Quality of Experience: Insights into the State of Internet Connectivity

In-depth Research Covering Services from Leading Internet Service Providers

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NetForecast®

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1 Executive Summary

This report provides an in-depth evaluation of Internet Service Providers (ISPs) across the United States and Western Europe, drawing on data from Cloudflare's Aggregated Internet Measurement (AIM) project. By focusing on critical user experience metrics such as download/upload speeds, latency, jitter, and packet loss, we've identified significant disparities in ISP performance. The term '***latency***' throughout this report specifically refers to ***'loaded latency'***. This focus allows us to closely represent the internet performance users experience under typical usage conditions, rather than the basic 'unloaded latency' which might not fully capture the impact of network congestion. Our findings offer valuable insights for both ISPs and users.

1.1 Key Insights from the United States

- *Performance Highlights*: Comcast and Verizon stand out for their superior speeds and lower latency. These ISPs demonstrate tightly clustered latency distributions, with median download latencies of 33 ms and 24 ms, respectively.
- *Latency Variability*: AT&T and T-Mobile exhibit higher standard deviations in latency (66 ms and 54 ms, respectively), indicating potential fluctuations in user experience. T-Mobile users experienced the highest median latency of 86.7 ms, closely followed by Verizon Wireless at 81 ms.
- *Statistical Analysis*: An ANOVA test confirms significant differences in download latency among ISPs, evidenced by a high F-statistic (4437.03) and a P-value of 0.0.
- *City-Specific Performance*: Washington presents challenging network conditions, with AT&T's median download latency peaking at 249 ms. Conversely, San Francisco and Dallas showcase uniformly strong ISP performances, suggesting superior infrastructure or less congestion.
- *Starlink's Performance*: Tukey's HSD test shows Starlink significantly outperforms fixed wireless ISPs like T-Mobile and Verizon Wireless, highlighting LEO technology's promise for better connectivity in underserved regions.
- *Latency Trend*: Time series analysis of latency data reveals a steady improvement in service quality, evidenced by a consistent trend of decreasing median latency figures across the major ISPs. This trend highlights ongoing network optimizations contributing to enhanced user experience.

1.2 Insights from Western Europe

- *Germany:* ISPs generally offer comparable service levels, with minor differences suggesting a uniform network landscape.
- *United Kingdom:* The broadband scene is varied, with British Telecom exhibiting the highest latencies among a competitive field that includes Opal Telecom, Sky, Virgin, and Vodafone.
- *France:* A balanced competition is observed between Bouyg Telecom and SFR, with Proxad leading in efficiency and Orange providing intermediate performance.
- *Spain:* The ISP landscape shows varied performance, with Orange offering the best performance, Telefonica facing higher latency challenges, and Vodafone and Xtra Telecom delivering comparable performance.
- *Italy:* The performance landscape is stratified, with Tim's latency significantly higher than its peers, contrasting with the closely matched performances of Fastweb, TelItalia, Vodafone, and Windtre.

2 Introduction: Enhancing Digital Connectivity Through ISP Performance Analysis

In today's interconnected world, the efficacy of ISPs is pivotal, not just for seamless online browsing but as a cornerstone of modern living and global commerce. This analysis embarks on a comprehensive evaluation of ISPs within the United States and selected European nations, scrutinizing critical performance metrics—download and upload speeds, latency, jitter, and packet loss—that dictate the quality of digital experience. These factors are instrumental in the smooth operation of video streaming, online gaming, cloud services, telehealth, and remote work, thereby influencing daily activities and business operations.

Leveraging data from Cloudflare's Aggregated Internet Measurement (AIM), this study not only assesses the current landscape of ISP performance, drawing comparisons between conventional terrestrial networks and the burgeoning technologies of 5G and satellite internet, but also sheds light on disparities in service quality. Through this analysis, we endeavour to inform ISPs on areas ripe for enhancement, while equipping consumers with the knowledge to make informed decisions in selecting their internet service provider, ultimately fostering a digital environment that supports and enhances user needs and expectations.

2.1 Evaluating AIM Methodology

The AIM methodology is instrumental in assessing ISP performance, offering insights grounded in real-world internet usage. By harnessing user-initiated tests, AIM captures essential performance metrics—latency, jitter, download/upload speeds, and packet loss—providing a nuanced view of ISP capabilities beyond simple bandwidth measurements. Its value lies in reflecting everyday user experiences, making it particularly relevant for evaluating the stability required for applications like video conferencing and online gaming.

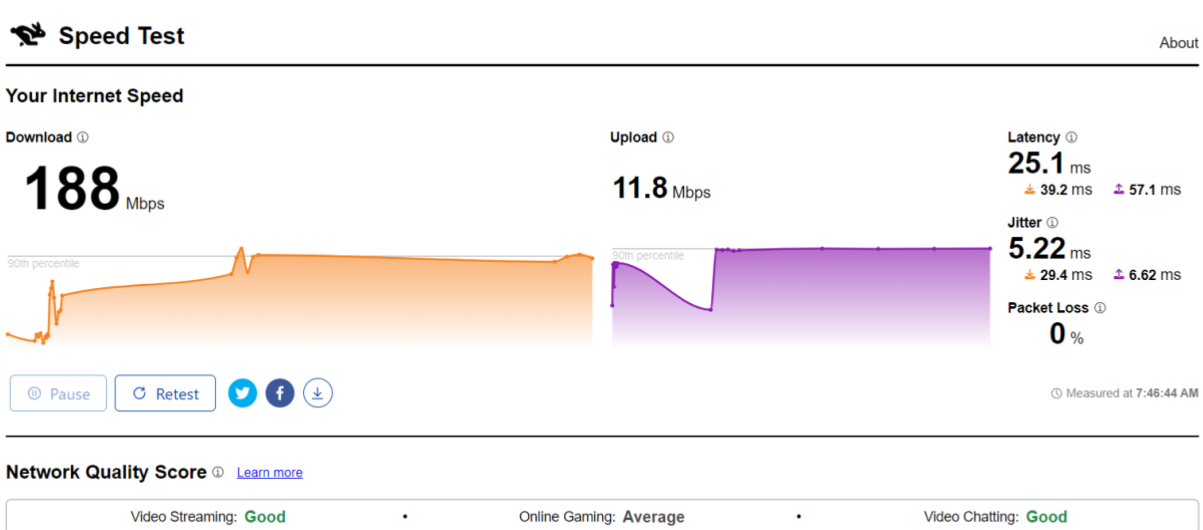


Image 1 – Speed Test Result from Cloudflare

AIM's strength resides in its comprehensive capture of **diverse performance indicators** and its reflection of real-world usage scenarios. The methodology's reliance on open-source code enhances its transparency, fostering trust in its findings. In addition, it benefits from Cloudflare's robust infrastructure and significant global presence. While Cloudflare's network has a capacity of over 248 terabits per second and spans more than 310 cities in 120 countries, the speed test uses the Cloudflare anycast network to test network performance. By leveraging the anycast network, the closest data center is found by network routing. This extensive network facilitates AIM's goal of capturing a wide array of performance data, benefiting from Cloudflare's reach to gauge internet performance across a vast portion of the global internet-connected population.

Granularity and Dynamic Analysis

AIM's detailed geographical and temporal data enable a dynamic analysis of ISP performance, offering the ability to monitor trends and identify improvements over time and across different regions. This level of detail provides stakeholders with the tools to make informed decisions and track ISP progress.

Addressing Limitations

Despite its robustness, AIM is not without limitations. The methodology's dependency on voluntary participation may skew data towards specific user demographics or geographic areas. External factors, such as Wi-Fi interference, also pose challenges to test accuracy. Recognizing and addressing these limitations is vital for ensuring the reliability of AIM data and the conclusions drawn from it.

2.2 Deciphering Data with Violin Charts

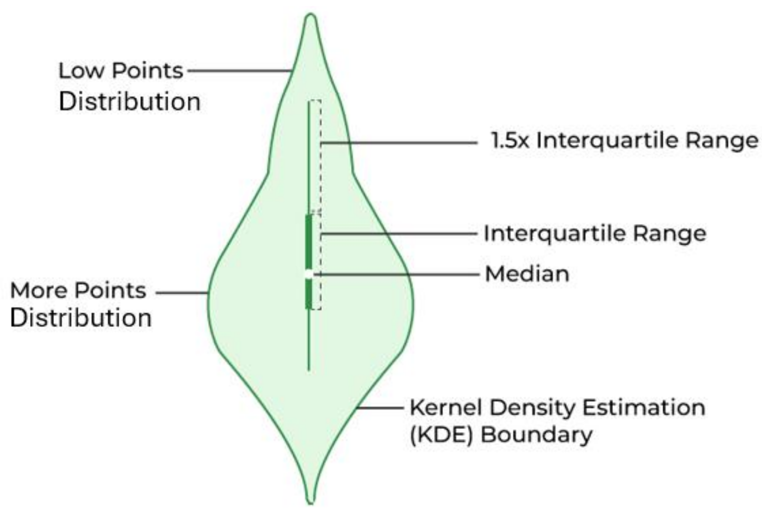


Figure 1: Data Distribution Visualization with a Violin Plot
Image credit – Geeksforgeeks.org

Throughout this report, we extensively use violin charts to visually represent data distributions. Violin charts combine features of box plots and density plots to offer a comprehensive view of data distribution. At their core, these charts depict the probability density of the data at different values, smoothed out and mirrored along a central axis, resembling a violin. The 'box' inside the violin shows the interquartile range (IQR), with a white dot representing the median. The thickness of the violin at various levels indicates the frequency of data points, providing insight into peaks and tails of the distribution.

3 Data Integrity: Methodology Overview

Our methodology harnessed the power of data pre-processing to ensure the accuracy and relevance of our ISP performance analysis. We utilized the rich dataset from Cloudflare's Measurement Lab (M-Lab) project, which includes complex data structures across multiple packet sizes for each test, reflecting diverse internet usage scenarios. Detailed descriptions of our data extraction and pre-processing methods are available in the Appendix, emphasizing our commitment to accuracy and thorough analysis.

We concentrated on a selection of **15 major U.S. cities** and identified eight key ISPs through their Autonomous System Numbers (ASNs). This approach allowed us to dissect essential performance metrics, including download/upload speeds, latency, jitter, and packet loss, providing a well-rounded view of ISP service quality.

In an effort to streamline our analysis, ASN codes were translated to recognizable ISP names, enhancing the interpretability of our findings. Our statistical toolkit included calculating fundamental statistics—mean, median, minimum, maximum, and standard deviation for latency and jitter, as well as feature engineering techniques to delve into average bandwidth and performance scores for gaming, VoIP, and streaming applications.

3.1 Outlier Treatment

Initially, our outlier detection employed a z-score threshold of three standard deviations to identify and remove extreme values. However, upon closer examination and visual analysis, we observed that the data distribution was not normal but lognormal, prompting a need for a more robust approach. We transitioned to a method based on realistic latency boundaries, where outliers are defined as data points outside the median latency range of 8 ms to 400 ms. This range was determined through extensive domain knowledge, recognizing that values beyond this range likely represent atypical network conditions or outages rather than regular user experiences.

This meticulous filtering process resulted in a robust dataset of 104,000 records from an initial pool of approximately 110,000, ensuring our subsequent analyses reflect true user conditions. We applied the same criteria to our time series analysis, covering data from January 2023 through March 2024 with a total dataset of 226,700 records. These preparatory steps laid a solid foundation for a detailed comparative analysis of ISP performance across the selected regions, setting the stage for insights into the current state of digital connectivity.

