

Unveiling Network and Service Performance Degradation in the Wild with mPlane

Pedro Casas, Pierdomenico Fiadino, Sarah Wassermann, Stefano Traverso, Alessandro D'Alconzo, Edion Tego, Francesco Matera, and Marco Mellia

ABSTRACT

Unveiling network and service performance issues in complex and highly decentralized systems such as the Internet is a major challenge. Indeed, the Internet is based on decentralization and diversity. However, its distributed nature leads to operational brittleness and difficulty in identifying the root causes of performance degradation. In such a context, network measurements are a fundamental pillar to shed light on and unveil design and implementation defects. To tackle this fragmentation and visibility problem, we recently conceived mPlane, a distributed measurement platform that runs, collects, and analyzes traffic measurements to study the operation and functioning of the Internet. In this article, we show the potentiality of the mPlane approach to unveil network and service degradation issues in live operational networks, involving both fixed-line and cellular networks. In particular, we combine active and passive measurements to troubleshoot problems in end-customer Internet access connections, or to automatically detect and diagnose anomalies in Internet-scale services (e.g., YouTube) that impact a large number of end users.

INTRODUCTION

Since the early days of the Internet, network measurements have always constituted a pillar in understanding the behavior of the network, especially when something goes wrong. To address this issue we recently conceived mPlane, a large-scale network measurement and analysis framework. mPlane is a distributed measurement architecture to coordinate traffic measurements, with built-in support for iterative measurement and, most of all, automated and advanced analysis. Probes, which perform measurements; Repositories, which store, aggregate, correlate, and analyze them; and a Supervisor, which orchestrates components are the basics of mPlane. Reasoners are intelligent building blocks that extract knowledge, and offer support to network administrators.

The complete mPlane architecture was previously presented in [1], where only some simple examples of applications were discussed. In this

article, we briefly recall the mPlane architecture. Then we fully develop use cases that focus on highlighting and troubleshooting on end-customer Internet issues. In particular, we show how to use mPlane to detect and diagnose network and service performance degradation events in operational Internet service provider (ISP) networks, exploiting the richness of the measurements mPlane probes perform, and the analysis capabilities in terms of anomaly detection. We focus on three different case studies:

- Diagnosis of performance degradation in end-customer Internet access connections using hybrid measurements
- Detection and diagnosis of service availability issues in cellular networks
- Detection and diagnosis of quality of experience (QoE)-relevant issues in YouTube

We additionally present a fourth analysis scenario in which we implement a proximity location service to analyze inter-AS paths between selected servers (e.g., YouTube servers, Facebook servers, etc.), based on distributed active measurements through RIPE Atlas.

After briefly summarizing related platforms in the second section, we give an overview of the mPlane architecture. We then provide details on the operational ISPs considered in the case studies and detailed traffic datasets. The results obtained in the application of the deployed mPlane framework are then presented. Finally, we conclude the article.

RELATED PLATFORMS

Many measurement platforms have been proposed in the past, such as iPlane [2], PerfSONAR [3], and RIPE Atlas.¹ Each of them targets specific needs, and focuses mostly on the monitoring of the network layer, relying exclusively on active measurements. For instance, iPlane focuses on network topology discovery via traceroute measurements to build a predictive model of path latency; PerfSONAR and RIPE Atlas offer active measurements from a distributed platform (throughput, ping, traceroute, etc.), to again monitor network paths. They offer limited processing capabilities or algorithms for advanced diagnosis, even if it is possible to run (custom) algorithms on top of collected measurements.

Unveiling network and service performance issues in complex and highly decentralized systems such as the Internet is based on decentralization and diversity. However, its distributed nature leads to operational brittleness and difficulty in identifying the root causes of performance degradation.

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¹ <https://atlas.ripe.net/>.

The proposed distributed platform is an instance of the more generic mPlane architecture. The mPlane monitoring system is composed of four different entities: probes, repositories, supervisor, and reasoners. They inter-operate thanks to a standard protocol, and are logically organized into three layers.

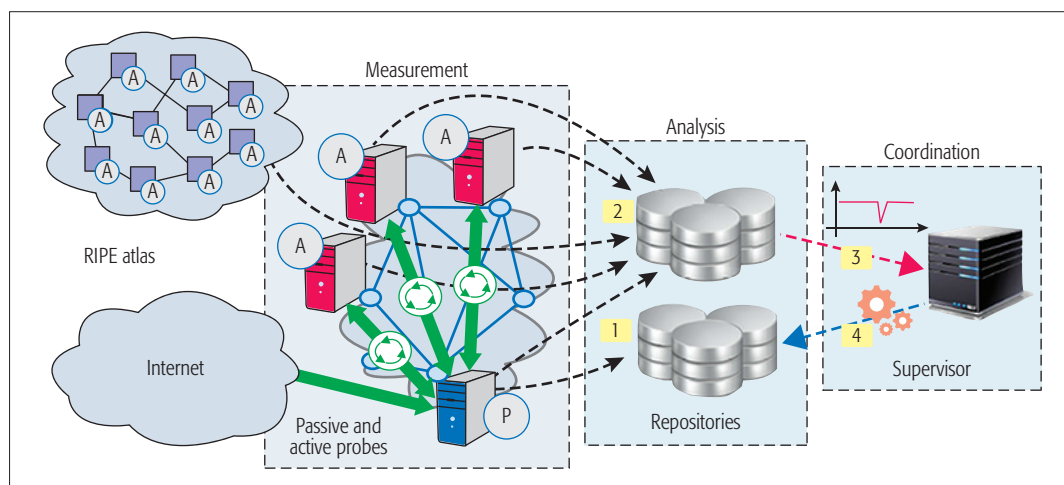


Figure 1. The distributed measurement platform following the mPlane architecture for ISP network troubleshooting and its workflow. Green arrows correspond to both active and passive measurements. Black arrows correspond to measurement data that are exported from probes to repositories. Red arrows correspond to anomaly notification reports. Blue arrows depict the requests made by the Supervisor to trigger deeper data analysis, using, for example, external distributed measurement frameworks such as RIPE Atlas.

