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# Assessing the Progress of Transition to IPv6: A Global Perspective

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**ABSTRACT**
This paper provides a comprehensive overview of the current status of IPv6 deployment globally. It highlights the progress made in the adoption of IPv6 and the challenges that still need to be addressed. Moreover, it recommends further investigations in areas where the industry's approach towards transitioning to IPv6 is not yet clear and unified. This paper emphasises the importance of continued efforts to ensure a smooth and efficient transition to IPv6 to facilitate the growth and innovation of the digital world.

**KEYWORDS**
IPv6; IPv6 Transition mechanisms; ISP; Access networks; Tunnelling; Protocol translation

## 1. INTRODUCTION

IPv6, which is the subsequent version of IPv4, presents a multitude of benefits including an expanded address capacity and enhanced security functionalities. Notwithstanding its advantages, the implementation of IPv6 on a large scale has been sluggish. There are many things in the business that make this hard to do. IPv6-IPv4 coexistence, which is when IPv6 and IPv4 are both used in the same network infrastructure, is a big problem for the smooth application of IPv6. The aforementioned circumstance creates complexity within the network framework and increases the cost associated with implementation. Moreover, the industry is facing a dearth of proficiency in IPv6, which poses a challenge for entities to migrate to IPv6 without substantial investment in education and training [1–3].

The insufficient incentive for entities to undertake the transition constitutes an additional impediment to the implementation of IPv6. Organisations may delay investing in IPv6 deployment until the depletion of available IPv4 addresses, as IPv4 addresses are still obtainable in the market [1]. In addition, the adoption of IPv6 may face hindrances due to compatibility challenges with legacy systems and devices that lack support for this protocol. The aforementioned concerns necessitate a substantial allocation of resources towards the modernisation or substitution of current systems, a financial burden that may be insurmountable for numerous entities [1].

The aforementioned article [1] elucidates certain hindrances and suggests remedies to surmount them. The article posits that the implementation of IPv6 would benefit from governmental policies and regulations that offer incentives. Additionally, it underscores the significance of industry collaboration and standardisation in guaranteeing interoperability.

The principal aim of this document is to perform an all-encompassing examination of the present status of IPv6 implementation and evaluate the advancements achieved thus far. The survey aims to investigate the accomplishments and challenges encountered during the migration to IPv6 networks, while concurrently accommodating the persistent presence of IPv4 services. Our goal in writing this essay is to provide a current viewpoint on the projects and tactics being used to adopt IPv6. In order to build a clear and comprehensive transition plan, we want to encourage further efforts toward IPv6 integration and highlight certain areas that need more analysis and debate [4–9]. We also intend to explore the driving forces behind IPv6 adoption and provide instances of enterprises that have effectively adopted the protocol in the real world. In the end, our major goal is to motivate enterprises to switch to IPv6, while highlighting the value of standardisation and teamwork among industry players [10–14]. This will be achieved by identifying the advantages and drawbacks of IPv6.

Furthermore, the present document shall examine the obstacles that arise in the simultaneous operation of IPv6 and IPv4 and propose viable remedies to tackle them. The study will additionally evaluate the industry's IPv6 proficiency and suggest measures to augment it, thereby streamlining the transition process.

This article is divided into six sections that give an in-depth explanation of the current state of IPv6 deployment as well as the issues and possible solutions related with its adoption.

Section 1 introduces IPv6, its advantages, and the challenges preventing widespread adoption. This section includes information on worldwide IPv6 adoption, including the pace of growth and the proportion of IPv6-enabled networks and devices. It also illustrates regional and industry variances in adoption rates, offering a full picture of IPv6 implementation today.

Section 2 examines IPv6 implementations in a variety of settings, including ISPs, corporations, and colleges. This section gives insights into the many incentives for adopting IPv6 in certain environments, as well as a knowledge of the various IPv6 deployment methodologies. ISPs may adopt IPv6 to improve customer experience and support the growing number of connected devices, while universities may do so to improve academic research and collaboration. The IPv6 transition's major challenges are covered in section 3. Section 4 reviews transition mechanisms such as dual-stack, tunnelling, and protocol translation. Section 5 identifies barriers to IPv6 adoption and suggests strategies to mitigate them. Finally, section 6 summarises findings and proposes directions for future research and policy recommendations.

## 2. GLOBAL TRENDS IN IPV6 ADOPTION AND DEPLOYMENT

IPv6 adoption dominates this section. The number of IPv6 users, which is a key indicator of its adoption rate, and IPv4 depletion, which is commonly cited as a major driver, are among them. Public policies and initiatives to promote IPv6 and the percentage of websites accessible via IPv6 will also be examined. Global institutions like Regional Internet Registries (RIRs) monitor these variables because they reveal IPv6 adoption rates.

### 2.1 The Depletion of Available IPv4 Addresses

According to [15], Internet-based gadgets per person will exceed three times the world population by 2023. M2M connections will make up 50% of all connected devices at 14.7 billion. Consumers will account for 74% of device distribution, while businesses will account for 26%. The Internet-based applications are expected to experience the fastest growth rate and will represent the majority (48%) of M2M connections by 2023. Over 70% of the world's population is expected to own a mobile device by 2023, and 5G technology is expected to power more than 10% of all mobile devices [15]. Forecasts predict that among device categories, mobile M2M will have the

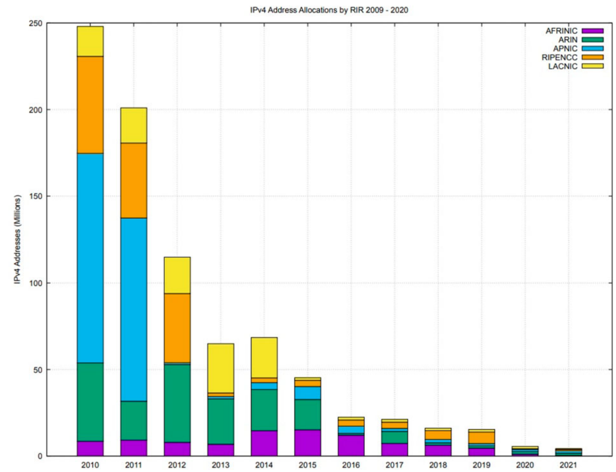


**Figure 1:** IPv4 address allocation by regional Internet registries. Source: Ref. [15]

fastest growth, with a Compound Annual Growth Rate (CAGR) of 30% from 2018 to 2023. The CAGR for smartphones is predicted to be 7%, therefore this rate of growth will likely outpace it [15]. The limitations of the limited pool of accessible IPv4 addresses will be made worse by the growing number of devices and connections, as well as the growth of the IoT and M2M connections. IPv4 addresses are limited, and many locations have already run out. To meet the increased demand for IP addresses, more enterprises may consider switching to IPv6, which has a much bigger address space. However, this change would very certainly need significant expenditures in infrastructure and technology and may take some time. In the meanwhile, network address translation (NAT) and other methods might be used to prolong the life of IPv4 addresses [15]. Figure 1 depicts the distribution of IPv4 addresses from 2010 to 2021.