Note

In our analysis, AT&T is represented under ASN 7018. Unlike ASNs for other providers, which distinctly categorize services as either wired or wireless, the classification for AT&T's services is not explicitly defined. This leads to a potential blend of both wired and wireless service data in our analysis. Given AT&T's broad geographic presence across all analyzed cities, and a latency profile that aligns closely with wired ISPs yet exhibits variability akin to wireless networks, we treat this data cautiously. We acknowledge the possibility of mixed types of service contributing to our findings. This ambiguity should be considered when interpreting performance metrics associated with AT&T.

4 Analyzing Performance of the United States' Top ISPs

Our comprehensive analysis of ISP performance metrics reveals critical insights into latency, jitter, bandwidth, and packet loss across different ISPs and regions.

4.1 Download Latency: Comparative Analysis

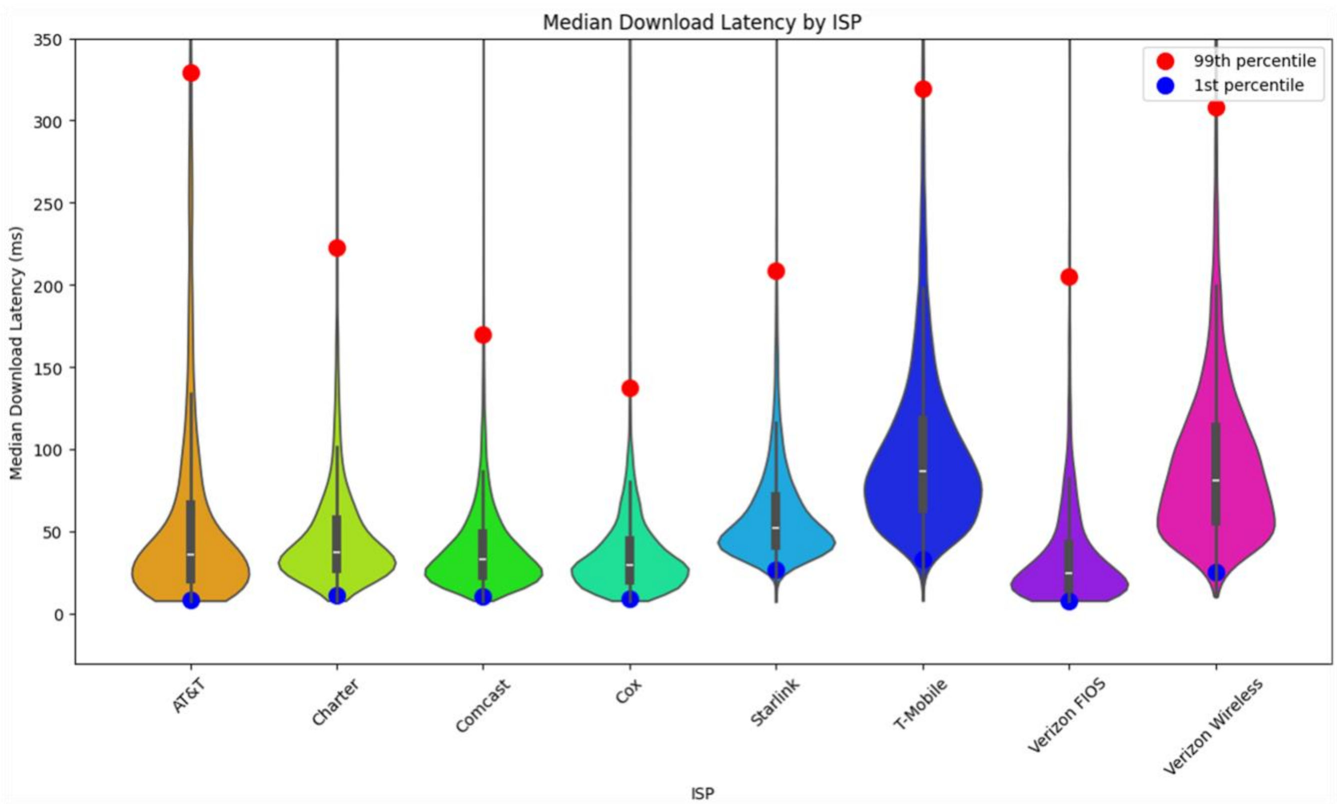


Figure 2: Download Latency for Leading ISPs

The analysis presents a comparative overview of median download latency across various ISPs, highlighting disparities in network performance efficiency. Verizon FIOS and Comcast lead with tightly clustered latency distributions, with median latencies of 24.85 ms and 33 ms respectively. Notably, Cox achieves a competitive 29.8 ms median latency in Phoenix, suggesting high performance there. These figures signify superior network efficiency and are supported by low standard deviations, emphasizing consistent performance.

Conversely, T-Mobile shows the highest median latency at 86.7 ms, which coupled with a significant standard deviation of 54.37 ms, indicates potential performance bottlenecks for latency-sensitive applications. This is further compounded by a high 75th percentile latency of 118 ms, suggesting that a considerable portion of T-Mobile's network traffic experiences delays.

Table 1 - Key Statistics for Latency

Median Download Latency (Ms) Metrics						
ISP	Mean	Median	Standard Deviation	25th Percentile	75th Percentile	IQR
AT&T	59.5	36	66.2	21	66.3	45.3
Charter	49.2	37.7	38.6	27.7	57.3	29.6
Comcast	41.3	33	31.7	23	48.6	25.6
Cox	36.9	29.8	27.8	20.5	44.5	24
Starlink	62.4	52	35.1	41.5	71.6	30.1
T-Mobile	100	86.7	54.4	64.5	118	53.5
Verizon FIOS	36	24.9	36.2	15.3	42.2	26.9
Verizon Wireless	92.9	81	53.2	56.1	113.5	57.4

The data highlights that Verizon FIOS, Comcast, and Cox excel in the lower quartile, with at least 25% of latency measurements below 15.3 ms, 23 ms, and 20.5 ms, respectively. These figures indicate efficient and reliable network performance. In contrast, higher quartile latencies for T-Mobile and Verizon Wireless suggest significant delays, as their 75th percentile latencies reach 118 ms and 113.5 ms respectively. Starlink delivers competitive median latency at 52 ms and remains a strong connectivity option in remote areas, evidenced by its 75th percentile latency at 71.55 ms.

When analyzing latency variability among ISPs, Comcast, Charter, and Cox demonstrate notable stability, with their standard deviations closely aligned with their means, indicating consistent network performance. Conversely, Verizon shows more significant variability, with its standard deviation of 36.15 ms exceeding the mean latency by approximately 1.4 times, suggesting a less consistent user experience. Additionally, AT&T and T-Mobile display even higher standard deviations, highlighting potential fluctuations in latency levels and emphasizing the superior network stability and reliability of wired ISPs. Overall, the findings underscore the diverse latency landscape across providers, with implications for users of latency-dependent applications.

4.2 Latency Across the Urban Landscape: Insights by City and ISP

Our analysis of the median download latency reveals a nuanced tapestry of ISP performance across 15 major American cities. A standout observation is performance consistency among wired ISPs, with Comcast demonstrating exceptional stability across multiple cities—maintaining a median latency as low as 27 ms in Dallas to 41 ms in Washington DC. Verizon FIOS showcased commendable consistency with median latencies confined to a narrow band of 23-30 ms across its service regions. Cox and Charter similarly demonstrated reliability with median latencies recorded at 30 ms in Phoenix and 38 ms in Los Angeles, respectively. This suggests a robust infrastructure capable of delivering consistent service despite the diverse demands of urban settings.

Starlink's satellite technology delivers commendable median latencies ranging from 49 ms in Los Angeles to a modest 56 ms in Seattle, reinforcing its viability in urban areas. In contrast, the higher median latencies of T-Mobile and Verizon Wireless, peaking in Denver at 114 ms and 100 ms respectively, reflect the inherent challenges of wireless connectivity in dense urban environments.

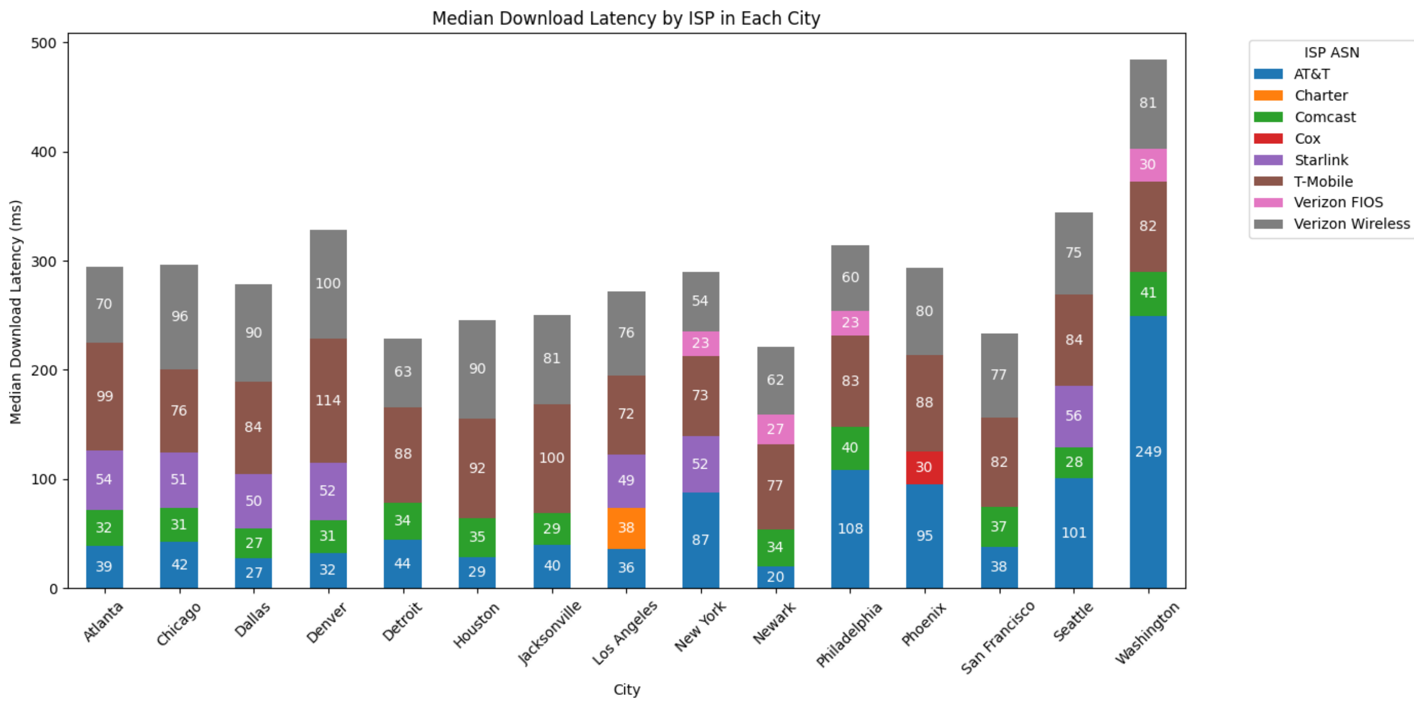


Figure 3: City-Specific Latency Comparison

Notably, AT&T presents a mixed picture, with median latencies as low as 29 ms in Houston (comparable to wired ISPs), and surging to 249 ms in Washington DC—hinting at potential regional discrepancies in service provisioning. The substantial standard deviations for AT&T, notably 95.7 ms in Washington, suggest a broader range of user experiences, potentially due to the blend of its wired and wireless services within the same ASN.

4.3 Comcast: City-Specific Performance Comparison

Comcast stands out as a national leader, present in 12 of the 15 major cities surveyed. This highlights the need for a closer look at Comcast's performance across these cities.