For instance, Calyam proposed an anomaly detection system specifically designed to be integrated on top of PerfSONAR measurements [4].

The mPlane platform is instead specifically designed to integrate existing and new measurement probes. Indeed, mPlane already integrates RIPE Atlas, so it is possible to instrument RIPE measurements from an mPlane reasoner. In addition, mPlane offers support for passive and hybrid measurements. For instance, in this article we leverage passive measurements collected by Tstat [5] to compare with active test and to feed the anomaly detection algorithms with rich information about the status of complex platforms, such as the YouTube infrastructure. Note that capturing and processing passive measurements in operational networks such as those analyzed in this article pose a much more complex problem in terms of volume and analysis techniques than relying on pure active measurements.

Besides coordinating probes, mPlane offers storage capabilities, where data can be collected and processed by analytic components, which, for instance, integrate methodologies to identify anomalies. Furthermore, mPlane does not target the monitoring of the network layer only. For instance, we show its ability to monitor content delivery networks, and their direct impact on end-user QoE. In summary, mPlane is the first flexible, open, and intelligent platform to aim at providing monitoring and analysis capabilities for Internet services at large, and not only of pure network layer problems.

Considering anomaly detection algorithms, many proposals are present in the literature — see, for instance, the survey of Chandola [6]. Most of them could easily be integrated into mPlane. The most innovative part offered by mPlane is the ability to design complete workflows, where actions can be triggered as a consequence of alarms, and domain knowledge can easily be integrated. This goes in the same directions as the proposal by Kanuparth in [7, 8], where the Pythia system is introduced; still,

different from mPlane, Pythia focuses mainly on network path troubleshooting, relying exclusively on active measurements.

SYSTEM DESCRIPTION, COMPONENTS AND APPROACH

The proposed distributed platform is an instance of the more generic mPlane architecture. The mPlane monitoring system is composed of four different entities: *probes*, *repositories*, *supervisor*, and *reasoners*. They interoperate thanks to a standard protocol, and are logically organized into three layers in Fig. 1.

The Measurement Layer: Consists of probes located at vantage points within the monitored networks, which typically generate large amounts of measurement data. The system supports *active measurements* (e.g., ping or traceroute), *passive measurements* (e.g., the analysis of traffic flowing on a link), and *hybrid measurements* (e.g., the passive observation of active probing traffic). Measurement campaigns may be triggered on demand, with results returned as soon as the measurement is completed, or be run continuously, with results periodically exported into an mPlane repository to limit the storage utilization at the probe. For this specific instantiation of mPlane, the measurement layer includes the RIPE Atlas active platform using so-called mPlane *proxies* [1].

The Analysis Layer: Consists of *repositories*, which collect and aggregate data generated by the probes. Apart from the storage capacity, the analysis layer is provided with a set of analysis modules that process the data imported from the probes. Such processing may involve filtering, grouping, aggregation of the raw data imported from the probes, or more complex analytics such as anomaly detection. The results are a higher level of aggregation and visibility on the monitored network, and can be directly accessed through a standard queryable SQL-like interface.

The Coordination Layer: Consists of the

supervisor and the *reasoner*. The first orchestrates probes and repositories. The latter receives output of analysis modules, and may trigger alarms or initiate additional operations in a reactive fashion (e.g., perform additional on-demand measurements to investigate the anomaly).

As indicated in Fig. 1, the measurement layer is decomposed into three different measurement approaches: hybrid measurements combine active and passive measurements, and are used in the analysis of end-customer Internet access connections; passive measurements are instrumented by deploying sniffers at points of presence (PoPs) aggregating a large number of customers; finally, active measurements are performed through both the RIPE Atlas and the IQM platforms.

MEASUREMENT COMPONENTS

In more detail, the passive probe used in all fixed-line scenarios is Tstat [5]. Tstat is an open source packet analyzer capable of monitoring links up to several gigabits per second speed using commodity hardware. It extracts information about both TCP and UDP traffic flows at all the layers of the protocol stack, from simple flow size, or RTT average and standard deviation [9], up to layer 7 data (i.e., application-related). When considering cellular networks, we rely on the METAWIN passive monitoring probe [10], which is capable of handling the complete 3GPP protocol stack.

We use two different active platforms: RIPE Atlas probes and Internet QoS Measurement (IQM) probes.² Both probes are capable of RTT and path measurements using ping and traceroute tools; in addition, the IQM offers more complex measurements, for example, speed-tests and HTTP/HTTPS performance metrics. RIPE Atlas probes are maneuvered through a custom interface³ that launches measurements and retrieve results automatically.

As a repository, we use DBStream [11]. DBStream is a data stream warehouse tailored for large-scale traffic monitoring applications. It continuously analyzes the measurements obtained by the probes. In particular, multiple instances of an anomaly detection analysis module (ADAM) run in parallel on top of DBStream, flagging anomalous behaviors in different traffic features. We briefly describe ADAM next.

Finally, the mPlane Supervisor is the standard one, provided by the mPlane Reference Implementation (RI).⁴ The reasoner is a custom set of python code that, interacting with the supervisor, collects the output of the analysis module, and eventually starts measurement for further investigations.