The allocation and availability of IPv4 addresses by RIRs for recent years are presented in Table 1. Based on our latest analysis that extends beyond the data in [16], we can observe several significant trends in IPv4 address allocation across Regional Internet Registries (RIRs).

Our analysis of this updated data reveals several critical insights about the continuing evolution of IPv4 address allocation globally. APNIC shows a steady decline in both available and reserved address pools from 2021 to 2023, with available addresses decreasing by approximately 18.4% over two years. This consistent reduction indicates a more predictable pattern of address consumption.

IPv4 restrictions in Europe are seen in RIPE NCC's total depletion of addresses until 2023 and its 48.4% reduction

**Table 1: IPv4 Available and Reserved Pools – Updated Analysis through 2023**

| RIR | AVAILABLE 2021 | AVAILABLE 2022 | AVAILABLE 2023 | RESERVED 2021 | RESERVED 2022 | RESERVED 2023 |
|---|---|---|---|---|---|---|
| APNIC | 3,533,056 | 3,145,728 | 2,883,584 | 1,787,904 | 1,572,864 | 1,310,720 |
| RIPE NCC | – | – | – | 762,104 | 524,288 | 393,216 |
| ARIN | 4,608 | 4,096 | 3,072 | 5,244,160 | 4,718,592 | 4,194,304 |
| LACNIC | 7,168 | 5,120 | 4,096 | 224,768 | 196,608 | 163,840 |
| AFRINIC | 1,652,480 | 1,310,720 | 1,048,576 | 4,065,024 | 4,587,520 | 5,242,880 |
| TOTAL | 5,197,312 | 4,465,664 | 3,939,328 | 12,083,960 | 11,599,872 | 11,304,960 |

in reserved pools since 2021. The moderate but consistent fall in available addresses at ARIN and the 20% reduction in its reserved pool over two years reflect a carefully controlled drain of IPv4 resources. LACNIC's reserved pool has dropped 27.1% and its available addresses have dropped 42.9% since 2021. From 2021 to 2023, AFRINIC reduced addresses by 36.5% but increased its reserved pool by 29%. Over two years, available addresses dropped 24.2% from 5,197,312 in 2021 to 3,939,328 in 2023. The reserved pool has declined 6.4% during the same time, reflecting a slower pace of IPv4 address depletion than in past years. These results emphasise the importance of IPv4 address availability and the necessity for rapid IPv6 adoption worldwide.

According to a study cited in [16], the exhaustion of IPv4 addresses can be addressed through both address transfer and Network Address Translation (NAT). IPv4 address transfer can be executed under the control or registration of a RIR or through third-party grey market operations that facilitate the buying and selling of IPv4 addresses. In all cases, a recipient organisation acquires a set of IPv4 addresses to expand their address range. The amount of transfers to recipient organisations in different regions can be observed in [17] and [18], with Cloud Service Providers (CSPs) being the most active buyers of IPv4 addresses, as they need to provide IPv4 connectivity to their tenants. NAT systems can absorb a portion of the demand for public IPv4 addresses by enabling private addressing on internal networks while restricting public address use on their WAN-facing side. However, NAT presents several architectural and operational challenges, such as the inadequacy of private address space for large organisations and the complexity of address reuse. Networks may also have multiple levels of address translation, such as Carrier-Grade NAT (CGN) [19], which involves two stages of translation, resulting in economic and operational burdens.

While this data provides valuable insights, it is important to consider potential inaccuracies due to different measurement methodologies used by respective sources. Variability in ISP network configurations, sampling methods, and regional reporting inconsistencies may contribute to minor deviations in observed trends. These factors must be taken into account when interpreting the reported IPv6 adoption rates and deployment figures.

## 2.2 The Status of IPv6 and IPv4 Address Allocation per Person

The IPv4 per capita ratio denotes the quantification of IPv4 addresses possessed by a country in relation to its population. The process of determining a country's IPv4 address allocation per capita involves dividing the total number of IPv4 addresses assigned to the country by its population. The aforementioned ratio is utilised for evaluating the imbalanced dispersion of IPv4 addresses globally, which stems from the initial allotment of addresses during the nascent stages of the Internet. The IPv4 addresses per capita ratio is determined by utilising data obtained from the RIRs in conjunction with global population statistics. One instance of such data sources are the distribution files furnished by [20]. Through a comparative analysis of the quantity of assigned IPv4 addresses and the demographic size of a nation, it is possible to ascertain the approximate number of addresses that are potentially available per capita.

The table, as reported in reference [20], combines the IPv4 addresses per capita ratio with the degree of IPv6 adoption in the corresponding nation. The aforementioned comparison is conducted by quantifying the extent of IPv6 implementation in a given nation through the metric of the quantity of users who possess the capability to utilise IPv6. Table 2 presents data pertaining to the 15 most populous countries as of May 2023, with a focus on the IPv4 addresses per capita ratio. The table is arranged in a manner that reflects this priority. The IPv4 addresses per capita ratio serves as a valuable metric for comprehending the global allocation of IPv4 addresses. Policymakers and network managers must manage the IPv6 transition and maintain universal Internet access.

Table 2 shows the link between IPv4 address allocation and IPv6 uptake in different nations. The most used and oldest internet communication protocol is IPv4. IPv6 was developed to meet the growing demand for IP addresses caused by the internet. IPv6's main goal was to increase

**Table 2: IPv4 addresses and IPv6 adoption per capita ratio for 15 countries. Source: Ref. [20]**

| Country Code | The Ratio of Allocated IPv4 Addresses to Population | IPv6 Adoption |
|---|---|---|
| US | 4.763 | 54.8% |
| SG | 4.275 | 16.17% |
| CH | 3.035 | 41.97% |
| NO | 2.853 | 39.22% |
| SE | 2.85 | 15.18% |
| NL | 2.838 | 47.53% |
| LU | 2.708 | 48.49% |
| FI | 2.485 | 50.46% |
| IS | 2.364 | 8.36% |
| KR | 2.172 | 20.82% |
| DK | 2.034 | 9.56% |
| IE | 2.034 | 24.45% |
| AU | 1.827 | 39.80% |
| CA | 1.783 | 38.29% |
| GB | 1.757 | 44.69% |

address space. The adoption of IPv6 serves as a measure of a nation's preparedness to migrate to the novel protocol. The correlation between the number of allocated IPv4 addresses and the population of a particular country serves as an indicator of the quantity of IP addresses that are at the disposal of each individual within that nation. A greater ratio denotes a higher number of IP addresses that are accessible per capita in the given country. On the contrary, a reduced ratio implies that there exists a comparatively lesser number of IP addresses that are accessible per individual. Upon examining the table, it is evident that there is no discernible correlation between the allocation ratio of IPv4 addresses and the adoption of IPv6. The United States exhibits a notable IPv4 allocation ratio of 4.763, however, its IPv6 adoption rate is comparatively lower at 54.8% in contrast to certain other nations. Likewise, Singapore exhibits a substantial IPv4 allocation ratio of 4.275, yet a comparatively low rate of IPv6 adoption, standing at 16.17%. Conversely, certain nations exhibiting a reduced IPv4 allocation ratio demonstrate a greater propensity for IPv6 implementation. Iceland exhibits a noteworthy IPv6 adoption rate of 8.36%, despite its IPv4 allocation ratio of 2.364, which surpasses that of certain countries with a greater IPv4 allocation ratio.