The analysis of Comcast's network performance exhibits consistent efficiency across different urban landscapes with a few exceptions. The standard deviation points to **Jacksonville** as experiencing the most pronounced fluctuations in user experience with a value of 36 ms, hinting at the potential for varied network speeds. In stark contrast, **Detroit's** standard deviation of **19.65** ms portrays a more uniform and reliable service.

A closer look at the quartile distributions shows that **Atlanta** boasts commendable network responsiveness with a 25th percentile latency at 25 ms, suggesting that a significant number of users enjoy faster connectivity. Meanwhile, the 75th percentile latency in **Washington** reaches up to 62 ms, indicating that a noticeable population may encounter moderately higher latency levels.

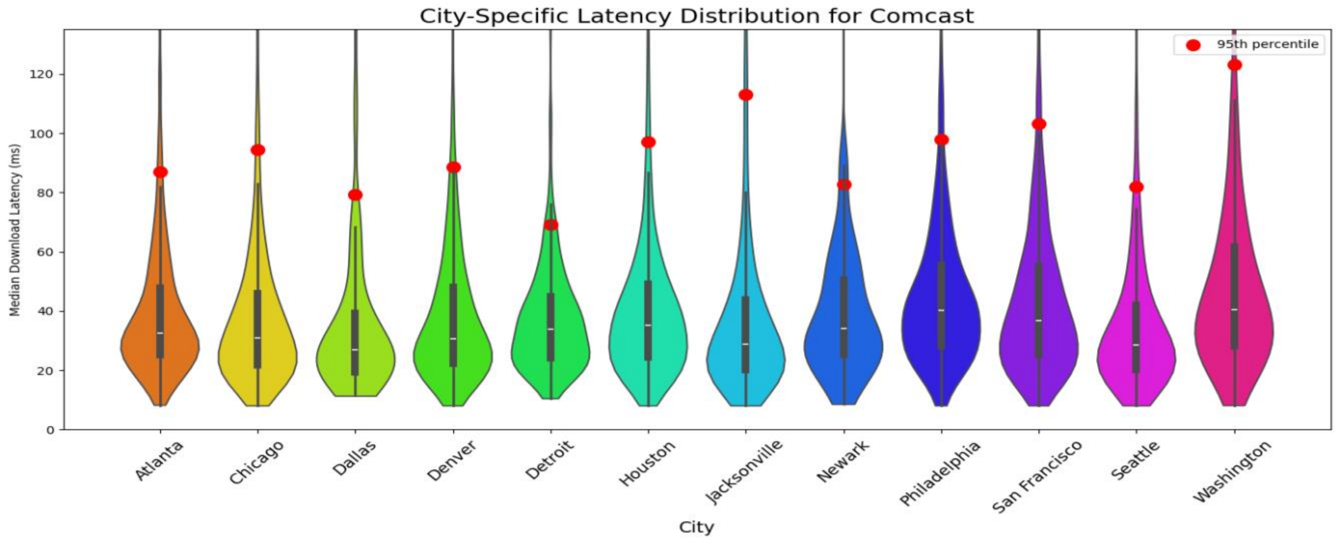


Figure 4: Variability in Comcast's Network Performance

4.4 Jitter, Bandwidth and Loss Ratio

The jitter analysis across various ISPs highlights notable differences in network stability and response time variability, offering insights into each provider's service consistency. AT&T and Charter exhibit significant variability in network performance, with AT&T showing a median jitter of 23.41 ms and a high standard deviation of 73.34 ms, and Charter close behind with a median of 21.19 ms and a standard deviation of 76.26 ms. Both ISPs have a wide spread between the 25th and 75th percentiles, indicating inconsistent network conditions.

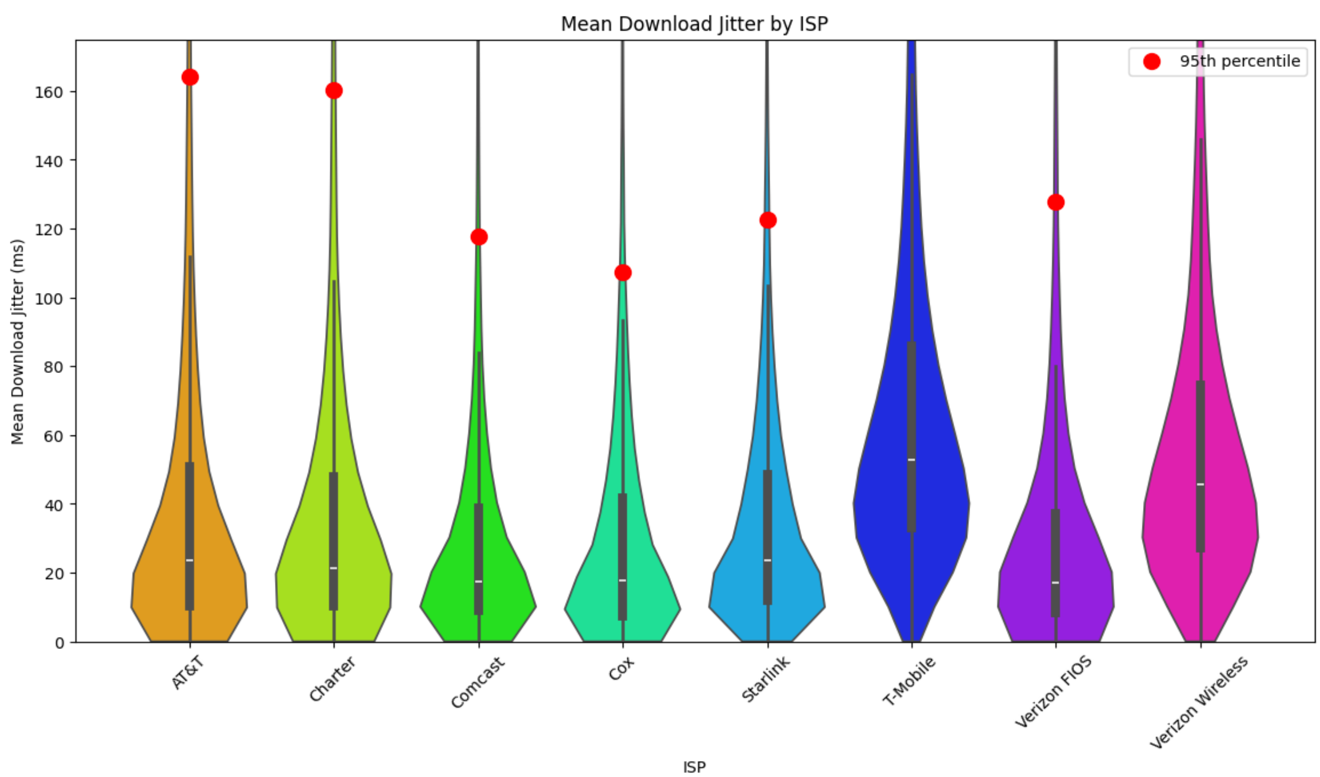


Figure 5: Variance in Network Stability

Comcast and Cox show more stable jitter metrics, with lower medians of 17.50 ms and 17.83 ms, respectively, and narrower interquartile ranges that suggest less variability. Despite being satellite-based, Starlink's median jitter is similar to that of Comcast and Cox but with higher variability—likely influenced by the inherent challenges of satellite connections.

T-Mobile stands out with the highest median jitter of 52.79 ms, accompanied by the largest standard deviation, pointing to a highly variable network that could adversely affect latency-sensitive applications. Verizon FIOS offers stable jitter with a low median but also experiences occasional spikes that widen its standard deviation. Verizon Wireless shows higher inconsistency with a median jitter of 45.52 ms and substantial variability.

Speed Variations

The analysis of median download speeds across major ISPs highlights a spectrum of performance levels, reflecting their diverse technology and infrastructure. Verizon FIOS stands out with an impressive average of 183 Mbps, peaking at 689 Mbps, which showcases its capability to support high-demand users. Comcast and Cox also offer strong performances with averages around 137 Mbps and peaks above 500 Mbps, indicating effective high-speed delivery.

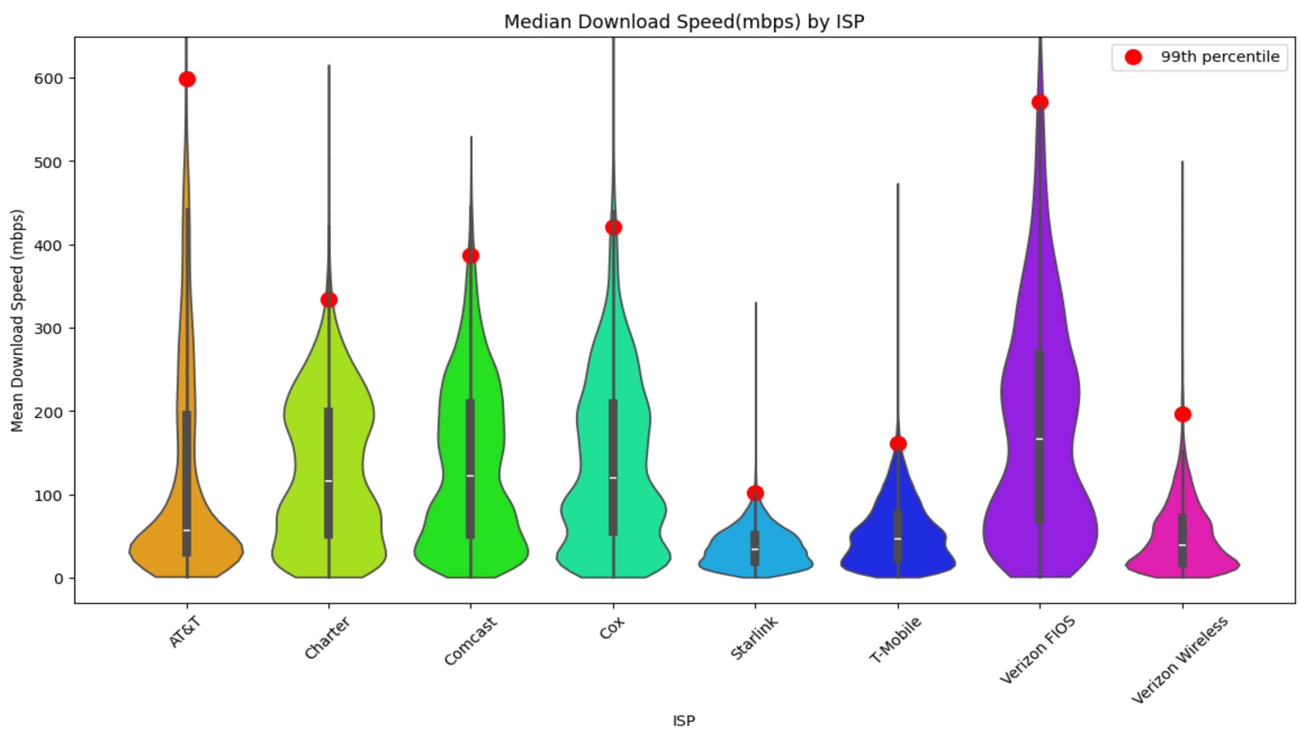


Figure 6: Spectrum of Speed Capabilities Across Providers

Charter and AT&T show commendable performance with averages above 125 Mbps, though their wide range of speeds suggests variability dependent on location or service tier. In contrast, Starlink provides an average of 36.9 Mbps, typical of satellite internet.

