A Survey on Internet Performance Measurement Platforms and Related Standardization Efforts

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***Abstract*—A number of Internet measurement platforms have emerged in the last few years. These platforms have deployed thousands of probes at strategic locations within access and backbone networks and behind residential gateways. In this paper we provide a taxonomy of these measurement platforms on the basis of their deployment use-case. We describe these platforms in detail by exploring their coverage, scale, lifetime, deployed metrics and measurement tools, architecture and overall research impact. We conclude the survey by describing current standardization efforts to make large-scale performance measurement platforms interoperable.**

***Keywords*—measurements, platforms, broadband, fixed-line, mobile, metrics, measurement-tools, standardization**

I. Introduction

An Internet measurement platform is an infrastructure of dedicated probes that periodically run network measurement tests on the Internet. These platforms have been deployed to satisfy specific use-case requirements. Fig. 1 provides a taxonomy of these platforms based on their deployment use-case. For instance, a number of early measurement studies utilized these platforms to understand the macroscopic network-level topology of the Internet. Several years of research efforts have matured this area and led to a number of algorithms that decrease the complexity of such topology mapping efforts. Recently we have seen a shift towards deployment of performance measurement platforms that provide network operational support and measure fixed-line and mobile access networks. This has been motivated by the emerging need to not only assess the broadband quality but also to verify service offers against contractual agreements. For instance, the Federal Communications Commission (FCC), the national regulator in the United States, has launched a campaign[1] with an intent to use the gathered measurement dataset to study and compare multiple broadband provider offerings in the country. The Office of Communications (Ofcom), the national regulator in the United Kingdom, has already been using similar datasets[2] as input to frame better broadband policies. Such initiatives are being run to help regulate the broadband industry.

We focus our survey on these Internet performance measurement platforms, and provide a comprehensive review of their features and research impacts with an exploration on standardization efforts that will help make these measurement platforms interoperable. Platforms focussing on inferring the network topology have been surveyed in the past [1], [3]. Techniques used to mine the active measurement data to model and generate the Internet topology have been surveyed as well [2]. Metrics and tools usually employed in such active measurements have also been surveyed [4], [5]. Therefore, we do not survey topology discovery platforms such as Archipelago [6], DIMES [7] and iPlane [8], but refer the reader to the aforementioned surveys.

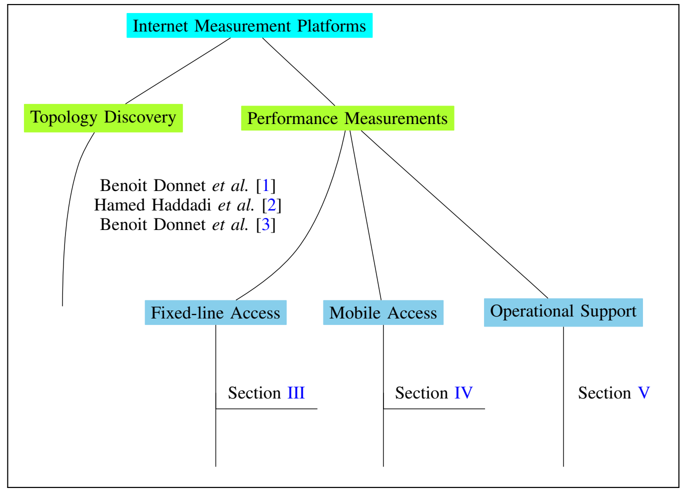

Fig. 1. *A graph representing the taxonomy of Internet measurement platforms. They can largely be divided into two classes: topology discovery (labels depicting references to earlier surveys) and performance measurements. We further subdivide performance measurement platforms into three classes depending on their deployment use-case: measurements within fixed-line access networks, mobile access networks and measurements to provide operational support. Labels indicate sections where we survey them in detail.*

There are platforms deployed by academic consortiums and government bodies to allow researchers to achieve geographical and network diversity for their network research. PlanetLab [9] for instance is a platform to support development and testing of new network services [10] but is specifically not a measurement platform. In fact for many types of measurements, PlanetLab is rather unusable due to unpredictable load issues and the tendency of nodes to be located in national research networks. Measurement Lab (M-Lab) [11] on the other hand, is primarily a server infrastructure that is designed to support active measurements and facilitate exchange of large-scale measurement data. Its resource allocation policies encourage active measurement tools to utilize M-Lab servers

[1] *http://www.fcc.gov/measuring-broadband-america*
[2] *http://maps.ofcom.org.uk/broadband*

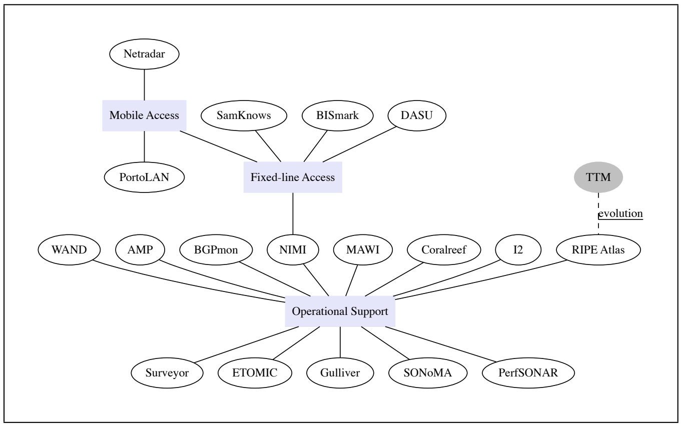

Fig. 2. *A graph representing the taxonomy (in purple) of Internet performance measurement platforms (in white) based on their deployment use-case. Greyed out measurement platforms have been superseded by their successors. We only survey currently active measurement platforms from within this set. Table III provides a summary of this survey.*

as a sink of measurement traffic and as a repository to hold measurement results. We define such infrastructures separately as measurement facilitators and do not survey them in this work. This is to allow a more longitudinal analysis of platforms we have scoped our survey to. We also survey only currently active performance measurement platforms. We refer the reader to [12] for a survey and a webpage[3] maintained by Cooperative Association for Internet Data Analysis (CAIDA) on measurement platforms that have existed in the past.

Fig. 2 provides a high-level overview of currently deployed Internet performance measurement platforms. We provide a taxonomy based on their deployment use-case: a) platforms deployed at the periphery of the Internet that measure performance over fixed-line access networks, b) platforms that measure performance over mobile access networks, c) platforms deployed largely within the core of the Internet that help provide network operational support. These platforms, although disparate in their scope, utilize a rather popular list of measurement tools to achieve their objectives. Fig. 3 provides a representation of common measurement tools used by the Internet performance measurement platform ecosystem.

The rest of the paper is organized according to the described taxonomy. In Section III and IV we cover platforms that measure performance on fixed-line and mobile access networks. In Section V we survey platforms that perform measurements to provide support to network operators and the scientific community. We explore upcoming efforts to standardize components of a measurement infrastructure to make these measurement platforms interoperable in Section VI. We discuss collaboration amongst these platforms, the usage of measurement facilitators and an overall timeline of the surveyed work in Section VII. The survey concludes with an overall summary in Section VIII.

[3] *http://www.caida.org/research/performance/measinfra*

II. Background

We start with early studies that predate the performance measurement platforms era. Multiple techniques ranging from remote probing and passive monitoring to running one-off software-based probes were being employed to infer network performance. We provide a brief survey of these techniques.

The curiosity to understand the performance of the Internet from a user's vantage point led to the development of techniques that remotely probe fixed-line access networks. Marcel Dischinger *et al.* in [26] for instance, inject packet trains and use responses received from residential gateways to infer broadband link characteristics. They show that the last-mile is a bottleneck in achieving high throughput and last-mile latencies are mostly affected by large router queues. Aaron Schulman *et al.* in [27] use PlanetLab [9] vantage points to remotely send `ping` probes to measure connectivity of broadband hosts in severe weather conditions. They found that network failure rates are four times more likely during thunderstorms and two times more likely during rainy conditions in parts of the United States.

Karthik Lakshminarayanan *et al.* in [28] deployed an active measurement tool, PeerMetric to measure P2P network performance experienced by broadband hosts. Around 25 hosts volunteered across 9 geographical locations for a period of 1 month. During this period, they observed significantly assymetric throughput speeds and poor latency-based peer-selections adopted by P2P applications.

Matti Siekkinen *et al.* in [29] investigate a day long packet trace of 1300 Digital Subscriber Line (DSL) lines. They observed throughput limitations experienced by end users. On further analysis they identified the root-cause to be P2P applications that were self-imposing upload rate limits. These limits eventually were hurting download performance. In a similar study, Gregor Maier, *et al.* in [30] analyzed packet-level traces from a major European Internet Service Provider (ISP) covering 20K DSL customers. They used this data to study typical session durations, application mixes, Transmission Control Protocol (TCP) and performance characteristics within broadband access networks. They use the same dataset in [31] and go further to quantify Network Address Translation (NAT) deployments in residential networks. They observed that around 90% of these DSL lines were behind NAT, 10% of which had multiple hosts active at the same time.

These studies led to the development of a number of software-based solutions such as `speedtest.net` that require explicit interactions with the broadband customer. Marcel Dischinger *et al.* in [32] for instance, describe Glasnost, a tool that can help end-users detect whether the ISP implements any application blocking or throttling policies on their path. The tool was used to perform a measurement study to detect BitTorrent differentiation amongst 350K users across 5.8K ISPs. Partha Kanuparthy *et al.* in [33] describe ShaperProbe, which is a similar tool that can also help detect traffic shaping policies implemented by the ISP. Christian Kreibich *et al.* in [34], describe the `netalyzr` tool that communicates with a farm of measurement servers to probe key network performance and diagnostic parameters of the broadband user. The tool

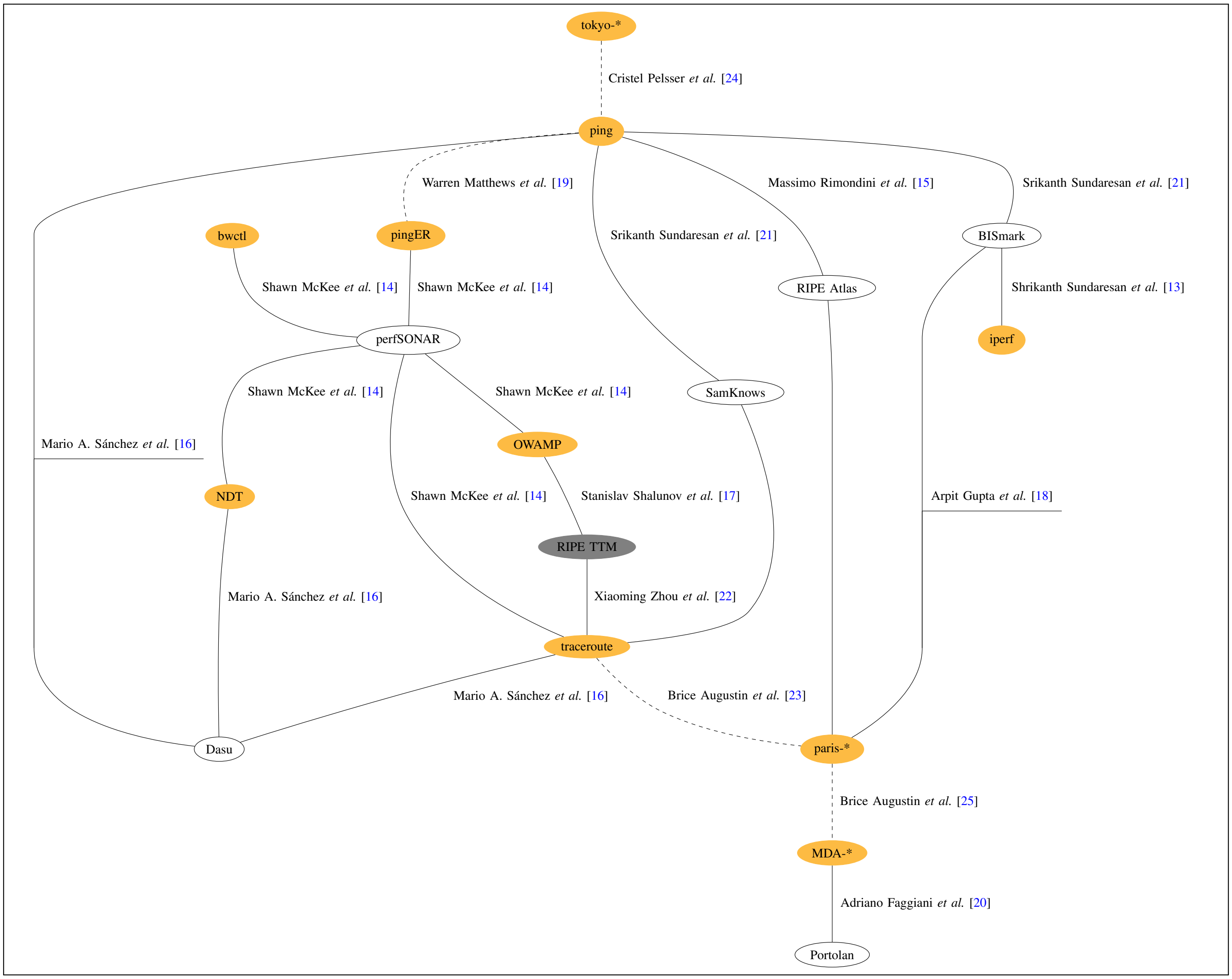

Fig. 3. *A graph representing common tools (in gold) used by Internet performance measurement platforms (in white). Tools that are specifically used by only one platform are not included in this graph, but are described in the paper. Greyed out measurement platforms have been decommissioned and superseded by their successors. Dotted lines indicate an evolution of the tool along with the research paper that describes this evolution marked in labelled edges. Straight lines connect a measurement platform with a tool, along with the labelled edges that mark the research paper that describes how they use it.*

can detect outbound port filters, hidden Hypertext Transfer Protocol (HTTP) caches, Domain Name System (DNS) and NAT behaviors, path Maximum Transmission Unit (MTU), bufferbloat issues and IPv6 support. Mohan Dhawan *et al.* in [35] describe Fathom, a Firefox extension that provides a number of measurement primitives to enable development of measurement tools using Javascript. Fathom has been used to port the java applet based `netalyzr` tool into native Javascript. Lucas DiCioccio *et al.* in [36] introduce HomeNet Profiler, a tool similar to `netalyzr` that performs measurements to collect information on a set of connected devices, running services and wireless characteristics of a home network.

The accuracy of these software-based measurement tools has recently been under scrutiny. For instance, Oana Goga *et al.* in [37] evaluate the accuracy of bandwidth estimation tools. They found that tools such as `pathload` [38] that employ optimized probing techniques can underestimate the available bandwidth capacity by more than 60%. This happens because home gateways cannot handle high-probing rates used by these methods. Another study by Weichao Li *et al.* in [39] investigates the accuracy of measurements using HTTP-based methods. They found discernible delay overheads which are not taken into account when running such measurements. These overheads also vary significantly across multiple browser implementations and make the measurements very hard to calibrate.

These inadequacies have ushered rapid deployment of measurement platforms that have specifically been designed to accurately measure broadband performance. These platforms use dedicated hardware-based probes and can run continuous measurements directly from behind a residential gateway requiring minimal end-user participation.

III. Fixed-line Access

There are three stakeholders involved in an effort to measure performance within an access network: ISPs, consumers and regulators. Marc Linsner *et al.* in [40] enlist and describe their respective use-cases. For instance, an ISP would like to use broadband measurements to not only identify, isolate and fix problems in its access network, but also to evaluate the Quality of Service (QoS) experienced by its users. The data made public through such a measurement activity will also help the ISP benchmark its product and peek into its competitor's performance. Consumers, on the other hand, would like to use these measurements as a yardstick to confirm whether the ISP is adhering to its Service-Level Agreement (SLA) offers. The user can also use these measurement insights to audit and diagnose network problems in its own home network. The insights resulting from these measurements are useful to network regulators. They can use them to compare multiple broadband provider offerings and frame better policies to help regulate the broadband industry.

A. SamKnows

SamKnows is a company specializing in the deployment of hardware-based probes that perform continuous measurements to assess broadband performance. These probes are strategically[4] deployed within access networks and behind residential gateways. Fig. 4 provides an overview of the architecture of the SamKnows measurement platform.