In general, it can be posited that the adoption of IPv6 is motivated by factors beyond the proportion of assigned IPv4 addresses in relation to the populace. Various factors such as government policies, infrastructure development, and ISP readiness can significantly impact the rate of adoption of a country.

## 2.3 IPv6-capable Users

The number of IPv6 users is a crucial metric for assessing the adoption of IPv6. Many organisations continuously monitor IPv6 usage by collecting data from various sources. Figure 2 shows the worldwide yearly adoption of IPv6. The Internet Society closely tracks the volume of IPv6 traffic for networks participating in the World IPv6 Launch initiative [21]. This measurement combines statistics from organisations like [22], which provide data at the individual network level by measuring the number of hits to their content delivery platform.

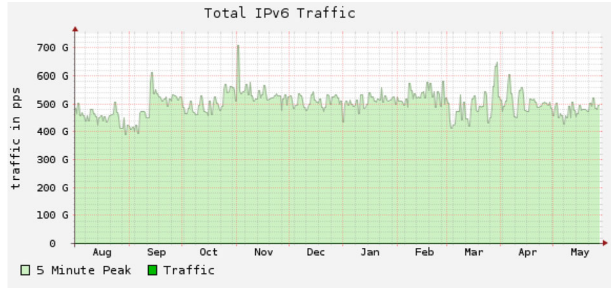


**Figure 2:** total IPv6 traffic from August 2022 until May 2023.

For the purposes of this document, we will consider the approach used by APNIC, which involves running a script on a user's device to quantify the adoption of IPv6 [23]. To provide a rough estimate of the relative growth of IPv6, we present Table 3, which aggregates the total number of estimated IPv6-capable users as of January 1, 2023, and compares it to the total number of Internet users.

There are two significant trends to examine. For starters, the number of IPv6 Internet users is rapidly expanding, with a CAGR in the double digits. This suggests a significant and consistent growth in the number of people utilising IPv6 for internet access. Second, the proportion of IPv6 users to total internet users is rapidly growing. This means that IPv6 adoption is gaining traction and becoming more common among internet users globally. These trends demonstrate IPv6's rising importance and universal adoption as the main protocol for internet communication.

## 2.4 The Global Reach of IPv6 in Web Content

W3Techs [24] monitors the utilisation of various technological components of websites throughout the globe using various analytical engines. Table 4 shows the IPv6 consumption for websites, where the percentages relate to the websites that are accessible through IPv6. The growth rate reported in Table 4 may not seem to be very great. However, keep in mind that not all websites carry the same weight. When compared to lesser websites, the top content providers that currently offer IPv6 provide substantially more material. According to Cisco data [25],

**Table 3: Comparison of Estimated IPv6-capable Users and Total Internet Users (as of January 1, 2023)**

| | JAN 2018 | JAN 2019 | JAN 2020 | JAN 2021 | JAN 2022 | JAN 2023 | CAGR |
|---|---|---|---|---|---|---|---|
| IPv6 | 512.5M | 572.4M | 988.7M | 1135.8M | 1208.2M | 1313.7M | 26% |
| Worldwide | 3409.5M | 3468.9M | 4062.6M | 4089.5M | 4092.3M | 4093.1M | 4.67% |
| Ratio | 15% | 17% | 24% | 28% | 30% | 32% | 21% |

**Table 4: IPv6 use in websites**

| Website All Over the World | JAN 2018 | JAN 2019 | JAN 2020 | JAN 2021 | JAN 2022 | JAN 2023 | CAGR |
|---|---|---|---|---|---|---|---|
| The percentage of IPv6 | 11.4% | 13.3% | 15% | 17.5% | 20.6% | 21.3% | 17.3% |

213 of the top 500 sites worldwide have incorporated IPv6 as of the beginning of January 2022. Given that large content providers such as Google, YouTube, Facebook, TikTok, and Twitter account for more than half of all mobile traffic, and in some instances as much as 65% [25], the amount of material available through IPv6 becomes more important than the number of websites with IPv4 enabled. It would be fascinating to know the particular proportion of IPv6 content included within that 50% of mobile traffic, but this data is presently unavailable.

In connection with this, a question often arises regarding the accessibility of content stored by content providers in the hypothetical scenario of a sudden switch-off of IPv4. While this is purely speculative, the aforementioned numbers suggest that it is likely the case. This observation strengthens the notion that, in terms of quantity, a significant portion of the content is accessible via IPv6.

## 3. AN ANALYSIS OF IPV6 DEPLOYMENTS

In this section, we will delve into the current status of IPv6 adoption within service provider and enterprise networks.

### 3.1 Allocation of IPv6 Addresses

RIRs play a crucial role in the distribution of IPv6 address blocks, which are essential for the functioning of the Internet. These RIRs are entrusted with the task of allocating these address blocks to various entities such as ISPs, Local Internet Registries (LIRs), enterprises, and other organisations.

When assessing IP address allocation, IPv6 progress must be considered alongside IPv4. IPv6 allocates addresses differently than IPv4. The service provider decides the size of each customer's IPv6 address prefix. The IAB and IESG issued [26] recommendations in 2001. These suggestions suggested using /48 as the IPv6 end site prefix. Each client or end site would obtain a 48-bit prefix block of addresses. The technique became more flexible as long-term address conservation became more important. The end site prefix size was left to the service provider. This lets service providers assign IPv6 address blocks of different sizes depending on their needs and network design. This adaptability meets the demands of various service providers, taking into consideration consumer end device counts, network structure, and future scalability.

Service providers may choose the address prefix size to improve IPv6 address allocation for resource consumption and network administration. various IPv6 providers utilise various end-site allocation units. Many providers use /56 allocation units, although others use /60.

Additionally, some providers use /48 allocation units. Note that allocation unit choice greatly affects address space needed for a same client base. ISPs using /48 end site prefixes require 256 times more address space than those using /56. Similarly, an ISP using a /48 allocation would require 4,096 times more address space than an ISP using a /60 end site allocation [27–29].

This variation in allocation units makes it somewhat misleading to compare the count of allocated IPv6 addresses alone. A comprehensive analysis should consider both the number of discrete IPv6 allocations and the total amount of space allocated. When statistics from 2021 to 2022 are compared, it is discovered that the number of individual IPv6 address space assignments has fallen by 25%. Figure 3 shows that the number of IPv4 allocation operations has decreased by 36% within the same time period. These graphs show the trends and dynamics of IPv6 adoption and allocation throughout the specified time period.

It is worth noting that IPv6 allocation figures can vary due to differences in reporting standards, policy changes among Regional Internet Registries (RIRs), and variations in self-reported data from ISPs and enterprises. These discrepancies should be considered when analyzing IPv6 deployment trends.

