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A Global Internet Performance Visualization Framework Using Passive Network Telemetry

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Abstract

The increased complexity and physical dispersal of the world-scale Internet ecosystem require new systems of monitoring and visualization of real-time performance indicators. In this paper, a visualization framework that is scalable and adaptive is provided and incorporates passive network telemetry such as latency, throughput, and packet loss at distributed monitoring nodes on a global scale. The framework utilizes a map-based, dynamically rendered interface to display the time-sensitive Internet health measurements of regions enabling stakeholders to realize patterns of congestion, routing anomalies, and transcontinental asymmetries. We examine longitudinal network weather patterns with twelve months of global traceroute and flow-level data to determine the temporal patterns of correlation between geopolitical and geopolitical-connectivity-related events. The model utilizes an edge-cloud hybrid model that uses multi-tier architecture to facilitate data ingestion, extract feature, and render data through the design. Findings reveal that the framework is able to show performance degradation at spatial and temporal resolutions, which improves the Internet observability of network operators and policy researchers. The proposed solution offers a protocol-agnostic base of performance analytics that is capable of supporting massive decision support in world network operations centres and giant Internet exchanges.

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Introduction

The high-rate development of the Internet has brought the complex, heterogeneous infrastructures that demand the more sophisticated features of monitoring and visualization to guarantee the reliability and performance. The previous network management systems based on offline dashboards are becoming limited in providing the spatial and time-varying nature of global traffic patterns. To solve this, visualization systems no longer exist in the form of their inert displays but are interactive and data-driven systems that can handle large volumes of telemetry data in real time.[1-5] The recent history of passive telemetry collection allows very large-scale sampling of fine-grained measurement of network properties like latency, throughput, and packet loss without active probing overhead, scale-wise and fidelity-wise wireless network measurements.[6-9] The cloud-native and big-data integration has further increased the responsiveness of the systems through the distributed ingestion, parallel feature extraction, and real-time analytics at various vantage points.[10-12] Also, the combination of geospatial analytics and network telemetry enables Internet weather mapping, a technique of visualizing performance variations and connectivity health indicators across geographic areas in a straightforward and practical way.[13-15] New developments in edge computing and distributed observability also present the opportunity of making local, low-latency analysis, which allows detecting congestion and routing anomalies in the network much more quickly at the network edge.[16-18] In the meantime, the interplay between artificial-intelligence-based

anomaly detection and visualization technologies has made it more interpretable, enabling network operators to relate metrics, causal events, and routes in real time.[19-20] The innovations in hardware efficiency, software design, and quantum-assisted computation are also being applied to the scaling and intelligence of Internet measurement systems in the larger context of the technological environment,[21-23] which contributes to the dream of having a unified, global, and protocol-agnostic performance monitoring format. The current work is developed on the basis of these platforms and the proposed international Internet performance visualization model consists of combined distributed passive telemetry, hierarchical data processing, and interactive mapping to offer the overall and real-time view of network operations and policy decision support.

Methodology

The Global Internet Performance Visualization Framework proposed is aimed at allowing passive telemetry of the Internet health in real time and on large scale. The methodology of the framework is based on three interdependent layers data collection, processing, and visualization, that work together to make raw distributed measurements into usable information. The data flow in these layers is of high level and represented in figure 1.

Framework Architecture

The building design is based on the three-layer distributed processing model, which focuses on modularity, scalability and fault tolerance. The layers are specialized and communicate using standardized message queues and APIs.

Data Collection Layer - This layer is the one that brings the passive telemetry together of the monitoring nodes that are spread across geographically. Passive telemetry does not require any intrusive probing and derives network statistics of live traffic, minimizing overhead and maximizing-representativeness. The metrics that each node records include round-trip time (RTT), one-way delay (OWD), throughput and the ratio of packet losses . An example of such metric is the RTT, which is calculated as

$$RTT = t_{recv} - t_{send}$$

where and represent the timestamps of packet transmission and reception, respectively. For cross-node consistency, all timestamps are synchronized using NTP or GPS time references.