1) Scale, Coverage and Timeline: SamKnows started in 2008, and in seven years they have deployed around 70K probes all around the globe. These probes have been deployed in close collaborations with 12 ISPs and 6 regulators: a) FCC, United States, b) European Commission (EC), European Union, c) Canadian Radio-Television Commission (CRTC), Canada, d) Ofcom, United Kingdom, e) Brazilian Agency of Telecommunications (Anatel), Brazil, f) Infocomm Development Authority of Singapore (IDA), Singapore.

2) Hardware: The probes are typical off-the-shelf TP-Link router devices[5] that have been flashed with a custom snapshot of OpenWrt firmware. The firmware has been made open-source with a GPL licence[6]. The probes function only as an ethernet bridge and all routing functionality has been stripped off the firmware. The wireless radio is used to monitor the cross-traffic to make sure active measurements are only run when the user is not aggressively using the network. The probe never associates to any wireless access point. As such, there is no IP-level configuration provisioned on the wireless port. Due to privacy concerns, the probe neither runs any passive measurements nor does it ever look into the user's traffic crossing the network.

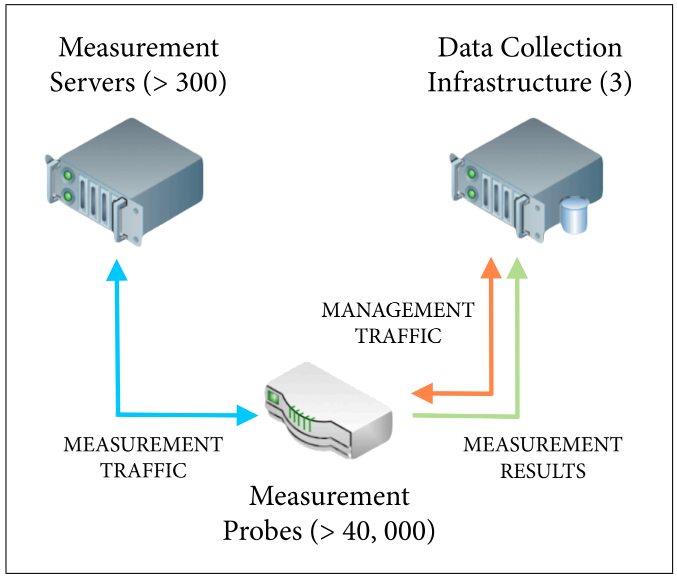

Fig. 4. *An architecture of the SamKnows measurement platform. A measurement probe is managed by a Data Collection Server (DCS) from which it receives software updates and measurement schedules. Probes periodically run measurements against custom SamKnows measurement servers. Measurement results are pushed to nearby DCS on an hourly window: http://ietf.org/proceedings/85/slides/slides-85-iesg-opsandtech-7.pdf*.

3) Metrics and Tools: Probes typically measure end-to-end latency, last-mile latency, latency-under-load, forward path, end-to-end packet loss, upstream and downstream throughput and goodput, end-to-end jitter, network availability, webpage download, Voice over IP (VoIP), Peer to Peer (P2P), DNS resolution, email relays, File Transfer Protocol (FTP) and video streaming performance. The raw measurement results sent by the probes are archived in geographically distributed and sharded MySQL instances. Hourly, daily and weekly summaries of the data are precomputed and stored in MySQL as well, to allow for rapid generation of reports. On specific measurement panels, where measurements are conducted in close collaboration with the ISP, the results are also validated against service-tier information. The obtained measurement reports are viewable via the SamKnows performance monitoring dashboards[7]. Hosts also receive monthly email report cards giving an overview of their broadband performance. iOS[8] and Android[9] smartphone apps have been released for Brazil, Europe and US regions.

4) Architecture: The active measurement tests and their schedules are remotely upgradeable by the Data Collection Server (DCS). The DCS functions both as a controller and as a measurement collector. The communication with the DCS is only server-side authenticated and encrypted over Transport Layer Security (TLS). Probes typically measure against a custom SamKnows measurement server. These are servers that only respond to measurement traffic and do not store any

[4] *http://goo.gl/ez6VTH*
[5] *earlier generations have used Linksys, Netgear, and PC Engines hardware*
[6] *http://files.samknows.com/~gpl*
[7] *https://reporting.samknows.com*
[8] *http://goo.gl/8tJVWu*
[9] *http://goo.gl/NH7GP6*

measurement results. There are around 300 such measurement servers deployed around the globe. The locality of these servers is critical to the customer, and therefore Round Trip Time (RTT) checks are periodically made by the probe to make sure that the probe is measuring against the nearest measurement server. Measurement servers can either be deployed within the ISP (called on-net test nodes) or outside the access network (called off-net test nodes).

5) Research Impact: Ofcom and FCC regularly publish their regulator reports on broadband performance using the SamKnows platform. These publicly available datasets have actively been utilized in multiple studies. Steven Bauer *et al.* in [41] for instance, use the FCC dataset to measure the subtle effects of Powerboost. They show how the scheduling of measurement tests needs to be improved to make sure different tests remain independent. They also show how the warm-up period used in the SamKnows throughput test needs a fair treatment to take the Powerboost effects into account. Zachary S. Bischof *et al.* in [42] demonstrate the feasibility of crowdsourced ISP characterization through data gathered from BitTorrent users. They used the Ofcom dataset to compare and validate their results. Zachary S. Bischof *et al.* in [43] go further to show how BitTorrent data can be used to accurately estimate latency and bandwidth performance indicators of a user's broadband connection. They used the FCC dataset to validate their results for users in the AT&T network. Giacomo Bernardi *et al.* in [44] describe `BSense`, a software-based broadband mapping framework. They compare their results by running a `BSense` agent from a user's home that also participates in SamKnows broadband measurements. They performed evaluation for a period of two-weeks and obtained comparable results. Igor Canadi *et al.* in [45] use the crowd-sourced data from `speedtest.net` to measure broadband performance. They use the FCC dataset to validate their results. Daniel Genin *et al.* in [46] use the FCC dataset to study the distribution of congestion in broadband networks. They found that DSL networks suffer from congestion primarily in the last-mile. Cable networks on the other hand are congested elsewhere, and with a higher variability. Vaibhav Bajpai *et al.* in [47] deploy SamKnows probes within dual-stacked networks to measure TCP connection establishment times to a number of popular services. They observed that websites clustering behind Content Delivery Network (CDN) deployments are different for IPv4 and IPv6. Using these clusters they show how CDN caches are largely absent over IPv6. They go further in [48] where they study effects of the happy eyeballs algorithm. They show how a 300ms advantage imparted by the algorithm leaves 1% chance for a client to prefer connections over IPv4. They show how this preference impacts user experience in situations where an IPv6 happy eyeballed winner is slower than IPv4. Saba Ahsan *et al.* take this further in [49] to show how TCP connection establishment times to YouTube media servers makes the happy eyeballs algorithm prefer a connection over IPv6 even when the measured throughput over IPv4 is better. This results in lower bit rates and lower resolutions when streaming a video than can be achieved if streamed over IPv4. They show how this is due to the disparity in the availability of YouTube content caches which are largely absent over IPv6.

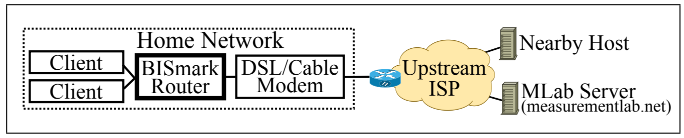

Fig. 5. *An architecture of the BISmark measurement platform. A measurement probe is wired behind a DSL or a cable modem. The probe can run both active and passive measurements. Measurement servers are source/sinks of measurement traffic. They are primarily M-Lab servers. A management server is used to remotely administer probes and collect measurement results [51].*

B. BISmark

Broadband Internet Service Benchmark (BISmark) [50] is an initiative by Georgia Tech to develop an OpenWrt-based platform for broadband performance measurement. The platform is similar to SamKnows as shown in Fig. 5. The probes primarily run active measurements. Passive measurements, however, can be enabled on a case by case basis by providing written consents. This is necessary to ensure volunteers are aware of the risk of exposing personally identifiable information.

1) Scale, Coverage and Timeline: BISmark started in 2010 and in five years they have deployed around 420 measurement probes on a global scale. Although more than 50% of the probes are deployed in developed countries, a significant effort has recently been made to increase the geographical diversity of the platform as shown in Fig. 6. A real-time snapshot of the coverage is also available on the network dashboard[10].

2) Hardware: BISmark uses off-the-shelf Netgear routers that have been custom flashed with an OpenWrt firmware. The firmwares run a measurement overlay that is composed of a number of active measurement tools and scripts that have been packaged by the BISmark team. The entire BISmark software-suite has been open-sourced through a GPL v2 licence[11]. The probe unlike that of a SamKnows probe is a full-fledged router. The probe by default provides wireless access points on both 2.4 GHz and 5 GHz radio interfaces.

3) Metrics and Tools: The probes support both active and passive measurements. All probes actively measure end-to-end latency, last-mile latency, latency under load, end-to-end packet loss, access-link capacity, upstream and downstream throughput, and end-to-end jitter. Occasionally, they also send special heartbeat packets to report their online status and uptime information to BISmark management servers. The metrics are measured using popular specialized tools. For instance, probes run ShaperProbe [33] to measure the access link capacity, `iperf` to measure the upstream and downstream throughput, D-ITG [52] to measure jitter and packet loss, `paris-traceroute` [23] to measure forward and reverse path between probes and M-Lab servers, and Mirage [53] to measure the webpage load time. On explicit volunteer consent, probes can also run some passive measurements. For instance, probes can count the number of wired devices, devices associated on a wireless link, and number of wireless access points in the vicinity. Probes also passively measure

[10] *http://networkdashboard.org*
[11] *https://github.com/projectbismark*

packet and flow statistics, DNS responses and Media Access Control (MAC) addresses. The obtained measurement results and overall statistics are available via the network dashboard.

4) Architecture: The BISmark architecture consists of measurement probes, a management server and several measurement servers. The management server functions both as a controller and as a measurement collector. Measurement servers are strategically deployed targets used by active measurement tools. These are primarily M-Lab servers hosted by Google. The measurement probe periodically sends User Datagram Protocol (UDP) control packets to the controller. This punches a hole in the gateway's NAT and allows the controller to push configuration and software updates.

5) Research Impact: Srikanth Sundaresan *et al.* in [54] use the BISmark platform to identify a collection of metrics that affect the performance experienced by a broadband user. They show that such a *nutrition label* provides more comprehensive information, and must be thus advertised by an ISP in its service plans to increase transparency. Hyojoon Kim *et al.* in [55] use the BISmark platform to demonstrate how broadband users can monitor and manage their usage caps. It proposes an OpenFlow control channel to enforce usage policies on users, applications and devices. Srikanth Sundaresan *et al.* in [21], [13] use the BISmark platform to investigate the throughput and latency of access network links across multiple ISPs in the United States. They analyze this data together with data publicly available from the SamKnows/FCC study to investigate different traffic shaping policies enforced by ISPs and to understand the bufferbloat phenomenon. Swati Roy *et al.* in [56] use the BISmark platform to measure end-to-end latencies to M-Lab servers and Google's anycast DNS service. They propose an algorithm to correlate latency anomalies to subsets of the network path responsible for inducing such changes. They observed low last-mile latency issues, with higher middle-mile issues in developing regions, indicating scope of improvement along peering links. Srikanth Sundaresan *et al.* in [53], [57], [58] use the BISmark platform to measure web performance bottlenecks using Mirage, a command-line web performance tool. They show that latency is a bottleneck in access networks where throughput rates exceed 16Mbits/s. They also show how last-mile latency is a significant contributor both to DNS lookup times and time to first byte. They demonstrate how these bottlenecks can be mitigated by up to 53% by implementing DNS and TCP connection caching and prefetching on a residential gateway. Sarthak Grover *et al.* in [51] use the BISmark platform to perform a longitudinal measurement study on home network properties. They use continuously running active and passive measurements to study home network availability, infrastructure and usage patterns. They show how network usage behavior patterns differ across countries in developed and developing regions, how the 2.4 GHz wireless spectrum is significantly more crowded (specially in developed countries) when compared to the 5 GHz wireless spectrum, and how majority of the home traffic is destined to only few destinations. Marshini Chetty *et al.* in [59] use the BISmark platform to measure fixed and mobile broadband performance in South Africa. They show how broadband users do not get advertised rates, how throughputs achievable on mobile networks are higher when compared to fixed networks, and how latency to popular web services is generally high. Arpit Gupta *et al.* in [18] go further and study ISP peering connectivities in Africa. Using `paris-traceroute` they show how local paths detour via remote Internet Exchange Point (IXP)s in Europe leading to increased latencies to popular web services. They also show how ISPs either are not present or do not peer at local IXPs due to economic disincentives. Srikanth Sundaresan *et al.* in [50] reflect upon the success of BISmark by discussing design decisions faced during the implementation work. A summary of research projects using this platform and on-going experiments are enumerated. Lessons learned during the four-year deployment effort are also described. Srikanth Sundaresan *et al.* in [60] use passively collected packet traces from a subset of BISmark probes to study the relationship between wireless and TCP performance metrics on user traffic. They show how with an increase in access link capacity, wireless performance starts to play an increasing role on achievable TCP throughput. They show how the wireless performance is affected more over the 2.4 GHz spectrum (when compared with 5 GHz spectrum) where the latency impacts are worse with higher retransmission rates. They also show how latency inside a home wireless network contributes signficantly towards end-to-end latency.

Fig. 6. *The coverage of the BISmark measurement platform as of Feb 2015. The green and red dots represent connected (around 119) and disconnected probes respectively: http://networkdashboard.org.*

C. *Dasu*

Dasu is an initiative by Northwestern University to develop a software-based measurement platform that allows network experimentation from the Internet's edge. The platform started with an objective to perform broadband characterization from home, but it has evolved into facilitating end-users to identify service levels offered by their ISP. Fig. 7 provides an architecture of the Dasu measurement platform. The platform allows clients to run both active and passive measurements.

1) Scale, Coverage and Timeline: Dasu started in 2010 and in five years they have around 100K users connected behind around 1.8K service networks. These users are located around the globe and span around 166 countries as shown in Fig. 8.

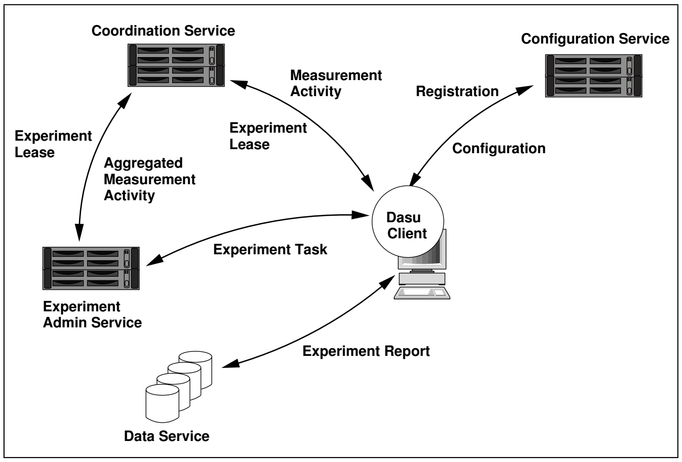

Fig. 7. *An architecture of the Dasu measurement platform. A client on startup registers with a coordination service to retrieve configuration settings and the location of the measurement collecter. The client periodically contacts the EA service to retrieve a set of assigned measurement tasks. Once the tasks are assigned, the client contacts the coordination service to pick up a lease to start measurements. Measurement results are eventually pushed to the data service. The configuration, coordination and EA service together function as a controller, while the data service functions as a measurement collector [16].*

2) Hardware: Dasu is a software plugin that hooks into Vuze/Azureus BitTorrent client application. Vuze is chosen for its increasing popularity and its modular architecture that easily allows installation of third-party plugins. Vuze also seamlessly handles software updates for installed plugins. For users that do not use BitTorrent, a standalone client is also available online in its current beta stage[12]. The platform prefers a software-based approach to not only eliminate the cost factor involved in deployed hardware probes, but also to increase the control, flexibility and low-barrier to adoption of software-based models.