Wireless providers T-Mobile and Verizon Wireless exhibit lower averages around 53 Mbps, with their performance reflecting the inherent challenges of wireless technology in matching wired speeds. Notably, the high standard deviations for AT&T (141.7 Mbps) and Verizon FIOS (136.0 Mbps) highlight the diversity in user experiences, influenced by varying subscription plans and hardware capabilities.

Packet Loss Analysis

Minimal packet loss was noted for most ISPs, indicating good network quality overall. Starlink encountered slightly higher packet loss, suggesting areas for future technological advancements.

4.5 Statistical Validation: ANOVA (Analysis of Variance) and Tukey's HSD Tests

Using ANOVA and Tukey's Honest Significant Difference (HSD) tests, we confirmed significant performance differences among ISPs, underscored by a robust F-statistic of 4437.03 and a p-value of 0.0. These tests are crucial for discerning variations in ISP performance, providing detailed insights into network quality and reliability across the national landscape.

AT&T typically exhibits higher latency relative to Cox, Comcast, Charter, and Verizon FIOS, with disparities ranging from approximately 18 ms with Comcast to about 23 ms with Verizon FIOS. These ISPs are benchmarks for lower latency, suggesting better network responses. Conversely, AT&T's latencies align more closely with Starlink, which, despite being a satellite provider, delivers competitive latencies akin to traditional broadband services. Starlink in particular, showcases its capability by delivering lower latency compared to traditional wireless ISPs, demonstrating that low Earth orbit (LEO) technology **can rival or even surpass** other technologies in specific scenarios.

Comparisons between wireless ISPs like T-Mobile and Verizon Wireless with wired services reveal significantly higher latencies for the former. For example, T-Mobile's latency exceeds that of Cox and Comcast by over 60 ms and 58 ms respectively, highlighting the performance gap between wireless and wired internet services. (Ref: Table 2 in the Appendix)

4.6 Strategic Insights for Consumers

Cloudflare assesses ISP performance for streaming, gaming, and VoIP by calculating scores based on key metrics: throughput, unloaded and loaded latency, jitter, and packet loss. The resulting scores reflect the internet connection's suitability for each scenario, offering a benchmark for comparing ISPs.

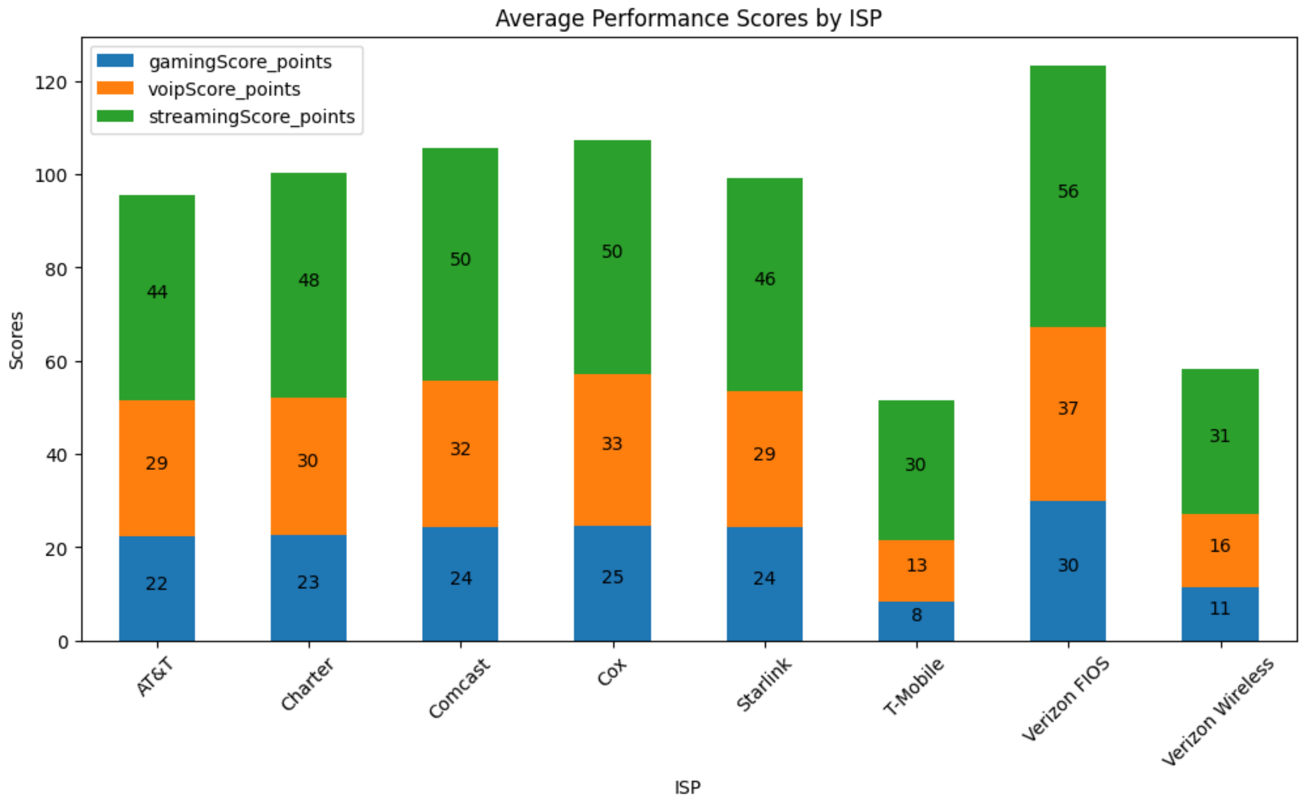


Figure 7: ISP Performance in Gaming, VoIP, and Streaming

Cloudflare's data reveals distinct performance tiers among ISPs in gaming, VoIP, and streaming services, highlighting variations in customer experience. Verizon FIOS leads in all categories, indicating superior service quality with scores higher than other providers, especially in gaming where it scores an impressive 30. Comcast and Cox also perform well across all metrics, suggesting robust and reliable service offerings. In contrast, T-Mobile and Verizon Wireless show considerably lower scores in all categories, particularly in gaming and VoIP, which could impact user satisfaction for latency-sensitive applications. Starlink shows competitive scores in gaming and streaming, closely aligning with some of the traditional broadband services, but its VoIP performance, while better than wireless ISPs, slightly trails behind the leading wired providers. For consumers, this analysis provides a basis to evaluate ISPs against specific use cases, such as high-speed data, low-latency gaming, or reliable rural connectivity.

5 Comparative Analysis of European ISP Performance

5.1 Germany

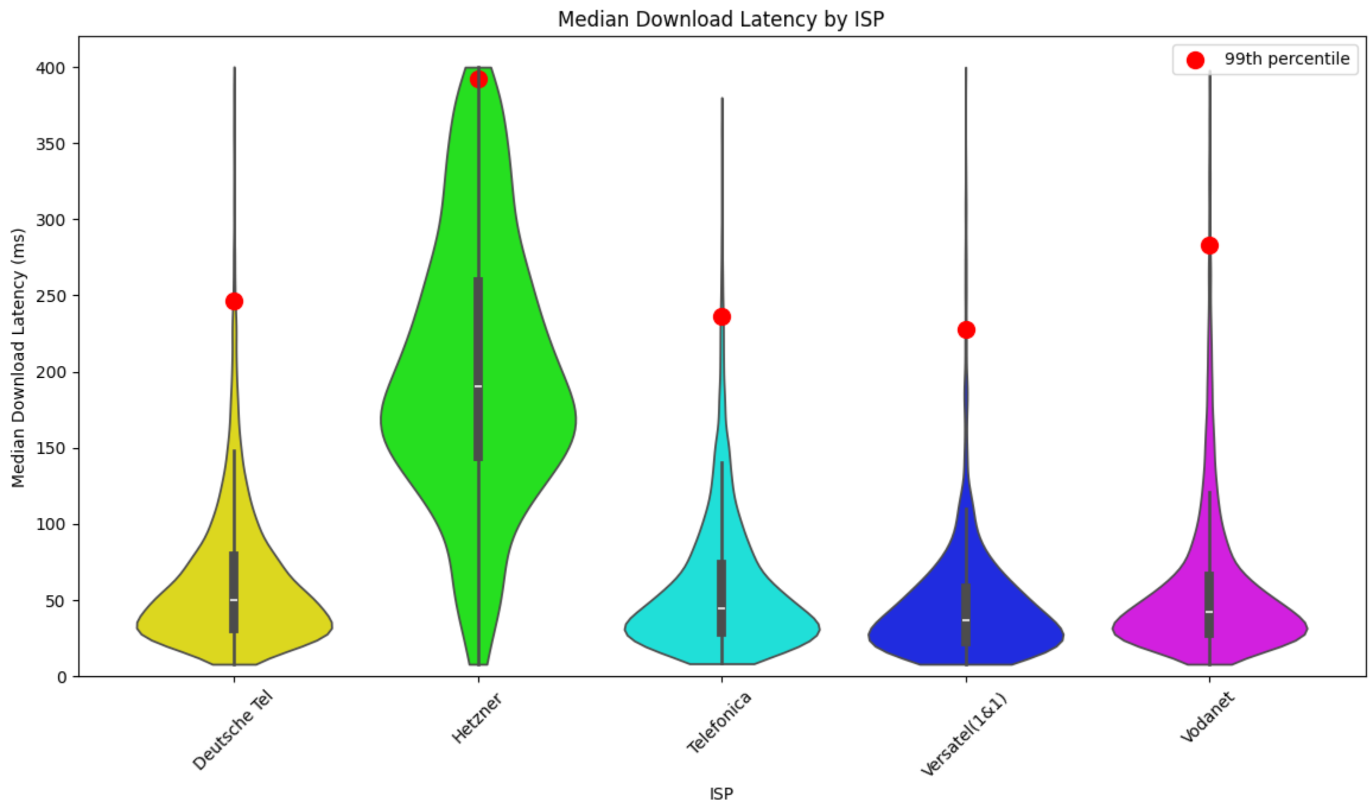


Figure 8: Comparative Latency Distribution by ISP in Germany

The chart for download latency among Germany's leading ISPs reveals significant variability and performance differences. Hetzner stands out with a notably high median latency of 190 ms, considerably higher than its peers, reflecting its unique position with potentially larger variations in network performance, as indicated by its high standard deviation (87 ms) and wide interquartile range (IQR) stretching from 144 ms to 258 ms. In contrast, Deutsche Telekom and Telefonica show similar median latencies around 75 ms, with Deutsche Telekom displaying a slightly wider IQR (48 ms) compared to Telefonica (44 ms), suggesting a broader distribution of latency values among its users. Versatel (1&1) presents the lowest median latency at 37 ms, paired with a relatively compact IQR (35 ms), indicating more consistent and potentially efficient network performance. Vodanet, despite a median latency (42 ms) comparable to Deutsche Telekom and Telefonica, exhibits higher standard deviation (51 ms).

Statistical Validation

The ANOVA results, with an F-Statistic of 1854 and a highly significant P-Value close to zero, indicate substantial differences in mean download latencies among Germany's ISPs. Tukey's HSD test further delineates these disparities: comparisons between Deutsche Telekom and both Telefonica and Versatel (1&1) showed significant difference, suggesting nuanced performance variation. Notably, Hetzner's latency is markedly higher than all other groups. Comparing Telefonica and Vodanet reveals a minor but non-significant difference with a p-value of 0.99, hinting at similar performance. These findings highlight the distinct network efficiency and performance challenges faced by Hetzner, while also illustrating a generally comparable service level among the other ISPs, with specific exceptions denoting minor performance disparities.