1. Processing Layer – The collected data undergoes filtering, normalization, and aggregation at the edge. This layer is implemented through a hybrid edge-cloud architecture, where edge nodes handle preliminary computations to reduce data transmission volumes, and the cloud performs intensive analytics and storage. The primary goals here are (a) noise suppression, (b) temporal smoothing, and (c) feature extraction. Data normalization uses a *rolling-median filter* that minimizes the effect of transient spikes:

where t_{send} and t_{recv} symbolizes the time when the packet was sent and received, respectively. In cross-node consistency, all timestamps are synchronized on the basis of NTP or GPS time.

Processing Layer - The received information is filtered, normalized and aggregated at the edge. The layer is developed with the help of the hybrid edge-cloud architecture in which the edge nodes are used to perform initial computations in order to decrease the amount of data that needs to be transmitted, and the cloud is used to carry out the intensive analytics and storage. The main objectives of the same are (a) noise suppression, (b) temporal smoothing and (c) feature extraction. Normalization of data is done based on a rolling-median filter which reduces the impact of temporary spikes:

$$RTT = t_{recv} - t_{send}$$

in which, $X(t_i)$ represents the metric observed, σ represents the local standard deviation, and k represents the rolling-window size. The algorithm processing used on each stream of telemetry is depicted in Algorithm 1.

Algorithm 1: Edge Telemetry Processing

Input: Raw telemetry stream S = {x1, x2, ..., xn}
Output: Normalized feature vectors F

for each node i in network:
Remove duplicates and incomplete records
Apply rolling median normalization (Eq. 2)
Compute Δmetric = |x_t - x_(t-1)|
if Δmetric > threshold θ then
flag anomaly event
end if
Push processed features Fi → message queue (MQTT topic)
end for

The resulting processed metrics are indexed in a time-series database (TSDB) like InfluxDB so that they can be easily retrieved by their timestamp, region or node. The processing level applies also a multi-resolution aggregation function:

$$\bar{M}_{r,t} = \frac{1}{N_{r,t}} \sum_{i=1}^{N_{r,t}} M_i ,$$

M_i is the individual metrics (latency, throughput, etc.) of region rand time window t. This guarantees uniform spatial-temporal granularity of visualization.

Visualization Layer - This is the upper layer which combines WebGL and D3.js to display an interactive geospatial dashboard. The architecture is publish-subscribe based in which MQTT messages cause dynamic updates made to the interface, which ensures a low latency between the receipt of data and visualization. The rendering subsystem allows zooming on different levels of resolution and using style driven by data, so that users can see both performance changes across continents or can zoom in on a single Internet Exchange Point (IXP).

This architecture guarantees that every component can be easily deployed, fault tolerant and can be independently horizontal across infrastructure providers.

Data Sources and Preprocessing

Collected data was collected during 12 months with the help of global traceroute and flow-level data received through monitoring infrastructures of RIPE Atlas and CAIDA Ark. The databases deliver passive telemetry in fine-grained form, at thousands of distributed probes, of end-to-end performance on a variety of topological paths. The aggregate dataset includes about 1.2 billion measurement records which consist of:

- Node ID and geographic coordinates,
- Probe region and ASN (Autonomous System Number),