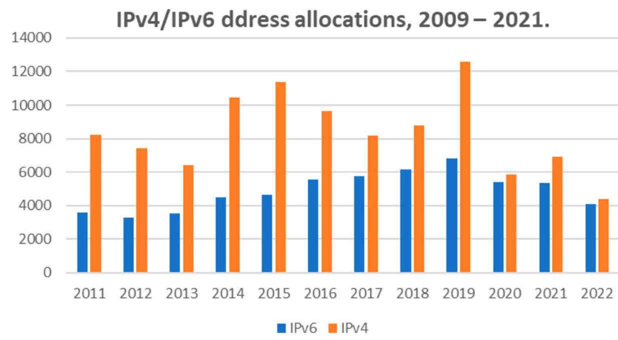


**Figure 3:** allocations per address family (2009–2021).

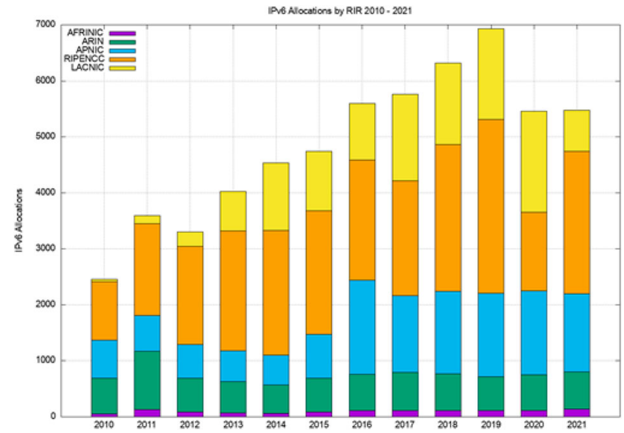


**Figure 4:** IPv6 allocations (2010–2021)

In terms of regional allocation activity, most RIRs experienced IPv6 allocation levels in 2021 that were similar to those of the previous year. However, one notable exception was the RIPE NCC, which observed a significant decrease of 50% in IPv6 allocations compared to the previous year. While the specific reasons for this decrease in RIPE NCC's IPv6 allocations are not mentioned, it suggests a different trend compared to the other RIRs. The decrease could be attributed to various factors, such as changes in network infrastructure, allocation policies, or specific circumstances within the RIPE NCC region [30].

The address assignment data presents a slightly different perspective. Figure 4 displays the number of allocated IPv6 /32 address blocks per year. In comparison to 2021, the total allocation volume was slightly lower in the specified year. However, it's worth noting that ARIN made several significant allocations in 2022. ARIN's allocations in 2022 included /20 address blocks to notable organisations such as the US Department of Health and Human Services, the US National Oceanic and Atmospheric Administration, and the US Department of Veterans Affairs. These allocations are particularly interesting because they indicate signs of protocol migration within sectors that are not directly associated with the consumer Internet. In this case, the US federal government agencies have made notable strides in adopting IPv6 for their networking infrastructure. This information highlights the importance of considering address allocation trends beyond the consumer Internet sector. The allocation of IPv6 addresses to government agencies suggests a growing recognition of the significance of IPv6 and its implementation in critical sectors that require reliable and scalable communication protocols.

## 3.2 IPv6 and ISPs Access Networks

The depletion of available IPv4 addresses is a primary driver for ISPs to embrace IPv6 in their networks. The objective of any solution is to persuade the Internet community, including ISPs and end-users, that the process of adopting IPv6 carries numerous potential benefits or, at the very least, no drawbacks. From a business standpoint, ISPs are unlikely to initiate IPv6 deployment, considering the additional operational costs, as long as public IPv4 addresses are still available. Furthermore, ISPs must recognise that installing IPv6 opens up new services and revenue prospects, especially in large-scale contexts such as the mobile Internet. However, providing IPv6 to subscribers necessitates enhancements and updates to the present IPv4 network infrastructure. As a consequence, it is not in the best interests of ISPs to begin offering IPv6 services alongside IPv4 inside their infrastructure [1].

The Internet Engineering Task Force (IETF) has proposed the IPv6 Rapid Deployment on IPv4 Infrastructures (6rd) method [31] to help ISPs install IPv6 over their current IPv4 infrastructure. The term "6rd" comes from its ability to allow ISPs to quickly launch IPv6 service over local IPv4 access networks by encapsulating IPv6 traffic inside IPv4 and sending it via IPv4 infrastructure.

In contrast to the 6to4 technique, 6rd uses a Network-Specific Prefix (NSP) approach, which allows each ISP to install its own prefixes. ISPs now have more control and management over their IPv6 traffic. Furthermore, without the need of relay routers, the ISP can assure that IPv6 data reaches its target. The 6th protocol allows tunnels to be established between the service provider's border relay (6th gateway) and the customer edge (CE) without the need for any extra components outside the scope of the ISP. IPv6 packets originating from the Internet and intended for an ISP's 6rd site may use NSPs (6rd prefixes) unique to that ISP to traverse that ISP's 6rd gateway.

There exist several limitations that can hinder ISPs from deploying IPv6 using the 6rd mechanism. These limitations include the requirement for upgrading and changing the Customer Edge (CE) equipment, which can incur expenses during the deployment process. Additionally, after the equipment upgrade, configuration of the CEs is necessary for 6rd functionality. Another limitation is the possibility of firewall blockage of tunnelled 6rd packets. Furthermore, there is a limited availability of CEs that support 6rd. Lastly, it's worth noting that 6rd does not support multiple levels of Dynamic Host Configuration Protocol for IPv4 (DHCPv4) between the border router and the customer edge. It has been suggested that these restrictions can be overcome by deploying IPv6 service across local IPv4 access networks (D6across4) [32], configuring hosts to automatically detect network connectivity (IPv6, IPv6-in-IPv4, or IPv4) (CHANC) [5], and deploying IPv4-only connectivity across local IPv6-only access networks (D4across6). However, this research does not include these mechanisms, hence they will not be further explored here.

### 3.3 IPv6 Adoption in Enterprise Networks

NIST [33] offers estimations regarding the deployment progress of IPv6 across various domains within the United States. This assessment encompasses multiple industries, including telecommunications, indicating that the term "enterprises" might be relatively broad in this particular context. Nevertheless, it serves as an initial indicator of IPv6 adoption across several industry sectors in the United States. The analysis aims to determine IPv6 support by examining external aspects of a company's network, such as the support for IPv6 in external services like DNS, mail services, and websites. Similarly, BGR [34] provides comparable data for China, while CNLABS [35] presents the status of IPv6 adoption in India.

The enterprise adoption data presented here is derived from multiple external reports, which may use varying sampling techniques. As a result, the numbers should be interpreted as indicative trends rather than absolute values.

Table 5 shows the enterprise-wide implementation of IPv6 support for external services until July, 2023.

