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IPv6 Diffusion on the Internet Reaches a Critical Point

Keywords:

**IPv6; Internet; Internet Protocol; Technology
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PEER – REFEREED PERSPECTIVE



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IPv6 Diffusion on the Internet Reaches a Critical Point

ABSTRACT

Every device communicating on the Internet requires a unique Internet Protocol (IP) address which is used to identify that device and to facilitate communication. There are two standards of IP addresses in use today, IPv4 and IPv6. IPv4 was the first version of the protocol and has been in use on the Internet since its inception. IPv6 was developed in the mid-1990s as a successor to IPv4 in order to manage the exponential growth of IP addresses required to support new technology. The problem facing the Internet is that there is only a very limited number of unallocated/available IPv4 addresses remaining today, and the entire Internet infrastructure will need to transition to IPv6 if it is to continue to grow.

IPv6 represents a virtually unlimited number of addresses to support Internet growth. However, according to Google's IPv6 adoption statistics report ("Google IPv6 Statistics," n.d.), usage of IPv6 by devices connecting to the Internet has only reached the 15% mark. IPv6 adoption, or lack thereof, has been a major research topic over the past 20 years as conventional wisdom established the need to transition beyond IPv4. This paper investigates the trend of global IPv6 adoption using six metrics for empirical analysis to evaluate adoption based on Rogers' diffusion of innovation theory. The results show that IPv6 adoption is just entering the early majority phase of Rogers' diffusion curve. Further, the analysis predicts that IPv6 diffusion on the Internet has reached a point of critical mass in the latter half of 2017 and will reach the point of 50% adoption in early 2021. Industrial organizations considering a transition to IPv6 need to act now, and institutions of higher education with technology management curriculum must include IPv6 content to meet the coming technology demand.

Introduction

Transmission Control Protocol/Internet Protocol (TCP/IP) became the official protocol suite on the Internet in 1983 (Kleinrock, 2010). Since then, it has become the most ubiquitous suite of network communication protocols and is used on virtually every private network to connect computers, phones, mobile and smart devices. To communicate on a TCP/IP network, a device must have a unique Internet Protocol (IP) address to indicate its location on the network so that it can exchange data packets with other devices.

There are currently two versions of IP, IP version 4 (IPv4) and IP version 6 (IPv6). The version number refers to the version identification field in the IP header. Versions 1, 2, 3 and 5 were never standardized for adoption, which is why only version 4 and version 6 are in use today. IPv4 was designed as an experimental protocol as part of the Advanced Research Projects Agency Network (ARPANET) (Postal, 1978). Its design was appropriate and worked well for the Internet during its adoption in the 1980s, but over time as the Internet has grown in size and complexity, its inherent technological and security limitations have made it anachronistic and unsuitable for today's Internet requirements.

The chief technological limitation of IPv4, and the one that threatens the sustainability of Internet growth, is the number of unique IP addresses it supports. This is determined by the address field of the IP header, which in IPv4 is 32 bits in length. With a 32-bit address field, IPv4 is only capable of supporting 4.3 billion unique addresses. Considering that there are already 3.7 billion Internet users today with projections for as many as 50 billion Internet-



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connected smart devices by the year 2020 (Nordrum, 2016), it is easy to see that IPv4 has reached its technological limitations. In fact, data from Huston (2017a) shows that four of the five Regional Internet Registries (RIRs) have already exhausted their pools of IPv4 addresses, meaning that they can no longer accommodate requests from service providers or enterprise organizations for more IPv4 addresses.

The IP addressing limitations of IPv4 were recognized as far back as the late 1980s as the number of hosts on the Internet, or the National Science Foundation Network (NSFNET) as it was known then, was doubling every nine months (Coffman & Odlyzko, 2002). In 1993, the Internet Engineering Task Force (IETF) began working on a successor to IPv4 and in 1995 standardized IPv6. Not only did IPv6 provide a permanent solution to the shortage of IPv4 addresses by having a 128-bit IP address field to support 340 undecillion (that's 340 with 36 zeros) unique addresses, it also included many technical improvements over its predecessor. These improvements included a simplified protocol header allowing for faster router processing, a stateless auto-configuration mechanism for easy address provisioning of smart devices, and improved support for mobility, quality of service, and security (Deering & Hinden, 1998).

IPv6 is an evolutionary improvement on IPv4, and while they have many functional similarities, they are in fact two different protocols and are not backward compatible; a device that uses only IPv4 cannot communicate directly with a device that uses only IPv6. Therefore, to take full advantage of the features of IPv6, an organization must upgrade its entire network infrastructure to support IPv6 while at the same time maintaining IPv4 support for legacy systems that cannot be upgraded. Upgrading the infrastructure requires a considerable investment in resources and can take years to complete if being done only during normal upgrade cycles.