3) Metrics and Tools: The platform allows the clients to perform both active and passive measurements. The BitTorrent plugin passively collects per-torrent (number of TCP resets, upload and download rates), application-wide (number of active torrents, upload and donwload rates) and system-wide statistics (number of active, failed, and closed TCP connections). The client is composed of multiple probe modules that allow active measurements. These probe modules actively measure end-to-end latency, forwarding path, HTTP GET, DNS resolution and upstream and downstream throughput. `ping` is used to measure end-to-end latency, `traceroute` for capturing the forwarding path and Network Diagnostic Tool (NDT) to measure upstream and downstream throughput. Active measurements are scheduled using a `cron`-like scheduler. All the clients synchronize their clocks using Network Time Protocol (NTP). This allows synchronization of a task that covers multiple clients. To allow a finer synchronization, clients can establish a persistent TCP connection to the coordination server. Each measurement runs in its own Java Virtual Machine (JVM) sandboxed environment with a security manager that applies policies similar to those applied to unsigned Java applets. The configuration files sent by the server are digitally signed. All client-server communications are also encrypted over a secure channel. The client also monitors resources such as CPU, network bandwidth, memory and disk usage to make sure measurements only run when the resource utilization is below a certain threshold. The client employs watchdog timers to control CPU utilization. It uses `netstat` to monitor the network activity and couples it with the maximum bandwidth capacity estimate retrieved from NDT to control bandwidth utilization. It also assigns quota limits to control memory and disk space utilization.

4) Architecture: The Dasu architecture consists of a distributed collection of clients, a measurement controller composed of the configuration, coordination, and Experiment Admin (EA) service and a measurement collector called the data service. A client on bootstrap registers with a configuration service to retrieve a set of configuration settings. These settings assign duration and frequency of measurement operations and instruct which coordination and data service must this client use in future interactions. The client periodically polls the EA service to retrieve measurement tasks. The measurement tasks are defined using a rule-based declarative model. A set of rules describe a program, while a set of programs form a measurement task. The EA service assigns measurement tasks to clients based on the requirements and client characteristics. The client must pickup a lease from the coordination service before it can start measurements for an assigned task. Leases are used to ensure fine-grained control of the measurement infrastructure. Leases grant budgets, which are upper bounds on the number of measurement queries a client can run at specific point in time. These budgets are elastic and can vary dynamically depending on the aggregated load of the measurement infrastructure. The EA service is composed of

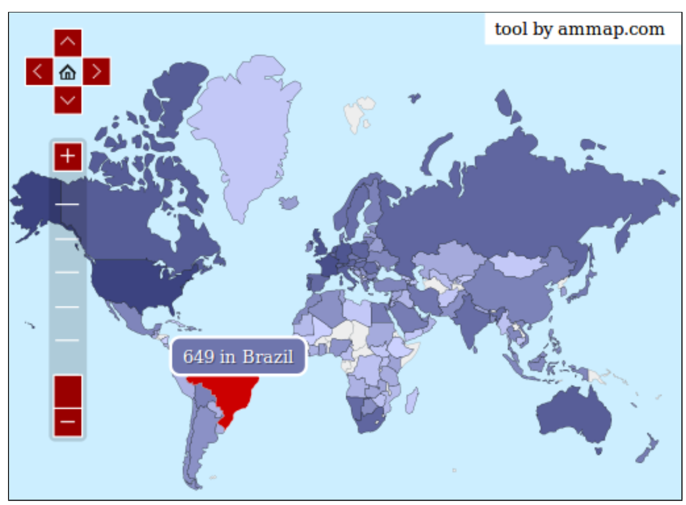

Fig. 8. *The network coverage of the Dasu measurement platform as of Feb 2015. The different shades of blue indicate the number of clients participating in the measurement: http://www.aqualab.cs.northwestern.edu/projects/115-dasu-isp-characterization-from-the-network-edge.*

[12] *http://www.aqualab.cs.northwestern.edu/running-code*

a primary EA server and several secondary EA servers. The primary EA service ensures that the aggregated measurement activity is within defined bounds. This is used to set values for the elastic budgets for specific leases. Secondary EA services then are responsible for allocating these leases to the coordination service. The coordination service hands out these leases to clients when they contact them. The coordination service runs on top of the PlanetLab infrastructure to ensure replication and high availability. The collected measurement results are finally pushed to the data service.

5) Research Impact: Mario A. Sánchez *et al.* in [61] introduce Dasu as a platform that can crowdsource ISP characterization from the Internet's edge. They describe how it can capture end user's view by passively monitoring user-generated BitTorrent traffic from the host application. They specifically show how measurement rule specifications are defined and how they trigger measurement tests from within the client application. Zachary S. Bischof *et al.* in [42] demonstrate the feasibility of this approch by analyzing data gathered from 500K BitTorrent users. They show how this data can be used to a) infer service levels offered by the ISP, b) measure the diversity of broadband performance across and within regions of service, c) observe diurnal patterns in achieved throughput rates, d) measure visibility of DNS outage events, and e) relatively compare broadband performance across ISPs. They used the SamKnows/Ofcom dataset to compare and validate their results. They go further in [43] to show how this approach can be used to accurately estimate latency and bandwidth performance indicators of a user's broadband connection. They measure last-mile latencies of AT&T subscribers and validate their results using the SamKnows/FCC dataset. They also validate the soundedness of their throughput measurements by comparing BitTorrent throughputs against those obtained by the NDT tool. Mario A. Sánchez *et al.* in [16], [62] describe the design and implementation of the platform alongwith a coverage characterization of its current deployment. They use the platform to present three case studies: a) measuring Autonomous Systems (AS)-level assymmetries between Dasu and PlanetLab nodes, b) studying prefix-based peering arrangements to infer AS-level connectivities, and c) measuring the performance benefits of DNS extensions. They go further in [63] to leverage Universal Plug and Play (UPnP) to study home device characteristics from 13K home users. They use the Digital Living Network Alliance (DLNA) specification to further categorize the UPnP devices. They also utilize received traffic counters and couple them with the data collected through their client's passive monitoring tools to identify whether the cross-traffic originates locally from another application or from entirely another device. Zachary S. Bischof *et al.* in [64] use a 23-months long Dasu and SamKnows/FCC dataset to study broadband markets; particularly the relationship between broadband connection characeteritics, service retail prices and user demands. They show how the increase in broadband traffic is driven more by increasing service capacities and broadband subscriptions, and less by user demands to move up to a higher service-tiers. They also find a strong correlation between capacity and user demands and show how the relationship tends to follow the law of diminishing returns.

IV. Mobile Access

A number of platforms have recently emerged that specifically focus on measuring performance in mobile access networks. The challenges faced by these platforms are very different from platforms that operate on fixed-line networks. Factors such as signal strength, device type, radio type, frequency of handovers and positioning information of cellular devices need to be taken into account when doing measurements. The service plans on these mobile devices are also very restrictive, and measurements need to ensure that they take usage caps into account when generating network traffic. Additionally the measurements run on top of cellular devices. These devices are not homogenous, but rather run varying flavors of mobile operating systems. The measurement overlay needs to specifically be developed for each mobile platform.

A. Netradar

Netradar is a mobile measurement platform operated by Aalto University. The objective is not just to run tests and present measurement results to the end-user, but also to provide an automated reasoning of the perceived results. Towards this end, Netradar runs measurements that cover a wide-range of key network performance indicators to be able to do analysis that can provide a rationale behind the observations.

1) History: Netradar is a successor to the Finish specific mobile measurement platform, Nettitutka[13]. Nettitutka started in early 2011. The platform was designed to serve the local user population in Finland, and therefore measurements were targeted to a single server located within the Finnish University and Research Network (FUNET). With the increasing popularity of the platform, Nettitutka has been replaced by Netradar.

2) Scale, Coverage and Timeline: Netradar started in 2012 and in three years they have performed around 3.8M measurements from mobile devices. The client itself has been installed 150K times on a wide variety of (around 5K) mobile handsets. Fig. 9 shows the geographical coverage of these measurements.

[13] *http://www.netradar.org/fi*

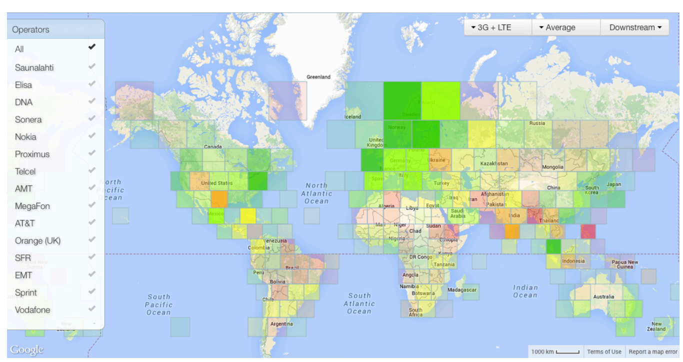

Fig. 9. *The coverage of the Netradar measurements as of Feb 2015. The quality is measured based on network download and upload speeds, latency and signal strength: https://www.netradar.org/en/maps. The threshold intervals used to define different colors on the map are described here: https://www.netradar.org/about/map.*

3) Hardware: The Netradar measurement platform is a software client that can install on bare-bones smartphone devices. The client is available for Google Android, Apple iOS, Nokia Meego, Symbian, BlackBerry, Microsoft Windows and Sailfish phones. The measurement capability of each platform is identical with minor differences. For instance, iOS does not expose signal strength details that can be utilized by the Netradar platform.

4) Metrics and Tools: Netradar performs both active and passive measurements. Passive measurements report parameters such as signal strength, operating system, device type, radio type, positioning information, handovers using base station ID, and vendor information. Active measurements include measuring latency and TCP goodput using upload and download speed tests. Handovers, signal strength and location information are also measured during an active measurement. Each measurement tags measurement result with timestamps at millisecond resolution. The speed test measurements are run for 10 seconds on a single TCP connection against the closest Netradar measurement server. The speed test results are stored with a resolution of 50ms. The speed test also skips the first 5 seconds as a warmup phase to skip TCP slow-start. Internet disconnectivity is also recorded to map the distribution of best-connectivity areas. Netradar uses GPS, wireless, cellular, and IP address information to accurately map the positioning information of a device. The latency measurements run over UDP both before and after a speed test measurement. Netradar also uses TCP statistics to store RTT values during the speed test measurement.

5) Architecture: Netradar relies on a client-server based architecture. Servers are measurement targets that are deployed in the cloud and globally distributed. Clients measure against closest measurement servers. The measurement result databases and web servers are replicated to achieve scalability. The number of instances are scaled by real-time monitoring of server load. The number of simultaneous connections to a server instance is also limited by a threshold.

6) Research Impact: Sebastian Sonntag *et al.* in [65] use the Netradar platform to study various parameters that affect bandwidth measurements in mobile devices. They show how the used radio technology and signal strength are the most significant factors affecting bandwidth. They also describe how the bandwidth is cut by a third, due to poor provisioning and congestion at the cell tower. The device type and frequency of handovers are also limiting factors. They go further in [66] to study the correlation between signal strength and other network parameters. They show how signal strength has low correlation to TCP goodput. They show how taking the time of the day and motion speed parameters into account still does not increase this correlation. As such, coverage maps drawn using signal strength as a parameter are limited. They provide recommendations on the tile size and on using TCP goodput as a parameter for drawing these coverage maps. Le Wang *et al.* in [67] show how the energy consumption of mobile devices is suboptimal when browsing web content both over wireless and cellular networks. They present an energy-efficient proxy system, that utilizes bundling of web content, Radio Resource Control (RRC) state based header compression and selective content compression to reduce the operating power of mobile devices during web access.

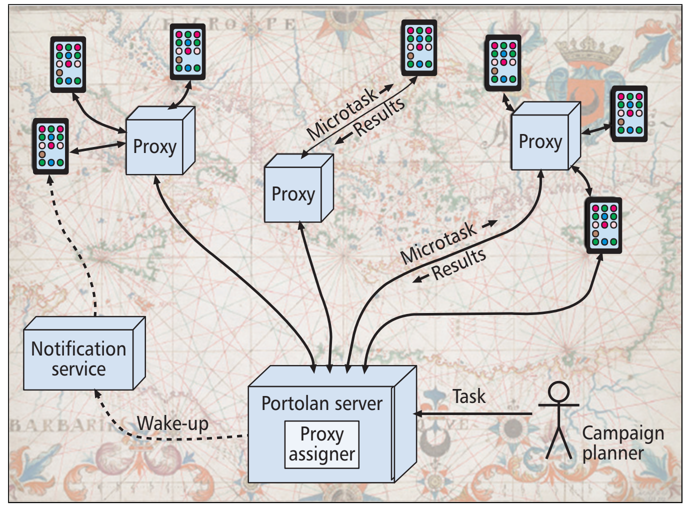

Fig. 10. *The architecture of the Portolan measurement platform. A human prepares a XML specification of a measurement campaign and deploys it on a central server. The server validates the specification and bifurcates it into a set of microtasks. Microtasks are handed out to regional proxies who mediate the deployment of measurement instructions and collection of results between mobile devices and the central server [68].*

B. Portolan

Portolan is a crowd-sourced mobile measurement platform operated by the University of Pisa and the Informatics and Telematics Institute of the Italian National Research Council. The objective is twofold: a) provide a comprehensive mapping of the signal strength coverage over the globe and b) facilitate topology mapping efforts at the AS-level by contributing measurements from mobile devices. Fig. 10 provides an overview of the architecture of the Portolan measurement platform.

1) Scale, Coverage and Timeline: Portolan started in 2012 and in three years they have around 300 active users all around the globe as shown in Fig. 11. The concentration is higher in Italy from where the platform originated.

2) Hardware: The Portolan measurement platform utilizes a software client that one can install on stock smartphone devices. It currently supports Google Android, however a client for Apple iOS is in the works. The client itself has received around 8 version releases [69]. The client treats the mobile device as a sensor that can measure network-related properties. The client is therefore subdivided into multiple measurement subsystems. Each subsystem measures a particular network property and is described using a SensorML specification [70].

3) Metrics and Tools: The platform supports both active and passive measurements. It actively measures latency, forwarding path (both at the Internet Protocol (IP) and AS level), and achievable bandwidth. It passively scans available wireless networks, signal strength and cell coverage. It also periodically runs a traffic shaping detection tool to check if your bittorrent traffic is treated differently. Portolan uses `SmartProbe` [71] to measure the achievable bandwidth and `MDA-traceroute` [25] to capture the forwarding path. The implementation has been modified to utilize UDP-based probing using the `IP_RECVERR` socket option to perform `traceroute` measurements without superuser privileges. It is also made multi-threaded to utilize multiple sockets to parallelize the probing operation. These adaptations however limit the possibility of performing fingerprinting-based alias-resolution on the client side. As such, alias-resolution is performed in a post-processing stage by the server. Not more than 200 measurements are run per day. This limitation is enforced to ensure that Portolan does not consume roughly more than 2MB/day on `traceroute` measurements. The signal strength results must be geo-referenced using the device's Global Positioning System (GPS). In order to avoid draining the battery, Portolan does not actively enable the GPS but waits to reuse the location information when the user (or an application started by the user) enables it. Portolan suspends all activity when the battery level goes below 40%. The server-side components are written as Java Servlets running on Apache Tomcat.

4) Architecture: Portolan is based on a centralized architecture. A central server acts both as a controller and as a measurement collector. However, in order to achieve scalability, a number of regional proxies have been deployed to mediate the deployment of measurement instructions and retrieval of measurement results from a set of geographically clustered mobile devices. Proxies are deployed at a country-level resolution, given mobile devices tend to show a quasi-static behavior at this granularity. Each mobile device is identified in the system using a pseudo-randomly generated ID. These IDs are assigned to a regional proxy by a proxy assigner implemented within the central server. A measurement campaign is formally described in a Extensible Markup Language (XML) specification by a human and submitted to the central server, where it is validated and decomposed into a set of loosely-coupled instructions, called *microtasks*. These microtasks are then shipped to regional proxies for local deployment. The microtasks are pulled (and not pushed) by mobile devices. This call-home mechanism allows devices to traverse the NAT. However high-priority microtasks can also be directly pushed to devices by the central server. The server uses the Google Cloud Messaging (GCM) service as a notification service to push high-priority microtasks as network events. The notification service is also used to tune device polling intervals to adapt to the number of the devices associated with a regional proxy. The XML specification of a measurement consists of the type of metric, source and target destination lists, duration, metric parameters and an urgent flag. The validation of the specification is performed using Sensor Planning Service (SPS) component, while the Sensor Observation Service (SOS) component is used to retrieve measurement results. These components are standards specified within the Sensor Web Enablement (SWE) framework [72]. The polling beacon messages piggyback device's location, IP address, battery status, network load and base station ID. Regional proxies use this as a guideline to choose mobile devices for a specific microtask.