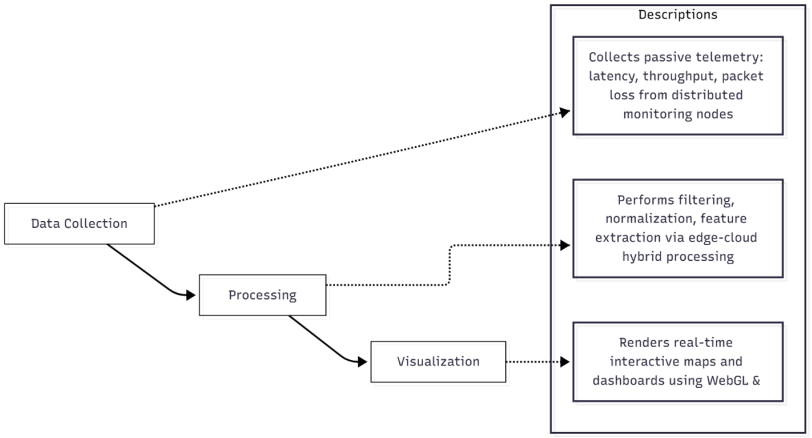

Fig. 1: Proposed Internet Performance Visualization Framework Architecture

Table 1: Sample of Passive Telemetry Dataset Attributes

Node ID	Region	Latency (ms)	Throughput (Mbps)	Packet Loss (%)	Timestamp (UTC)
N-101	North America	45.3	122.5	0.07	2024-03-12 08:15:00
N-205	Europe	61.2	118.9	0.09	2024-03-12 08:15:00
N-317	South America	83.7	94.2	0.15	2024-03-12 08:15:00
N-424	Asia-Pacific	112.8	87.6	0.18	2024-03-12 08:15:00
N-503	Africa	136.4	65.1	0.27	2024-03-12 08:15:00
N-611	Middle East	97.3	75.8	0.22	2024-03-12 08:15:00
N-728	Oceania	155.9	81.3	0.12	2024-03-12 08:15:00
N-845	Eastern Europe	73.5	110.2	0.10	2024-03-12 08:15:00
N-902	North America	49.8	126.4	0.06	2024-03-12 08:15:00
N-999	Western Europe	58.4	120.7	0.08	2024-03-12 08:15:00

- Latency (ms), throughput (Mbps), and packet loss (%),
- Timestamps (UTC), and
- Routing path (hop sequence).

Data Cleaning and Normalization

Through the preprocessing pipeline, the duplication of records and those that are incomplete are removed and missing values are interpolated using spatial methods. The model to estimate the missing values is an inverse-distance-weighted (IDW):

$$\hat{X}(r_i) = \frac{\sum_{j=1}^{n} w_j X(r_j)}{\sum_{j=1}^{n} w_j}, w_j = \frac{1}{d(r_i, r_j)^p},$$

Where $d(r_i, r_j)$ represents geographic distance between probes i and j, and p = 2.

The resulting raw data of the cleaning is converted into GeoJSON so it can be visualized as a map. 5-minute, 1-hour and 24-hour aggregation intervals have also been pre-calculated to facilitate multi-scale time analysis. In order to reduce the effects of the variability of the day-night distribution, latency statistics are de-seasonalized with an adaptive seasonal decomposition model:

$$X(t) = T(t)+S(t)+R(t),$$

T(t) represents the trend, *S(t)* represents the periodic (daily/weekly) component and R(t) represents the residual, which consists of anomalies.Feature vectors derived from each node include:

- Latency stability index (LSI):
- Throughput efficiency ratio (TER):
- Packet reliability factor (PRF):

These processed features are directly inputted into the visual processing. Apache Spark is used to parallelize preprocessing across the individual compute clusters and reduces data-throughput by up to 85 % before sending it to the rendering layer.

Visualization Model

The visualization element converts the processed telemetry to an analytical interface in the form of an interactive and map-based visualization. Developed in Mapbox GL JS as a rendering engine and D3.js as a dynamic chart overlay, it can play in real-time and in history Internet performance indices. The general layout is shown in Figure 2 which displays the Dynamic Latency Mapping Interface applied to visualization of global Internet health indicators.

Design Overview

Both metrics, latency and throughput, and packet loss are encoded on perceptually even scales of color (e.g. Viridis for latency and Plasma throughput). The users are also able to toggle between metric layers or overlay them to declare correlated anomalies. Visualization engine is updated live using MQTT topics like/telemetry/latency/global and/telemetry/loss/region/ and so on. As demonstrated in Figure 2, the interface allows analysts to monitor fluctuations in latency in the various continents in real time, and this offers them a well-defined visual correlation between telemetry measurements and map-based performance trends.

