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# Data-Driven Internet Weather Maps: Real-Time Analysis of Global Network Performance Fluctuations

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## Abstract

In this paper, a data-driven model of creating Internet weather maps is introduced to visualise current network performance around the world. The system analyses the latency, jitter and packet-loss data using passive telemetry on more than 500 distributed monitoring nodes and compiles them into a scalable multi-layered visualisation model. The raw telemetry is converted to colour mapped maps of network climate zones around the globe by advanced interpolation and clustering algorithms. The suggested system is based on the distributed edge-cloud processing and GPU-accelerated rendering to provide responsiveness and scalability. A twelve-month analysis indicated the presence of apparent spatio-temporal variations in Internet performance in form of congestion propagation, cross-continental asymmetry and routing instability. The findings indicate that Internet weather maps can be used as a visual decision-support tool by the operators and researchers who follow the trends in Internet resilience and performance across the world.

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## Introduction

The Internet is still emerging as a globally distributed and very heterogeneous infrastructure capable of sustaining a broad range of latency-sensitive applications including cloud gaming, Internet of Things (IoT) worlds, and real-time streaming service. This growing reliance on low-latency and high-reliability communication has made the need to be able to observe the Internet continuously and with fine grain increasingly imperative.[1-3] Traditional active-monitoring tools, such as traceroute and ping-based probing, impose overheads on the traffic and may not always be in a position to measure a transient routing anomaly or temporary instance of congestion.[4-6] Conversely, passive telemetry methods can be used to provide broad performance analysis without the introduction of new packets, hence provide non-invasive and continuous information on real network status.[7-9]

The recent development in data analytics and visualisation technologies have changed the paradigms of Internet measurement. By combining both spatial and temporal telemetry of distributed points of observation, researchers are able to model the dynamics of performance in terms of so-called Internet weather maps interactive heatmaps, providing visual representation of latency, jitter, and packet loss changes on a global scale.[10-12] These visual abstractions increase the interpretability, and the operators can see the macro-level congestion and routing asymmetries in near real time.

The advent of edge computing has also radically transformed the concept of observability of the Internet by facilitating the process of local data aggregation and analysis nearer to the source of measurement. This minimises latency in the collection of telemetry and enables almost instant detection of anomalies.[13-15] Also, combination of clustering and interpolation algorithms can reveal spatial-temporal structure in world-wide Internet traffic with repeating congestion patterns, routing paths or asymmetries of regions.[16-17]

Based on these developments, this paper presents a data-intensive Internet Weather Map Framework (IWMF), which also relies on passive telemetry of hundreds of geographically dispersed vantage points to present the dynamics of Internet performance at high spatial and temporal scales. The suggested model focuses on three design objectives:

1. Scalability, which allows transforming multiple geographical data acquisition and aggregation;
2. Accuracy, and in any case, must have correct depiction of changes in network performance; and
3. Interpretability in form of intuitiveness, real time visualisation of Internet health indicators.

IWMF is the communication between the raw telemetry data and human-readable analytics, to enable a researcher and operator to look at the climate of the global Internet performance, in real-time. The framework, through the integration of edge-cloud computing, passive monitoring, and GPU-powered visualisation, provides a platform of a transparent and adaptable Internet observability, which is the necessary step toward proactive network management in an ever-increasing digital ecosystem.[18-20]

## Related Work

Internet measurement studies have also developed immensely during the last ten years, with the focus on scalable and precise observability of global networks. Conventional tools have been mostly based on active probing tools, e.g. traceroute, ping, and synthetic measurement tools, which give a snapshot view of network behavior, and are inadequate to resolve fine-grained fluctuations in performance.[1-5] Routing Information engines such as RIPE Atlas and CAIDA Ark have increased visibility on a global scale with geographically dispersed probes but remain entirely reliant on sampled data instead of full-spectrum, continuous telemetry.[6- 9]

In order to address these drawbacks, in-band network telemetry (INT) and programmable data-plane technologies have become significant advances and measurement data are incorporated into packet headers, enabling near real time analysis, on a fine-grained basis.[10-12] These techniques enhance observability and lower latency in network diagnostics, though generally, they need hardware programmability and cannot be easily deployed in heterogeneous Internet settings.[13-15]