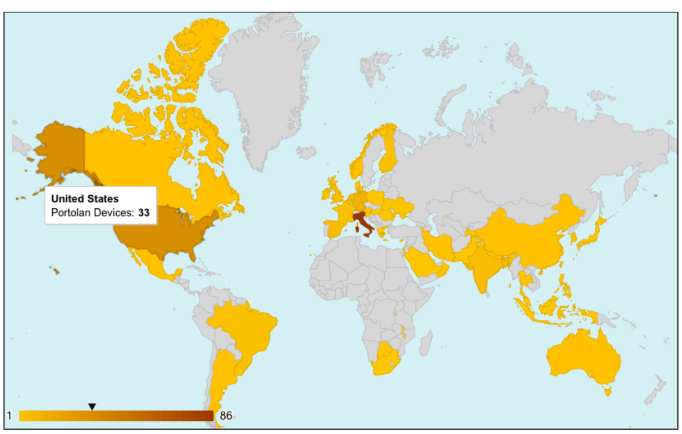

Fig. 11. *The network coverage of the Portolan measurement platform as of Oct 2014. The different shades of brown indicate the number of clients participating in the measurement: http://portolan.iet.unipi.it.*

5) Research Impact: Adriano Faggiani *et al.* in [20] present their idea on smartphone-based crowdsourced measurements. They describe the design of such a measurement system, alongwith details on the implementation and validation of running `MDA-traceroute` measurements from an Android device. Enrico Gregori *et al.* in [70] describe the implementation of the Portolan measurement platform alongwith preliminary results. They present how they use standards defined in the SWE framework to treat mobile devices as sensors to provision measurement tasks and retrieve measurement results. They perform a preliminary study on measuring the AS-level topology using this platform. They run validations using ground-truth data obtained from network operators, and evaluate their results against publicly available AS topology datasets. Francesco Disperati *et al.* in [71] present SmartProbe, a link capacity estimation tool that is tailored for mobile devies. It is an adaptation of the packet-train based tool, PBProbe [73], for wireless and wired networks. Portolan uses it to measure acheivable bandwidth from mobile devices. Adriano Faggiani *et al.* in [69] share their experiences in building such a measurement platform. The challenges involve factors such as human involvement in a control loop, limited resources of mobile devices, handling big data, and motivating users to participate in measurements. They go further in [68] to describe their motivation behind choosing a crowdsourced-based monitoring approach. They illustrate opportunities and challenges that come with this approach, alongwith use-case scenarios where this could prove beneficial. They briefly describe the measurement platform with measurement results.

V. Operational Support

A number of Internet performance measurement platforms have been deployed with the goal to provide operational support to network operators. These platforms are being utilized by the operators to help diagnose and troubleshoot their network infrastructure. A large number of the probes within these platforms are therefore not deployed at the edge but within the core of the Internet.

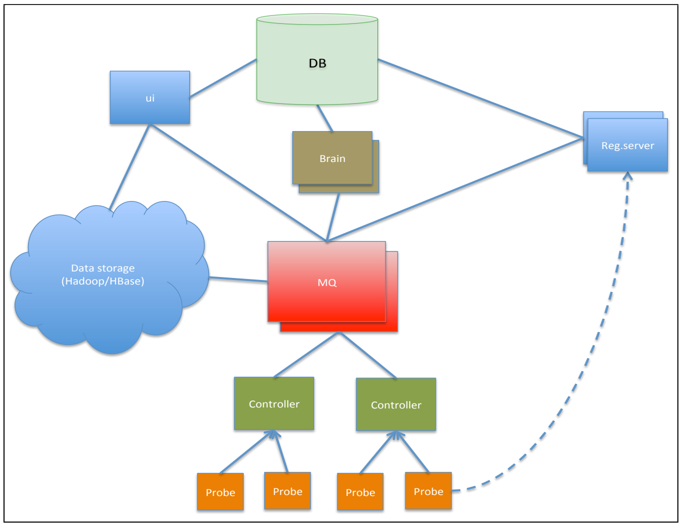

Fig. 12. *The architecture of the RIPE Atlas measurement platform. A measurement probe on bootstrap learns about the location of its controller by securely connecting to a registration server. The controller on receiving the initial request sends measurement schedules and software updates to the probe. The probe ships the measurement results to the controller. The brain supplements the results with information from third-party sources. The aggregated results are queued up to be later processed by Hadoop jobs and archived in HBase stores: http://www.ietf.org/proceedings/interim/2013/10/14/nmrg/slides/slides-interim-2013-nmrg-1-0.pdf*

A. *RIPE Atlas*

RIPE Atlas is a measurement infrastructure deployed by the RIPE Network Coordination Centre (RIPE NCC). It consists of thousands of hardware probes distributed all around the globe. These probes specifically perform only active measurements. The infrastructure has been designed with a goal to provide operational support to Local Internet Registrar (LIR)s. Fig. 12 provides an overview of the architecture of the RIPE Atlas measurement platform.

1) History: RIPE Atlas is a successor to the RIPE Test Traffic Measurement Service (TTM). RIPE TTM is a legacy measurement platform that started in 1997[14] and was designed to provide standardized measurements for one-way delay and one-way packet loss between probes. The platform had around 100 TTM boxes [74] distributed globally as shown in Fig. 13. The probes continuously measured one-way delay, packet loss, jitter, root-nameserver reachability, routing statistics, GPS satellite conditions and PMTU discovery. In addition, each TTM box was running `traceroute` measurements to one another. The platform was decommissioned on 1st July 2014 in favour of the RIPE Atlas platform.

2) Scale, Coverage and Timeline: RIPE Atlas started in 2010[15] and in five years RIPE has deployed around 12K hardware probes all around the globe as shown in Fig. 14. A large number of these probes have been deployed by network operators in their internal network. These probes are situated within access networks and at the core. A discernible number of enthusiasts do volunteer to host a probe at their home. As as result, quite a number of probes are also connected behind a residential gateway.

3) Hardware: The hardware probes have evolved over the years. The first and second generations were a custom hardware built around a Lantronix XPort Pro module. The limitations of the hardware led to a third generation probe running on top of an off-the-shelf TP-Link wireless router. Although the third generation is much more capable than the previous iterations, the firmware running on all the three variants is exactly the same. The measurement firmware runs on top of OpenWrt and has been open-sourced with a GPLv2 licence[16]. All wireless capabilities have been stripped off the firmware for privacy reasons. In addition to the probes, RIPE also deploys RIPE Atlas anchors[17]. Anchors are dedicated servers running the RIPE Atlas firmware. Fig. 15 shows the deployment coverage of these anchors. Anchors can serve both as a source and sink of measurement traffic. Anchors when acting as probes can run a large number of measurements in parallel. The regular probes can also schedule measurements targetted to these anchors, which serve as powerful targets to handle a large number of measurement requests. This way, anchors help provide information on regional connectivity and reachability. The RIPE NCC also periodically schedules baseline measurement to an anchor, called *anchoring measurements* from a batch of several hundred regular probes and every other anchor to continously measure regional reachability.

4) Metrics and Tools: The probes only run active measurements[18]. They perform RTT, `traceroute`, HTTP and Secure Sockets Layer (SSL) queries to a number of preconfigured destinations as built-in measurements. They also specifically run RTT measurements to the first and second hop alongside DNS queries to DNS root servers. All of these built-in measurements are run both over IPv4 and IPv6. The probes also send their local uptime, total uptime, uptime history and current network configuration information periodically to mea-

[14] https://labs.ripe.net/Members/dfk/ripe-ttm-user-survey-results
[15] https://atlas.ripe.net/about/future-plans
[16] https://atlas.ripe.net/get-involved/source-code
[17] https://atlas.ripe.net/about/anchors
[18] https://atlas.ripe.net/about/faq

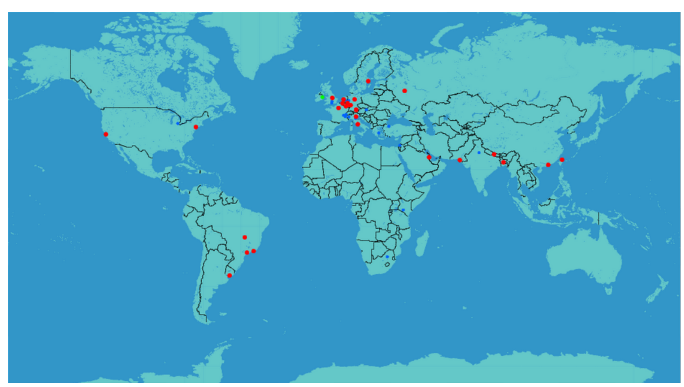

Fig. 13. *The coverage of the legacy RIPE TTM measurement platform as of Feb 2015. The red dots represent active probes respectively: http://ttm.ripe.net/Plots/map_index.cgi*

Fig. 14. *The coverage of the RIPE Atlas measurement platform as of Feb 2015. The green, red and grey slices represent connected (around 7.7K), disconnected and abandoned probes respectively. Around 12K probes have been deployed in total: https://atlas.ripe.net/results/maps/network-coverage*

surement controllers. The measurement tools are adaptations of the standard UNIX utilities available in busybox. The measurement code has been modified to make measurements run in an event-driven manner using `libevent` and to make them output the measurement results in JavaScript Object Notation (JSON) format. These modifications have resulted in: `evping`, `evtraceroute`, `evtdig` and `evhttpget`. The platform also includes an evented scheduler, `eperd`, which is similar to `cron` but with added capabilities: a) The scheduler in addition to the start time, can also take a stop time and runtime frequency of a test, b) it also adds jitter to make sure not all measurements start running at the same time, and c) it runs tests as separate functions and not as separate processes to overcome limitations of the Memory Management Unit (MMU). A non-evented version of the scheduler, `perd` is used to periodically run the SSL measurement test, `sslgetcert` and ship measurement results over HTTP. A `eooqd` daemon is used to provision one-off measurements (measurements that execute only once). A RIPE Atlas roadmap page[19] describes the future plans on deployment of newer metrics and measurement tools. The RIPE NCC is using measurement results to provide Internet scale latency and reachability maps[20] as a community service.

5) Architecture: The RIPE Atlas architecture consists of measurement probes, a registration server and several controllers. A probe bootstraps by securely connecting to a registration server. The address of the registration server and keys are hardwired on the probe. All of the communications are initiated by mutual authentication over two reverse `ssh` channels. These channels run on port 8080 to easily traverse firewalls. The registration server on a successful connection directs the probe to a nearby controller. The decision is based on the geographical proximity and overall availability of the controller. The controller, on receiving a request from the probe, sends a measurement schedule on one `ssh` channel, and sets up a periodic wait to receive measurement results on another `ssh` channel. The scheduling decisions are made by the controller based on the available measurement capacity and geographical proximity of the probe. The controller is also responsible for shipping software updates to the probe. There are less than 500 probes associated per controller[21]. The intermediate measurement results are queued up by RabbitMQ to be later archived in HBase measurement stores. The brain is responsible for running parallel Hadoop jobs to process these measurement results and incorporate information from Border Gateway Protocol (BGP) data sources. A central database is used to keep administrative information, measurement metadata, recent measurement results and credit stores. A user-interface is available to check status of the probes, measurement results and credit accumulation points. RIPE Atlas architecture also provides the capability to run custom measurements, User Defined Measurement (UDM). The ability to provision UDMs has been available since the launch of the platform. Running a UDM consumes credits, which are earned by either hosting or sponsoring probes. RIPE Atlas also provides a REST-based API[22] to not only provision such UDMs, but also retrieve measurement results programatically. Measurement results produced from within RIPE Atlas are made publicly available with an immutable reference, the measurement ID. This enables one to publish raw datasets to enable reproducible research. As a result, the platform is starting to gain traction within the academic community.

6) Research Impact: The RIPE NCC regularly publishes results derived from the RIPE Atlas measurement platform. These articles[23] range from studying an event (e.g. Hurricane and Superstorm Sandy), to troubleshooting issues (e.g. debogonising 128.0/16, BGP route filtering of IPv6 /48) to understanding the infrastructure changes (IPv6 reachability testing).

A number of independent researchers have used RIPE Atlas for measurement-based research. For instance, Massimo Candela *et al.* in [75] demonstrate a system, called `TPLAY` that

[19] http://roadmap.ripe.net/ripe-atlas
[20] https://atlas.ripe.net/results/maps
[21] https://atlas.ripe.net/results/graphs
[22] https://atlas.ripe.net/docs/rest
[23] https://atlas.ripe.net/results/analyses

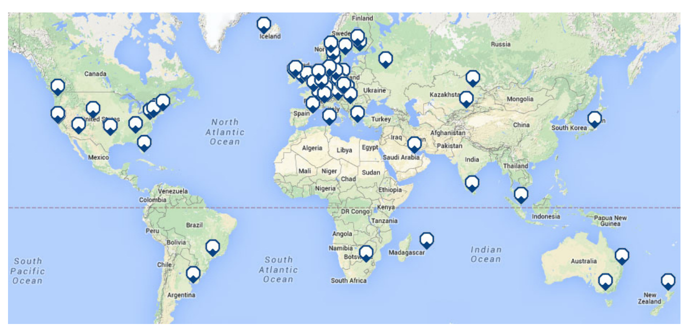

Fig. 15. *The coverage of the RIPE Atlas anchors as of Feb 2015. Around 100 anchors have been deployed in total: https://atlas.ripe.net/anchors/map/. A list of deployed anchors and anchoring measurements is available here: https://atlas.ripe.net/anchors/list/.*

can be used to visualize `traceroute` measurements performed by the RIPE Atlas probes. The visualization is a radial representation of a clustered graph where routers are vertices and clusters are adminitrative domains. Massimo Rimondini *et al.* in [15] present an automated matching method to evaluate the impact of BGP routing changes on network delays. They verify the effectiveness of the method on publicly available BGP data from RIPE Remote Routing Collectors (RIS) and RTT data from the RIPE Atlas platform. Andra Lutu *et al.* in [76] use the BGP Visibility Scanner [77] to categorize the visibility of announced IPv6 prefixes. They run `traceroute` measurements from the RIPE Atlas platform to measure the reachability of the categorized Limited-Visibility Prefixes (LVP) and Dark Prefixes (DP). They show that LVP are generally reachable, however DP are largely not. Nevil Brownlee *et al.* in [78] study patterns in `traceroute` responses caused by routing changes as seen by a cluster of RIPE Atlas probes. They use a combination of edit-distance and uncommon-distance measures to cluster probes. Adriano Faggiani *et al.* in [79] utilize the p2c-distance metric [80] to show how traceroute measurement infrastructures along with BGP route-collectors can increase the AS-level topology coverage by 48.5%. Collin Anderson *et al.* in [81] use RIPE Atlas to study censorship events in Turkey and Russia. They ran hourly DNS, `traceroute` and SSL connectivity tests towards social media websites to study content restrictions and blocking strategies employed during the event. Marco Di Bartolomeo *et al.* in [82] introduce an *empathy* relationship between `traceroute` measurements. They describe an algorithm that leverges this relationship to identify high-impact events from traceroute datasets. The effectiveness of the approach is presented by utilizing publicly available RIPE Atlas `traceroute` datasets.

A number of research papers have also been published in the past that have used the legacy TTM measurement platform. For instance, C. J. Bovy *et al.* in [83] study distributions of end-to-end delay measurements between several pair of TTM boxes. They witnessed around 84% of these distributions were typical gamma shaped with a heavy tail. Artur Ziviani *et al.* in [84] show how a measurement-based service can be used to geographically locate Internet hosts. They use geographically distributed TTM boxes (equipped with GPS sensors) as landmarks to infer the location of the target by matching network delay patterns of the target to one of these known landmarks. Xiaoming Zhou *et al.* in [85] use TTM boxes to measure end-to-end packet reordering using UDP streams. They show that packet reordering is a frequent phenomenon, with a relatively small number of reordering events ocurring in an individual stream. They also observed that reordered stream ratios are fairly asymmetric. They go further in [22] to measure end-to-end IPv6 delays and hopcount between the TTM boxes. They observe how for a given source and destination pair, IPv6 paths show higher delay and variation when compared to IPv4 paths. They attribute the difference to the presence of badly configured tunnels in IPv6. Finally, with the decline of TTM service, Tony McGregor *et al.* in [74] announced the availability of a public data repository hosted by RIPE NCC. The dataset comprises of measurements conducted by RIPE NCC projects, National Laboratory for Applied Network Research (NLANR) project, and other external research institutions.