ANOMALY DETECTION AND DIAGNOSIS

ADAM [12] is an mPlane analysis module that detects unusual deviations in the probability distribution of a monitored feature over time. In short, the ADAM base algorithm detects anomalies based on the degree of similarity between the distribution of a feature as currently observed, and a set of distributions describing the normal behavior of the monitored feature (i.e., a baseline). The latter is built through a progressive refinement heuristic, which takes into account the structural characteristics of traffic such as

time of day variations, presence of pseudo-cyclic weekly patterns, and long-term variations. The baseline thus evolves over time to adapt to the dynamics of the system. The similarity between distributions is computed on the basis of a symmetric extension to the well-known Kullback-Leibler divergence. When the difference is bigger than an (adaptive) confidence threshold, ADAM raises an alarm. More details on ADAM can be found in [12], where we apply the same base algorithms to detect anomalies in content delivery network (CDN) services.

Multiple instances of ADAM run in parallel, each analyzing multiple traffic features at the same time. We split the monitored features into two groups, referred to as symptomatic and diagnostic features. Symptomatic features are defined such that their abrupt change directly correlates to the presence of abnormal and potentially harmful events. Diagnostic features provide contextual details of the anomalies, pointing to their root causes. In a nutshell, by locating those diagnostic signals that show a change at the same time or same temporal scope as the detected anomaly, one gets a more targeted and specific indication of which features might be causing the anomaly.

ANALYSIS WORKFLOW

The detection and diagnosis of anomalies runs as a continuous process. The supervisor instructs passive probes to run continuously, measuring and exporting the obtained data to the DBStream repository. When an alarm is triggered, the reasoner can instruct active probes to run further measurements. The measurement and analysis workflow depends on the specific case study, but apart from particular instrumentation details, all the scenarios follow the same basic steps, described in Fig. 1.

Step 1 — Passive Traffic Monitoring: Passive probes are deployed at vantage points. In the case of large-scale service monitoring, probes are deployed at PoPs aggregating a large number of customers, and their real traffic is captured, discarding all privacy-sensitive information.⁵ In the case of end-customer access monitoring, Tstat is installed at the same server that instantiates active measurements (a simple FTP server used for speed tests), resulting in the aforementioned hybrid measurement approach.

Step 2 — Active Probing: Active probes scattered in the ISP (five per region) continuously perform speed tests to measure the available bandwidth on the network paths reaching the ISP customers, periodically downloading (uploading) files from (to) the FTP server. Active probes log the achieved application layer throughput, transferring the results to the same DBStream repository.

Step 3 — Detection of Anomalies: Multiple instances of ADAM run on top of DBStream, analyzing a set of features. As soon as an abrupt change is detected in a symptomatic feature, an alarm is raised to the reasoner.

Step 4 — Correlating Multi-Source Measurement Data: When alarms suggesting unexpected performance degradation are detected, the reasoner runs correlation analysis (e.g., factor analysis) to investigate which features show

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² IQM probes are directly deployed by the ISP.

³ <https://github.com/pierdom/atlas-toolbox>.

⁴ <https://github.com/lp7mplane/protocol-ri>

⁵ The deployment and the information collected for this has been approved by the ISP security and ethics boards.

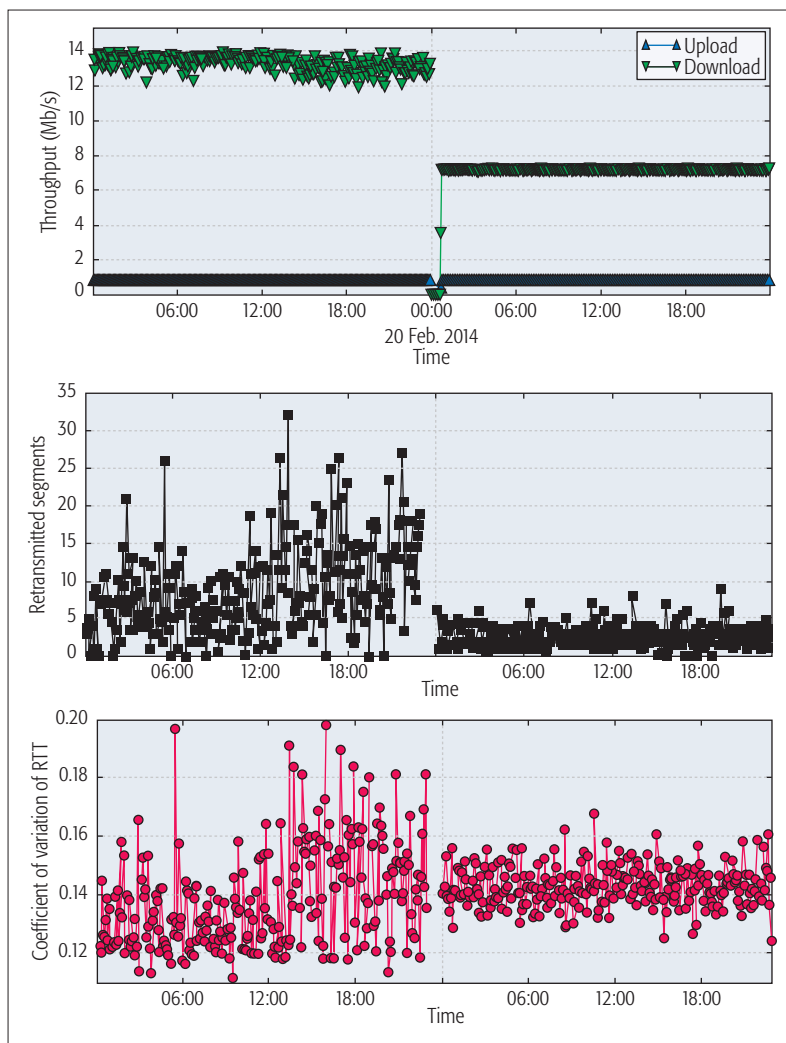


Figure 2. Evolution of time of the throughput measured by one active probe (top), the number of retransmitted segments (center), and the coefficient of variation of the RTT (bottom). U-1 Mb/s/D-16 Mb/s ADSL probe.

a similar abrupt change. Correlated features are then compared against a catalog of known anomaly patterns or signatures, and if a match is found, the most probable cause(s) are reported to the network operator.

