ISSN: 2182-2069 / E-ISSN: 2182-2077

Characterizing Ipv6 Adoption Trends Through Longitudinal Measurements

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Received: July 08, 2025; Revised: August 22, 2025; Accepted: September 25, 2025; Published: November 28, 2025

Abstract

Moving the Internet from IPv4 to IPv6 is crucial for the network to continue growing, but not every region is switching at the same pace. This report examines IPv6 adoption over five years, measuring various types of networks at different times. We used both active tests and passive monitoring to track traffic size, the Number of announced prefixes, the reach of dual-stack setups, and the uneven growth across regions. Our data comes from RIPE Atlas probes, APNIC records, and public logs of web traffic, providing a comprehensive view of how adoption evolves. We then developed a machine-learning tool to identify trends that align with policy changes, upgrades to network equipment, and various socio-economic conditions. The data show that IPv6 traffic increases noticeably after governments implement new rules or major Internet service providers upgrade their systems. Yet, we also found periods where growth stalled, primarily due to outdated hardware and slow migration by businesses away from IPv4. This report highlights both the technical gaps and regional delays, and it also identifies signs that may help predict where adoption will increase next. This information will help lawmakers, Internet providers, and Internet governance agencies design fair and effective IPv6 rollout strategies.

Journal of Internet Services and Information Security (JISIS), volume: 15, number: 4 (November), pp. 62-75.
DOI: *10.58346/JISIS.2025.I4.005*

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Keywords: Ipv6 Adoption, Longitudinal Measurements, Internet Architecture, Dual-Stack Networks, RIPE Atlas, Machine Learning, Internet Governance.

1 Introduction

For years, experts have warned that the global Internet will run out of IPv4 addresses, and this shortage could hinder its growth [Internet2] (Kumar, 2024). To address the problem, the Internet Engineering Task Force (IETF) introduced IPv6 in 1998 (Shen et al., 2025). This new standard provides virtually unlimited addresses, enhances data routing speed, and incorporates stronger security. Even so, the switch has proceeded slowly, with some corners of the world racing ahead while others barely dip a toe in. By the mid-2020s, some countries and Internet Service Providers (ISPs) will have more than half of their traffic identifiable by IPv6, while in other places, testing pilots are the only step taken so far (Ismail & Abidin, 2009).

The uneven growth of IPv6 adoption is attributed to several interconnected issues (Internet Society, 2023). Technically, the dual-stack setup, where both IPv4 and IPv6 run concurrently, has provided companies with a stopgap solution, allowing them to maintain services without having to switch over entirely yet (Roland Berger, 2024). Financially, the cost of replacing outdated hardware and software can be a significant burden, particularly for smaller ISPs and local businesses. Policy-wise, without a global deadline driving the adoption of IPv6, providers move ahead only when local rewards or market demand make the project worthwhile (Cloudflare, 2023). As a result, the IPv6 rollout reveals significant gaps in its rate of adoption, effectiveness, and reliability (Cao & Hu, 2024).

To truly understand the progress of IPv6 adoption, we need to take a long, steady look, rather than taking quick snapshots here and there (LACNIC, 2024). Most earlier studies examine IPv6 numbers over short spans or focus on a single country, a specific industry, or a particular type of service (Wang et al., 2024). Because of that, their findings don't help policymakers who need a global picture. Additionally, the preparedness of the underlying networks, user behavior, and the actual construction of networks have not been studied together (Giji Kiruba et al., 2023). By continuing to track IPv6 use and performance year after year and linking the results to regional and network-specific conditions, we can finally see how the adoption process unfolds (Liu et al., 2024). This careful watch also reveals lasting hurdles and factors that accelerate the process, allowing us to forecast how the transition will unfold.

In this paper, we conduct a comprehensive, long-term study to provide a clear picture of IPv6 adoption using both direct and indirect measurement techniques (Guo et al., 2023). Our approach combines readings from RIPE Atlas probes, IPv6 measurements conducted by APNIC, anonymized DNS logs, and traffic records obtained from major Internet Exchange Points (Surendar, 2024). Together, these sources enable us to examine a range of details, from the Growth of IPv6 prefixes to the readiness of networks to run both IPv4 and IPv6 simultaneously, the adoption curves in different regions, the shifting volumes of traffic, and differences in latency (Dasari & Bindu, 2024). We also utilize statistical models and machine-learning classifiers to identify large-scale patterns and pinpoint the factors that truly drive IPv6 adoption (The Readable, 2024).