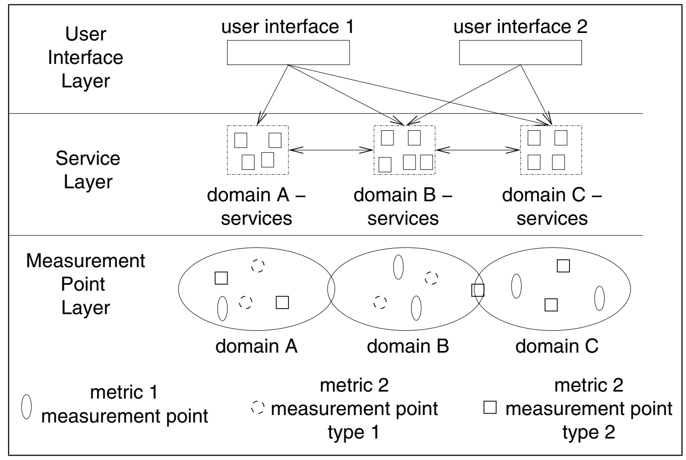

Fig. 16. *An architecture of the perfSONAR measurement platform. The architecture is divided into three layers. The middleware layer is a network management web service layer. The bottom layer is a network measurement layer responsible for running active (or passive) measurement tests. The top layer interfaces with the user encompassing a number of visualization tools and methods to allow the user to trigger a measurement test [86].*

B. *perfSONAR*

Performance Focused Service Oriented Network Monitoring Architecture (perfSONAR) is a collaborative initative by The Energy Sciences Network (ESnet), GÉANT, Internet2, and Brazil's National Education and Research Network (RNP). perfSONAR is a network monitoring framework that seeks to solve end-to-end performance problems on paths crossing multi-domain networks. It is designed to support collaborative scientific experiments that rely on ubiquitous and high performing global network infrastructure. The support primarily involves identifying and isolating performance problems in network paths that underpin scientific data exchange. perfSONAR is a federation of measurement sites within these network paths. These sites are equipped with a set of measurement tools that can help localize the performance problems. Fig. 16 provides an overview of the architecture of the perfSONAR measurement platform.

1) Scale, Coverage and Timeline: perfSONAR started in 2004 and in 11 years they have deployed around 7.6K perfSONAR web services all around the globe as shown in Fig. 17. perfSONAR Performance Toolkit (perfSONAR-PS), a perfSONAR-based performance measurement toolkit developed by ESnet and Internet2, was first released as an open-source software in 2006. The US ATLAS project has been using this toolkit since 2008. US ATLAS is a subset of the ATLAS project. ATLAS is a particle physics experiment at the Large Hadron Collider (LHC). ATLAS itself is a subset of Worldwide LHC Computing Grid (WLCG), which is a grid computing infrastructure that aims to provide location-agnostic access to data incubating from LHC experiments. WLCG currently operates around 150 sites for exchange and analysis of scientific data. These sites are distributed all around the globe and are equipped with perfSONAR monitors as shown in Fig. 18. These monitors continously measure the performance of the multi-domain network path along which the scientific data is exchanged. perfSONAR Multi-Domain Monitoring (perfSONAR-MDM), a perfSONAR framework implementation by GÉANT, was released in 2010. Since then, around 60 measurement points running the perfSONAR-MDM toolkit have been deployed around the globe as shown in Fig. 19. These measurement points are deployed at multiple European National Research and Education Networks (NREN). perfSONAR-PS and perfSONAR-MDM are interoperable with one another since 2010.

2) Hardware: perfSONAR does not deploy dedicated hardware probes. The measurement software has been open-sourced and made freely available. There are two major software implementations available for the measurement framework: a) The perfSONAR-PS and b) The perfSONAR-MDM. The perfSONAR-PS toolkit is packaged as a CentOS bootable image (perfSONAR-PS tools were earlier packaged together in a Knoppix-based bootable CD, called PS-NPToolkit). A perfSONAR measurement point can be made operational by running this image on a 1U server chassis. Running a perfSONAR measurement point from a desktop hardware is not recommended though. Detailed hardware requirements are made available online[24]. Instructions are also available on how to host a perfSONAR-PS measurement point in a virtualized environment, however, running the overlay on bare-metal servers is preferred. The perfSONAR-MDM toolkit on the other hand provides binary packages for Debian-like and RedHat-like distributions. Detailed hardware requirements are available online[25]. A dedicated hardware is recommended, however, some components (visualization and lookup service) can be virtualized. perfSONAR-MDM is also available in a USB-stick form factor (perfSONAR2Go). perfSONAR-PS has been implemented to allow a distributed support model, while perfSONAR-MDM implementation provides a more coordinated and centralized support model.

3) Metrics and Tools: perfSONAR supports both active and passive measurements. perfSONAR-PS is being used by

[24] *http://psps.perfsonar.net/toolkit/hardware.html*
[25] *https://forge.geant.net/forge/display/perfsonar/Downloads*

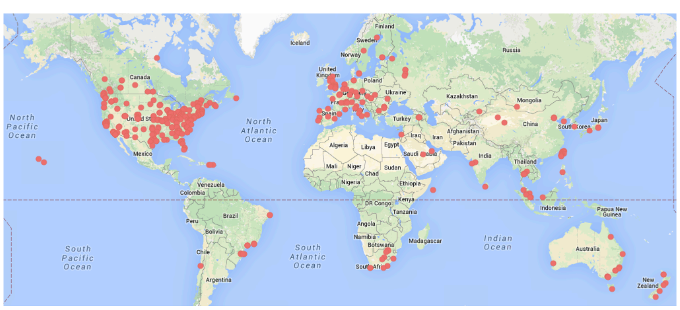

Fig. 17. *The global coverage of the perfSONAR deployment as of Feb 2015 with around 7.6K operational web services: http://stats.es.net/ServicesDirectory/.*

Fig. 18. *The coverage of the perfSONAR-PS deployment within WLCG as of Feb 2015 with around 150 operational sites. The different shades of green (darker being better) indicate the current status of the monitoring sites as reported by ATLAS SSB and OSG GOC dashboards: https://grid-deployment.web.cern.ch/grid-deployment/wlcg-ops/perfsonar/conf/monde/V11.*

the Brookhaven National Laboratory (BNL) and the Fermi National Accelerator Laboratory (FNAL), which serve as tier-1 facilities for the WLCG. The toolkit supports measuring network utilization, available bandwidth, end-to-end latency, packet loss, connection stability and forwarding path. These metrics are measured using specialized tools. For instance, perfSONAR-PS uses `bwctl`[26] to measure available bandwidth, `pingER`[27] [19] to measure end-to-end latency, end-to-end jitter and end-to-end packet loss, `OWAMP`[28] to measure one-way latency, one-way jitter and ony-way packet loss, `traceroute` to measure the forwarding path, NDT and Network Path and Application Diagnosis (NPAD) to generate network diagnostic reports for end-to-end and last-mile paths. A perfSONAR-BUOY service is used to configure a set of `OWAMP` and `bwctl` tests, archive their measurement results and provide a query interface for easy retrieval of measurement results. It also supports passive network monitoring such as `rrdtool` for network data polling using Simple Network Management Protocol (SNMP) and graphing using `cacti`. It also provides support for lookup and archival services to store SNMP, end-to-end and one-way latency and bandwidth measurements. The archives can be stored using either a Round-Robin Database (RRD) or a SQL instance. An `apache2` server and a `ntp` daemon is also packaged within the toolkit. perfSONAR-MDM on the other hand is used by the Port d'Informació Científica (PIC) (tier-1), the Centro de Investigaciones Energticas, Medioambientales y Tecnológicas (CIEMAT) (tier-2) and the Institut de Fisica d'Altes Energies (IFAE) (tier-2) which also are part of the WLCG. perfSONAR-MDM provides three software components: a) Hades Active Delay Evaluation System (HADES), b) Bandwidth Controller Measurement Point (BWCTL MP), and c) The Round Robin Database Measurement Archive (RRD MA). HADES is used to perform and store one-way delay, jitter, `traceroute`, and packet loss measurements. BWCTL MP is used to measure achievable

[26] *http://software.internet2.edu/bwctl*
[27] *http://www-iepm.slac.stanford.edu/pinger*
[28] *http://software.internet2.edu/owamp*

bandwidth, RRD MA is used to measure link utilization, link capacity, input errors and output drops on a link. These tests can be initiated on-demand or in a scheduled fashion. A new weather map integration also provides the possibility to view live monitoring data in the dasboard interface. The metrics can also be visualized using the available iOS and Android mobile applications. A number of visualization tools have been developed to view the perfSONAR measurement archives. For instance, network-based maps are provided to the end-users using Customer Network Management (CNM) and Network Monitor System (Nemo) tools. CNM[29] is deployed within the DFN (Germany) network, while Nemo[30] is used within the UNINETT (Norway) network. Traceable network paths and diagnostics are provided to the staff members using VisualperfSONAR[31] and perfSONARUI[32] tools. These tools are deployed by GÉANT, Internet2 and ESnet.

4) Architecture: perfSONAR provides web-based services that perform measurements in a federated environment. These services are middlewares between measurement tools and visualization and diagnostic tools. perfSONAR implements a Service-Oriented Architecture (SOA) allowing network management functions to become services accessible over the Simple Object Access Protocol (SOAP). Each measurement probe can then be invoked as a web service to perform network diagnostic operations. The schema description of the network monitoring tasks are specified by the Open Grid Forum (OGF). The web services layer is broadly divided into two families: a) performance data services, and b) enabling services. The performance data services interact with elements that are associated with measurement data. They are further subdivded into three families: a) Measurement Points, b) Transformation services, and c) Measurement archives. Each family can have multiple instances. For instance, the measurement archives can either be stored as a RRD instance or as a SQL instance. Similarly a measurement point can be composed of instances of multiple disparate measurement tools. The enabling services provide authentication, authorization and information facilities. The Information Service (IS) services is used for registration, service and data discovery and network topology representation (The IS was formed by merging previously existing Lookup Service (LS) and Topology Service (TS) components). The IS services can be queried using XQuery. The authentication and authorization services have been federated across domains with the help of EduGAIN[33]. A dashboard framework is a centralized location to see the performance of the entire network at once. The dashboard also provides the capability of triggering alarms when a perfSONAR site detects a potential problem to allow rapid response to such events. There are multiple dashboard instances supporting individual networks. For instance, the Site Status Board (SSB) provides operational support through a dashboard interface to the ATLAS community, while Grid Operations Center (GOC) at Indiana University is another instance that provides support to the Open Science Grid (OSG) community. The OSG is an initiative supported by the Department of Energy (DOE) and the National Science Foundation (NSF). The US contributes computing and storage resources to the WLCG through the OSG. The status checks of the monitoring sites performed by perfSONAR-PS as viewed through these dashboards is shown in the Fig. 18. A real time dashboard on the status of the perfSONAR-PS monitors is available online[34].

5) Research Impact: Andreas Hanemann, *et al.* in [86] motivate the need for a network monitoring framework that can scale on multi-domain networks. They propose a SOA-based approach and describe the overall architecture of the perfSONAR framework. They describe how this framework will be used to facilitate the performance monitoring needs of the GÉANT service area, associated NRENs and the Internet2 backbone. They go further in [87] and introduce a set of perfSONAR visualization tools and their feature sets. They reason how a variety of such tools have been developed to serve the needs of different use-cases such as end-users, research staff, operations staff and project managers. Jason Zurawski, *et al.* in [88] describe the data models and schemas used within the perfSONAR framework. They show how measurements are encoded in XML format and exchanged using SOAP. The base schemas are defined within OGF Network Measurement Working Group (NM-WG), while extensions are allowed using XML namespaces. They go further in [89] to describe a registration and discovery mechanism, the perfSONAR Lookup Service (perfSONAR LS), which can be used to locate available measurement services. They describe how LS instances are projected in LS rings, where leaders of each ring exchange summary information to help scale the LS across multi-domain networks. The leaders are chosen using

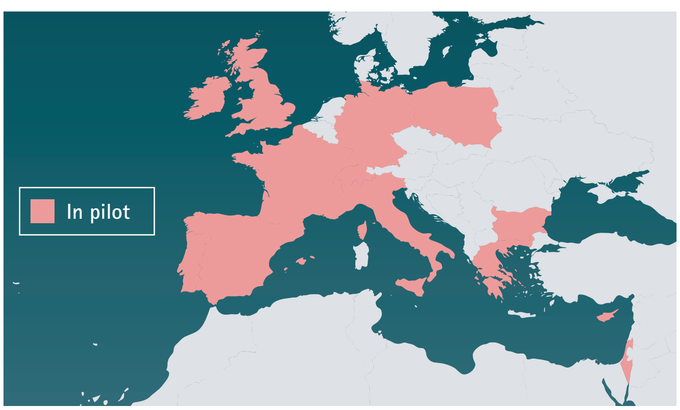

Fig. 19. *The coverage of the perfSONAR-MDM deployment as of Feb 2015. Around 60 measurement points have been deployed in total (43 in GÉANT. service area, 8 in ESnet, 9 in Internet2). The measurement points within the GÉANT are situated at multiple European NREN, such as, RedIRIS (es), DFN (de), PIONIER (pl), SWITCH (ch), HEAnet (ie), GARR (it), GRnet (gr), RENATER (fr), JANET (uk), FCCN (pt), BREN (bg), CYNET (cy), IUCC (il) and DANTE (for the GÉANT backbone): http://services.geant.net/perfsonar/resources.*

[29] *http://www.cnm.dfn.de*
[30] *http://drift.uninett.no/kart/nemo*
[31] *http://www.perfsonar.net/visualperfSONAR.html*
[32] *http://www.perfsonar.net/perfsonarUI.html*
[33] *http://edugain.org*
[34] *http://ps-dashboard.es.net*

an election algorithm. Brian Tierney, *et al.* in [90] describe the deployment of perfSONAR for the LHC community. The LHC generates 10TB of data per day, which is exchanged amongst 11 tier-1 LHC sites using dedicated 10Gbps links that are part of the LHC Optical Private Network (LHCOPN). Over 150 tier-2 institutions are connected to these tier-1 sites using a multipoint-to-multipoint network, called the LHC Open Network Environment (LHCONE). A large number of tier-3 institutes are connected to tier-2 institutes to form the entire grid infrastructure. In order to ensure consistent throughput, perfSONAR is used to create a persistent baseline of network performance across all segments of the paths traversed while exchanging this data. Prasad Calyam, *et al.* in [91], [92] present an ontology-based semantic priority scheduling algorithm for active measurements. The algorithm uses an inference engine to dynamically prioritise measurement requests, mitigate oversampling under high loads and is conflict-free. The evaluation performed using a perfSONAR-inspired simulation setup shows how generated schedules have low cycle times and high satisfaction ratios. Experiments on real-world perfSONAR traces show how the algorithm can mitigate oversampling under high loads. They go further in [93] to present OnTimeSecure, a secure middleware for perfSONAR. It provides user-to-service and service-to-service authentication and federated authorization based on hierarchical policies. It uses a REST-based approach and can also interface with the aforementioned meta-scheduler to handle prioritized measurement requests. Inder Monga, *et al.* in [94] describe their experiences in deploying and running the ESnet4 hybrid network. The hybrid network consists of a circuit-based core designed to carry large scientific data flows and an IP-based core to handle commodity traffic. The circuit-based core is controlled by the On Demand Secure Circuits and Reservation System (OSCARS), a network management system built on top of Multiprotocol Label Switching (MPLS). They describe how perfSONAR has been deployed within ESnet and is planned to be integrated within OSCARS to monitor dynamic virtual circuits. Shawn McKee, *et al.* in [14] describe their experiences in deploying perfSONAR-PS at US ATLAS sites. They also introduce the monitoring dashboard that not only provides a centralized view of the performance of the entire network but also adds support for alarms. Arne Øslebø in [95] introduce perfSONAR NC, a Network Configuration Protocol (NETCONF)-based implementation of perfSONAR that uses the YANG data modeling language to specify schemas for each measurement archive. Julia Andreeva, *et al.* in [96] introduce the SSB, an implementation of the dashboard framework. The SSB provides an aggregated view of the real-time performance of distributed sites. They show how the SSB is integrated into the US Atlas operations and describe implementation aspects of deployed SSB sensors and alarm systems. Jason Zurawski, *et al.* in [97] describe how the Brown University Physics Department and the National Energy Research Scientific Computing Center (NERSC) are using perfSONAR to regularly monitor sites handling exchange of scientific data flows. Raphael A. Dourado, *et al.* in [98] present a software library that implements spatial composition of performance metrics [99]. They show how delay composition and delay variation composition can be done by running experiments against performance data collected by perfSONAR within the ESnet and GÉANT networks. Partha Kanuparthy, *et al.* in [100], [101] introduce Pythia, a domain-knowledge based overlay that leverages active measurement infrastructures to detect, diagnose and localize performance problems using formally described pathology definitions. They use 11 such definitions and show how a deployment on perfSONAR monitors was able to detect congestion-related performance problems. Hao Yu *et al.* in [102] introduce CMon, an end-to-end multi-domain circuit monitoring system. It uses GÉANT's perfSONAR-MDM and Automated Bandwidth Allocation across Heterogeneous Networks (AUTOBAHN) to provisions circuits for high-volume data transfers. Prasad Calyam, *et al.* in [103] introduce a network topology-aware correlated anomaly detection and diagnosis scheme for perfSONAR deployments. They use the scheme to prioritize detected events by applying a set of filters. These filters can further be used to identify spatially and temporally critical network paths. They used the `traceroute` and one-way perfSONAR measurement data for validation.