Table 5 highlights the conclusions of an assessment of delivering IPv6 support for external services in business settings by July 2023, with a focus on three key categories: websites, DNS, and mail services. The table covers data on the state of IPv6 adoption in the United States, China, and India, shedding insight on how these countries are using IPv6 for business external-facing services. Starting with the United States, roughly 25.8% of the 1070 evaluated domains use IPv6 for their websites. While this acceptance percentage is modest, it implies that a substantial fraction of organisations in the United States are taking measures to embrace IPv6 for their online presence. IPv6 support in DNS services has improved to 62.3%, signifying substantial progress. Like website adoption, IPv6 mail service adoption is minimal, with 15.6% of domains. China has lower IPv6 website and DNS adoption rates than the US. IPv6 is utilised 18.5% for websites and 70.6% for DNS in 241 domains. These numbers suggest that Chinese companies have invested heavily on IPv6 for their DNS and online presence. Only 1.5% of domains support IPv6 in mail services, which is concerning. This gap emphasises the necessity for further IPv6 promotion in the country's postal services. In all three areas, India's data reveal a similar pattern of relatively low IPv6 usage. Only 14.8% of the 104 domains tested had embraced IPv6 for websites, 54% for DNS, and 13.7% for mail services. These figures show a considerable disparity in IPv6 usage in Indian business contexts, emphasising the importance of increasing awareness and offering incentives to encourage greater adoption.

**Table 5: enabling IPv6 support for external services in enterprise environments until July, 2023**

| Country | Examined Domains | Websites | DNS | Mail |
|---|---|---|---|---|
| USA | 1070 | 25.8% | 62.3% | 15.6% |
| CHINA | 241 | 18.5% | 70.6% | 1.5% |
| India | 104 | 14.8% | 54% | 13.7% |

According to a survey conducted in early 2022 among a group of large enterprises in North America, operational issues related to IPv6 support are found to be even more crucial than those faced by ISPs. Analyzing the current implementations, it was revealed that nearly one third of the enterprises have dual-stacked networks, while 20% of them have declared that certain parts of their networks are IPv6-only. Moreover, 35% of the enterprises either haven't implemented IPv6 at all or are still in the training phase. None of the surveyed enterprises have fully transitioned their networks to rely solely on IPv6. In terms of training needs, the survey indicated that the most critical areas are IPv6 security and IPv6 troubleshooting, as highlighted by two-thirds of the respondents. Following closely is address planning and network configurations, identified by 57.41% of the participants. Regarding implementation concerns, the top three areas of focus are IPv6 security (31.48%), training (27.78%), and application conversion (25.93%). Interestingly, 33.33% of the respondents consider all three areas to be simultaneously significant.

**Table 6: Global Assessment of IPv6 Adoption in Governmental Institutions' External-Facing Services**

| Country | Examined Domains | Websites | DNS | Mail |
|---|---|---|---|---|
| USA | 1238 | 53.4% | 89.3% | 16.4% |
| CHINA | 52 | 99.4% | 3.4% | 2.8% |
| India | 618 | 9.5% | 11.4% | 8.3% |
| European Union | 19 | 23.8% | 51.7% | 1.7% |

### 3.4 Government and Academia

This section concentrates on the implementation of IPv6 in government and academic institutions. Regarding governmental agencies, the adoption of IPv6 support for DNS, mail, and websites in second-level domains associated with US federal agencies is assessed in [33]. These domains typically follow the format of example.gov or example.fed. The same analytical approach employed in [33] has been utilised to gauge IPv6 support in other countries, including China [34], India [35], and the European Union [36]. However, when assessing IPv6 adoption in the European Union, additional post-processing steps are necessary to filter out non-European domains from the analysis. Table 6 illustrates the international evaluation of IPv6 adoption in external-facing services of governmental institutions.

Table 6 shows the adoption of IPv6 in four countries: the United States, China, India, and the European Union, with an emphasis on three major categories: websites, DNS, and mail services. In the United States, around 53.4% of the 1238 evaluated domains have embraced IPv6 for their websites, suggesting a moderate degree of adoption. DNS service adoption is much greater, with around 89.3% of domains supporting IPv6, indicating a favourable trend toward IPv6 deployment in this sector. However, with just roughly 16.4% of domains supporting IPv6, usage of IPv6 for mail services remains very low. With 99.4% of 52 domains on the list, China has a high IPv6 website adoption rate. With just 3.4% and 2.8% of domains supporting IPv6, DNS and mail services are quite different. This discrepancy between website adoption and support for other services suggests that China's comprehensive IPv6 deployment across all external-facing services might be improved. India has substantially lower IPv6 adoption rates in all three areas. IPv6 was enabled for 9.5% of the 618 domains tested for websites, 11.4% for DNS, and 8.3% for mail services. These results highlight the challenges India will face in migrating to IPv6 for its government agencies' external services. Finally, the European Union exhibits moderate IPv6 adoption for websites (23.8%) and DNS services (51.7%), showing development in these areas. However, mail service adoption is very low, with just 1.7% of the 19 analyzed domains supporting IPv6. This conclusion implies that, although there has been improvement in certain areas, the European Union needs to concentrate on strengthening IPv6 support for mail services.

The adoption of IPv6 in the United States surpasses that of many other countries, likely influenced by the IPv6 mandate set forth by [37]. On the contrary, India and China show relatively lower levels of IPv6 support. However, it is worth noting that China does exhibit a notable exception with a significant proportion of IPv6-enabled websites for government-related organisations.

The statistics for IPv6 adoption in higher education institutions are also available for various countries. [38] evaluates data from second-level domains associated with universities in the United States (e.g. example.edu). Meanwhile, [34] concentrates on Chinese education-related domains, [35] examines Indian domains (mainly at the third level), and [36] gives a list of European Union universities (at the second level), with non-European domains filtered away.

The January 2022 IPv6 adoption assessment in universities' external-facing services is shown in Table 7. The table compares websites, DNS, and mail services in the US, China, India, and EU. These findings show how universities in various nations have used IPv6 for their online presence and critical external services. About 24.7% of 346 US university domains use IPv6 for their websites. Despite its low acceptance rate, several US colleges have begun IPv6 implementation for their online platforms. DNS services are improving, with 51.1% of university domains supporting IPv6. IPv6 mail services are still supported by 21.4% of university domains. This shows US institutions have prioritised IPv6 mail uptake above websites and DNS. China has far greater IPv6 website and DNS adoption than the US. IPv6 is used by 81.4% of the 111 university domains for websites and 39.8% for DNS. These numbers show that Chinese colleges are committed to IPv6 for their online platforms and DNS infrastructure. Like the US, just 1.4% of university domains support IPv6 in mail services. This shows that Chinese institutions may do more to promote IPv6 mail services. India's IPv6 adoption rates across all three categories are lower than the US and China's. Only 7.7% of 100 university domains use IPv6 for websites, 34.2% for DNS, and 58.1% for mail services. While websites and DNS adoption is limited, Indian colleges have emphasised IPv6 adoption for mail services, demonstrating a distinctive IPv6 implementation strategy. Finally, EU universities deploy IPv6 at varied rates.