5.2 United Kingdom

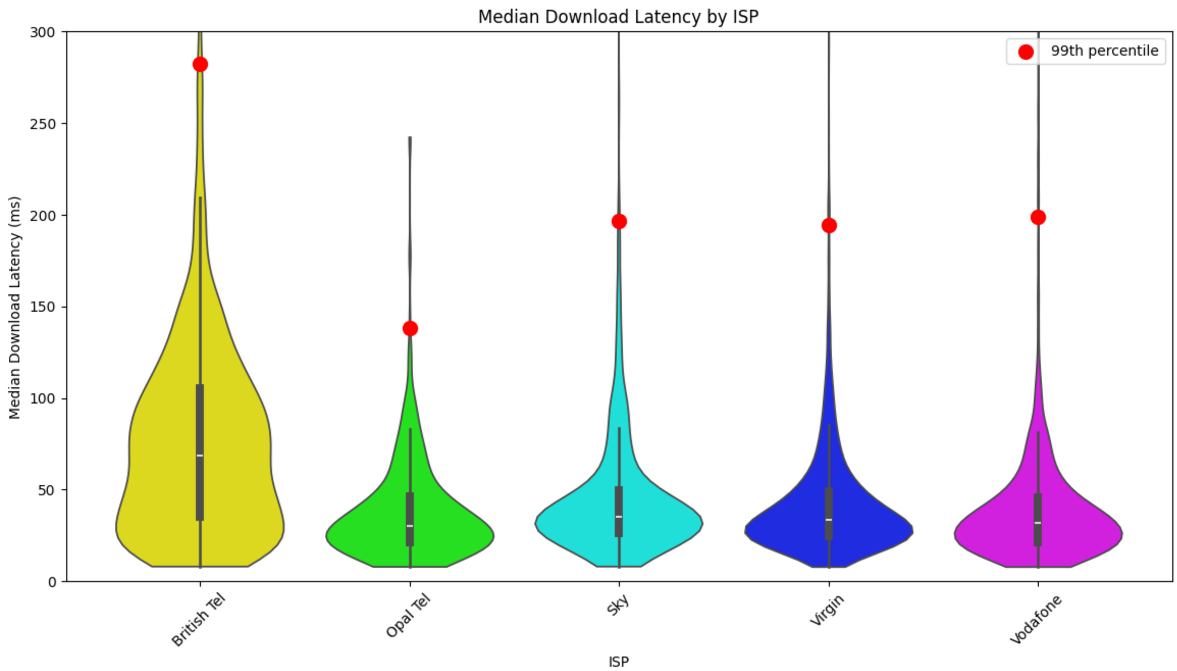


Figure 9: Comparative Latency Distribution by ISP in UK

The chart for download latency across the UK's leading ISPs reveal varied network performances, with British Telecom showing the highest median latency at 68 ms, reflecting its broader range of network response times. Opal Telecom presents the lowest median latency at 30 ms, indicating more efficient service, supported by a relatively lower standard deviation (28.51 ms) that suggests consistent network quality. Sky and Virgin occupy the middle ground with median latencies around 35 ms, but Virgin demonstrates a slightly higher range in latencies, as evidenced by its 75th percentile. Vodafone, with a median of 31.55 ms, closely follows Opal Tel in efficiency but exhibits a wider range of latency experiences, as shown by its higher standard deviation (31.75 ms). The interquartile range (IQR) across ISPs highlights the variability in service consistency, with British Telecom showing a particularly wide IQR, suggesting a more varied user experience.

Statistical Validation

The ANOVA analysis, revealing an F-Statistic of 302 and a P-Value significantly below the threshold (5.08e-74), indicates substantial differences in download latency among UK ISPs. Tukey's HSD test highlights British Telecom's latency as notably higher compared to Opal Tel, Sky, Virgin, and Vodafone, with mean differences ranging from -31 ms (Sky) to -39 ms (Opal Tel), all statistically significant. Interesting contrasts emerge between Opal Tel and the other ISPs, with significantly lower latency compared to Sky (8.4 ms), but not Vodafone and Virgin, suggesting nuanced performance differences. Sky and Virgin show no significant latency disparity, indicating similar service levels, whereas both have significant differences when compared to Vodafone, with Sky and Virgin experiencing reductions of -7.6 ms and -4 ms, respectively. These results underscore the variability in network performance across ISPs, with British Telecom showing the highest latencies and lesser distinctions among Opal Tel, Sky, Virgin, and Vodafone, reflecting a competitive and diverse broadband landscape.

5.3 France

The chart for download latency across France's leading ISPs exhibits considerable diversity in network performance. Proxad stands out with the lowest median latency of 21.45 ms, reflecting its superior network efficiency, and also displays the smallest standard deviation (29.09 ms), indicating consistent service quality. In contrast, Bouyg Tel and SFR show higher median latencies, at 42.3 ms and 39.80 ms respectively, with SFR's latency extending into the higher range, as seen in its 75th percentile (94 ms). This suggests a wider spread of latency experiences among its users. Orange presents a median latency (33 ms) that places it between the highest and lowest performers, with a relatively moderate standard deviation (50 ms), pointing to a balance between efficiency and variability in network performance. The IQRs highlight the variability within each ISP, with Bouyg Tel and SFR showing significant spreads, indicating a broad spectrum of user experiences.

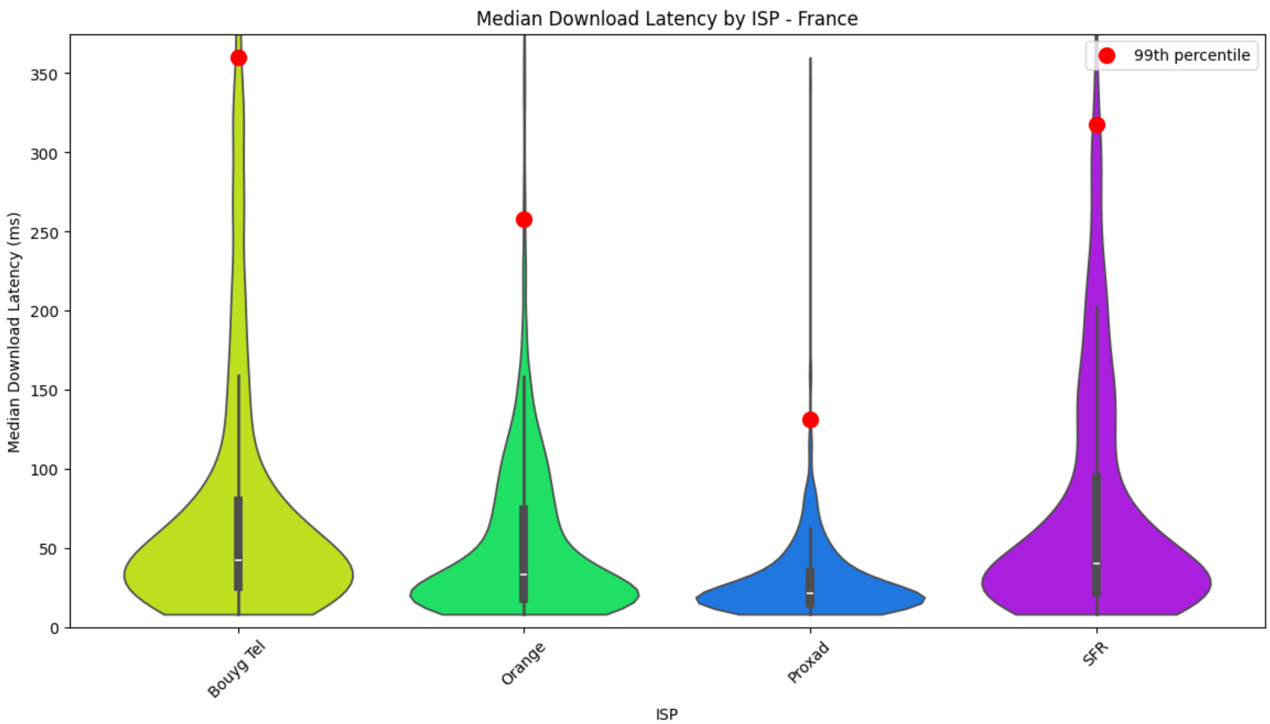


Figure 10: Comparative Latency Distribution by ISP in France

Statistical Validation

The ANOVA results, with an F-Statistic of 90 and a P-Value significantly less than 0.05, indicate strong evidence of differences in download latency among France's ISPs. Tukey's HSD test reveals distinct disparities: Bouyg Tel's latency significantly exceeds that of Orange and Proxad by 24.66 ms and 50 ms, respectively, affirming notable efficiency gaps. However, no significant difference is noted between Bouyg Tel and SFR, suggesting comparable performance levels between these two. Additionally, Orange exhibits higher latency than Proxad by 25.29 ms and is surpassed by SFR by 30 ms, while Proxad's latency is significantly lower than SFR's by 55 ms. These findings underline the varied landscape of ISP latency performance in France, highlighting Proxad's superior efficiency in minimizing latency, contrasted with Bouyg Tel's higher latency figures. The lack of significant difference between Bouyg Tel and SFR indicates a parity in their service levels, setting them apart from the more efficient Proxad and the intermediary performance of Orange.

5.4 Spain

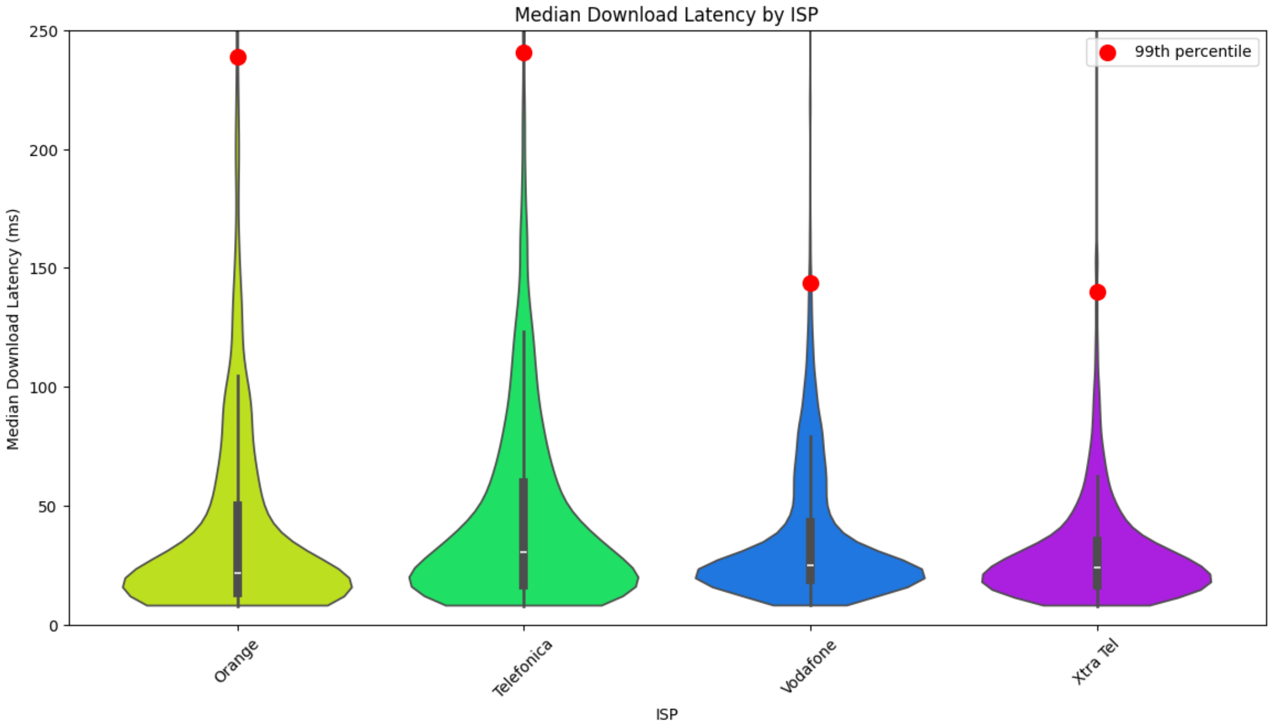


Figure 11: Comparative Latency Distribution by ISP in Spain

In Spain, the leading ISPs exhibit varying levels of download latency performance. Telefonica, with a median latency of 30.60 ms, shows the highest among the ISPs, and its range of latency experiences is broad, as indicated by a standard deviation of 46 ms and an IQR of 37 ms. This suggests a wider spectrum of user experiences within their network. Vodafone and Xtra Tel offer better median latencies at 24.74 ms and 24 ms, respectively, and both demonstrating a tighter spread of latency values with an IQR of 20. Orange, with a median latency of 21.72 ms, not only offers the lowest among the ISPs but also has a higher standard deviation (46 ms) and a relatively high IQR (37 ms), pointing to a significant range of latency experiences for its users.