VI. Standardization Efforts

Research findings from surveyed measurement studies have been a valuable input to the regulators in understanding how today's broadband services perform in practice. However, in order to not only allow the regulators to frame better broadband policies but also to allow the ISPs to manage networks on a finer granularity, the measurement activities need to scale up. This has been hard to achieve due to the sheer proprietary

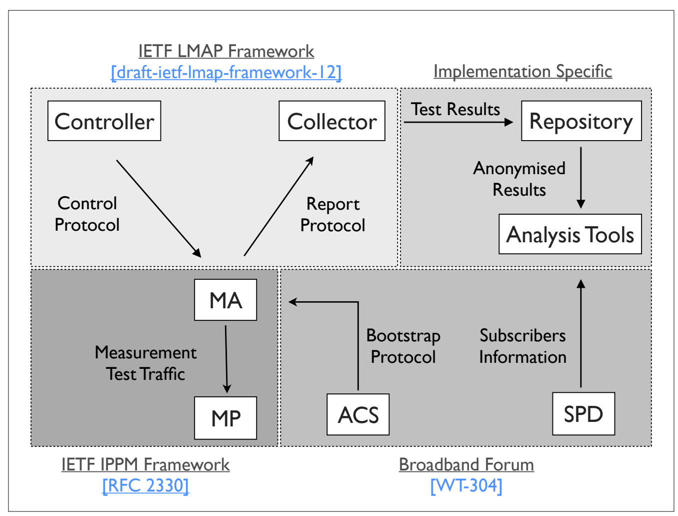

Fig. 20. *A high-level overview of bodies involved in the standardization of large-scale measurement platforms. The IPPM working group defines standardized IP-based metrics that a MA uses to generate measurement test traffic directed towards a MP. The LMAP working group defines the architectural framework and the protocols involved in controlling the MA and reporting of measurement results. The BBF defines a bootstrap process to initialize a CPE. It supplies subscriber information to enrich measurement results. The query mechanism to retrieve measurement results and development of data analysis tools to mine the data are not standardized but are implementation-specific.*

nature of the measurement efforts. Each involved organization uses its own dedicated measurement probes that not only need to be separately deployed but also the coordination with them is based on custom-designed mechanisms. This lack of interoperability makes it difficult for regulators to view measurement results from a macroscopic scale. Work is underway across multiple standardization bodies to describe use cases of interest and protocol requirements to pave way for a large-scale broadband measurement architecture. Such an architecture will make it possible to implement measurement capabilities directly in the Customer-Premises Equipment (CPE) and give away the need to deploy dedicated measurement probes. The interaction with the CPE will be based on a standardized protocol to enable interoperability. A high-level interpretation of how each standardization body is trying to contribute (see Table I) is shown in Fig. 20. Trevor Burbridge gave a talk giving an overview of all these building blocks and how they fit together at the RIPE 66 meeting[35].

A. IETF LMAP

The Internet Engineering Task Force (IETF) Large-Scale Measurement of Broadband Performance (LMAP) working group is standardizing an overall framework for large-scale measurement platforms. This involves configuration and scheduling of measurements through a control protocol and reporting of measurement results through a report protocol. The abstract definitions of information carried by these protocols is being defined along with specific data models targeted to a specific protocol. Marcelo Bagnulo, *et al.* in [104], [105], [106] describe the motivation and provide an overview of the standardized architecture envisioned within LMAP.

1) Background: The Internet Architecture Board (IAB) in 2012 organized a plenary on *Challenges of Network Performance Measurement* at IETF 85[36] to invite discussions on creating a standards-based network performance measurement architecture. In the plenary, Sam Crawford gave a talk describing the SamKnows measurement platform and he outlined the usefulness of performing end-to-end performance measurements. The data and operational challenges encountered in the process were also discussed. This was followed by Henning Schulzrinne describing the regulator's motivation towards developing a standardized network measurement and management infrastructure. The requirements to perform ISP diagnostics and planning, consumer diagnostics and public policy data collection were discussed. The plenary concluded with the attendees expressing interest towards the standardization effort. The plenary led to a LMAP Birds of a Feather (BOF) meeting at IETF 86[37] where the scope and goals of the proposed working group were discussed. The LMAP BOF led to the formulation of the LMAP working group.

2) LMAP Scope: The LMAP working group has a charter[38] defining their milestones. The charter clarifies that a measurement system is assumed to be under the control of a single organization, whereby potential overlap amongst different measurement systems can occur. A potential coordination within this overlapped region, however, is out of the scope of this work. A mechanism to bootstrap the Measurement Agent (MA) and discovery of service parameters is also out of the scope. Protection against malicious self-insertion of inaccuracies is also out of the scope. Both active and passive measurements are in scope and privacy is a critical requirement. The MA interaction with the controller and collectors must be based on simple transport protocols to facilitate a prototype implementation.

3) LMAP Requirements and Use-Cases: Mohamed Boucadair, *et al.* in [107] raise requirements and issues from a provider's perspective to help scope the problem. Marc Linsner in *et al.* in [40] describe multiple use-cases of interest for broadband performance measurement. Scenarios around end-users, ISPs and third-party use-cases are described. Kenichi Nagami, *et al.* in [108] describe the LMAP use case from a measurement provider's perspective. A measurement provider measures the network performance from a user's vantage point, by deploying either hardware (or software) probes that run measurement tests against multiple content providers. They reason how this use-case directly complements the end-user's use case. Rachel Huang, *et al.* in [109] describe the LMAP use case for the service provider's network management systems. They propose measurement data collection in a common platform that can be used for variety of purposes such as network troubleshooting, performance evaluation and quality assessment.

4) LMAP Framework: Philip Eardley *et al.* in [110] describe the LMAP framework. The framework identifies key elements of a LMAP, and sketches a reference architecture of such a platform. The definition of large-scale, scope and

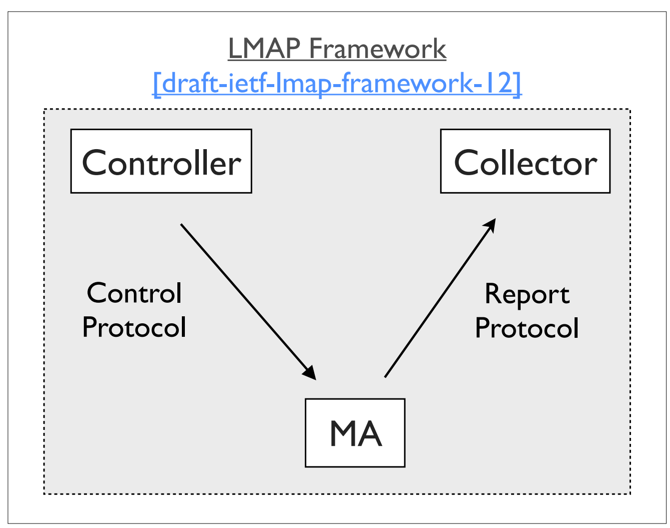

Fig. 21. *A high-level reference architecture of the LMAP framework. A MA uses a control protocol to receive instructions from a controller. It uses these instructions to provision a schedule for measurement tests. The collected measurement results are later pushed to a collector using a report protocol.*

[35] https://ripe66.ripe.net/archives/video/1259
[36] http://www.ietf.org/proceedings/85/combined-plenary.html
[37] http://www.ietf.org/proceedings/86/lmap.html
[38] http://www.ietf.org/charter/charter-ietf-lmap-01.txt

constraints of the LMAP work are also discussed along with a terminology to allow the efforts to converge into using a common language repertoire. The framework consists of a MA, a LMAP controller and a LMAP collector as shown in Fig. 21. A MA interacts with a controller to receive instructions on which measurement tasks are to be run, how to execute those measurements tasks using a measurement schedule, and how to report the collected measurement results. The interaction of the MA with a controller must be defined in a control protocol. The MA must periodically push the measurement results to a collector using a defined report protocol.

5) LMAP Information Model: The control and report protocol interaction requires a formal description of the exchanged information elements. The elements must be described at a level of abstraction that is agnostic to the device and used protocol implementation [111]. Trevor Burbridge, *et al.* in [112] describe such an information model. They enlist information elements (such as security credentials and controller server addresses) that must be pre-configured in a MA to allow initial communication with a controller. The configuration information subsequently pushed by the controller to provide additional contextual information to the MA is also described. The elements describing the instruction set sent by the controller and the elements of the measurement report sent to the collector are laid down alongside generic logging and status reporting information.

6) LMAP Protocol and Data Model: There has been a strong inclination in the IETF towards reusing protocols for the LMAP framework. The NETCONF [113] is one of the protocols that can be used by a LMAP controller to provision the MAs. Jürgen Schönwälder in [114] discusses some of the involved technical challenges such as a standardized call-home mechanism. Vaibhav Bajpai *et al.* in [115] deploy an optimized NETCONF server binary on a SamKnows probe to demonstrate the possibility of managing such MAs using the NETCONF protocol. NETCONF-based data models and protocol operations can be specified using the YANG data modeling language [116]. Jürgen Schönwälder *et al.* in [117] describe a YANG data model derived from the proposed LMAP information model that can be used to configure and schedule measurements. The YANG data model proposes to use a push-based design where the configurations are pushed from the LMAP controller to the MA. They take this further in [118] to describe how RESTCONF [119] can be used with such a YANG data model to configure MAs and report measurement results using stream notifications. Arne Oslebo in [120] adapt this YANG data model [117] to propose an alternative pull-based design. They propose the use of RESTCONF to pull configuration from a LMAP controller. In this model, a RESTCONF server needs to be deployed on the LMAP controller, while a RESTCONF client invokes Remote Procedure Call (RPC) calls to pull configuration according to a specific schedule. However, RESTCONF itself subsumes a push-based model in its design. It's unclear whether the protocol approach described in [120] can be deemed RESTCONF. The Internet Protocol Flow Information Export Protocol (IPFIX) [121] can also be used by the MA to report measurement results back to a LMAP collector. Marcelo Bagnulo, *et al.* in [122] discuss how an IPFIX reporting application will require a dedicated metering and exporting process on the MA and a collecting process on the collector. Application-Layer Traffic Optimization (ALTO) [123] is yet another protocol that can be used to perform queries on the LMAP measurement results repository. Jan Seedorf *et al.* in [124] discuss how ALTO provides the capability to define abstractions (network maps and cost maps) that can be used to tweak the aggregation-level of measurement results. The interaction is performed using a Representational State Transfer (REST) interface on top of HTTP while the carried data is encoded in JSON. David Goergen, *et al.* in [125] describe a methodology to derive the network topology from the FCC Measuring Broadband America dataset. The fabricated network and cost maps can then be used by an ALTO server. Marcelo Bagnulo, *et al.* in [126] use the information model to formulate a specific data model that describes the semantics of the information elements in a JSON encoded format. The data model can be used to exchange these information elements in a structured format using a REST architecture on top of HTTP. As such, HTTP can be used both as a control and report protocol in such a design. The Uniform Resource Identifier (URI) design of the proposed Application Programming Interface (API) is also discussed in detail. The proposal adheres to the charter requirement of a simple transport protocol to facilitate early prototype implementation. Vic Liu *et al.* in [127] provide an alternative proposal for a REST-based LMAP protocol. It utilises a push-based model (as opposed to a pull-based design as described in [126]) to configure and schedule measurements. At the state of this writeup, the LMAP working group is currently under discussion and a protocol selection is yet to be determined.

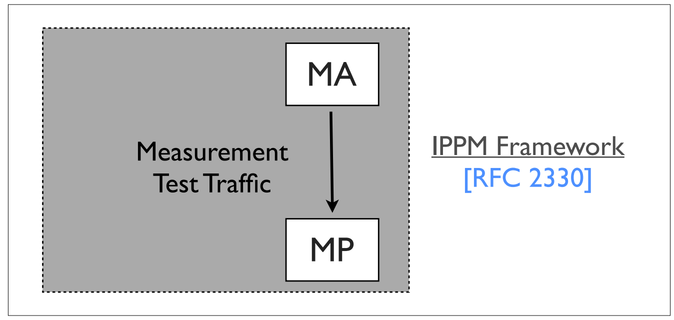

Fig. 22. *A high-level reference architecture of the IPPM framework. A MA uses a standard IPPM metric to generate measurement test traffic directed towards a MP. The standardization of this model enables accurate and reproducible results which are relevant across different implementations.*

B. IETF IPPM

The IP Performance Metrics (IPPM) working group defines metrics that measure the quality, performance and reliability of protocols and services that operate on top of the IP. Vern Paxson, *et al.* in [128] describe the core IPPM framework that encompasses the terminology, metrics criteria, methodology and common issues associated with accurate measurements.

The area of interest is scoped to particularly standardize the network path interaction and measurement test traffic of the measurement agents as shown in Fig. 22. The working group has produced several documents that define metrics to accurately measure this network path. Fabien Michaut, *et al.* in [4] provide a detailed survey on IPPM-defined metrics and available measurement tools. CAIDA also maintains a taxonomy[39] along with a summary and webpage pointers to each measurement tool.

Jamshid Mahdavi, *et al.* in [129], define metrics for measuring connectivity between a pair of hosts. Metrics to measure uni-directional and bi-directional connectivity at a particular instant or over an interval of time are also described. Al Morton, *et al.* in [130] define a metric to measure whether the ordered delivery of packets is maintained in the network. It also provides sample metrics to measure the extent and frequency of reordering, and provides an assessment of effects on TCP. The tools `owping/owampd` and `QoSMet` can measure such packet reordering by analyzing packet sequence numbers. `sting` [131] can also measure reordering by evaluating the number of exchanges between pairs of test packets

The asymmetry of network path, router queues and QoS provisioning procedures require that measurements be performed separately on a one-way path as opposed to a combined round-trip path. Guy Almes, *et al.* in [132] define a metric to measure the one-way delay in a network path. Carlo Demichelis, *et al.* take this further and in [133] define a metric to measure the variation in this one-way delay. Metrics to measure a single-shot observation and a sample covering a sequence of singleton tests are described. A number of statistics around the derived sample are also discussed. Guy Almes, *et al.* in [134] define a metric to measure one-way packet loss in a network path. Rajeev Koodli, *et al.* in [135] take this further and describe statistics around this packet loss pattern. These statistics can be used to calculate the average length of loss (or inter-loss) periods. Henk Uijterwaal in [136] defines a metric to measure one-way packet duplication in the network path. `owping/owampd` and `QoSMet` are the most popular tools to measure one-way delay, variation and packet loss. However, these tools require a server daemon installation on the remote end. Stefan Savage has overcome this limitation in [137] by introducing a non-cooperative tool, `sting` that measures one-way loss rate by observing TCP behavior.

