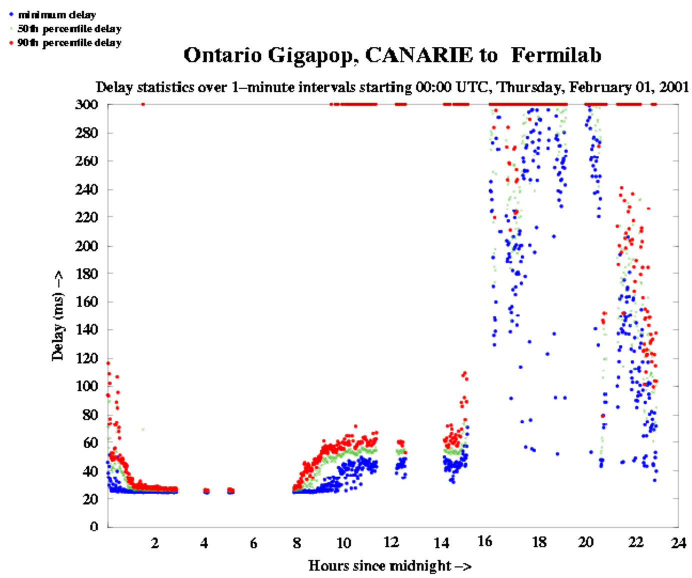

Fig. 10. Sample of Surveyor performance statistics: delay patterns for one day between Ontario and Fermilab nodes.

M. TRIUMF Network Monitoring

http://sitka.triumf.ca

http://sitka.triumf.ca/net/nodes.frameset.html

This Canadian national research facility uses perl scripts to trace paths toward specific nodes of interest to TRIUMF users. Packet loss and delay measurements are summarized and graphed daily from pings occurring at 10 minute intervals. Traceroute data for hopcount statistics and graphs is gathered four times daily. Network topology visualization maps are generated from the traceroute data. Figure 11 illustrates TRIUMF packet loss statistics using a table with included graphs.

N. University of Oregon's Route-Views Project

http://www.antc.uoregon.edu/route-views/

Route Views is a collaborative endeavor to obtain real-time information about the global routing system from the perspectives of several different backbones and locations around the Internet. The Route Views router, route-views.oregon-ix.net, uses multi-hop BGP peering sessions with backbones at interesting locations, but it neither announces any prefixes nor forwards any traffic.

O. WAND-Waikato Applied Network Dynamics, WITS-Waikato Internet Traffic Storage (University of Waikato and University of Auckland, New Zealand)

http://wand.cs.waikato.ac.nz/wand/wits/

The WAND research group builds its own high-speed passive measurement hardware [20], archives passive measurement traces for use by Internet researchers, and builds statistical models of Internet traffic for analysis and simulation.

VI. Conclusion

We have summarized and compared research-oriented measurement infrastructures that attempt to measure global Internet behavior and offer public web-accessible reports. We have not compared other ISP-specific or private service measurement infrastructures here because access to them is insufficient to make a fair comparison. In fact, no single organization is truly measuring global Internet behavior, because the global Internet is simply not instrumented to allow such measurement.

A measurement infrastructure can help sites identify abnormal or threatening network activity, facilitate traffic engineering and capacity planning, track long-term trends, and enable collection of special-purpose data for experiments. Two basic types of measurements, passive and active, incur different costs and benefits to sites using them. Both types of measurement still require research into improved aggregation and data correlation techniques, as well as methods for coherent data sharing among ISPs and users.

Identifying areas in which current measurement infrastructures can complement one another, or evolve to use more standard and comparable methodologies, would advance efforts to measure global Internet behavior. In particular, leveraging already occurring Internet measurements will benefit both Internet operations and research. We hope that dissemination of the analysis and visualization methods discussed in this paper will encourage further consideration of enhancement, growth, and cooperation among measurement infrastructures to enable new insights into the vital and dynamically changing global Internet.