DEPLOYMENT AND DATASETS

For the sake of end-customer connection monitoring, we deployed active probes in more than 30 locations scattered in the operational country-wide network of the ISP. As regular customers, active probes connect to the network using an asymmetric DSL (ADSL) or fiber to the home (FTTH) access technology. The FTP server is installed in the ISP data center. This ISP offers three configurations for ADSL connections (U-1 Mb/s/D-16 Mb/s, U-1 Mb/s/D-12 Mb/s, and U-0.5Mb/s/D-8Mb/s) and one for FTTH (U-10Mb/s/D-10Mb/s). Each probe periodically runs a speed test by uploading (downloading) files of predefined size, measuring the application layer throughput. Tstat runs on the same server where the FTP is, and logs each TCP flow related by the active tests. We ran the system for three months (February 1–April 30, 2014), observing the time series of application-layer

throughput. Speed tests are scheduled every 4 min, resulting in a total dataset of 1.2 million speed test reports produced by the active probes, and as many TCP entries in the log generated by Tstat.⁶

For the analysis of cellular network traffic and service availability, that is, the possibility for a client to obtain a response from servers of given service, we deployed the METAWIN passive probe at the core of a cellular ISP network in the EU. Traffic flows were captured at the well-known Gn interface for two consecutive days in mid-2014. In this case study, we only consider Domain Name System (DNS) traffic. The DNS is the core component of the Internet, providing flexible decoupling of a service's domain name and the hosting IP addresses. Anomalies in Internet-scale services are likely to change the normal DNS usage patterns. For example, users accessing a temporarily unreachable service would generate a new query at every connection retry. For that reason, we extract features derived from the DNS, including frequency of DNS requests, error codes, and so on.

Finally, QoE-based service performance analysis is performed again using Tstat, which passively monitors traffic from a PoP where there are 30,000 residential customers. We focus on the analysis of YouTube traffic, which we extract using Tstat classification modules. The complete dataset corresponds to four weeks of YouTube video traffic flows captured during the second quarter of 2013.

RESULTS AND DISCUSSION

In this section we report some of the results obtained with the deployed mPlane framework in the aforementioned case studies. Due to lack of space we do not provide a fully detailed description on the complete diagnosis process for the presented scenarios, but refer the interested reader to <https://www.ict-mplane.eu/public/public-deliverables> (reports D4.1-4) for further details.

COMBINING ACTIVE AND PASSIVE MEASUREMENTS

For the sake of brevity, we report here two examples of anomalies that could be present in ADSL access links: low SNR in ADSL channels and path congestion.

Low SNR in ADSL Lines: Figure 2 (top) reports the evolution over time of the throughput measured by an active probe accessing the ISP network through a U-1 Mb/s/D-16 Mb/s ADSL interface for two days.⁷ Observe that the download throughput curve appears to be noisy during the first day, while after midnight, the ADSL line was re-calibrated to U-1 Mb/s/D-8 Mb/s. After then, speed test measures are much more stable over time. By correlating such output with the statistics provided by Tstat, we notice a fairly large fraction of retransmitted segments during the first day (center), and a constant coefficient of variation of the RTT (bottom). The absence of evident day-night patterns let us exclude that this situation might be due to network congestion, since this typically emerges only during peak periods.

The most probable cause for this anomaly is the occurrence of low signal-to-noise ratio (SNR)

⁶ Access lines for experiments are devoted to test only, with no actual customer using those. As such, the testing traffic has minimal interference with customers' traffic that crosses the same path to the FTP server. Similarly, no privacy issues are raised.

⁷ The throughput reported in the plots is below the nominal bandwidth since it is measured at the application level.

⁸ SNR and BER can be read from SNMP measurements as defined by RFC 2662.

events at the physical link, which can lead to large bit error rate (BER).⁸ Losses due to noise cause TCP congestion control to (randomly) slow down the download. The confirmation of this hypothesis is given by the second half of the plots in Fig. 2, when the ADSL modem automatically reduces the downlink capacity to improve the SNR (i.e., negotiating 8 Mb/s instead of 16 Mb/s), thus considerably reducing the packet loss rate and making RTT measurements more stable.

Congestion in the Network: Figure 3 (top) reports the evolution over time of the throughput measured by second active probe (U-1 Mb/s/D-12 Mb/s ADSL). During both days, a clear degradation in throughput is detected, with stable values during the night, that is, when the network is typically lightly loaded. Conversely, available capacity greatly decreases during peak time. This suggests that congestion may appear in the path toward the FTP server. By inspecting the statistics provided by Tstat at the server side, we confirm this intuition. Indeed, notice how the RTT coefficient of variation (bottom) and the rate of retransmitted packets (center) considerably increase during the peak utilization period. From verification with the ISP, such a probe accesses the Internet through a bottlenecked virtual leased line, the available bandwidth of which is out of the control of the operator.

DETECTING AND DIAGNOSING AVAILABILITY ISSUES

We now present a case study based on the detection and diagnosis of a large-scale anomaly that occurred in the aforementioned cellular network. A significant and anomalous increase in the number of DNS requests is observed between 9:00 and 10:00 of the second day. Conversations with the network operations team revealed that the anomaly caused heavy stress in specific parts of the network. Figure 4a depicts the output of ADAM when applied to the distribution of DNS requests per device, which is defined as the symptomatic feature. ADAM systematically generates anomaly warnings during the one hour duration of the anomaly.