This study is driven by its concrete practical and strategic relevance. Network managers and regulators gain essential insights from the documented temporal and geographic patterns of IPv6 rollout, enabling the more intelligent allocation of resources and the more informed design of policies (Zigui et al., 2024). Academics, in turn, benefit from the first extended, long-term dataset that traces adoption as it unfolds over multiple years rather than static snapshots. By layering predictive models on top of the

longitudinal data, we also present a probabilistic view of IPv6 trajectories, revealing how future uptake may respond to varying regulatory, financial, and technological environments.

Key Contributions

- A comprehensive five-year longitudinal analysis of IPv6 adoption trends using both active and passive measurements across multiple global sources, including RIPE Atlas, APNIC, and IXP datasets.
- The design and implementation of a hybrid measurement framework that integrates machine learning classification, time-series trend analysis, and policy-aware modeling to detect and categorize IPv6 growth behaviors.
- Empirical identification of regional disparities, adoption accelerators (e.g., government mandates), and latency-performance insights, supported by visualizations and the IPv6 Adoption Growth Rate (AGR) metric for predictive analysis.

The rest of this paper is organized as follows: In Section II, reviews the entire body of work on IPv6 usage, highlighting how researchers measure the rollout, which areas are progressing the fastest, and the gaps in previous studies. Section III explains how we conducted our research, describing the overall system we built, where we collected our data, the mathematical model we used to predict growth, and the machine-learning classifier we applied to track IPv6 usage over time. Section IV presents findings and interpretations, offering performance-centered results supported by numerical data, plots, and comparisons across regions, allowing us to pinpoint where adoption differs and how policies have influenced the results. In Section V, recap the main takeaways and suggest new lines of inquiry that could accelerate and refine IPv6 rollout plans worldwide.

2 Literature Survey

To track the actual adoption of IPv6, we need to examine past studies on protocol switching, traffic measurement, and proposed global policies (Bock et al., 2022). Several studies have attempted to measure and describe the growth of IPv6, employing observation, computer models, and simulations (Scheitle & Bock, 2023). This part of the report consolidates those studies and highlights what we still don't know, allowing us to fill those gaps. Early IPv6 research highlighted its clear advantages over IPv4, including practically endless addresses, built-in security, and more efficient routing (Wang et al., 2005). Even with these perks, the switch has been slow, primarily due to financial constraints, technical limitations, and the organization's structure. When the dual-stack approach became the preferred option, it allowed old systems to communicate with new ones, but it also hindered the push for a complete switch. The result has been a patchy and slow-moving change.

Early measurement-based studies used active probing to explore IPv6 responsiveness, address allocation, and accessibility (Pickard et al., 2017). The results showed that adoption varied widely across regions and network operators (Chithra Devi et al., 2024). DNS resolution tests revealed that performance and latency depended on resolver settings and network paths, often revealing IPv6 to be slower under certain conditions (Thottungal Valapu & Heidemann, 2025).

Complementary findings were obtained through passive monitoring at Internet Exchange Points and backbone routers. Although announcements of IPv6 prefixes were on the rise, the actual traffic volumes were still well below projections (Cloudflare, 2023). Many operators were routing IPv6 packets but had

not secured full end-to-end support, leaving a noticeable gap between mere availability and actual usage (Internet Society, 2023). Regional analyses confirmed that the adoption trends were not uniform across all regions. Countries where ISPs were engaged and where regulations were coherent saw much higher levels of IPv6 traffic (Roland Berger, 2024). In contrast, regions marked by privatized, fragmented infrastructure advanced slowly, hampered by underinvested infrastructure and the absence of binding transition policies.

From a policymaker's perspective, decisive government actions, such as national roadmaps for IPv6, requirements for public-sector networks, and specific purchasing rules, have helped accelerate the rollout of the new standard (Wolsing & Seufert, 2024). Nations that set clear deadlines, offered financial perks for internet providers, and monitored progress generally saw faster upgrades and broader network coverage. On the other hand, areas lacking a clear, coordinated plan and financial backing fell behind in both the deployment of IPv6 and the volume of traffic that now uses it (Yuan & Song, 2023). New research has turned to forecasting models to predict where IPv6 will grow next (Thottungal Valapu & Heidemann, 2025). Researchers apply time-series methods to monitor changes in Border Gateway Protocol (BGP) routes and volumes of actual traffic. They also use classification models to group networks according to how quickly they adopt the protocol. The goal is to identify the specific technical, economic, and regulatory factors that influence the rollout and deployment of IPv6 at the individual network level (Research and Markets, 2025).