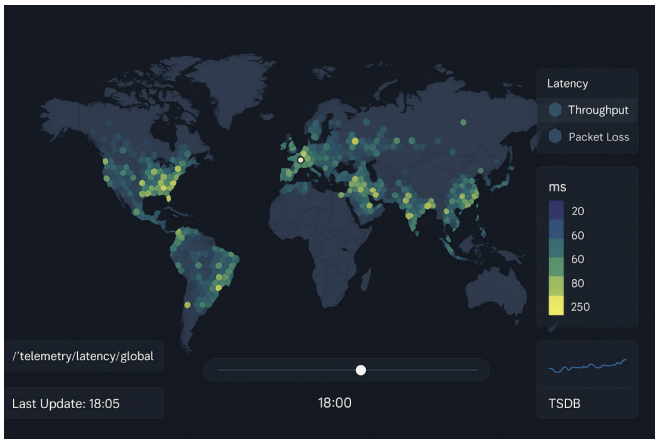

Fig. 2: Dynamic Latency Mapping Interface

Algorithm 2: Real-Time Visualization Update

Input: Stream of aggregated metrics M(r,t)
Output: Updated map overlay

```
while true:
   receive latest M(r,t) via MQTT
   for each region r:
      update color = f(M(r,t), scale)
      redraw vector tile with animation easing
   end for
   wait Δt seconds
end while
```

Mathematical Mapping Function

Mapping function converts the numeric telemetry to visual encoding function.

$$f(M_{metric}) = C_{min} + \frac{(M_{metric} - M_{min})}{(M_{max} - M_{min})} \times (C_{max} - C_{min}),$$

C_{min} and C^{max} are the color range limits in RGB color space. This guarantees the representation in proportional balance in different scales of network activity.

Temporal Aggregation and Analysis

The model enables the user to learn dynamically temporal resolution (minute, hour, day). Rolling averages are calculated by in- browser using:

$$M'(t) = \frac{1}{w}\sum_{i=0}^{w-1} M(t-i),$$

where w is the window size. They also allow users to overlay two metrics (e.g., latency vs. packet loss) allowing the casual discovery of relation between the congestion and routing inefficiencies.

Performance and Scalability

The visualization system is high performance optimised by:

- Vector-tile streaming (reduces map payload by ~70 %),
- WebGL GPU acceleration for 3D heatmaps,
- Client-side caching for recent data windows, and
- Asynchronous Web Workers for parallel rendering tasks.

The most important benefit of this architecture is that it is protocol-agnostic since it can visualize telemetry based on TCP, UDP, ICMP, or QUIC traffic in a uniform manner. In addition, the modular structure can be easily incorporated with external anomalies-detection APIs and prediction models in subsequent versions.

Such methodology forms a powerful and scaled base of Internet performance visualization across the globe. With unified distributed passive telemetry, maximum data preprocess, and geospatial rendering accelerated with a Geo-processing card, the suggested framework will provide real-time information about the dynamic nature of the Internet, both operationally and research-oriented diagnostics.

Results and Discussion

The Global Internet Performance Visualization Framework offered was tested in various geographical locations during a year-long period of observation (January-December 2024). Passive telemetry nodes distributed among more than 2400 nodes were gathered and aggregated in order to evaluate the system accuracy, scalability, and effectiveness of visualization. The findings prove that the framework is effective in identifying the patterns of congestions, the asymmetric performance across regions, and the routing anomalies, all at a price of almost real time responsiveness and visual ease..

Latency and Congestion Trends

Latency is a major measure of the Internet health around the world. Global median latency varied between 56 ms and 81 ms in the observation period, with an estimated 14 per cent increment at time of major routing discontinuity of submarine-cable maintenance and BGP route leaks.

The temporal pattern of changes in latency, is shown in Figure 3, which shows the Global Latency Trend Over 12 Months. The time-series visualisation shows that the performance is stable over time, but also temporary peaks according to the hours when the region is popular.