Statistical Validation

The ANOVA results, with an F-Statistic of 90 and a P-Value significantly less than 0.05, demonstrate clear differences in download latency among Spain's ISPs. Tukey's HSD test identifies significant latency differences between Orange and Telefonica, with Telefonica having an average of 6.23 ms higher latency than Orange, indicating Telefonica's comparatively slower network. Orange also shows a statistically significant, albeit smaller, difference with Xtra Tel, which has a 9.43 ms lower average latency than Orange, suggesting a slight efficiency edge for Xtra Telecom. Very little difference is observed between Orange and Vodafone, and between Vodafone and Xtra Tel, indicating similar performance. Conversely, Telefonica's latency significantly exceeds both Vodafone and Xtra Tel by 9.69 ms and 15.66 ms respectively, reinforcing its position as the ISP with the highest latency among the compared groups. These findings highlight the varied performance landscape among Spain's ISPs, with Orange presenting a balance of efficiency, Telefonica higher on the latency spectrum, and Vodafone and Xtra Tel showing comparable service quality.

5.5 Italy

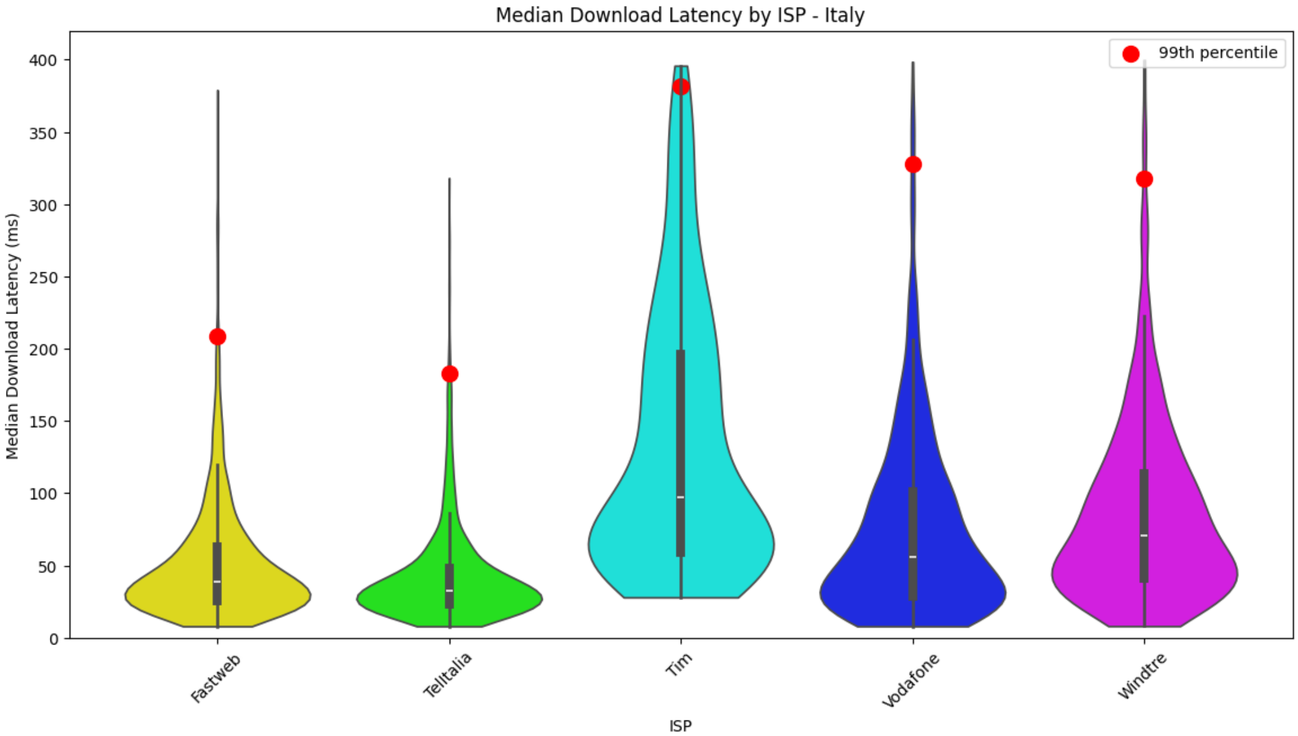


Figure 12: Comparative Latency Distribution by ISP in Italy

The data for download latency among Italy's leading ISPs reveal a diverse performance spectrum. Tim exhibits the highest median latency at 97.25 ms, significantly outpacing its competitors, coupled with the largest standard deviation (135.55 ms) and a wide interquartile range (IQR), indicating substantial variability in its network performance. Fastweb and TelItalia present lower median latencies of 38.60 ms and 32.40 ms, respectively, with Fastweb showing a slightly higher IQR, suggesting a broader spread of latency experiences among its users. Vodafone and Windtre occupy the middle ground, with median latencies of 56.25 ms and 71 ms, respectively, and both demonstrate similar standard deviation of 64 ms, highlighting more pronounced fluctuations in network latency.

Statistical Validation

The ANOVA analysis, indicating a F-Statistic of 236 and a P-Value close to zero, confirms significant differences in download latency among Italy's ISPs. Tukey's HSD test reveals that Tim significantly underperforms compared to all other ISPs with a higher mean difference, notably 84 ms more than Fastweb, highlighting Tim's pronounced latency. Conversely, comparisons between Fastweb and TelItalia show a minor difference of 8.2 ms, suggesting comparable performance levels between these two. Vodafone and Windtre also show significant increases in latency when compared to Fastweb, by 23.73 ms and 34.84 ms, respectively. Furthermore, Vodafone and Windtre have a significant mean difference of 11 ms, pointing to Windtre's slightly higher latency. These results highlight a stratified latency landscape among Italy's ISPs, with Tim's network latency markedly higher than its peers, and a relatively varied performance band among Fastweb, Vodafone, and Windtre.

5.6 Comparative Analysis of Global ISP Performance

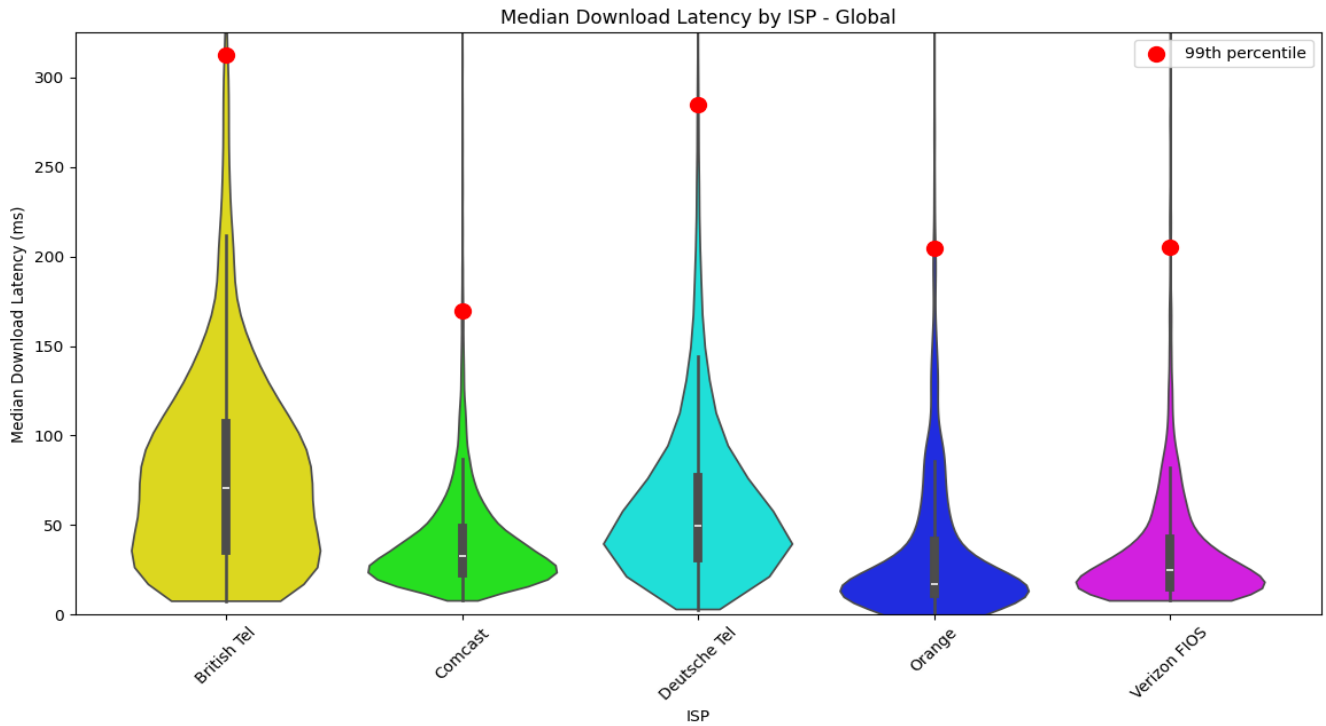


Figure 13: International ISP Latency Performance Comparison

Significant disparities in ISP performance are evident between the US and Western Europe, underscoring the impact of regional infrastructure and technological progress on service quality. British Telecom and Deutsche Telekom exhibit higher median latencies of 70.65 ms and 49.60 ms respectively, with Deutsche Telekom showing a significantly wide spread of latency values, as indicated by its large standard deviation 69.57, pointing to some extreme latency events. Comcast and Verizon FIOS, representing US ISPs, show lower median latencies at 33 ms and 24.85 ms, respectively, with Comcast having a more compact interquartile range (IQR) and 99th percentile below 175 ms, suggesting more consistent latency experiences among its users. Orange (Spain) stands out with the lowest median latency of 17 ms, coupled with a relatively small IQR, indicating a narrower spread of latency and potentially more reliable network performance.

6 Trends and Seasonality

In our exploration of latency trends using AIM's 'loaded Latency' data, we conducted a time series analysis from January 2023 to March 2024 using resampled download latency data to weekly medians.

The Augmented Dickey-Fuller (ADF) test yielded an ADF statistic of -1.53 with a p-value of 0.51, confirming the non-stationarity of our series. This result highlighted the presence of a trend or seasonality that impacts the series predictability.