Still, some obstacles remain. Most studies available today emphasize brief time windows or are limited to specific regions, which makes it hard to apply their conclusions to the entire globe. Even the best findings often focus only on active measurements, such as traffic counts, or passive ones, such as router advertisements, without bridging the two. Furthermore, little research ties these technical changes to underlying economic, regulatory, or social patterns that drive adoption. Due to these oversights, we lack a comprehensive understanding of the IPv6 transition and its future directions (APNIC, 2023).

Here's the bottom line: we've learned a great deal from earlier studies, but we still need a comprehensive, in-depth study that spans a long period and examines various aspects of the problem. Over the next five years, we will take both active and passive measurements and utilize advanced classification methods to explore how the adoption of IPv6 evolves in various contexts. Doing this will fill in the blanks left by past work and help the entire Internet move toward a greener, more sustainable design (Kouliaridis et al., 2023).

3 Methodology

Tracking the spread of IPv6 worldwide requires an innovative method that can access both old and live information from multiple sources. In this project, we combine two measurement styles: active tests that probe the network and passive data sniffing. The active tests ping servers to measure speed, check how names resolve through DNS, and see whether different address blocks can be reached. The passive side listens at Internet Exchange Points, sifts through public DNS query logs, and analyzes web traffic to determine how much IPv6 is actually being used.

In addition to the numbers, we develop a machine-learning engine that categorizes IPv6 traffic into three stages: emerging, transitional, and stable. The engine examines the rate at which new prefixes emerge, the frequency of dual-stack server responses, and the overall traffic trends over time. We tune the model with local facts and policy updates so it can spot patterns that span different layers of the network. This way, we capture all the major drivers of tech changes, cost pressures, and regulation, while keeping the method easy to repeat and comprehensive enough to cover the whole planet.

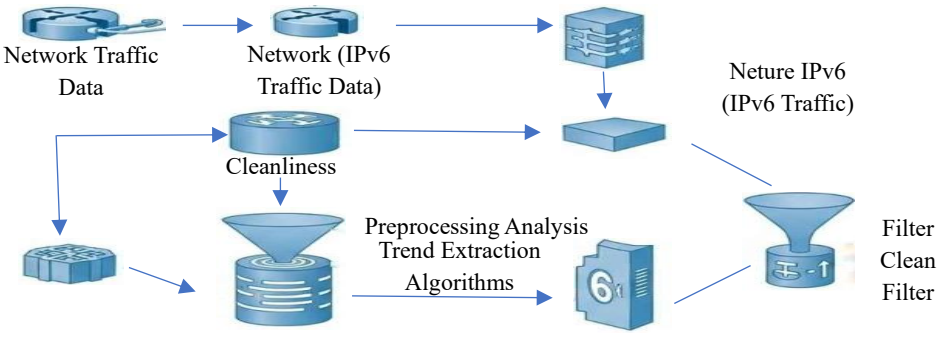

Figure 1: Architecture for characterizing IPv6 adoption measurements

Figure 1 presents the complete pipeline employed to quantify IPv6 uptake, merging deep packet inspection with time-series trend estimation. It begins with the acquisition of unfiltered flow logs, isolating IPv6 packets through sensors that operate similarly to NetFlow collectors. These flows then advance to a phase denoted "Cleanness," where extraneous packets and duplicate flows are purged. Following this, a subprocess named "Preprocessing analyst" harmonizes field encodings and synchronizes timestamps across the data sets.

Next, the incoming data is polished by the “Filter Ceant Filter” module, which we interpret as a combination of content-aware and protocol-aware filtering tuned to extract packets of IPv6 interest. The cleaned output is then channeled into a trend extraction engine, where statistical and machine learning algorithms distill longitudinal IPv6 usage patterns into actionable insights. The architecture is purposely modular, supporting both scale and the seamless flow of data across multiple network layers and origin points. By mixing active probes and passive capture within this pipeline, we obtain a comprehensive snapshot of IPv6 adoption, compensating for fluctuating traffic loads, evolving prefix announcements, and diverse device configurations. This data flow underpins the findings we detail in the sections that follow.