VII. Acknowledgements

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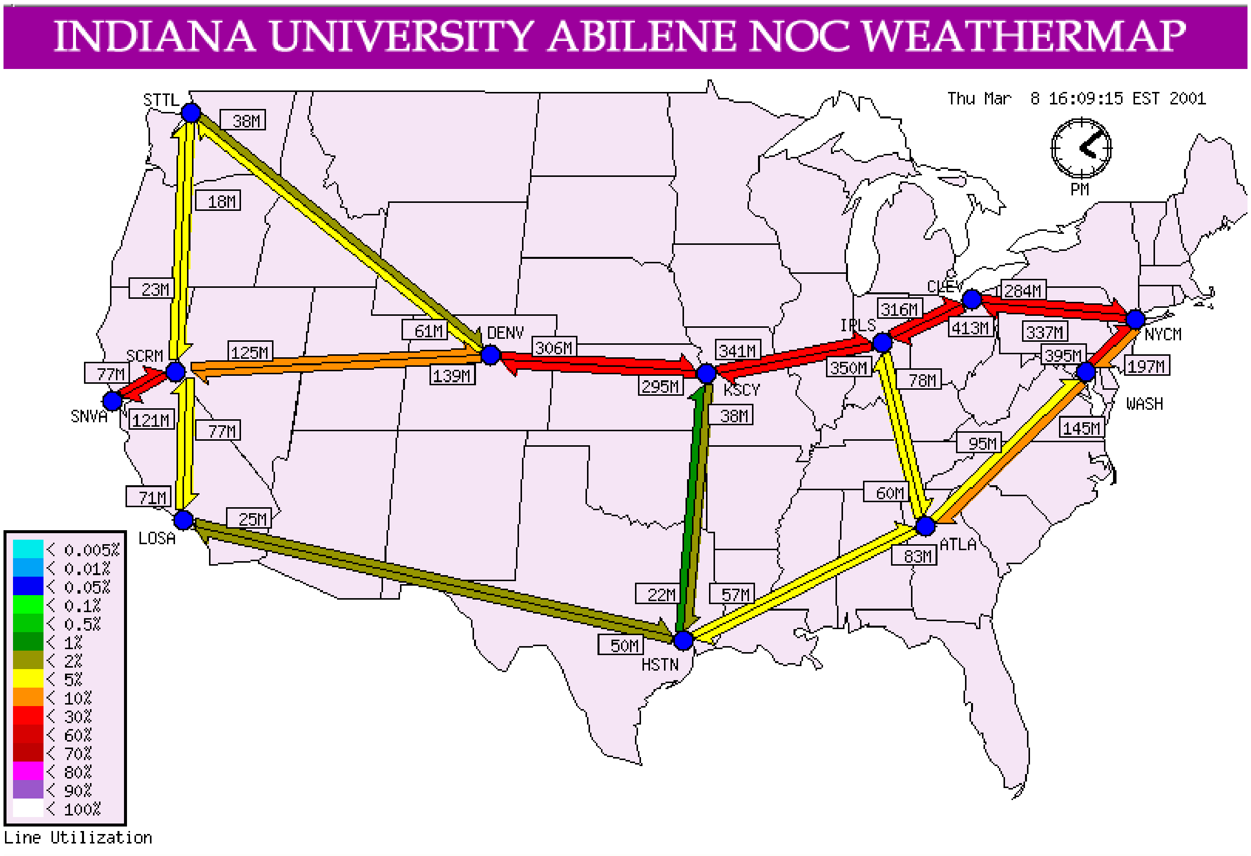

Fig. 3. Internet2 (Abilene) mping network utilization map. (Arrows indicate traffic flow direction; color reflects line utilization.)

Packet Loss summary from TRIUMF

Measured from sitka.triumf.ca
at Wed Mar 7 16:10:00 PST 2001 *Updated every 10 minutes*
(please wait for table)

Address	% Packet Loss			Delay (ms)				Hops (255–ttl)	
(about node)	recent	2 hours	Last 24 hrs	min.	avg.	Last 24 hrs	max.	recent	Last 24 hrs
alph04.triumf.ca	0	0		0.917	1.24		1.915	0	
ubcax1.physics.ubc.ca	100	100		0	0		0	0	
uvphys.phys.uvic.ca	0	0		8.911	10.32		12.079	4	
www.phys.sfu.ca	0	11		5.655	8.02		11.106	5	
sarcee.phys.ualberta.ca	0	0		22.893	25.66		28.957	8	
hepcan.onet.on.ca	0	7		189.528	205.79		222.047	12	
challenger.aa.washington.edu	0	0		10.854	12.45		17.363	8	
bnlku7.phy.bnl.gov	0	0		83.729	85.64		87.515	15	
fsui01.fnal.gov	0	0		57.763	61.01		64.669	13	
ns2.slac.stanford.edu	0	0		65.419	66.24		67.212	14	
www.cern.ch	0	0		165.518	167.06		168.908	0	
x4u2.desy.de	0	0		208.675	214.25		219.370	23	
is2.kek.jp	0	0		155.316	172.44		213.049	15	
vancouver-webpages.com	0	7		153.914	162.70		169.553	8	
sv.cache.nlanr.net	0	0		67.113	69.08		73.748	12	
pupnet.princeton.edu	0	0		76.797	78.68		83.800	14	
cr1001800-a.rchmd1.bc.wave.home.com	0	3		27.887	32.52		41.476	7	
sgiserv.rmki.kfki.hu	0	7		203.372	206.85		212.853	22	

Fig. 11. TRIUMF loss, delay, and hopcount statistics and graphs for one (10 minute) measurement interval.