On the other hand, measurements involving a round-trip path can leverage Internet Control Message Protocol (ICMP) ECHO to subvert the requirement of a remote-end daemon installation. This ease of deployment coupled with the ease of result interpretation makes round-trip path metrics feasible. Guy Almes, *et al.* in [138] define a metric to measure the round-trip delay in a network path. They identify how the issue of synchronization of source and destination clocks has been reduced to an (easier) issue of self-synchronization on the source end. Al Morton in [139] defines a metric to measure the round-trip packet loss in a network path. `ping` is the most popular tool to measure round-trip delay and packet-loss.

Phil Chemento, *et al.* in [140] introduce a nomenclature to measure capacity and available bandwidth both over a link and over an end-to-end path. The variable packet size model and tailgating model are popular methodologies for measuring the per-hop link capacity. `pathchar`, `bing`, `clink`, `pchar`, and `nettimer` are popular per-hop capacity measurement tools. The end-to-end capacity can be measured using the per-hop capacity metrics, however a packet-pair dispersion methodology can be used to directly measure it. `bprobe`, `sprobe`, `pathrate`, and `nettimer` are popular end-to-end capacity measurement tools. There are three methodologies defined to measure available bandwidth of a link or an end-to-end path. `cprobe` is a popular tool that implements the packet train dispersion methodology. `pathload`, and `pathchirp`, implement the probe rate model methodology, while `IGI/PTR`, and `spruce` implement the probe gap model methodology. Ravi Prasad, *et al.* in [5] provide a detailed survey on available bandwidth estimation metrics, techniques and tools.

Matt Mathis, *et al.* in [141] propose a framework for defining Bulk Transfer Capacity (BTC) metrics. The BTC metric measures the *achievable* throughput of a TCP connection on an end-to-end path. `treno`, `cap`, `ttcp`, `netperf` and `iperf` are popular BTC measurement tools. Barry Constantine, *et al.* in [142] propose a framework to measure the achievable TCP throughput for business class services. This requires a phase of pre-determining the path MTU, bottleneck bandwidth and RTT before test initiation.

Matt Mathis, *et al.* in [143] define a metric to evaluate a network path's ability to carry bulk data. They propose TCP-based models that can be used to apply independent performance tests on smaller subpaths. The results from each subpath can then later be used to predict the end-to-end path's capability. This is made possible by opening up the TCP control loop. The model is designed to be independent of the measurement vantage point.

The IPPM working group has also designed communication protocols to enable interoperability amongst multi-vendor MA and Measurement Peer (MP). For instance, Stanislav Shalunov, *et al.* in [17] introduce the One-Way Active Measurement Protocol (OWAMP) to standardize a method for collection of one-way active measurements. This allows widespread deployment of open OWAMP servers and help one-way measurements become as common as the `ping` measurement tool. Similarly, Kaynam Hedayat, *et al.* in [144] introduce the Two-Way Active Measurement Protocol (TWAMP) to standardize two-way measurement capabilities. TWAMP in addition to the self-synchronization on the source end, also employs a timestamp at the remote end to facilitate greater accuracy. Saverio Niccolini, *et al.* in [145] describe an information and a data model to store `traceroute` measurement results using XML. This is closely related to the `DISMAN-TRACEROUTE-MIB` module [146], which instead uses SNMP to access `traceroute` results. Al Morton in [147] define a problem statement for conducting access rate measurements. It describes how the capability to test in two-directions with asymmetric size packets and asymmetric rates are critical functions needed in today's production network measurements.

[39] *http://www.caida.org/tools/taxonomy*

The working group recently underwent a charter revision[40]. The focus now is to minimize defining newer metrics and measurement protocols, but instead reuse or improve developed standards. Efforts that introduce additional methods for metric calibration or describe the applicability and tradeoffs of current metrics will be encouraged. In this pursuit, Joachim Fabini, *et al.* in [148] have updated the IPPM framework to accomodate this evolution. Al Morton, *et al.* in [149] summarize two different formulations of delay variations used in wider context of active measurements: Inter-Packet Delay Variation (IPDV) and Packet Delay Variation (PDV). They provide recommendations on where each are applicable. Kostas Pentikousis, *et al.* in [150] are proposing to employ Internet Protocol Security (IPsec) to protect OWAMP and TWAMP protocols. This will not only secure the measurement traffic but also facilitate the applicability of these measurement protocols to current IPsec networks.

A MA is a common denominator within the LMAP and IPPM frameworks as shown in Fig. 23. A MA runs measurement tests that adhere to a standard metric defined within the IPPM working group. The decision on which measurement tests are to be run by a MA are dictated by the LMAP control protocol. The MA also later tags measurement results with the metric when pushing them using the LMAP report protocol. As such, these protocols need a mechanism to refer to a IPPM-defined metric. Marcelo Bagnulo, *et al.* in [151] describe a core registry for performance metrics and rules for

[40] *http://www.ietf.org/charter/charter-ietf-ippm-05.txt*

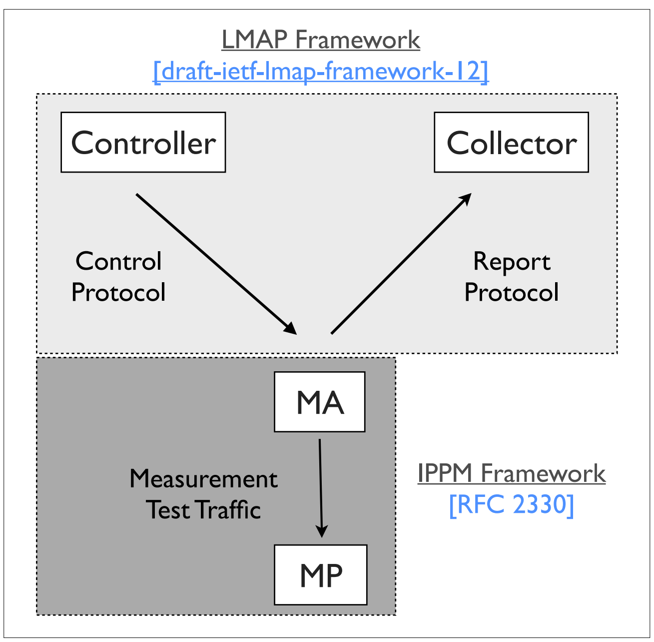

Fig. 23. *A high-level interaction between LMAP and IPPM frameworks. The LMAP effort standardizes interaction of a MA with a controller and a collector. The IPPM effort standardizes metrics for measurement tests. A metrics registry acts a glue to allow LMAP protocols to refer to IPPM-defined metrics.*

metric assignments alongwith initial allocations. The LMAP control protocol can now refer to an IPPM-based metric through a URI scheme that hooks into the metrics registry. Marcelo Bagnulo, *et al.* in [152] take this further and define a reference path for LMAP by assigning a set of identifiable measurement points. The LMAP control protocol can now define a measurement path at a finer granularity using a set of defined measurement points. A reference path can also help complement the measurement results with additional information required for diagnostic and data analysis. Use cases mapping a particular network technology to a viewed reference path are also discussed.

C. IETF Xrblock

Henning Schulzrinne, *et al.* in [153] have defined the Real-time Transport Protocol (RTP) that facilitates applications in transmitting real-time audio and video data by providing an end-to-end network transport method. They have also defined a companion protocol, RTP Control Protocol (RTCP), that helps provide feedback on the quality of RTP data distribution by sending one or more reception report blocks as part of the sender (or receiver) reports. Kevin Almeroth, *et al.* in [154] have taken this further and defined RTCP Extended Reports (RTCP XR) that convey information beyond these reception report blocks. They have defined seven report block types that fall within three categories. The packet-by-packet block types report reception timestamps for each packet in addition to conveying encountered packet losses and duplicates. The reference time block types that convey receiver-end wallclock timestamps and the delay encountered in the reception of these blocks. Finally, summary metric block types convey summary statistics and metric to monitor VoIP calls. The authors also propose a framework which can be used to add additional block types in the future.

The Metric Blocks for use with RTCP's Extended Report Framework (xrblock) working group has been chartered to use this framework to invite proposals on new report blocks definitions. As a result, a number of documents describing newer performance metrics have emerged recently. Alan Clark, *et al.* in [155] define a RTCP XR block type that helps identify a measurement period to which other RTCP XR blocks may refer to indicate the span of the report. The receivers can use this information to verify the metric blocks. Alan Clark, *et al.* in [156] define a RTCP XR block type that allow statistical reporting of the network round-trip delay between RTP endpoints. The information can be used by the receivers for receive buffer sizing and selecting an appropriate playout delay. The information can also be used to troubleshoot the network path in general. Alan Clark, *et al.* in [157] define a RTCP XR block type that provides information on packet delay variation. The information can be used by the receivers to adapt the size of the jitter buffers to improve performance. Alan Clark, *et al.* in [158] define a RTCP XR block type that allows reporting of burst and gap loss metrics. The information is useful to applications that use jitter buffers but do not use stream repair means.

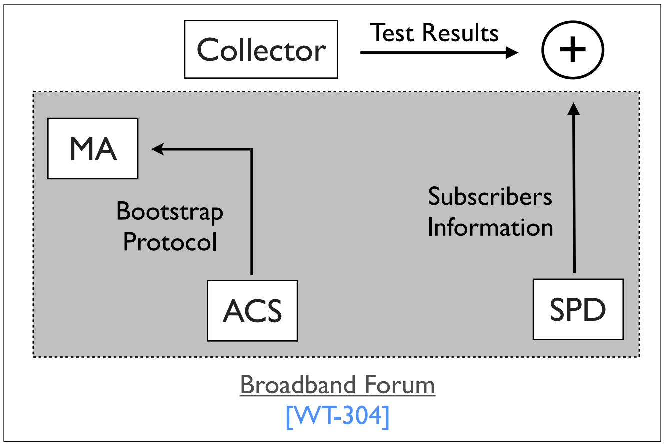

Fig. 24. *A perceived BBF standardization contribution as seen from the LMAP and IPPM frameworks. The BBF can use TR-069 as a protocol to bootstrap the MA with preconfigured information to bring it within a LMAP ecoystem. The BBF can also supply subscriber information that can be later spliced into the measurement results for validation purposes.*

D. Broadband Forum

The Broadband Forum (BBF) takes a unique position of being able to apply the standardization work incubating out of the IETF directly on vendor devices. This can be coupled with existing BBF protocols such as CPE WAN Management Protocol (TR-069)[41] or Data Over Cable Service Interface Specification (DOCSIS) [160] that can act as enablers to help expedite the adoption process. The Enabling Network Throughput Performance Tests and Statistical Monitoring (TR-143) project[42], for instance, has been working on defining CPE data models to initiate performance throughput and latency tests and monitor CPEs using diagnostic mechanisms defined in TR-069. Both network-initiated and CPE diagnostics are in scope. The tests can be run either in an ongoing or on-demand fashion. Active monitoring of the broadband network will help base lining nominal service levels and validating QoS objectives. It also helps the service provider characterize the performance of end-to-end paths. Such an active monitoring using performance metrics will facilitate establishment of SLAs for guaranteed service offerings.

The Broadband Access Service Attributes and Performance Metrics (WT-304) project[43], started in 2012, takes TR-143 further by developing additional performance tests such as packet loss, jitter, emulated streaming and browsing. The project intends to develop a framework to allow standards-based broadband performance testing and reporting. It plans to develop test methodologies that can segregate and measure a network segment. Tests metrics must be standardized to support multiple operator networks. Development of test schedule intervals and capability to trigger on-demand tests are in scope.

The LMAP information model [112] assumes that a number of configuration elements are pre-baked within a MA, even before the MA attempts a registration with the LMAP controller. These elements particularly include the MA security credentials and the Fully Qualified Domain Name (FQDN) of the controller that must be pushed to the MA during an initial bootstrap process. The MA must also perform an exchange to make the remote end learn about its capabilities. The possibility of triggering an on-demand test is also useful. These interactions can be done either using the TR-069 or DOCSIS protocol depending on the access technology used by the gateway. The service provider (part of the BBF) is also in a unique position to own the customer's subscription information. This subscriber parameter information, once spliced into the measurement results at the collector-end, can be used to validate the service offerings against the signed agreements as shown in Fig. 24. A TR-069-based data model using the IETF LMAP information model [112] was presented at a Leone workshop[44] on large-scale measurements co-located with the BBF meeting.

E. IEEE

The Institute of Electrical and Electronics Engineers (IEEE) 802.16 working group[45] on Broadband Wireless Access Standards develops standards to promote the growth of broadband Wireless Metropolitan Area Networks (MAN). The working group is currently developing the $P802.16.3$ project[46] on Mobile Broadband Network Performance Measurements, which is targeted to evaluate the performance of mobile broadband networks from a user's perspective. The architecture and requirements document, however, scopes the project only to mobile users. It introduces the concept of both private and public measurement peers, which can be used for conducting measurements. Private measurement peers can be useful in situations where the client wishes to perform measurements towards an exact location of interest. The model also introduces public and private data collectors. The data on public collector must be anonymized, however the data on private collector can be kept as is to facilitate more accurate data analysis.

VII. Discussion

A number of measurement platforms have utilized datasets from more mature platforms to validate their experimental results during the early stages of their deployment as shown in Fig. 25. For instance, Enrico Gregori *et al.* in [70] use publicly available AS topology datasets collected by Archipelago and AS edges dataset collected by the DIMES measurement platform to validate AS-level topology graphs generated by Portolan. Adriano Faggiani *et al.* in [161] use the publicly available AS links datasets to validate the AS-level topology of Italian ISPs as revealed by Portolan.

Independent researchers have also made use of multiple measurement platforms to pursue a research question. For instance, Artur Ziviani *et al.* in [84] use RIPE TTM boxes

[41] *broadband-forum.org/technical/download/TR-069_Amendment-5.pdf*
[42] *http://www.broadband-forum.org/technical/download/TR-143.pdf*
[43] *http://www.broadband-forum.org/technical/technicalwip.php*
[44] *http://workshop.leone-project.eu*
[45] *http://www.ieee802.org/16*
[46] *http://www.ieee802.org/16/mbnpm*

TABLE I. LIST OF SURVEYED STANDARDIZATION WORK

	Document	Type	Date ↓	Status
IETF LMAP	LMAP Use Cases [40]	WG I-D	2015	Active
	A Framework for LMAP [110]	WG I-D	2015	Active
	Information Model for LMAP [112]	WG I-D	2015	Active
	A YANG Data Model for LMAP MA [117]	WG I-D	2015	Active
	Using RESTCONF with LMAP MA [118]	Individual I-D	2015	Active
	REST Style LMAP Protocol [127]	Individual I-D	2015	Active
	A YANG based Data Model for the LMAP Controller [120]	Individual I-D	2014	Active
	LMAP Protocol [126]	Individual I-D	2014	Expired
	Considerations on using NETCONF with LMAP MA [114]	Individual I-D	2013	Expired
	An LMAP application for IPFIX [122]	Individual I-D	2013	Expired
	ALTO for Querying LMAP Results [124]	Individual I-D	2013	Expired
	Aggregating large-scale measurements for ALTO Protocol [125]	Individual I-D	2013	Expired
	Use Case for LMAP Used in Data Collection of Network Management Systems [109]	Individual I-D	2013	Expired
	Use Case from a Measurement Provider Perspective for LMAP: [108]	Individual I-D	2013	Expired
	LMAP: Requirements and Issues from a Network Provider Perspective [107]	Individual I-D	2013	Expired
IETF IPPM	Registry for Performance Metrics [151]	WG I-D	2015	Active
	IKEv2-based Shared Secret Key for O/TWAMP [150]	WG I-D	2015	Active
	Model Based Bulk Performance Metrics [143]	WG I-D	2015	Active
	Rate Measurement Test Protocol Problem Statement and Requirements [147]	RFC 7497	2015	–
	A Reference Path and Measurement Points for LMAP [152]	RFC 7398	2015	–
	Advanced Stream and Sampling Framework for IP Performance Metrics (IPPM) [148]	RFC 7312	2014	–
	Round-trip Packet Loss Metrics [139]	RFC 6673	2012	–
	Framework for TCP Throughput Testing [142]	RFC 6349	2011	–
	A One-way Packet Duplication Metric [136]	RFC 5560	2009	–
	Packet Delay Variation Applicability Statement [149]	RFC 5481	2009	–
	Information Model and XML Data Model for Traceroute Measurements [145]	RFC 5388	2008	–
	A Two-Way Active Measurement Protocol (TWAMP) [144]	RFC 5357	2008	–
	Defining Network Capacity [140]	RFC 5136	2008	–
	Packet Reordering Metrics [130]	RFC 4737	2006	–
	A One-way Active Measurement Protocol (OWAMP) [17]	RFC 4656	2006	–
	IP Packet Delay Variation Metric for IPPM [133]	RFC 3393	2002	–
	One-way Loss Pattern Sample Metrics [135]	RFC 3357	2002	–
	A Framework for Defining Empirical Bulk Transfer Capacity Metric [141]	RFC 3148	2001	–
	A Round-trip Delay Metric for IPPM [138]	RFC 2681	1999	–
	A One-way Packet Loss Metric for IPPM [134]	RFC 2680	1999	–
	A One-way Delay Metric for IPPM [132]	RFC 2679	1999	–
	IPPM Metrics for Measuring Connectivity [129]	RFC 2678	1999	–
	Framework for IPPM [128]	RFC 2330	1998	–
IETF xrblock	RTCP XR Block for MPEG-2 TS PSI Independent Decodability Statistics Metrics Reporting [159]	RFC 6990	2013	–
	RTCP XR Block for Burst/Gap Loss Metric Reporting [158]	RFC 6958	2013	–
	RTCP XR Block for Delay Metric Reporting [156]	RFC 6843	2013	–
	RTCP XR Block for Packet Delay Variation Metric Reporting [157]	RFC 6798	2013	–
	Measurement Identity and Information Reporting Using a SDES Item and an RTCP XR Block [155]	RFC 6776	2012	–