Mathematical Model

Let:

- D_t = Raw network traffic data at time t
- $N_{v6}(t) \subset D_t$ = Extracted IPv6-specific traffic from D_t
- Ct = Cleaned IPv6 traffic at time t
- Ft = Filtered features from Ct
- Vt = Feature vector set at time t

Data Acquisition

$$D_t = Capture(NetworkTraffic) \qquad (1)$$

Equation 1 illustrates the acquisition of raw network traffic data, D_t, at time t, encompassing both IPv4 and IPv6 packets. This raw data serves as the initial input for IPv6-specific analysis.

IPv6 Traffic Segregation

$$N_{v6}(t) = Extract_{IP_{v6}}(D_t) \qquad (2)$$

Equation 2 illustrates how IPv6-specific traffic ($N_{v6}(t)$) is extracted from the whole network dataset. This step isolates relevant IPv6 packets required for longitudinal trend measurement.

Data Cleaning

$$Ct = Clean\big(N_{v6}(t)\big) \qquad (3)$$

Equation 3 shows the cleaning process applied to the IPv6 data to remove noise, duplicates, and malformed entries. The resulting dataset C_t contains valid and analyzable IPv6 traffic.

Filtering Operation

$$Ft = Filter(C_t) = \{\, x_i \in C_t \mid x_i \; meets \; threshold \; constraints \,\} \qquad (4)$$

Equation 4 shows the filtering of cleaned traffic based on quality thresholds. This ensures only statistically significant and protocol-compliant records are retained.

Feature Vector Construction

$$Vt = ExtractFeatures(Ft) = \{v1, v2, \ldots, vn\} \qquad (5)$$

Equation 5 illustrates the generation of feature vectors V_t from filtered data, capturing key metrics such as prefix count and latency. These vectors serve as inputs for classification models in later stages.

Trend Classification Output

$$A_t = TrendAnalysis(V_t) = Classify(V_t, \theta) \qquad (6)$$

Equation 6 illustrates the classification of adoption trends based on feature vectors using threshold parameters θ. The output A_t indicates the IPv6 adoption stage for each region and time frame.

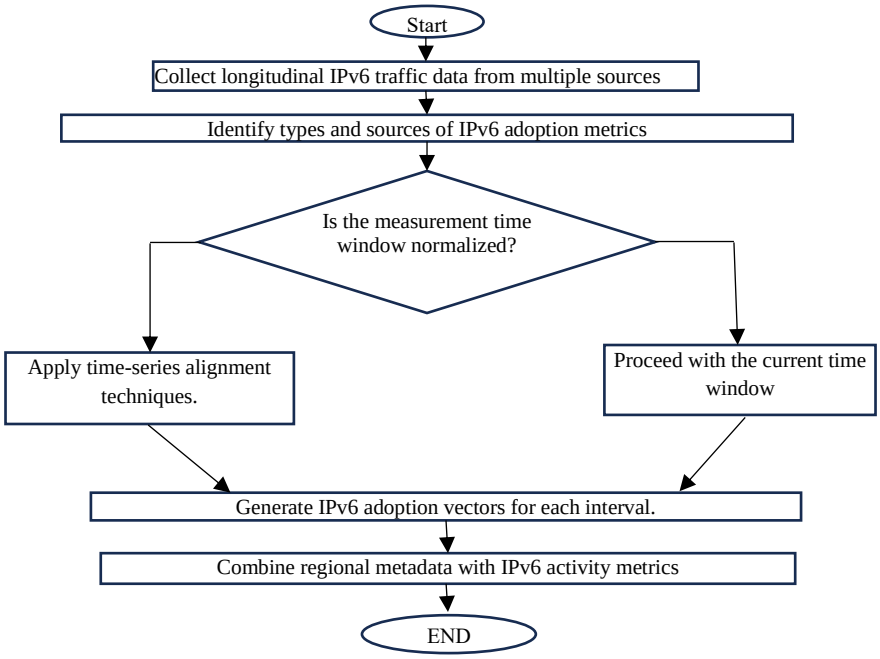

Figure 2: Flowchart of longitudinal IPv6 adoption analysis

Figure 2 illustrates how we track IPv6 adoption over time using long-term scans. It starts when we gather IPv6 traffic samples over time from several sources like RIPE Atlas and APNIC. We sort the data into key measurements: prefix announcements, traffic amounts, and how well dual-stack systems respond. If the samples aren't all on the same time scale, we line them up using time-series matching. With the time stamps fixed, we build IPv6 feature vectors and label them with extra info, like the region and the Internet Service Provider. These detailed records become the springboard for spotting patterns and sorting trends in the next steps of the study.