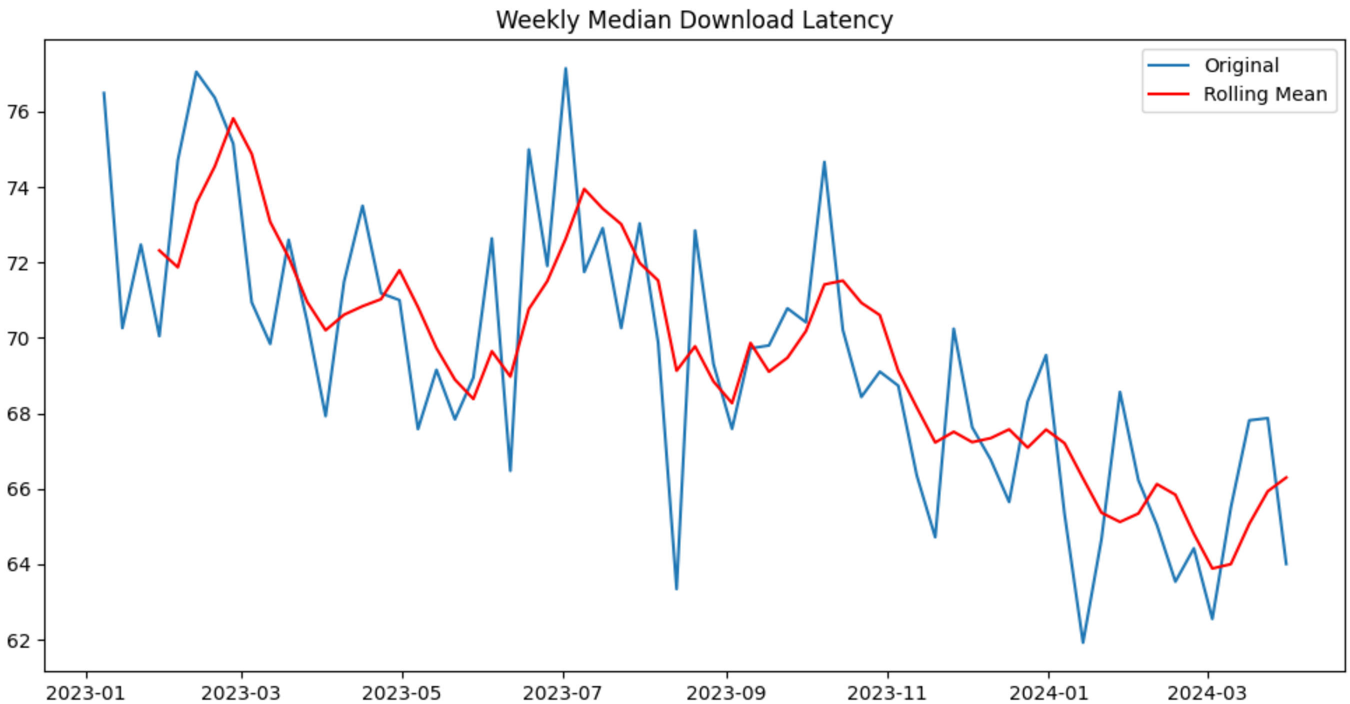


Figure 14: Latency Trend Analysis – 4-Week Rolling Mean

The visual representation of this trend analysis is embodied in Figure 14, with the original weekly medians plotted alongside the 4-week rolling mean to smooth out short-term volatility and bring the longer-term directional movement into clearer focus. The chart reflects a downward trend over the observed period, signifying service improvements. While weekly data points exhibit natural fluctuations, the rolling mean underscores a broader decrease in latency, affirming ISPs' progressive efforts to enhance their network infrastructure.

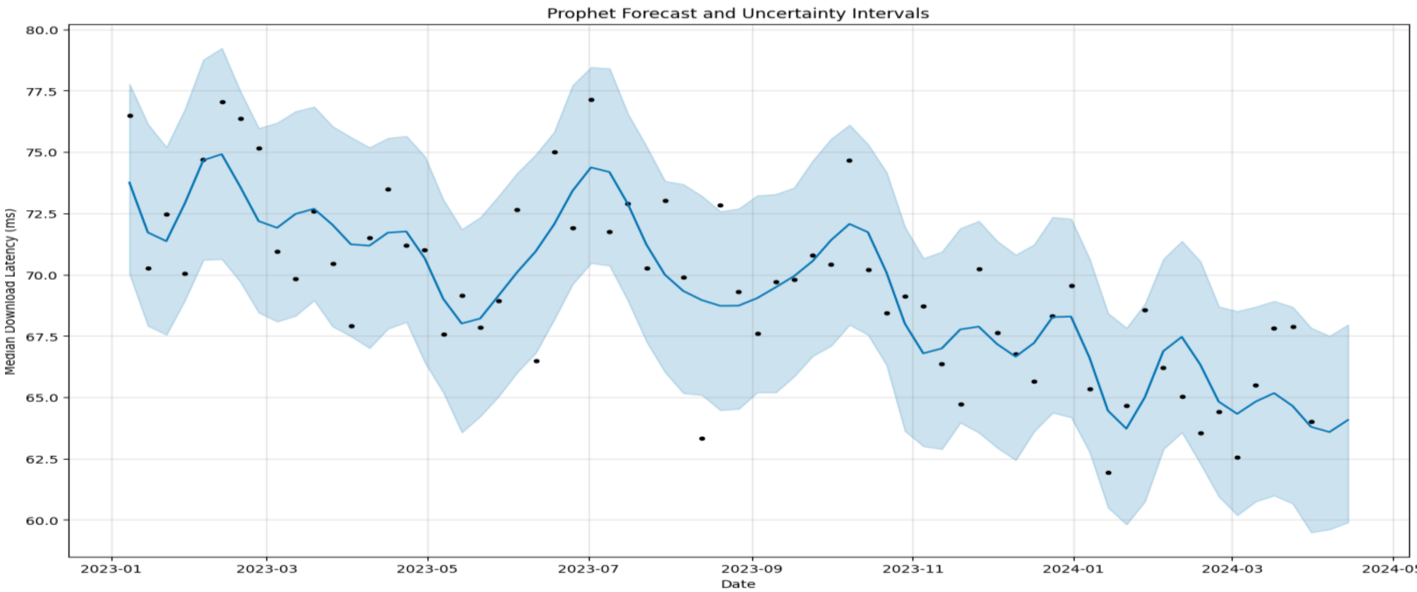


Figure 15: Prophet Model Forecast with Uncertainty Intervals

The time series forecast, visualized by the Prophet model in figure 15, employs past latency data to anticipate future trends. Historical latency values are marked by black dots, with the blue line indicating predicted trends and the shaded area reflecting a 95% confidence interval in these projections.

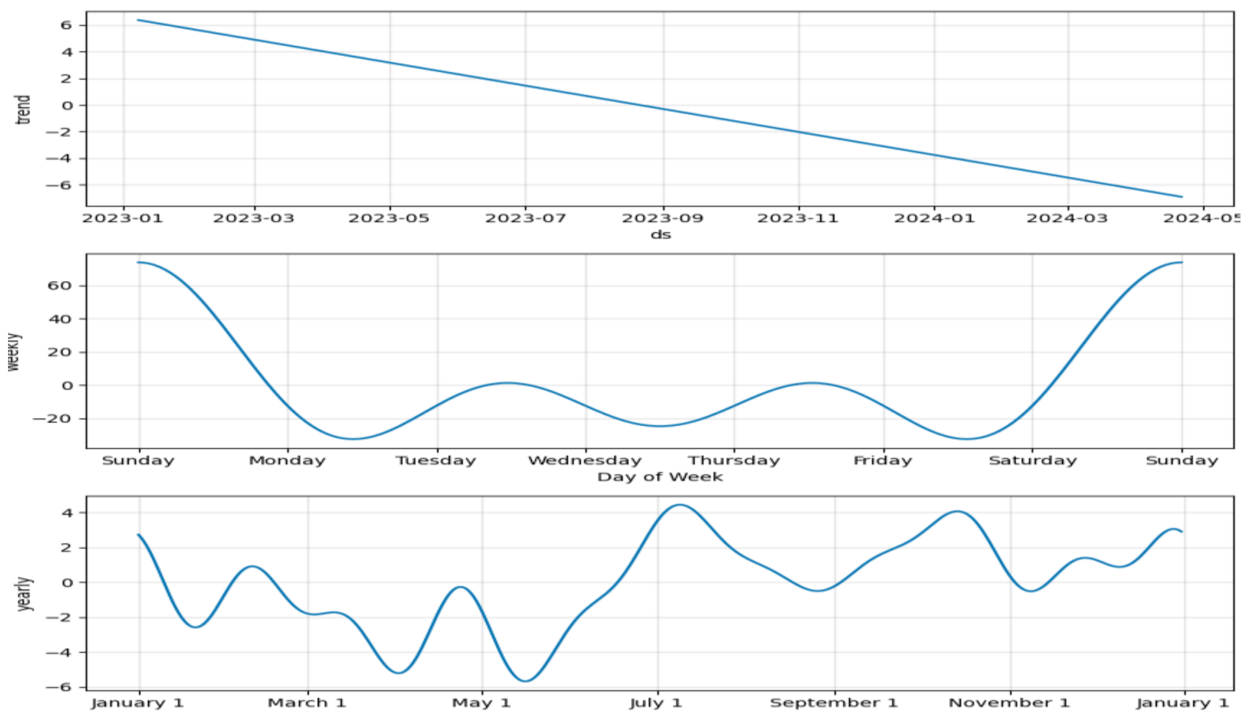


Figure 16: Latency Patterns – Daily and Annual Trends

The analysis offers a multifaceted view as seen in the above plots. The top graph in figure 16 shows a declining main trend in latency, hinting at an evolving enhancement in network quality. The middle graph showcases weekly fluctuations, with mid-week dips suggesting lighter network demand, contrasted by weekend peaks which imply heavier usage. The lowest graph captures annual trends, shedding light on expected variations due to seasonal factors like holidays. These projections are a guide, highlighting expected improvements and weekly rhythms in internet usage. However, they are not definitive; actual ISP performance could diverge from this forecast due to factors like new network upgrades or shifts in usage patterns.