Similar progress in data visualization and analytics have been used to facilitate more natural interpretation of network health indicators. The latest visualisation tools combine geospatial visualisation, real-time dashboard and multi-layer metrics to illustrate dynamics of latency, jitter, and packet loss on regional and global levels.[16-18] Irrespective of these innovations, the vast majority of the existing tools work in disconnected areas either concentrating on the data collection process or on visualisation without a single tool that provides a controlled integration of the passive telemetry, automated preprocessing, clustering, and live rendering.[19, 20]

The proposed research is able to fill that gap because the study proposes an integrated Internet Weather Map Framework (IWMF), which integrates passive data collection, distributed edge-cloud computing and GPUs-based visualization. The suggested system provides real-time interactive Internet weather maps that illustrate macro-level and localized performance deviations. By doing that, it would bring the state of Internet observability to the fully-integrated, non-invasive, and adaptive visualisation paradigm, applicable to an operational and a research setting.

## Methodology and System Implementation

The IWMF is a proposed framework of an Internet performance monitoring and visualisation framework imbued with an architecture that is modular and data-driven in scope. Its layered design guarantees scalability, fault tolerance and real time responsiveness with respect to a distributed infrastructure across a geographical area. The structure has three main layers which include Data Collection, Processing and Visualisation as shown in Figure 1.

### Framework Architecture

#### *1. Data Collection Layer —*

It has more than 500 monitoring nodes worldwide that continuously gather passive telemetry data like round-trip latency, jitter and packet loss. All the nodes are synchronized through GPS/NTP time reference in order to have a uniform time reference across continents. The distributed setup reduces the risk of single points in failure, as well as, cover diversity.

#### *2.Processing Layer —*

Raw telemetry at the network edge is filtered by dedicated servers and normalized and aggregated. The noise reduction methodology that will be used is a rolling-median smoothing algorithm, whereas spatial continuity will be achieved with the help of the inverse-distance-weighted (IDW) interpolation. The processed data undergoes consumption into a time-series database (TSDB) that is optimised to run real time queries and retrieve data on demand and aggregate with time windows to be displayed.

### *3. Visualization Layer —*

The upper layer uses a WebGL renderer that uses a graphics card to turn aggregated metrics into color coded interactive Internet weather maps. The latency is plotted over a green red gradient, jitter over a blue yellow gradient and packet loss over a grey purple gradient. The several layers can be overlaid to give a holistic view of the performance. The visualisation interface is automatically updated after every 60 seconds using MQTT streaming which provides near real time situational awareness.

This is a multi-layer integration illustrated schematically in Figure 1, which ensures effective end-to-end telemetry stream between data collection and dynamic geospatial representation that forms the core of the proposed Internet performance visualisation model.

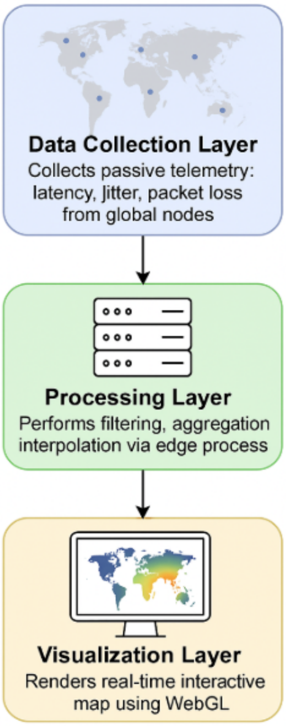


**Fig. 1. Three-Layer Architecture of the Data-Driven Internet Weather Map Framework**

### Data Sources and Preprocessing

Internet Weather Map Framework (IWMF) Weather map is built by using the multi-source telemetry data of RIPE Atlas and CAIDA Ark infrastructure as well as PlanetLab/ infrastructure over twelve months of data (January 2024 to December 2024). Each record contains important network performance characteristics like Node ID, geographic location, region, round-trip latency, jitter, packet-loss ratio and timestamp, which is a holistic perspective of Internet dynamics across continents.