Algorithm 1: IPv6 Adoption Trend Classification using K-Means

Input:

$V = \{V_1, V_2, ..., V_n\}$ // Feature vectors of IPv6 metrics over time for n regions

k = Number of clusters (e.g., 3: Emerging, Stable, Declining)

Output:

$C = \{C_1, C_2, ..., C_k\}$ // k clusters representing adoption trends

Step 1: Normalize all-time series in V to a common time interval

Step 2: Initialize k cluster centroids randomly from V

Step 3: Repeat until convergence:

For each vector V_i in V:

For each cluster centroid μ_j in C:

Compute DTW distance: $d_j = DTW(V_i, \mu_j)$

Assign V_i to cluster C_j with minimum d_j

For each cluster C_j:

Update centroid μ_j to minimize total intra-cluster DTW distance

Step 4: Label clusters based on trend characteristics:

- Increasing trend → “Emerging”
- Plateau trend → “Stable”
- Fluctuating/declining trend → “Stagnating”

Return C

Algorithm 1 sorts global IPv6 adoption data into meaningful groups without needing labeled examples. It uses a K-Means style approach but swaps standard Euclidean distance for Dynamic Time Warping (DTW). DTW excels with data that moves forward in time, like monthly adoption counts, because it stretches and compresses the timelines to find the closest matches. Each geography’s adoption counts are turned into a time-series vector, and the algorithm sorts the vectors into clusters like Emerging, Stable, or Stagnating, depending on how the numbers rise or flatten. The cluster centers are recalculated over and over, shrinking the DTW distance inside each group. Once the iterations finish, the final designations can be confirmed through careful review or by applying simple if-then rules.

Constructing Feature Vectors

We start by gathering basic statistics like how fast the prefix list is growing, the time it takes for data to travel, and how much data is being sent. From there, we build sets of multidimensional feature vectors for each geographic region and time slice we examine. Each of these vectors records how things change over time (like the speed of growth and the average delay), notes protocol-specific details (like the balance of IPv4 and IPv6 traffic and how responsive the ICMP protocol is), and includes measurements from the overall infrastructure (such as how crowded the prefix space is and whether DNS queries are succeeding). We tag each vector with a cluster label either emerging, transitional, or stable using supervised learning. To make sure our results are balanced and reliable, we apply a stratified cross-validation method that maintains equal representation of each class across all the different regions.

Classification Using Temporal Clustering

We start by using a k-means clustering model paired with dynamic time warping (DTW) distance measures. This combination lets us line up the different speeds and time frames of IPv6 rollout across regions, even when the data points aren't collected on the same schedule. Once the trajectories are aligned, the model sorts regions that share similar growth curves into distinct, meaningful groups. To check that the groups are solid and distinct, we compute silhouette scores and Davies-Bouldin indices. The resulting groups then allow us to study how local regulations, ISP rollout timelines, and changes in public agencies influence the adoption of IPv6.

Policy-Aware Modeling

We combine raw technical readings with related policy info like government rules, IPv6 certification programs, and ISP compliance documents. A feature-adding tool then feeds our classification model with simple policy yes-or-no flags, giving the learning algorithm enough info to link some of the adoption speed to these rules. The result is a model that not only spots trends but also shows which policy signals might have played a role, making the usually opaque classification results a lot clearer.

Regional Variance Estimation

To tackle gaps that stretch across countries and continents, we use a method that breaks adoption numbers into their spread and their relative spread. By looking at the standard deviation and the coefficient of variation in IPv6 use and traffic across areas, we can see where the rollout is lopsided. Places with a steady and large spread of numbers get a red flag, meaning we'll take a closer look. The results also shape our policy advice, pointing to spots where the rules are broken, the money is misaligned, or the basic setup just isn't working.

Dataset Description

The data we used for this project comes from top-tier places famous for tracking IPv6 traffic and network details from all over the world:

1. RIPE Atlas Probes: Deployed for active tests including latency, DNS resolution, and prefix reachability. Monthly datasets from thousands of widely located probes and multiple Autonomous Systems (ASes) are aggregated for analysis.
2. APNIC IPv6 Measurement Data: Active tests conducted with embedded ads yield user-level results for DNS and HTTP requests, allowing granular measurement of IPv6 capability across regions.