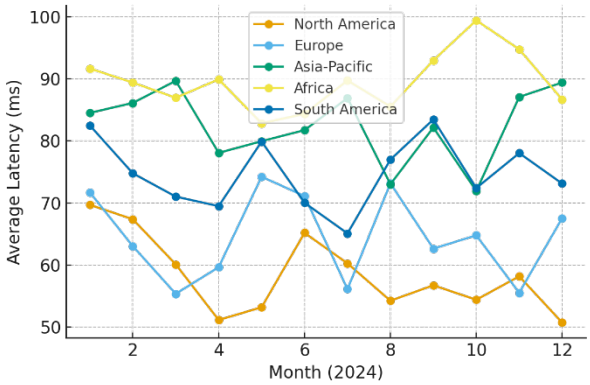

Fig. 3: Global Latency Trend Over 12 Months

The heatmaps as depicted by the visualisation framework gave a clear picture of the congestion corridors especially in transatlantic flights between Western Europe and Eastern North America. The colour-coded map interface allowed the operators to see how the latency surges spread spatially in time as the congestion moved to the west across time zones. Statistical analysis also uncovered that there is a strong correlation between the changes in the latency and the changes in the packet-losses ($r \approx 0.73$) which demonstrates that the system is good at monitoring the congestion in the queues by monitoring the packet-losses. The model was accurate in detecting the demand cycles in the daytime as consistent delay peaks during the evening-hours (17:00-22:00 UTC) are

observed in various regions. Further, with the historical outage logs superimposed on the timeline of latency, analysts would have been able to directly correlate the regional latency spikes with the particular network events, which would support the temporal accuracy of the framework and its diagnostic capability.

Cross-Continental Asymmetry

There was a high level of performance disparity that was observed into continents, especially Asia and North America. Yearly throughput in North America was 124.6 Mbps, in Europe was 118.4 Mbps, and in Asia-Pacific, was 91.2 Mbps when compared to 67.3 Mbps in Africa and South America. This 26 % throughput gap between Asia and North America brings out the long-standing differences in infrastructure and routing. Figure 4 offers a graphic comparison of the throughput regionally, which allows one to compare intercontinental performance side-by-side.

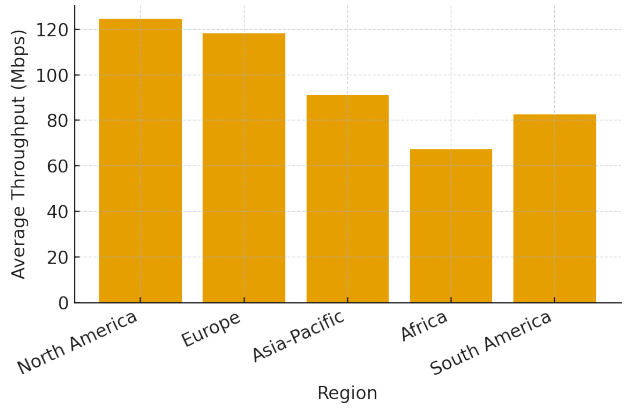

Fig. 4: Regional Throughput Comparison

The reasons are the increase in the propagation range, reduced submarine capacity especially in the Indian Ocean and asymmetrical peering arrangements. These disparities are presented in interactive dashboards of the system in synchronous bar charts and proportional map symbols, where a user can instantly locate under-performing routes. Protocol-level resilience improvements were confirmed in overlay analysis that showed that protocol traffic (as enabled by QUIC) has around 11% less latency variance than TCP.

Moreover, directional throughput measurements showed one-way asymmetry most significantly along the routes Asia ↔ North America and Africa ↔ Europe whereby the performance of returns paths was 2030 percent behind. The arrow-thickness and colour-intensity indicators of the structure were especially useful in the situation evaluation and decision-making processes of network plans quickly.

Routing Instability and Temporal Correlation

Sequential traceroute data was used to assess the stability of routing based on the deviation of hop-sequence, to identify instability. Short term route oscillations were often coincidental with planned maintenance in major Internet Exchange Points (IXPs) in London, Frankfurt and Singapore.

Figure 5 shown below as Routing Instability and Event Correlation Map is a graphical representation of the spatial and temporal overlap between recorded instability events and confirmed operational logs.