To discover the root causes of the detected anomaly, we define a set of diagnostic features related to the class of problems we target based on expert know-how. In particular, we consider the following set of features: anonymized mobile device identifier (MSID), contacted DNS server IP, radio access technology (RAT), access point name (APN), type allocation code (TAC), DNS requested full qualified domain name (FQDN), device manufacturer, device operating system (OS), and error code of the DNS response (DNS rcode). The first step of the diagnosis consists of identifying which of these features present a significant change in their probability distribution, simultaneous with the alarms generated by running ADAM on the symptomatic feature.

Figures 4b and 4c provide a closer look into the anomaly, comparing the output of ADAM when applied to two of the diagnostic features: the distribution requested FQDNs and the distribution of devices' OS type. Both ADAM outputs also flag anomalies in these two features exactly at the same time as the main anomaly trigger, suggesting that the issue might be due to spe-

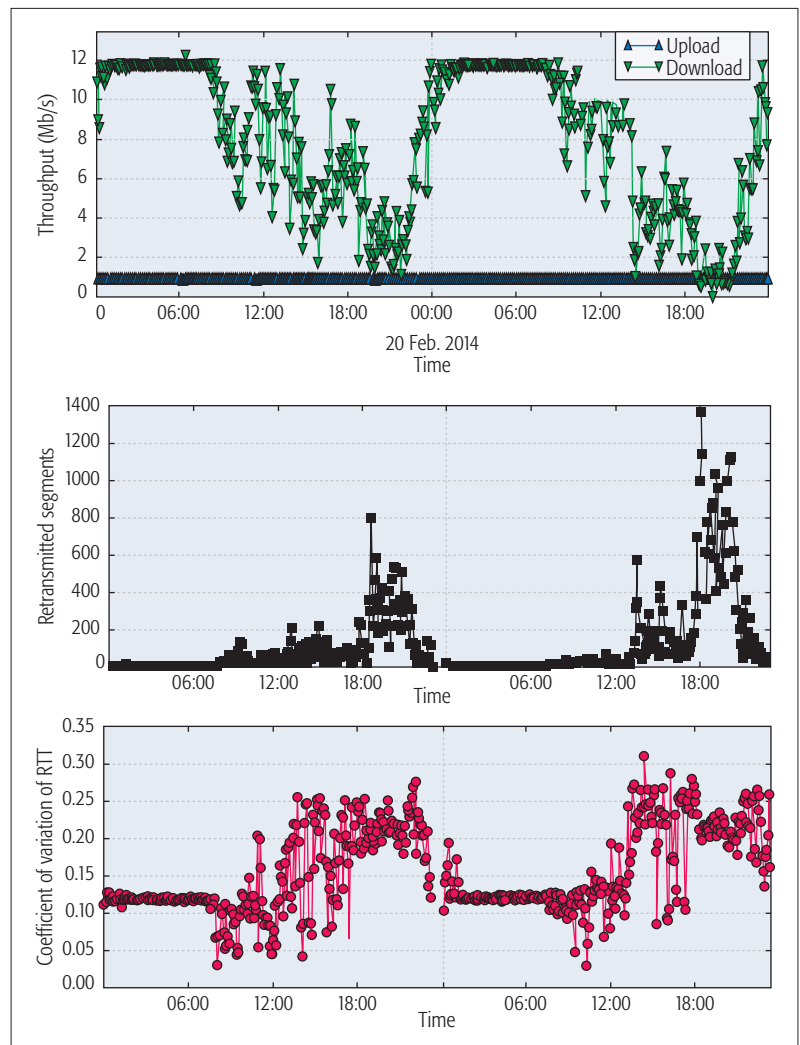


Figure 3. Evolution over time of the throughput measured by one active probe (top), the number of retransmitted segments (center), the coefficient of variation of the RTT (bottom). U-1 Mb/s/D-12 Mb/s ADSL probe.

cific devices (OS) querying for certain services (FQDN).

The next step of the diagnosis is to drill down into each of the dimensions that are highly correlated with the anomaly. This can be achieved, for example, by comparing the heavy hitters before and during the anomaly. For the specific case of the FQDN diagnostic feature, we observed that while some of the top elements present stable behavior (**.facebook.com* and **.google.com*), the FQDNs **.apple.com.akadns.net*, **.push-apple.com.akadns.net*, and *xy-courier.push.apple.com* show a significant increase, pointing to a problem in the availability of the push notification service deployed by Apple.

DETECTING AND DIAGNOSING QoE-RELEVANT ANOMALIES

The last case study consists of the detection and diagnosis of a major YouTube anomaly impacting the QoE of a large number of customers during several days at peak load times. As the issue was caused by an unexpected cache selection by Google (at least according to our diagnostic analysis), the ISP internal RCA did not identify any problems inside its boundaries. As reported by the ISP operations team, the anoma-

ly occurs on Wednesday, May 8, 2013. We therefore focus on the analysis of the week spanning the anomaly, from Tuesday the 7th to Sunday the 12th. In the following analysis, we generally use 50 percent percentile values instead of averages to filter out outliers.

Figures 5a and b plot the time series of two different symptomatic features related to the YouTube download performance and to the end-user QoE. Figure 5a depicts the median across all YouTube flows of the download flow throughput during the complete week. There is a normal reduction of the throughput on Tuesday at peak load time, between 20 h and 23 h. However, from Wednesday on, this drop is significantly higher, dropping way below a predefined bad QoE threshold of 400 kb/s, as found in [13].