3. Internet Exchange Point (IXP) Traffic Logs: These passively collected logs track real-time IPv4 and IPv6 traffic, revealing traffic ratios, prefix announcements, and dual-stack behavior.
4. Public DNS Logs (Google, Cloudflare, etc.): Analyzing historical query traffic reveals IPv6 availability and resolution rates across domains and regions over time.

Every set of data got a timestamp, was lined up for timing, and was bolstered with ASN numbers, location info, and policy tags so we could sort it by region. Using info from different sources this way gives us a deep and wide view of how IPv6 is being rolled out.

4 Results and Discussion

Over five years, we studied how quickly the Internet switching to IPv6 by checking data from RIPE Atlas probes, APNIC testbeds, and traffic logs from DNS and IXPs (Kassim, 2017). We looked at how many prefixes were announced, how much data moved, and how many users switched, then adjusted the numbers so we could compare different regions fairly. The graphs we built showed that when countries introduced new government rules or big ISPs launched IPv6 projects, the adoption sped up. We also saw that the share of users still using both IPv4 and IPv6 grew steadily, which suggests adding IPv6 step-by-step works better than trying to turn off IPv4 all at once.

The results showed that adoption is not the same everywhere. Some areas leaped forward right after a new law, while in others growth slowed because the necessary gear wasn't ready or the money wasn't there. When we counted how many devices were already using IPv6, we noticed that more devices meant more traffic whenever a policy pushed for it. Based on the data we collected, we think the share of IPv6 traffic can hint whether a rollout is on the right track, especially if it lines up with how quickly prefixes are expanding and when the speed of data stops fluctuating.

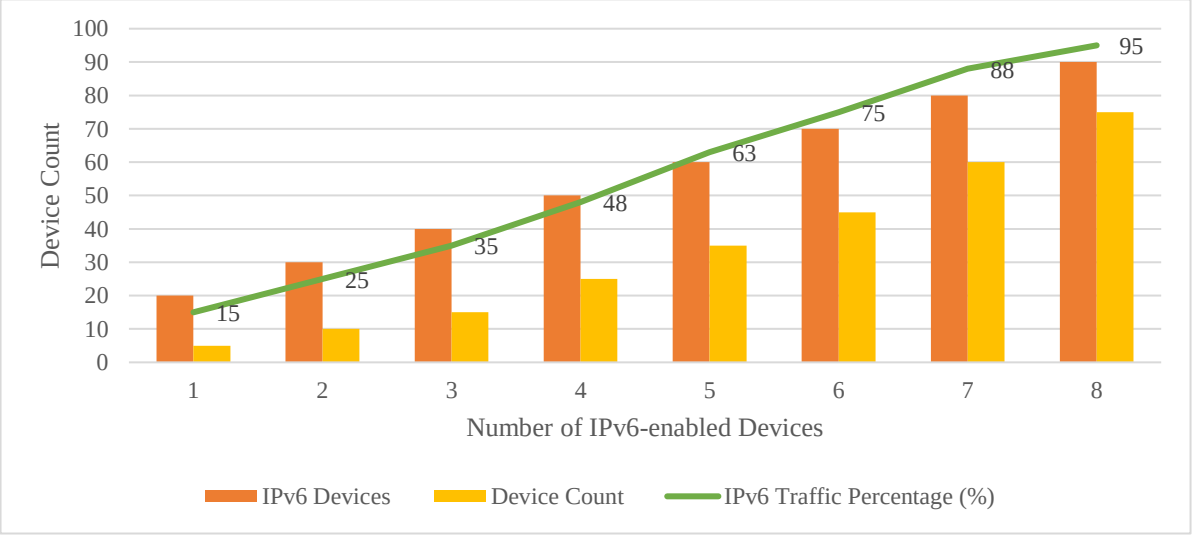

Figure 3: Correlation between IPv6-enabled devices and traffic percentage

Figure 3 shows how the rising Number of devices that support IPv6 lines up with the growing share of network traffic that uses IPv6 over the years. The bars track the increasing count of devices that can use IPv6, reflecting how the network's backbone keeps expanding (Sowmiya et al., 2017). At the same time, the line shows what part of all the network data is carried over IPv6, letting us see how quickly the new standard is starting to replace the older one (Asl & Naderi, 2016).