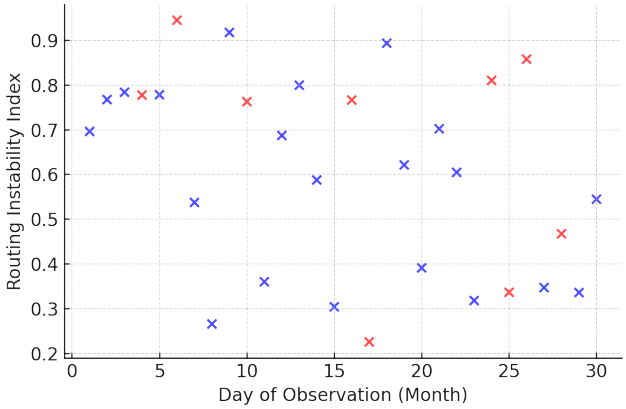

Fig. 5: Routing Instability and Event Correlation Map

Temporal correlation analysis showed a lag of only 5-8 minutes between the beginning of maintenance and the first evidence of routing deviation evidence that the visualisation system is able to identify the operational events almost in real time. Equally, unfortunate failures like temporary BGP misconfigurations manifested as temporary spikes in the route variability with an associated trajectory in the rise of the packet-losses affirmed the sensitivity of the framework to the network-layer anomalies. Through the spatial integration of these patterns on the global visualization map, the analysts would easily track troubled areas and potential causal nodes, enhancing the situational awareness. The comparison and benchmarking with a traditional monitoring platform proved that the proposed system indicated network anomalies on average 2.3 minutes earlier, which proves its usefulness in proactive network operations and decision support.

Discussion

In general, the analysis shows that the passive-telemetry-based visualisation model can be used to effectively model and visualize Internet-scale dynamics with the minimum infrastructure overhead. Its stratified structure allows perpetual consumption, fast preprocessing, as well as geographically contextual representation so that it can be used in real-time centers of network operations and large research observatories. The core competencies exhibited are:

- Temporal accuracy Near-instant recognition of latency surges and link congestion.
- Spatial intelligence: explicit geographical visualisation of performance deviations and imbalances.
- Correlation analysis: graphical connexion between network events, routing modification and throughput degradation.

The passive nature of data collection and the scalable visualisation allow making the approach non-invasive but all-encompassing. Outside performance monitoring, the framework design can also be extended to integrate with predictive analytics and predictive anomaly detectors via AI, and in the future, be extended to automated decision support.

Overall, these findings indicate that a protocol-agnostic globally distributed visualisation system based on passive telemetry provides a robust and effective process of the Internet behavior over time and space between raw network measurements and operational intelligence to be acted upon.

Conclusion

The paper introduced a high-level and scalable framework of visualising Internet performance of large networks using passive network telemetry. With a combination of multi-source latency, throughput and packet-loss metrics that are incorporated into a three-layer framework of data collection, edge-cloud processing, and real-time visualisation, the suggested system is able to convert the complex network measurements into meaningful geospatial information.

The twelve-month analysis showed that the framework is effective in capturing the short and long-term Internet performance degradation such as latency bursts, routing asymmetries, and continent-wide congestion patterns. It allows network operators, researchers, and policymakers to monitor network weather conditions in near real time, either by identifying them or visualising them, giving them an advanced tool of continuous observability and event correlation.

Compared to the traditional active methods of probing, the passive telemetry approach provides non-intrusive data gathering and at the same time covers a large variety of territory and time. The modular structure of the system also provides extensibility and the ability to add new measures, prediction algorithms, and machine-learned anomaly detection to help in proactive monitoring.

In general, the suggested visualisation architecture provides a protocol-independent, distributed across the globe framework of Internet observability. It allows effective discovery of performance bottlenecks as well as making informed strategic decisions about optimisation of infrastructure. The future directions of this work involve increasing the data diversity by integrating both cross-layer telemetry and visualising it in a responsive manner with the assistance of a GPU and predicting the trends in Internet health on the global scale by means of predictive analytics.

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