**Table 7: assessing IPv6 adoption in universities' external-facing services (January 2022)**

| Country | Examined Domains | Websites | DNS | Mail |
|---|---|---|---|---|
| USA | 346 | 24.7% | 51.1% | 21.4% |
| CHINA | 111 | 81.4% | 39.8% | 1.4% |
| India | 100 | 7.7% | 34.2% | 58.1% |
| European Union | 118 | 38.3% | 87.2% | 46.5% |

The adoption rate for websites is relatively moderate at 38.3%, while the DNS adoption is high at 87.2%, indicating significant progress in these areas. However, the adoption rate for IPv6 in mail services is relatively low at 46.5%, suggesting that more focus is needed to encourage broader IPv6 implementation in mail services among European universities.

## 4. IPV6 TRANSITION APPROACHES

The widespread usage of network-based devices, together with the expansion of the Internet and networking technologies, resulted in the depletion of public IPv4 address space. In order to overcome these concerns, the Internet Society (ISOC) created a new addressing system (IPv6). As previously stated, the IPv6 protocol has a 128-bit address space, a simple header structure, fast routing, support for both stateless and stateful address setup, built-in security, QoS, and other features. There will be no "flag day" for the transition to IPv6 due to the immensity of the Internet. The new protocol is intended to expand gradually across networks and the whole Internet. The cohabitation of both IPs will last for a long period, maybe more than a decade [8]. The IETF has recommended many transition techniques to ensure a seamless and effective transition to IPv6. A transition mechanism is a method of connecting hosts/networks that use the same or distinct IP protocols. IPv6 transition strategies are broadly categorised into three approaches: dual-stack, tunnelling, and translation. Each of these techniques is briefly described in the subsections that follow.

### 4.1 Dual-Stack Approach

The dual-stack strategy entails implementing both IPv4 and IPv6 protocol stacks as well as providing connection to both kinds of networks in devices that need access to both protocols. while interacting with IPv6 nodes, these devices utilise the IPv6 stack and connection; while communicating with IPv4 nodes, they use the IPv4 stack and connection. Dual-stack devices might be end-user devices, infrastructure devices, or routers. These devices may interact via dual IPs, thus they must be setup with both IPv4 and IPv6 addresses. These addresses may be allocated using viewpoint protocols authorised by a network administrator (for example, DHCPv4 and DHCPv6 servers). When talking with other hosts, programmes on dual-stack hosts will choose the appropriate IP stack based on the resolved IP address type received from the DNS server. For example, if the resolved address is an IPv4 address, the IPv4 stack and connection will be utilised for interacting with the target host. Similarly, if the resolved address is an IPv6 address, the IPv6 stack and connection will be utilised when connecting with the target host. If an IPv4 address and an IPv6 address are obtained while resolving the IP address of a target host, the sending host will utilise either the IPv4 or IPv6 stack when interacting with that host (depending on the sending host settings). The whole address selection policy is explained here [12].

One of the key IPv6 transition options is the dual-stack strategy [13]. The concept behind this method is that the transition to IPv6 begins with replacing the present enormous installed base of IPv4-only devices with dual-stack devices. Following that, additional IPv6-only devices may be progressively deployed, until IPv6 becomes the dominant protocol on the Internet.

However, despite its ease and flexibility in moving to IPv6, this strategy has several downsides. The dual-stack devices still need IPv4 addresses to function; this will not alleviate the issue of IPv4 address depletion. Furthermore, dual-stack devices offer dual management of addressing schemas and routing tables, which wastes the dual-stack devices' resources.

### 4.2 Tunnelling Approach

The tunnelling approach allows systems separated by various IP protocol infrastructures, such as hosts or networks, to interact using the same IP version. Tunnels, for example, may be used to link IPv6 systems that are separated by IPv4 networks. IPv6 packets are encapsulated inside IPv4 packets and sent through the IPv4 network architecture in this case. IPv6 packets are decapsulated at the destination to ensure seamless communication. IPv4 systems separated by IPv6 networks may be linked using tunnels. Tunnelling relies on IPv4 protocol number 41 [3, 8] to encapsulate IPv6 packets. This encapsulation and decapsulation method allows IPv6 data transport over IPv4 networks, bridging IP protocols. Tunnels may be established router-to-router, router-to-host, host-to-host, or host-to-host. These tunnelling methods allow systems with various IP versions to connect by adapting to network circumstances. Tunnelling allows ongoing communication and accessibility across IP protocol architecture, solving IPv4-IPv6 compatibility issues for network management.

### 4.3 Translation Approach

The last section showed how IPv6-in-IPv4 tunnels may be utilised to communicate across isolated IPv6 networks. Similar to IPv6, IPv4-in-IPv6 tunnels may be established across an IPv6 network architecture to enable IPv4 connection between separate IPv4 networks through IPv6. However, the translation method is utilised when a host or network that only supports IPvX needs to interact with a host or network that only supports IPvY. As a result, every IP packet needs its IP headers translated from IPvX to IPvY and vice versa. The IP addresses will be converted from IPvX to IPvY and vice versa when the IP headers are translated. Additionally, the translation approach is used inside hosts precisely when it is discovered that the connection of the present host and the currently running application are incompatible.

In addition to host-based protocol translation, there exist various other factors that can potentially contribute to the emergence of networks that solely rely on IPv6. Certain ISPs or network providers may opt to implement networks that exclusively utilise IPv6 for a range of reasons, encompassing considerations related to simplicity, efficiency, cost-effectiveness, and performance. These factors may prompt individuals to favour an infrastructure that is exclusively based on IPv6. As the adoption of IPv6 progresses, it is expected that certain stages of the implementation process may involve the creation of networks or websites that exclusively utilise IPv6 [2, 3].

Moreover, it is worth noting that there exist certain antiquated networks and hosts that solely support IPv4 and may never undergo the transition to IPv6. Consequently, there may arise circumstances wherein networks or hosts operating solely on IPv6 protocol are required to establish communication with networks or hosts that exclusively support IPv4 protocol. In the conventional sense, systems that exclusively utilise IPv6 are unable to establish direct connections with systems that exclusively employ IPv4, and vice versa. In order to enhance communication in such situations, it becomes imperative to implement comprehensive IP header translation for every IP packet. Interoperability between IPv6 and IPv4 settings is possible because the translation process routes data packets across IP versions. IPv4 and IPv6 networks and sites will coexist as the Internet evolves and IPv6 is adopted. Some networks may prefer an IPv6-only solution owing to its simplicity and efficiency, while others may struggle to move from IPv4. In these cases, the IP header translation promotes communication and connection between the two IP protocols, ensuring easy data transmission across heterogeneous networks.

To ensure communication between IP versions, IPv4 to IPv6 protocol translation must address several areas [1]:

1. Host-based protocol translation: Used when the application type and host connection are incompatible. When an application is written for IPvX but the host is connected to IPvY, host-based translation is needed. This method lets IPvX-only apps use an IPvY-only host's connection and vice versa, ensuring that programmes can communicate despite IP version differences.
2. Network-based translation involves translating IP headers for packets to link IPv4-only and IPv6-only networks. IPv4-only networks connecting to IPv6-only networks need full IP header translation. This technique guarantees that data packets are appropriately routed and understood across IP protocols, allowing IPv4 and IPv6 networks to communicate with one another.