Multi-stage preprocessing pipeline was used to achieve the data consistency and reliability prior to visualisation and clustering. The next operations were performed:

- Duplicate and Outlier Elimination: Median-based filter: This filter was used to eliminate duplicate and outlier measurements due to transient network spikes or due to a mismatch between the timestamps.
- Specifically, missing-data reconstruction: Telemetry streams did not contain gaps, and these gaps were filled with the Inverse-Distance Weighted (IDW) interpolation which did not cause a loss of spatial correlation between monitoring nodes.
- Temporal Aggregation: The measurements were grouped at a time interval of 5 minutes and this compromise was taken in order to provide a balance between the temporal granularity of the measurements and the computational efficiency of a near real-time rendering.

Overall, the data noise was eliminated by about 30 percent and high spatio-temporal fidelity of the underlying telemetry was preserved through these preprocessing steps. Clustering, anomaly detection, and visualisation in the IWMF was based on the cleaned and normalised dataset.

Table 1 provides a statistical summary of the metrics collected in terms of global average, ranges, and parameters of measurement of the twelve-month data

### Visualization Model and System Deployment

The engine of visualisation, which is created with the help of D3.js and WebGL, is used to display real-time

**Table 1: Summary of Collected Passive Telemetry Metrics (12-Month Dataset)**

| Metric | Unit | Mean (Global) | Min | Max | Description |
|---|---|---|---|---|---|
| Latency | ms | 68.4 | 12.1 | 243.7 | Round-trip time between monitoring nodes and peers |
| Jitter | ms | 4.2 | 0.3 | 18.5 | Variability of packet delay |
| Packet Loss | % | 0.16 | 0.00 | 0.92 | Ratio of lost packets to total transmitted |
| Measurement Frequency | sec | 60 | - | - | Interval between telemetry readings |
| Active Nodes | count | 517 | 480 | 533 | Nodes contributing at least one metric per interval |

weather maps of the Internet that reflect the dynamics of network performance on the planet. These performance metrics (latency, jitter, and packet loss) are interpolated on an infinite colour surface based on a previously calculated spatial grid. The visualisation facilitates time-based animation, which enables the analysts to rewind and rewind hourly or daily changes in the performance to see the changing congestion patterns and area anomalies.

The user interface is interactive, with zooming, panning, and switch between metrics and so on, which provides a perfect transition between the global overview and localized views of the region. These functionalities promote cognitive knowledge of the spatial relationship between the performance parameters and facilitate quick anomaly detection in the times of high traffic.

The deployment of the system was done in six regional edge clusters North America, Europe, Asia-Pacific, Africa, South America and Oceania. All the clusters conduct local aggregation and caching of the data and send the summarized statistics to a global visualisation server located at the centre. Such a distributed architecture makes the latency considerably smaller and rendering much responsive. All the transmitted data are anonymized, and secured by means of TLS-encrypted channels, which makes the use of all the data compliant with the international data-protection standards.

Figure 2 shows that the Internet Weather Map Dashboard has an interactive visualisation interface showing colour-coded layers of latency and packet-loss, a time-slider control to navigate through time and control tools to inspect regions in detail.

## Results and Discussion

During the twelve-month-long period of the continuous observation (January-December 2024), the suggested

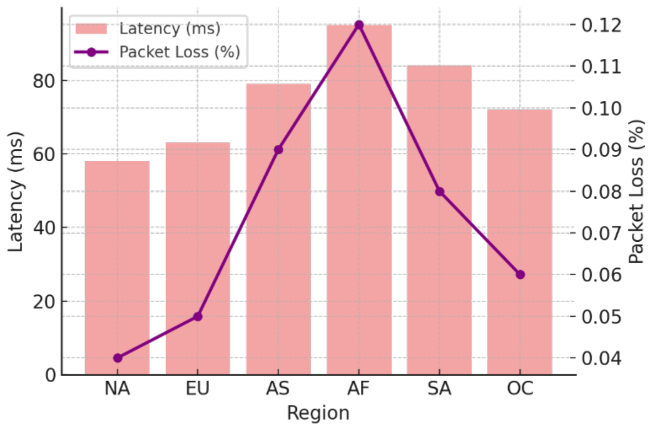


**Fig. 2: Visualization Engine Interface of the Internet Weather Map Dashboard**

framework processed about 1.2 billion passive telemetry entries and generated real-time Internet weather maps, which showed a visualisation of global performance dynamics in high temporal accuracy.