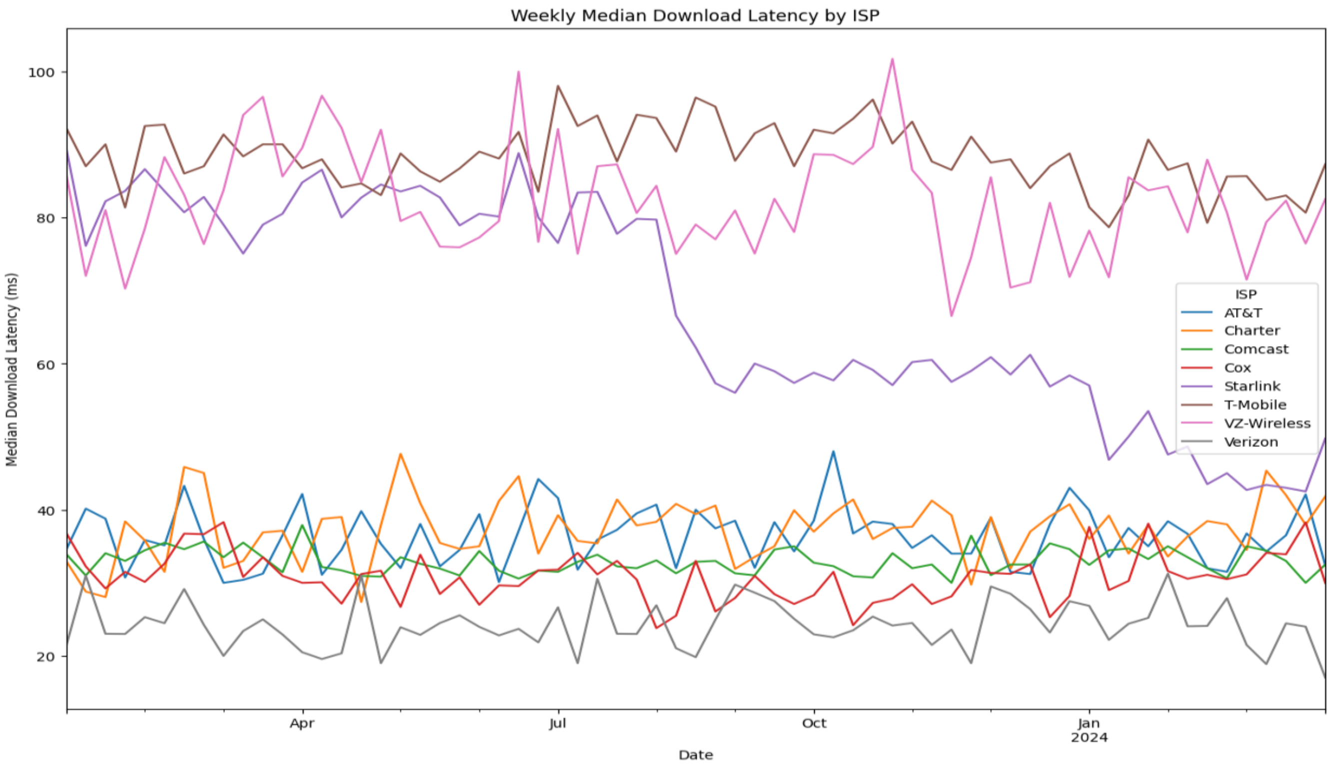


Figure 17: Latency Trend Across Multiple ISPs from January 2023 to March 2024

In examining the time series analysis of median download latency for various ISPs, Starlink emerges as a noteworthy contributor to the overall improvement observed across all ISPs. From the outset of January 2023 to March 2024, Starlink exhibited a pronounced improvement in latency performance. The data points to a significant downward shift commencing mid-August 2023, with further enhancement early January 2024, marking pivotal periods of latency reduction for the satellite ISP.

Starlink's median latency experienced notable declines from highs of around 89 ms down to near 50 ms. This descent suggests substantial enhancements in Starlink's network efficiency or potential upgrades in satellite technology and ground infrastructure. The ADF test results corroborate this non-stationarity, particularly for Starlink with a p-value of 0.608, underscoring the non-randomness of this trend. In the broader context, while the aggregated data across all ISPs show a downward latency trend with an ADF statistic of -1.536 and a p-value of 0.515, indicating non-stationarity, Starlink's marked improvement stands out, substantially contributing to this overall trend.

7 Essential Findings and Their Implications

Our analysis has illuminated significant disparities in ISP performance, attributable to the type of connectivity technology—whether fiber, satellite, or 5G wireless. Notably:

- **Technology's Role**: Unsurprisingly, wired connections consistently outperform other network technologies in speed and latency.

- **Performance Leaders vs Laggards**: ISPs such as Comcast, Orange (Spain), and Verizon exemplify the pinnacle of ISP performance, offering superior user experiences. In contrast, the lagging performance of some providers underscores a need for infrastructure and technology enhancements.

Figure 18: Orbital Planes of Communications Satellites
Image Credit: EOS Data Analytics

- **The Rise of Emerging Technologies***:* Starlink emerges as a formidable contender, offering competitive latency in several cities and showcasing the potential of ISPs in low Earth orbit (LEO) to bridge connectivity voids, especially in remote or underserved areas. This signals a significant shift, with innovative technologies challenging the status quo by providing viable alternatives to traditional service paradigms.

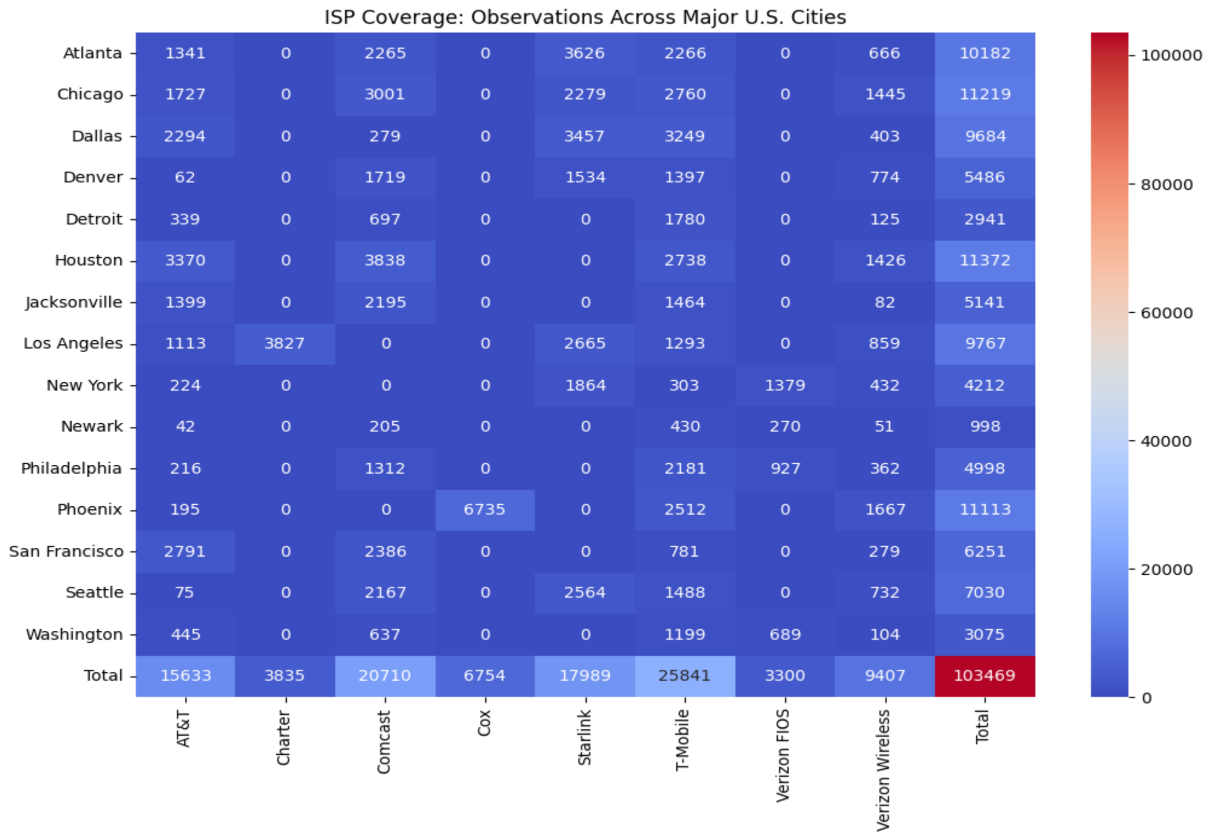
8 About The Authors

Chirag Mehta is a Senior Data Scientist and Business Intelligence Analyst for NetForecast, where he analyzes vast amounts of data to build predictive models and provide deep insights for strategic decision-making. He is passionate about unravelling insights from data. Throughout his journey, he has worked on impactful projects, crafting deep learning models and trading algorithms that delivered impressive results.

Alan Jones is NetForecast's Chief Technologist. He architects and deploys cloud-based internet performance measurement systems. He has a long history leading teams developing products and internal infrastructure for some of the largest telecom companies in the world. After five years designing and testing cellular handsets, he spent over a decade designing and deploying test systems for mobile networks.

9 Appendix

Table 1



ISP Coverage: Observations Across Major U.S. Cities

	AT&T	Charter	Comcast	Cox	Starlink	T-Mobile	Verizon FIOS	Verizon Wireless	Total
Atlanta	1341	0	2265	0	3626	2266	0	666	10182
Chicago	1727	0	3001	0	2279	2760	0	1445	11219
Dallas	2294	0	279	0	3457	3249	0	403	9684
Denver	62	0	1719	0	1534	1397	0	774	5486
Detroit	339	0	697	0	0	1780	0	125	2941
Houston	3370	0	3838	0	0	2738	0	1426	11372
Jacksonville	1399	0	2195	0	0	1464	0	82	5141
Los Angeles	1113	3827	0	0	2665	1293	0	859	9767
New York	224	0	0	0	1864	303	1379	432	4212
Newark	42	0	205	0	0	430	270	51	998
Philadelphia	216	0	1312	0	0	2181	927	362	4998
Phoenix	195	0	0	6735	0	2512	0	1667	11113
San Francisco	2791	0	2386	0	0	781	0	279	6251
Seattle	75	0	2167	0	2564	1488	0	732	7030
Washington	445	0	637	0	0	1199	689	104	3075
Total	15633	3835	20710	6754	17989	25841	3300	9407	103469

Table 2 - Tukey's HSD test results for US ISPs

Tukey's HSD Test Results - median_download_latency: Multiple Comparisons of Means, FWER =0.05						
Group1	Group2	Mean Difference	P-Value	Lower Bound	Upper Bound	Reject Null Hypothesis
AT&T	Charter	-10.3762	0.00	-12.9493	-7.8031	TRUE
AT&T	Comcast	-18.2012	0.00	-19.7141	-16.6884	TRUE
AT&T	Cox	-22.6699	0.00	-24.7491	-20.5907	TRUE
AT&T	Starlink	2.8457	0.00	1.2844	4.407	TRUE
AT&T	T-Mobile	40.4332	0.00	38.9864	41.88	TRUE
AT&T	Verizon FIOS	-23.5076	0.00	-26.243	-20.7721	TRUE
AT&T	Verizon Wireless	33.4032	0.00	31.5399	35.2664	TRUE
Charter	Comcast	-7.825	0.00	-10.3352	-5.3148	TRUE
Charter	Cox	-12.2937	0.00	-15.1808	-9.4066	TRUE
Charter	Starlink	13.222	0.00	10.6823	15.7616	TRUE
Charter	T-Mobile	50.8094	0.00	48.3384	53.2803	TRUE
Charter	Verizon FIOS	-13.1314	0.00	-16.5218	-9.7409	TRUE
Comcast	Cox	-4.4687	0.00	-6.4695	-2.4679	TRUE
Comcast	Starlink	21.047	0.00	19.5917	22.5023	TRUE
Comcast	T-Mobile	58.6344	0.00	57.3027	59.9661	TRUE
Comcast	Verizon FIOS	-5.3063	0.00	-7.9827	-2.63	TRUE
Comcast	Verizon Wireless	51.6044	0.00	49.829	53.3798	TRUE
Cox	Starlink	25.5157	0.00	23.478	27.5534	TRUE
Cox	T-Mobile	63.1031	0.00	61.1517	65.0545	TRUE
Cox	Verizon FIOS	-0.8376	**0.99**	-3.8704	2.1951	**FALSE**
Starlink	T-Mobile	37.5874	0.00	36.2009	38.9739	TRUE
Starlink	Verizon FIOS	-26.3533	0.00	-29.0574	-23.6493	TRUE
Starlink	Verizon Wireless	30.5574	0.00	28.7406	32.3742	TRUE
T-Mobile	Verizon FIOS	-63.9407	0.00	-66.5804	-61.3011	TRUE
Verizon FIOS	Verizon Wireless	56.9107	0.00	54.0218	59.7997	TRUE

10 References

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3. How Wireless Internet Service Via LEO Satellites will transform Business, by Outsource Computing Inc. https://www.oitc.ca/blog/how-wireless-internet-service-via-leo-satellites-will-transform-business/