In addition to host- and network-based translation, IPv4 and IPv6 address translation is performed. Address translation is crucial to translation. It enables devices with different IP versions to connect effectively since addresses must be translated to match the destination network's IP protocol. By easily changing IPv4 and IPv6 addresses, the translation process ensures data is routed to the right place.

## 5. ADDRESSING COMMON CHALLENGES IN IPV6 ADOPTION

The technological precautions put in place for the IPv6 transition were not as successful in ensuring a seamless and broad changeover. One of the reasons for this lack of success was that these metrics were largely technical in nature, too abstract, and aimed at specialists while ignoring the ordinary end-user. Furthermore, these measurements did not consider any obvious commercial justification that may have driven firms to adopt IPv6. To shed light on this topic, the Internet Society (ISOC) undertook the "Organization Member IPv6 Study," which focused on the operational aspects of IPv6 and was directed at the organisation's members. According to the research report, there are no tangible commercial motivations forcing enterprises to embrace IPv6. While some enterprises continued to use IPv6, they encountered issues with IPv6 network tools and applications, limiting its wider adoption. Many proposed IPv6 development standards have been implemented mainly in operational and research networks throughout the previous 25 years of IPv6 transition development inside IETF working groups. However, these standards were often intended for restricted and particular technological applications, with no obvious commercial justification in mind. Therefore, they may have been unsuited for wider commercial adoption. IPv6 adoption has been hampered by network tool and app difficulties and a lack of economic incentives. The following sections will discuss the main issues that affect IPv6 adoption and implementation. By addressing these issues, IPv6 may become more accessible, efficient, and beneficial for corporations and end users, enabling its widespread adoption throughout the Internet.

The next sections discuss the main issues that might hinder IPv6 adoption. These issues are critical to IPv6 protocol integration and deployment across networks and systems.

### 5.1 Residential Users

To achieve a seamless and transparent IPv4-IPv6 transition, residential end-users should not face technical challenges. To increase IPv6 adoption, end-user experience must be simple. Protecting end-users from disruptions throughout the changeover ensures continuity and ease of use. To guarantee a smooth transition, address these crucial issues:

- Consistent connectivity is essential for end users throughout the switch. IPv6 should not affect website accessibility, email delivery, or internet service performance. End-users may remain online without interruption due to seamless connectivity.
- Ensure end-user apps are interoperable with both IPv4 and IPv6. Software and apps must not malfunction during transitions. Users should be able to run their favourite apps regardless of IP version.
- Security: IPv6 transfer is feasible and trustworthy. End-user data and communications are safe throughout this major Internet infrastructure transition. Security must be constantly examined and improved to react to changing threats and safeguard end-users throughout the transition and beyond. Regular vulnerability assessments and security audits may discover vulnerabilities and dangers that require immediate attention. Educating end-users about security recommended practices like strong passwords and avoiding suspicious links may also improve transition security.
- Addressing: The transfer should not need manual IP address creation or management for end users. A smooth transition ensures that devices are automatically assigned relevant IPv6 addresses, freeing end-users of addressing complexity.
- Customer Support: Adequate customer support and resources should be available to help end-users with any transition-related questions or difficulties. Clear communication and easily available support channels will keep consumers informed and confident throughout the process.
- Backward Compatibility: Because IPv6 was incompatible with IPv4, transition techniques were developed [8]. IPv6 was initially designed to support both IPv4 and IPv6 traffic on the network backbone and end-user devices. This assumption did not consider that certain IPv4 devices may not be updated to enable IPv6. Thus, IPv6-only networks and devices needed transition techniques to communicate with IPv4-only ones. IPv6-only and IPv4-only networks coexisted, which proved difficult. It became clear that certain network infrastructures may stay IPv6-only while others stay IPv4. Transition mechanisms were created to enable data interchange across diverse networks. Additionally, IPv4 devices may never support IPv6. IPv6 devices have to talk to IPv4 devices without affecting network operations. Thus, numerous transition methods were created to allow devices on IPv4 and IPv6 networks to communicate efficiently, guaranteeing a seamless and progressive transition without interruptions or communication hurdles. IPv6 transfer procedures solved IPv4-IPv6 compatibility issues. These techniques allowed IPv6-only and IPv4-only networks to communicate. The Internet community takes a proactive approach to guarantee a seamless and successful move to IPv6 while retaining connection and interoperability between IPv4 and IPv6 infrastructures by creating these transition mechanisms.

End-users may have a smooth transition to IPv6 if these problems are addressed ahead of time. A user-centric strategy will encourage greater acceptance and adoption of IPv6, resulting in a seamless and transparent migration that improves the overall internet experience for all users.

### 5.2 ISP Network

ISPs are introducing IPv6 because IPv4 addresses are scarce. This essay aims to persuade the Internet community, including ISPs and end users, that adopting IPv6 may have many benefits, if not outright advantages, with few drawbacks. Switching to IPv6 is necessary for ongoing growth as public IPv4 addresses will ultimately run out. However, some ISPs may be hesitant due to higher running costs.

As IPv4 addresses become scarcer, ISPs must actively advocate IPv6 adoption to maintain growth and service delivery. In the future, IPv4 addresses may become scarce and expensive, making an IPv4-only strategy impractical. IPv6 may help ISPs overcome IPv4's address space constraints and future-proof their networks. IPv6 eliminates address depletion and opens up new business opportunities, notably with mobile Internet. ISPs may better meet consumers' growing demands by delivering IPv6 connections and services. The IPv6 transition may make IPv4 network infrastructure upgrades challenging. IPv6 may reduce expenses, improve service quality, and increase customer base, outweighing the early expenditures.

To be competitive and sustainable, ISPs should consider IPv6's advantages. Beyond meeting the pressing need for extra IP addresses, IPv6 adoption will promote innovation and improved services, benefiting ISPs and end users. ISPs who embrace IPv6 may capitalise on new economic opportunities as technology advances and the Internet changes. The Internet community must understand the compelling reasons for adopting IPv6 and work together to ensure a smooth transition. To switch to IPv6, ISPs require effective transition strategies. ISPs may easily deliver IPv6 services to users without an IPv6 network using these methods. These methods allow ISPs implement IPv6 without disrupting customer service.

Dual-Stack Deployment aids change. This approach configures IPv4 and IPv6 network devices and systems. Dual-stack allows ISPs to easily serve customers using IPv4 or IPv6 depending on their network capabilities. This lets IPv4 and IPv6 devices to coexist on the network without interference, and end-users may access services regardless of IP version.

Tunnelling connects IPv6-only and IPv4-only networks. Tunnelling allows IPv6 packets to transit IPv4 networks. ISPs may provide IPv6 even when their infrastructure is largely IPv4. Tunnelling allows IPv6 access across IPv4 networks.

ISPs may also benefit from NAT Protocol Translation. NAT Protocol Translation allows IPv6-IPv4 connectivity by converting packets or vice versa. This method assures IPv6-IPv4 compatibility as IPv6 usage develops.