To better monitor the QoE of YouTube videos from flow-level passive measurements, in [14] we introduced a novel QoE-based key performance indicator (KPI) defined as the ratio between the average download through-

put (ADT) and the corresponding video bit rate (VBR), $\beta = \text{ADT}/\text{VBR}$. Intuitively, when β is lower than 1, the player buffer becomes gradually empty, ultimately leading to the stalling of the playback, which is the most relevant impact on QoE [13]. In [14] we found that no stallings are observed for $\beta > 1.25$. Based on this observation, Fig. 5b actually confirms that the throughput drops, heavily affecting the user experience, as the time series of KPI β falls well into the video stalling region (i.e., $\beta < 1.25$).

To conclude, we report in Figs. 5c and 5d the output of ADAM for two selected features. Figure 5c considers the per /24 YouTube subnetwork served volume as the monitored feature. From Wednesday May 8 onward, ADAM alarms rise from 15:00 to 00:00, which correspond to a different selection of YouTube servers done by Google to serve the monitored customers. Figure 5d reports the ADAM output for the average video flows download rate. In this case, ADAM detects the anomalies only between peak hours (21:00–23:00) from the 8th onward, coherent with the observations drawn from Fig. 5a. Comparing the changes on the served traffic volume distribution against those on the video flows download rate distribution, we observe that the server selection policy used by Google resulted in a QoE degradation only during peak hours on high load days. This suggests that either the selected servers were not correctly dimensioned to handle traffic load peaks, or there is some heavy network congestion at peak time in the paths from the selected Google servers to the customers.

To unveil this kind of Internet paths performance issue within mPlane, we next propose a technique to perform direct traceroute measurements in the downlink direction, from the Google servers to the customers (i.e., a *reverse traceroute*). Our technique avoids relying on IP spoofing (normally blocked by many ISPs), as done in previous work [15].

DISTRIBUTED ACTIVE MEASUREMENTS FOR PATH ANALYSIS

To analyze the performance of server-to-customers Internet paths in the most general scenario using mPlane, we rely on the RIPE Atlas distributed active measurements framework. We developed DisNETPerf, a distributed Internet paths performance analyzer, to perform direct traceroute measurements in the downlink direction. In a nutshell, given a certain source server IP address IP_s , and a destination customer IP address IP_d , DisNETPerf locates the closest RIPE Atlas IP_{DNP} probe to IP_s , and periodically launches traceroutes from IP_{DNP} to IP_d , collecting different path performance statistics including RTT per hop, end-to-end RTT, losses, and so on.

Figure 6 (right) depicts the overall idea behind DisNETPerf. DisNETPerf uses a combined topological and geographical-based distance, as probes are located first by AS, Border Gateway Protocol (BGP) routing proximity, and then propagation delay. The selection of IP_{DNP} works as follows: given IP_s , we select all the probes in the same AS (or neighbor ASs if no local probes are found) and launch standard ping measurements toward IP_s . We consider the probe with the smallest minimum RTT as IP_{DNP} .

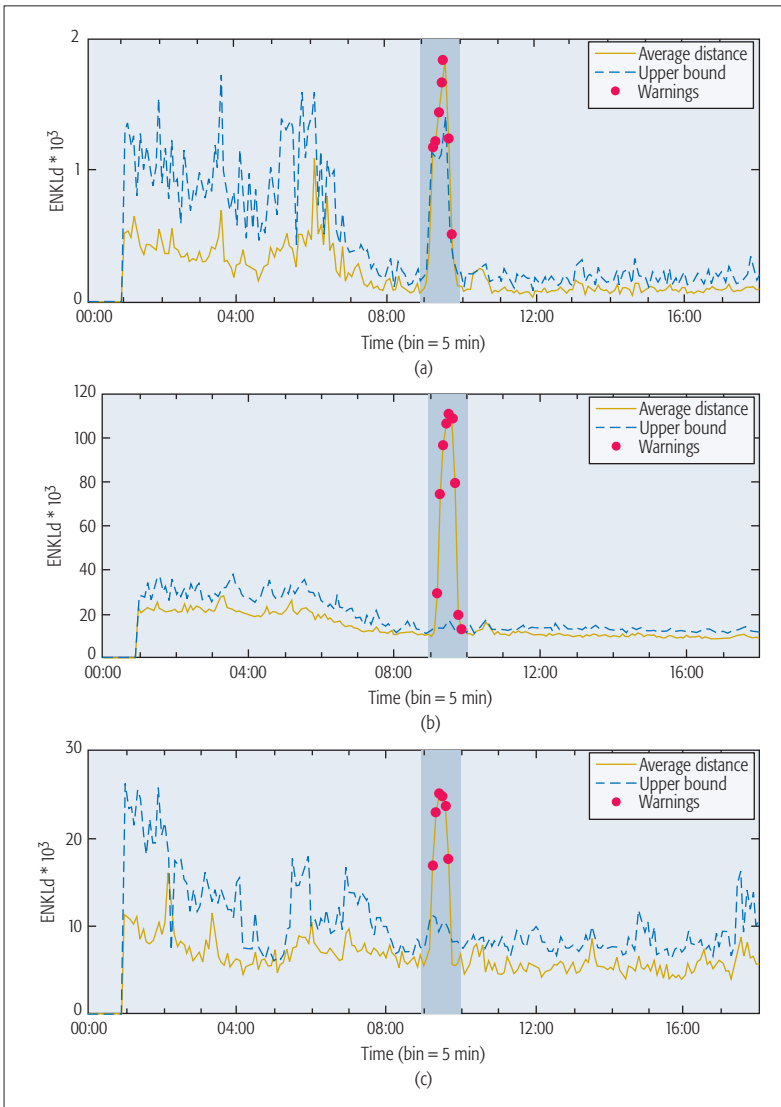


Figure 4. Output of the distribution-based detector for a — the symptomatic features (DNS query count per device) and two diagnostic features (b — FQDN and c — OS type). All the plotted features exhibit distribution changes during the anomalous event: a) ADAM output for the symptomatic feature; b) ADAM output for the diagnostic feature FQDN; c) ADAM output for the diagnostic feature OS type.