TABLE II. LIST OF INTERNET MEASUREMENT PROJECTS

	Projects	Description	Duration ↓	Website
	RIPE RIS	RIPE NCC Routing Information Service	2001–	http://ripe.net/ris
	RIPE DNSmon	RIPE NCC DNS Monitoring Service	2003–	http://ripe.net/dnsmon
	METRICS	Measurement for Europe: Training & Research for Internet Communications Science	2013–2017	http://metrics-itn.eu
	SMART	European Internet Traffic: Monitoring Tools and Analysis	2013–2015	http://internet-monitoring-study.eu
	RITE [162]	Reducing Internet Transport Latency	2012–2015	http://riteproject.eu
EU	M-Plane [163], [164]	An Intelligent Measurement Plane for Future Network & Application Management	2012–2015	http://ict-mplane.eu
	Leone [105]	From Global Measurements to Local Management	2012–2015	http://leone-project.eu
	DEMONS [165]	Decentralized, Cooperative, & Privacy-Preserving Monitoring for Trustworthiness	2010–2013	http://fp7-demons.eu
	PRISM [166]	Privacy-aware Secure Monitoring	2008–2010	http://fp7-prism.eu
	MOMENT	Monitoring and Measurement in the Next generation Technologies	2008–2010	http://www.fp7-moment.eu
	ITZ [167]	University of Adelaide Internet Topology Zoo	2010–	http://topology-zoo.org
APJ	MAWI [168]	Measurement and Analysis on the WIDE Internet	2002–	http://mawi.wide.ad.jp
	DIMES [7]	Distributed Internet Measurement and Simulation	2004–	http://netdimes.org
	WITS	Waikato Internet Traffic Storage Project	2003–2008	http://wand.net.nz
	Science DMZ [169]	ESnet: A Network Design Pattern for Data-Intensive Science	2010–	http://fasterdata.es.net/science-dmz
	BGPmon [170]	A Real-Time, Scalable, Extensible Monitoring System	2008–	http://bgpmon.netsec.colostate.edu
	Ark [6]	CAIDA Archipelago Project	2007–	http://caida.org/projects/ark
	ATLAS	Arbor Networks: Active Threat Level Analysis System	2007–	https://atlas.arbor.net
	iPlane [8]	An Information Plane for Distributed Services	2006–	http://iplane.cs.washington.edu
	PeeringDB [171]	A Peering Database of Networks	2004–	http://peeringdb.com
US	Network Telescope	UCSD/CAIDA Network Telescope Project	2002–	http://caida.org/projects
	E2Epi	Internet2 End-to-End Performance Initiative	2001–	http://e2epi.internet2.edu
	PCH IRTA	Packet Clearing House Internet Routing Topology Archive	1997–	https://pch.net
	PingER [19]	Ping End-to-End Reporting Project	1995–	http://www-iepm.slac.stanford.edu
	RouteViews	University of Oregon RouteViews Project	1995–	http://routeviews.org
	NAI [172]	NLANR Network Analysis Infrastructure	1995–2006	http://www.moat.nlanr.net
	IPMA	MERIT Internet Performance Measurement and Analysis	1997–2000	http://www.merit.edu/research/ipma

as geographical landmarks to locate Internet hosts. They use probes deployed within the NIMI measurement platform as target hosts. Srikanth Sundaresan *et al.* in [53], [57], [21], [54]

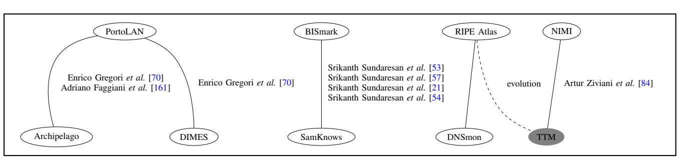

Fig. 25. *A graph representing collaboration amongst Internet performance measurement platforms (in white). Greyed out measurement platforms have been decommissioned and superseded by their successors. Dotted lines indicate an evolution along with the research paper that describes this evolution marked with labelled edges. Straight lines connect one measurement platform with another, along with labelled edges that mark the research paper that describes how they utilized each other's dataset for validation purposes.*

use the SamKnows/FCC data in conjunction with the dataset collected by the BISmark platform to study key broadband performance indicators within multiple ISPs in the US.

A number of platforms leverage one or more measurement facilitators to achieve geographical diversity as shown in Fig. 26. For instance, Srikanth Sundaresan *et al.* in [21] describe how SamKnows uses well-provisioned M-Lab servers as measurement targets to measure end-to-end latency, end-to-end packet loss and upstream and downstream throughput from SamKnows probes. Sarthak Grover *et al.* in [51] describe how BISmark uses strategically deployed M-Lab nodes as measurement servers that act as sources and sinks of measurement traffic for active measurement tools. A number of independent researchers have also used a combination of facilitators and measurement platforms to purse a research question. For instance, Massimo Rimondini *et al.* in [15] describe how they use the BGP data from RIPE RIS and RTT data from the

TABLE III. TAXONOMY OF INTERNET PERFORMANCE MEASUREMENT PLATFORMS

Class	Platform	Scale	Metrics	Tools	Hardware	Research Impact
FIXED-LINE ACCESS	SamKnows	$\sim 70K$	End-to-end latency, last-mile latency, latency-under-load, forwarding path, end-to-end packet loss, upstream and downstream throughput and goodput, end-to-end jitter, network availability, webpage download, VoIP, P2P, DNS resolution, email relays, FTP and video streaming performance.	`ping`, `mtr`, `cron`, `ntp` + custom-developed tools at SamKnows	OpenWrt-based TP-Link routers	[41], [42], [43], [44], [45], [46], [173], [48], [174], [115], [49], [47]
	BISmark	~ 420	End-to-end latency, last-mile latency, latency under load, end-to-end packet loss, access-link capacity, upstream and downstream throughput, end-to-end jitter, webpage load time, uptime using special hearbeats, number of wired devices, number of devices associated on wireless link, number of wireless access points, packet and flow statistics, DNS responses and MAC addresses.	`d-itg`, `shaperprobe`, `iperf`, `mirage`, `paris-traceroute`, `cron`, `ntp`	OpenWrt-based Netgear routers	[54], [55], [21], [13], [56], [53], [57], [58], [51], [59], [18], [50], [60]
	Dasu	$\sim 100K$	Number of per-torrent TCP resets, number of active torrents, number of active, failed and closed TCP connections, end-to-end latency, forwarding path, HTTP GET, DNS resolution, per-torrent, application-wide and system-wide upload and download throughputs.	`ping`, `traceroute`, `NDT`, `cron`, `ntp`, `netstat`	Vuze-based software plugin	[61], [42], [43], [16], [63], [64], [62]
MOBILE ACCESS	Netradar	$\sim 5K$	Signal strength quality, operating system, device type, radio type, positioning information, handovers using base station ID, vendor information, latency, TCP goodput using upload and download speed tests, TCP statistics, Internet connectivity.	custom-developed tools at Aalto University	Android, iOS, Meego, Symbian, and Windows mobile platforms	[65], [66], [67]
	Portolan	~ 300	Latency, IP and AS forwarding path, achievable bandwidth, available wireless networks, signal strength, cell coverage, traffic shaping detection.	`smartprobe`, `MDA-traceroute`	Android	[20], [70], [71], [73], [69], [68]
OPERATIONAL SUPPORT	RIPE Atlas	$\sim 12K$ + ~ 100	Latency, forwarding path, HTTP GET, and SSL queries to preconfigured destinations. Latency to first and second hop, DNS queries to DNS root servers. All built-in measurements run both over IPv4 and IPv6. Periodic local uptime, total uptime, uptime history and current network configuration measurements.	`perd`, `eperd`, `evping`, `evtraceroute`, `evtdig`, `evhttpget` `sslgetcert`, `eooqd`	OpenWrt-based TP-Link routers (previously Lantronix XPort Pro modules) + Soekris-based anchors (previously Dell PowerEdge-based units)	[75], [15], [76], [78], [79], [81], [82] + `http://atlas.ripe.net/results/analyses`
	RIPE TTM	~ 100	One-way latency, packet loss, jitter, root-nameserver reachability, routing statistics, GPS satellite conditions and Path Maximum Transmission Unit (PMTU) discovery.	`traceroute`	A PC and a GPS antenna	[83], [84], [85], [22], [74]
	perfSONAR	$\sim 7.6K$	Network utilization, available bandwidth, achievable bandwidth, one-way latency, one-way jitter, end-to-end latency, end-to-end jitter, end-to-end packet loss, connection stability, forwarding path, end-to-end and last-mile network diagnostics, link utilization, link capacity, link input and output errors.	`hades`, `bwctl`, `pingER`, `NDT`, `NPAD`, `OWAMP`, `traceroute`, `rrdtool`, `cacti`, `apache2`, `ntp`	perfSONAR-PS CentOS bootable image, perfSONAR-MDM RedHat and Debian packages and perfSONAR2Go USB stick	[86], [87], [88], [89], [90], [91], [92], [93], [94], [14], [96], [97], [98], [100], [103]

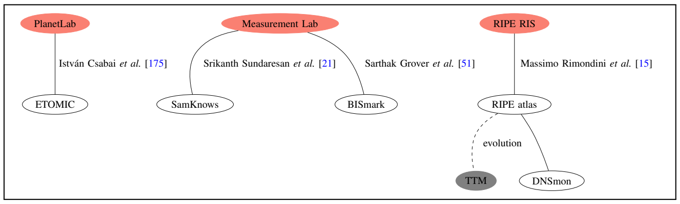

Fig. 26. *A graph representing facilitators (in salmon) used by Internet performance measurement platforms (in white). A number of platforms utilize more than one facilitator. Greyed out measurement platforms have been decommissioned and superseded by their successors. Dotted lines indicate an evolution of the platform, along with the research paper that describes this evolution marked in labelled edges. Straight lines connect a measurement platform with a facilitator, along with labelled edges that mark the research paper that describes how they use it.*

RIPE Atlas platform to study effects of BGP routing changes on network delays.

A timeline of the evolution of the Internet performance measurement platforms according to the taxonomy described in this paper is shown in Fig. 27. SamKnows was established in 2008 to meet the growing need of the regulators to measure broadband performance across multiple service providers. An academic interest to perform accurate measurements from the edge led to the development of Dasu and BISmark platforms in this area. The broadband performance measurement community has long been preceded by topology measurement platforms (not shown in the figure) and measurement platforms designed to provide operational support. RIPE TTM started in 1997 and has evolved into the RIPE Atlas measurement platform that provides support to network operators. perfSONAR was started in 2004 to support the scientific community. The mobile measurement space is starting to take shape with the developments within the Portolan and Netradar measurement platforms since 2012. The IETF IPPM and xrblock working group have been involved in standardizing measurement metrics for quite a while. However, the activities within the BBF and the IETF to design a standardize framework for large-scale measurements have only started recently.

A number of measurement-based research projects also utilize these measurement platforms for measurement research. The Leone project for instance, builds new metrics and measurement tools to study the Quality of Experience (QoE) of home users using the SamKnows measurement platform. The M-Plane project on the other hand aims to build a measurement plane that can incorporate measurements from multiple measurement platforms. A large-scale data analysis of these measurement results can allow a reasoner to perform root-cause analysis of issues in the network. The RITE project studies network conditions that contribute towards Internet latency. The aim is to develop and implement novel methods in end-systems that can help reduce latency at the transport layer. Table II provides a listing of such measurement-based projects. We also include in this list well-known topology measurement and deprecated performance measurement platforms that did not fall within the scope of this paper.

We also witnessed split preferences on the use of software/hardware probes. SamKnows, BISmark, and RIPE Atlas tend to deploy dedicated hardware-based probes, while Dasu, Netradar, Portolan and perfSONAR provide software installations for compatible hardware devices. In hindsight, performance measurement tools running on hardware probes are also software. The advantage of dedicated hardware probes comes instead from the ability to be able to gather round-the-clock measurements. The software measurements that can be installed directly on host devices are more susceptible to resource contention from other applications. The software-suite can also be installed on large variation of hardware devices that makes the measurements harder to calibrate. The software-based solution on the other hand has lower distribution costs. This not only provides low-barrier to entry; but also allows the measurement compaign to quickly span larger demographics. The standardization efforts eventually aim towards facilitating service providers to provide measurement-capable CPEs that will eliminate the need to deploy dedicated probes. As such the conundrum on the choice of a hardware/software probe deployment model may fade away in near future.

VIII. Summary and Conclusion

We have presented a taxonomy of Internet measurement platforms as: topology discovery and performance measurement platforms. We further classified the performance measurement platforms based on their deployment use-case: fixed-line access measurements, mobile access measurements and operational support. We described the performance measurement platforms in detail by exploring their scale, coverage, timeline, deployed metrics and measurement tools, architecture

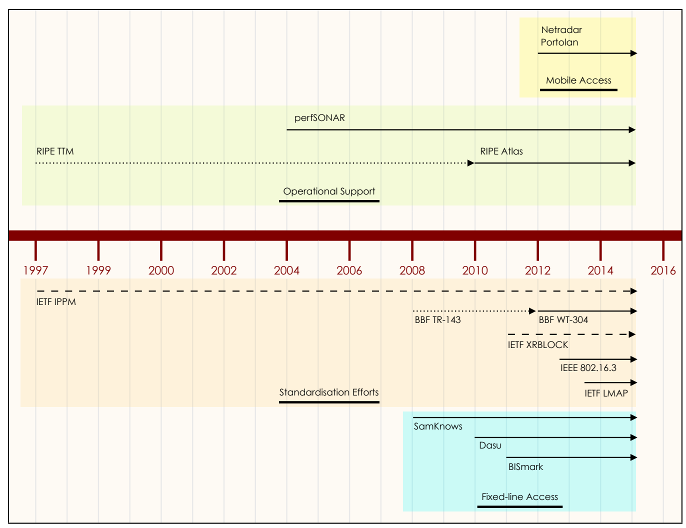

Fig. 27. *A timeline of Internet performance measurement platforms. Fixed-line access measurement platforms started with SamKnows in 2008 and the area has been further developed by Dasu and BISmark. They have been preceded by platforms that measure topology discovery (not shown) and provide operational support. The mobile access measurement platforms have more recently emerged since 2012. The relevant but less specific metrics standardization activities (in dashed lines) within the IETF have been active for a while. Work on designing a measurement framework within the BBF and the IETF has picked up only recently. The dotted lines indicate an evolution.*

and overall research impact. Table III provides a summary of this survey. We also presented common set of measurement tools shared by these performance measurement platforms along with the level of collaboration amongst them through the usage of publicly available datasets. We also showed how platforms have been using measurement facilitators to conglomerate data from multiple sources to pursue a particular research question. We concluded the survey by describing recent standardization efforts to make large-scale performance measurement platforms interoperable.

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