These transition approaches may help ISPs hasten IPv6 service deployment to clients even if they are not fully linked to IPv6 networks. These solutions enable IPv4/IPv6 coexistence and a seamless transition to the next-generation Internet protocol. In the evolving digital world, ISPs can lead the way to IPv6 and provide growth, scalability, and improved services.

## 6. CONCLUSIONS AND FUTURE WORK

Global IPv6 adoption and deployment trends provide compelling facts and values that demonstrate IPv6's rising importance in the internet ecosystem. The number of Internet-connected devices will exceed three times the world population by 2023, threatening IPv4 address depletion [15]. Although from 2020, this prediction shows the exponential development trend that continues now. M2M connections will make up 50% of connected devices, while the consumer sector will make up 74%. Many IPv4 addresses have run exhausted, necessitating the switch to IPv6. Internet of Things (IoT) and M2M links boost IPv6 usage. RIR IPv4 address allocation data show a reduction in available addresses. The Asia-Pacific Network Information Centre (APNIC) had 2,937,088 IPv4 addresses in 2019, but 3,533,056 in 2021. In 2021, AFRINIC had 1,652,480 IPv4 addresses, down from 2,638,848 in 2019. IPv4 address transfer and NAT are suggested solutions for IPv4 depletion. Cloud Service Providers (CSPs) acquire IPv4 addresses to connect tenants. However, NAT has drawbacks such insufficient private address space for big businesses and operational complexity. The IPv4 per capita ratio shows worldwide IPv4 address allocation imbalance. The US has 4.763 IPv4 allocation ratio and 54.8% IPv6 adoption. Singapore has 16.17% IPv6 adoption despite a 4.275 IPv4 allocation ratio. In contrast, nations with lower IPv4 allocation percentages embrace IPv6 more. With an IPv4 allocation ratio of 2.364, Iceland has 8.36% IPv6 adoption. IPv6-capable users are growing at 26%, with 1,313.7 million as of January 1, 2023. IPv6 use has grown significantly and consistently. The ratio of IPv6 users to internet users is rising quickly, reaching 32% in January 2023. IPv6 has become the standard internet protocol.

Several factors affect IPv6 adoption worldwide. IPv6 adoption patterns reveal the future of internet connection and the issues of IPv4 address depletion. Web Content IPv6 Adoption: IPv6 connectivity to websites has progressively increased to 21.3% by January 2023. Google, YouTube, Facebook, TikTok, and Twitter generate a lot of mobile traffic, thus IPv6 access to their content is crucial. Growing IPv6-enabled websites reflect a promising trend toward universal adoption. Address Allocation: Regional Internet Registries (RIRs) help ISPs and companies get IPv6 address blocks. Flexible IPv6 address allocation with prefix lengths like /48, /56, and /60 lets service providers maximise resource consumption and network administration. ARIN's large allocations to government agencies show IPv6's rising relevance in important industries, even though individual IPv6 address space assignments decreased in 2022. The depletion of IPv4 addresses has driven ISPs to use IPv6 in their networks. IPv6 Rapid Deployment over IPv4 Infrastructures (6rd) facilitates IPv6 deployment across IPv4 infrastructures. 6rd improves traffic encapsulation and network administration, however ISPs must solve equipment upgrades and firewall concerns throughout rollout.

Enterprise networks, government entities, and academic institutions use IPv6 differently in different nations. IPv6 adoption statistics reveal progress and problems. Enterprise Networks: IPv6 is used by 25.8% of analyzed domains for websites, 62.3% for DNS, and 15.6% for mail services in the US. Website adoption (18.5%) and DNS (70.6%) are rising in China, while mail services are just 1.5%. All categories have poor adoption rates in India: 14.8% for websites, 54% for DNS, and 13.7% for mail. These data highlight the need for IPv6 awareness and incentives to increase business adoption worldwide.

Government and Academia: 53.4% of US government domains support IPv6 for websites, 89.3% for DNS, and 16.4% for mail services. China has 99.4% website adoption, while DNS (3.4%) and mail (2.8%) lag. India's poor adoption rates across all categories suggest government entities may struggle to switch to IPv6. Website use is modest (23.8%) and DNS (51.7%) in the EU, however mail services are low (1.7%). USA has modest website adoption (24.7%) and DNS (51.1%) in academics, whereas China excels in website adoption (81.4%) but lags in DNS (39.8%) and mail services (1.4%). India emphasises mail service uptake (58.1%) but struggles with websites (7.7%) and DNS (34.2%). Website adoption in the EU is moderate (38.3%), DNS adoption is high (87.2%), and mail service adoption is low (46.5%).

IPv6 usage is growing, but certain areas need more focus and research to guarantee a seamless transition.

- IPv6 Education and Awareness: Educate end-users, companies, and organisations on the advantages and necessity of IPv6 adoption. Users should be educated about IPv6 and its role in internet development and stability via awareness campaigns, training, and resources.
- Improving IPv6 Security: As IPv6 use rises, it is important to enhance security measures. IPv6 network hazards and threats should be identified and addressed by comprehensive security audits, vulnerability assessments, and constant monitoring.

## 7. KEY CONCLUSIONS AND RECOMMENDATIONS

The study results suggest many important steps for governments and decision-makers to expedite IPv6 adoption. IPv6 adoption requires government leadership. Some nations, like China (99.4%), have strong online adoption among government institutions, while others lag. Governments should specify IPv6 compatibility requirements for all new IT systems, defined timetables for converting current systems, and IPv6 readiness for government procurement. Decision-makers should also provide private sector IPv6 adoption incentives. These might include tax incentives for firms that switch to IPv6, grants or subsidies to cover transition expenses, especially for SMEs, and recognition programmes for IPv6 leaders. A robust legislative framework that requires ISPs to deliver IPv6 services to all consumers by a certain date, supports IPv6 in all new consumer electronics and IoT devices, and certifies IPv6-compliant goods and services is also crucial.

To close the knowledge gap, education and training are essential. This involves integrating IPv6 into university courses, supporting professional certification programmes, and sponsoring IPv6 research. The study found substantial adoption rate variance across industries and locations, underscoring the need for comprehensive education and training initiatives. Global IPv6 adoption requires international cooperation. Countries should build worldwide IPv6 implementation standards, discuss best practices and lessons gained, and construct cross-border testing and validation frameworks. The study shows that IPv6 adoption rates vary widely across nations, underlining the necessity for coordinated international efforts to promote universal implementation.

Enterprise IPv6 Transition Planning: Many companies struggle to switch to IPv6. Create customised IPv6 transition plans and strategies for diverse sectors and organisations to make the switch easier and enjoy the advantages.

It is important to note that the figures presented in this study are based on datasets from multiple sources, each employing distinct methodologies. While these figures help illustrate global IPv6 adoption trends, variations in data collection techniques and reporting mechanisms may lead to minor discrepancies. Future studies should focus on standardising measurement approaches to enhance comparability and accuracy.

## DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author.

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