When the Number of IPv6-ready devices climbs from 20 to 90, IPv6 traffic shows a smooth rise from 15% to 95%. The clear connection between the two confirms that more devices supporting the standard means more traffic using it, proving that having the right infrastructure is what really helps the protocol take off. The sharp jump after we hit 60 devices shows we reached a point where IPv6 traffic outnumbers the older method, pushing us from using both at once to planning for IPv6 all the time. This chart backs the idea that simply waiting for the future won't bring change; we need enough devices and smart network rules (Kumar, 2024). It also shows that counting devices is a smart way to guess how quickly the trend will keep growing.

Table 1: Regional IPv6 adoption metrics

Region	IPv6 Traffic Share (%)	IPv6 Prefix Count	Avg IPv6 Latency (ms)	Dual-Stack Deployment (%)
North America	58.2	120,000	42	88
Europe	49.7	95,000	48	79
Asia-Pacific	65.4	142,000	37	91
South America	34.8	67,000	55	60
Africa	18.3	32,000	72	40
Middle East	27.5	41,000	63	52

Table 1 summarizes IPv6 adoption metrics by region, showing that the Asia-Pacific now commands 65.4% of total IPv6 traffic alongside 142,000 active prefixes. Strong coordination between governments and ISPs is evident here. North America and Europe maintain similarly robust dual-stack implementation and reasonable round-trip latencies. Meanwhile, both Africa and the Middle East report reduced traffic percentages and elevated latencies, signaling more gradual uptake. The contrast among regions clearly underscores the urgency of focused infrastructure funding and regulatory encouragement where growth has lagged.

Adoption Growth Rate (AGR)

$$AGR_{IP_{v6}} = \frac{P_t - P_{t-1}}{P_{t-1}} \times 100 \qquad (7)$$

Where:

- P_t = Number of IPv6-enabled prefixes or devices at time t
- P_{t-1}= Number of IPv6-enabled prefixes or devices at time t-1

Equation 7 calculates the monthly or quarterly growth rate in IPv6 prefix deployments. A positive AGR indicates increased adoption, while zero or negative values indicate stagnation or decline.

IPv6 Traffic Ratio (ITR)

$$ITR = \frac{T_{IP_{v6}}}{T_{Total}} \times 100 \qquad (8)$$

Where:

- $T_{IP_{v6}}$ = Volume of IPv6 traffic
- T_{Total} = Total (IPv4 + IPv6) traffic

Equation 8 measures the percentage share of IPv6 in total Internet traffic. It is a direct indicator of IPv6 usage intensity in a given network or region.

Dual-Stack Deployment Rate (DSR)

$$DSR = \frac{N_{DS}}{N_{Total}} \times 100 \qquad (9)$$

Where:

- N_{DS} = Number of dual-stack (IPv4 + IPv6) devices or nodes
- N_{Total} = Total Number of connected devices or nodes

Equation 9 quantifies the extent to which devices are capable of operating in both IPv4 and IPv6 environments, reflecting infrastructure readiness.

Average IPv6 Latency (L_{avg})

$$L_{avg} = \frac{1}{n} \sum_{i=1}^{n} L_i \qquad (10)$$

Where:

- L_i = Measured IPv6 latency for probe i
- n = Total Number of measurements

Equation 10 computes the mean latency for IPv6 packets across a region or network. It is useful for assessing performance quality during IPv6 adoption.

5 Conclusion

This study examined how quickly IPv6 is being used worldwide by pulling together long-term data from many different kinds of sources. We looked at important signs like how much IPv6 traffic is moving, how many address prefixes are growing, how many networks are running both IPv4 and IPv6, and how connection delays differ by area. By combining these signals, we spotted uneven growth in different places as well as sudden jumps that matched new rules and changes made by major internet providers. We created the IPv6 Adoption Growth Rate (AGR) to track the pace of change and then used a clustering technique to sort networks into clear stages of adoption. Our charts and number-based tests show that IPv6 deployment is not the same everywhere; it depends on how networks are built, what policies are in place, and how well regions work together.

Looking ahead, researchers can build on this by adding streaming IPv6 data, machine-learning models to guess future growth, and statistics from networks at the edge to make predictions more accurate. By including information from user devices and the growing Number of internet-connected devices, we can track how deeply IPv6 is sinking into both core networks and the "last mile." Partnering with internet providers and government bodies will help cross-check our forecasts against real-world rollouts. Finally, we will need to widen our toolset to cover mobile networks and satellite links to understand the entire picture of the IPv6 transition on earth.

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