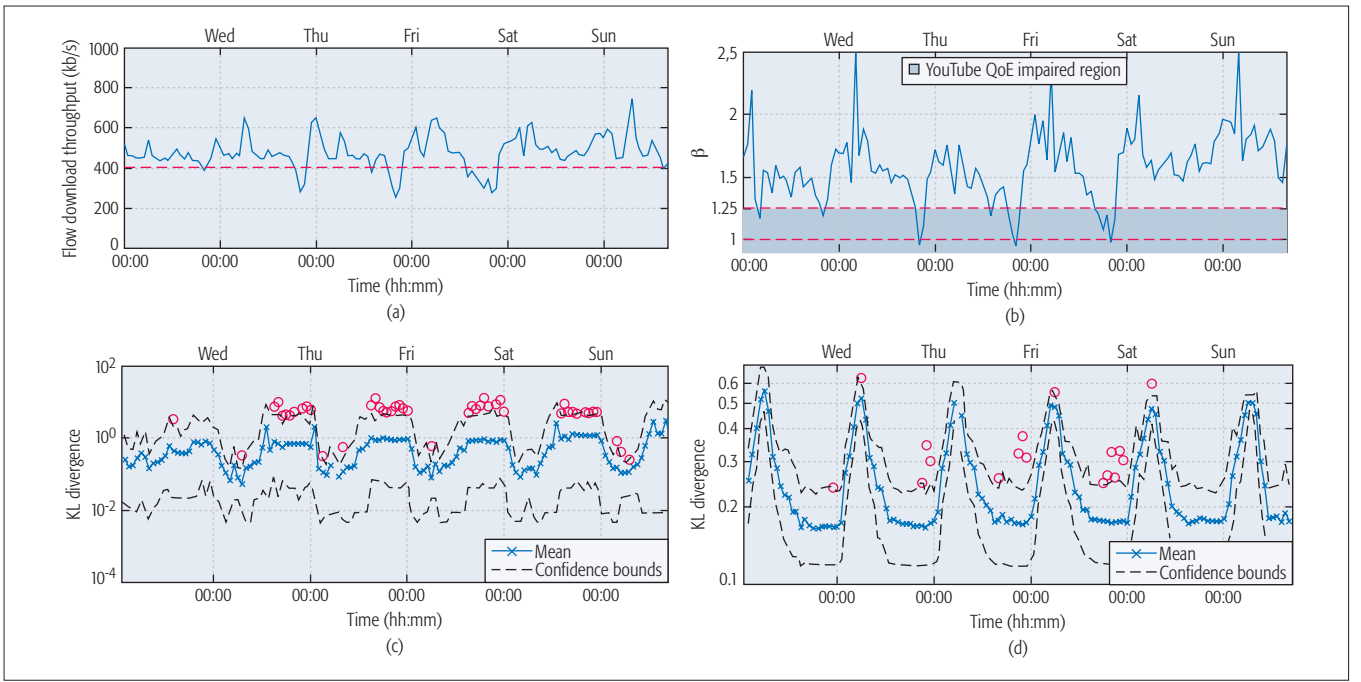


Figure 5. Detecting a QoE-relevant anomaly in a real ISP. There is a clear drop in the download flow throughput from Wednesday till Friday at peak load hours, between 20 h and 23 h. The additional drop in the QoE-based KPI β reveals a significant QoE degradation. The anomalies are flagged by ADAM in the selected symptomatic and diagnostic features: a) median of the flow download throughput per hour for all YouTube flows; b) median of β KPI per hour for all YouTube flows; c) anomalies in traffic volume served by YouTube /24 subnets; d) anomalies in the video flows average download throughput across YouTube users.

We say that the probe selected by DisNETPerf is a good probe w.r.t. IP_s and IP_d if the network path from IP_{DNP} to IP_d is highly similar to the path from IP_s to IP_d . Similar to [16], we define path similarity as the fraction of common links among both paths. Formally, we use the index route similarity (RSIM), defined as

$$RSIM(IP_{DNP}, IP_s, IP_d) = \frac{2 \times \text{common_links}(IP_{DNP}, IP_s, IP_d)}{\text{total_links}(IP_{DNP}, IP_s, IP_d)} \quad (1)$$

where *common_links* refer to the links shared in common by both paths, and *total_links* to the total number of links for both paths. Note that links can be defined at multiple granularities; in particular, for these evaluations we consider links at the AS level, the PoP level, and the router interface (IP) level. IP_s to AS mapping is done through the IP-to-ASN service provided by Team Cymru,⁹ whereas IP_s to PoP mapping is achieved through the datasets made available by iPlane [2].

In Fig. 6 (left) we present evaluation results showing the applicability of DisNETPerf in terms of path similarity. The goal of the evaluation is to investigate whether the probe selection approach used by DistNETPerf obtains probes that present the most similar path to the one we want to actually monitor. We use RIPE Atlas probes as source and destination (i.e., IP_s and IP_d) in order to compute the real path (i.e., the ground truth) between source and destination. In the evaluation, we randomly select 100 RIPE Atlas source probes IP_{s_i} , $i = 1, \dots, 100$, and consider a single fixed destination probe IP_d . For each of the sources IP_{s_i} we run DisNETPerf to locate the 100 closest probes IP_{DNP_i} , and obtain both

the ground truth path going from IP_{s_i} to IP_d and the DisNETPerf path going from IP_{DNP_i} to IP_d , and compute the RSIM index $RSIM(IP_{DNP_i}, IP_{s_i}, IP_d)$, $i = 1, \dots, 100$. We compute RSIM for AS level, PoP level, and IP level, and plot the CDFs for the three cases. Results are reported for two different groups, the former, in which $RSIM(IP_{DNP_i})$ and IP_{s_i} are located in the same AS (black dotted lines), and the latter, in which $RSIM(IP_{DNP_i})$ is located in a neighbor AS (red solid lines). When considering paths at the AS level, there is a significant difference between the groups, and the case of the same AS co-location results in near optimal results. Nevertheless, we observe that about 60 percent of the tests yield an RSIM index > 0.5 . Finally, we observe that probes selected by DisNETPerf generally correspond to paths with the highest similarity to the ground truth ones. Indeed, in more than 84 percent of the tests performed, $RSIM(IP_{DNP_i})$ results in the highest RSIM index among all the selected candidates.