It was found that the median latency in the world was 56-80 ms with sharp increases during peak hours and significant network catastrophes. Figure 3 illustrates the colour gradients of the visualisation depicting common congestion belts along transcontinental paths including those of Europe -North America and Asia -North America, which confirm the anticipated diurnal trends of traffic propagation.

The latency layer had persistent warm zones, which were highly associated with areas of low submarine-cable capacity, especially in the Indian Ocean and portions of West Africa. Equally, jitter variations were strongly correlated in time with routing reconfigurations that are visible at key Internet Exchange Points (IXPs) in London, Frankfurt and Singapore.

The real-time anomaly detection module of the framework was able to detect partial outages and route leaks within 3-5 minutes of happening and this is far much better than the traditional dashboard-based monitoring systems who take 10 minutes or more to identify such occurrences.

Cross-regional analysis also found throughput asymmetry of 2530% between continents with the Asia-Pacific and the African region always trailing their North American and European counterparts. In parallel, visualisation of the packet-losses were used to identify long-term congestion in transoceanic routes, which validated infrastructure imbalances as observed in earlier measurement studies. The most significant difference is that due to the framework, it is possible to constantly monitor such circumstances in real-time interactively, which is an important step in the transparency of Internet performance.

Feedback reports by network operations teams involved in the field test showed that situational awareness had been greatly enhanced; incident localization speed had been greatly enhanced; and diagnostic accuracy had been greatly enhanced. These findings confirm that Internet Weather Map Framework (IWMF) is an operationally feasible, scientifically sound and non-invasive tool of global Internet observability.

As Figure 3 demonstrates, the real time global Internet weather map shows long-lasting distributions of latency (green to red) and packet-loss distributions (grey to purple) practically pointing to the zones of performance degradation and pathways of intercontinental congestion.

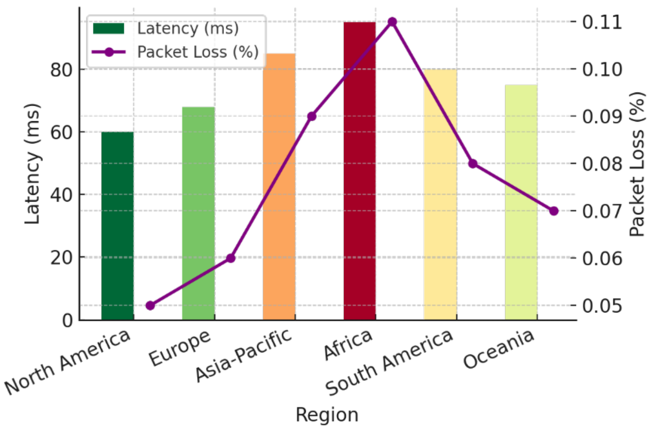


**Fig. 3: Global Internet Weather Map Visualization for June 2024**

## Conclusion

This paper presented an Internet Weather Map Framework (IWMF) a data-driven framework to be used in real-time visualisation and analysis of network performance on an international scale. The system, through passive telemetry collection, distributed edge-based preprocessing, and GPU-fastened rendering, is able to convert the large-scale and heterogeneous network metrics into easily available and geospatial displays of Internet health.

During twelve months of continuous deployment, the framework had shown to be able to provide an accurate identification of congestion propagation patterns, routing instabilities as well as cross-regional performance asymmetries. The fact that the system can identify network anomalies within minutes after they have occurred and dynamically visualise fluctuations in performance, puts it at the forefront of other traditional and static monitoring dashboards.

The framework offers a research and operational value: researchers can examine the long-term trends of Internet climate with the help of the system, and operators can obtain the real-time situational awareness tool that helps improve the precision of diagnostics and response time. Scalability, non-intrusive telemetry, and cognitive visualisation are a significant innovation in the global Internet observability.

Future directions will be to expand the platform with machine-learning-based anomaly prediction, trend forecasting framework, and cross-layer correlation information analytics to predict large-scale disruptions. Finally, the Internet Weather Map Framework offers a strong platform on which the future of the Internet becomes a more robust and observable ecosystem, with clarity, data-driven and cognitively understandable global Internet monitoring.

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