CONCLUDING REMARKS

Unveiling network and service performance issues in complex and highly decentralized systems such as the Internet is a major challenge. mPlane provides a distributed measurement platform, which, among other applications, can be used to shed light on such performance issues. By deploying mPlane in both fixed-line and cellular operational ISP networks, we have shown how to use this powerful and novel framework to automatically detect and diagnose performance issues with very different root causes in different scenarios. Finally, note that all the software tools used in this article are publicly available at the mPlane project website (<https://www.ict-mplane.org/>).

⁹ <http://www.team-cymru.org/IP-ASN-mapping.html>

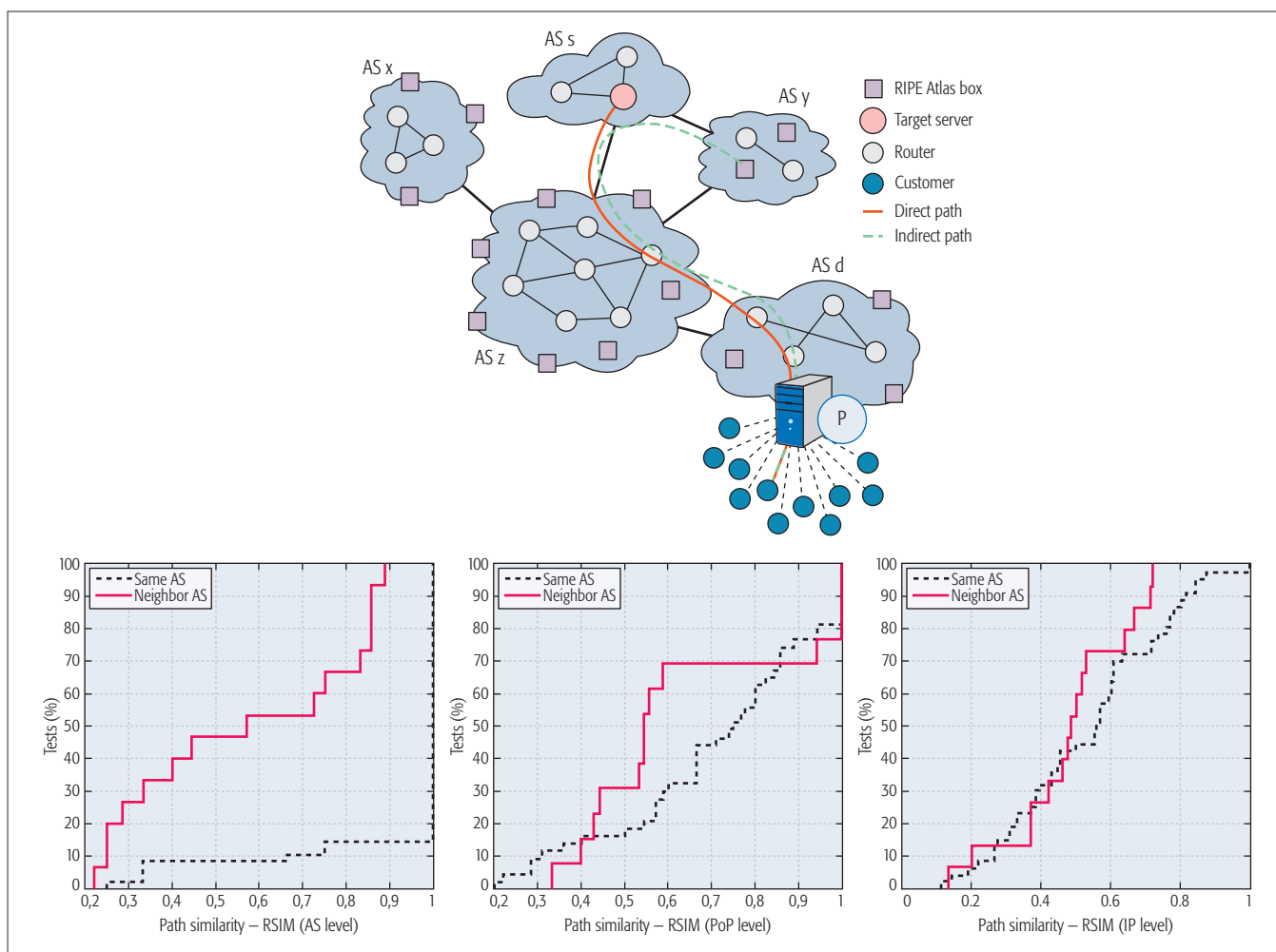


Figure 6. DisNETPerf approach. DisNETPerf achieves almost perfect path similarity at the AS level when IP_{DNP} is located in the same AS of IP_s , and path similarity above 50 percent for most of the cases, also at the PoP and interface level.

eu/). We refer the interested reader to <https://www.ict-mplane.eu/public/use-cases> for more details on how mPlane is applied to many other relevant use cases.

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