To allow time for organizations to adopt IPv6, technology and policy solutions were developed and standardized to extend the useful life of IPv4 so the Internet could continue to function and grow in the near term (Khan & Sindi, 2012). Technologies such as Network Address Translation (NAT) and Dynamic Host Configuration Protocol (DHCP) helped to slow down the rate of IPv4 address exhaustion (Droms 1997; Egevang & Francis, 1994). Additionally, Classless Inter-Domain Routing (CIDR) and the Regional Internet Registry (RIR) system helped to conserve and economically manage IPv4 addresses (Fuller, Li, Yu, & Varadhan, 1993; Hubbard, Koster, Conrad, Karrenberg, & Postel, 1996). The unintended consequence of these IPv4-extending solutions was that they worked so well in mitigating the immediate problems associated with the shortage of IPv4 addresses that many organizations saw no compelling reason to adopt IPv6. Consequently, after two decades of pundits championing a transition to IPv6 (Classe, 2003; Khan & Sindi, 2012; Ladid, 2009; Popoviciu & Dini, 2006), encouragement by governments (Coleman, 2014; Doyle, 2008; Garretson, 2005; Wu, Wang, & Yang, 2011), and various promotional initiatives ("Internet Society," n.d.; "World IPv6 Launch," n.d.), global IPv6 use on the Internet only reached approximately 15% as of January 2017 ("Google IPv6 Statistics," n.d.). The concern is that all modern client operating systems such as Windows, Linux, Apple OS X, Android, and Apple iOS not only come with IPv6 enabled by default, but actually prefer IPv6 over IPv4 when an IPv6 connection is available (Colitti, Gunderson, Kline, & Refice, 2010). As long as these systems have an IPv6 connection to the Internet, they are going to use IPv6 without their user's knowledge and may not be able to reach IPv4-only web resources. In some parts of the world where IPv4 addresses are no longer available, users will only be able to connect with IPv6, thus limiting their internet choices. The risk to an organization of becoming an isolated IPv4 island on the Internet is becoming very real.

Purpose

The review of literature for this paper revealed little recent research on the dynamics of IPv6 diffusion on the Internet and no forecasting model attempting to predict IPv6 adoption levels over time. The purpose of this paper is threefold: first is to offer a comprehensive assessment of the current level of IPv6 adoption on the Internet from the perspective of six adoption metrics, second is to offer a predictive model of the diffusion of IPv6 on the Internet, and third is to assess how Rogers' diffusion model translates from its "innovation" foundation to "technology advancement" as applied to the large scale diffusion of protocols on the Internet.

This paper addresses the need for quantitative analysis on the current level of IPv6 adoption on the Internet and the need for clear insight as to when overall IPv6 adoption will reach a level of critical mass which will, in turn, trigger a rapid acceleration of adoption. This research is valuable to organizations debating the risks and benefits of IPv6 implementation and deployment strategies. Additionally, this paper offers significant contribution to the body of knowledge on IPv6 adoption through its analysis into the current levels of IPv6 adoption as measured across six metrics and provides forward-looking insight into the likely progression of IPv6 diffusion on the Internet.

Given that the IPv4 addressing space is virtually exhausted and IPv6 adoption is still lagging, the goals of this paper are timely and useful for organizations to make the case for IPv6 adoption and for encouraging technology management programs to include IPv6 in the curriculum. Specifically, this study sought to address the following research questions:

1. What is the current level of IPv6 adoption on the Internet among Internet stakeholders?
2. Which IPv6 adoption metric best represents overall level of IPv6 diffusion on the Internet?
3. How will IPv6 adoption likely progress on the normal distribution curve over time?

The remaining sections of the paper detail the related works in IPv6 research, followed by the theoretical framework employed and a discussion on the research methodology. The paper concludes with a review of findings, and the implications and conclusions of the research.

Related Works

IPv6 adoption is the subject of a significant amount of research aimed at measuring levels of diffusion and predicting if and when it would reach mass global adoption. Many works in the extant literature provide valuable empirical and analytical data on the process and progress of adoption. Some studies took a narrow approach by focusing on one specific adoption metric or a single group of Internet stakeholders. For example, Nikkhah, Gurin, Lee, and Woundy (2011) used access to web content to measure and quantify IPv6 adoption. By comparing the web access performance over IPv4 and IPv6 from various geographic vantage points, the authors found that IPv6 performance was similar to that of IPv4 when the autonomous system (AS) paths were the same Nikkhah et al., (2011).

Colitti et al. (2010) analyzed client behavior and found that IPv6 adoption, while varied across geographic regions, was increasing rapidly and that latency over native IPv6 was comparable to that of IPv4 when connecting to IPv6-only and dual-stack hosts. Dhamdhare, Luckie, Huffaker, Elmokashfi, and Aben (2012) had similar findings in their analysis of the size, routing behavior, and structure of the IPv6 Internet based on historical Border Gateway Protocol (BGP) tables. Their study showed that the IPv6 Internet infrastructure was increasingly similar to that of IPv4 and that the IPv6 Internet topology experienced exponential growth around 2008 driven by core Internet transit providers, while adoption at

the Internet edge is lagging. They attributed the lag to lack of incentives for enterprises and small transit providers to deploy IPv6 (Colitti et al., 2010).

Other studies took a broader approach to assess IPv6 adoption using multiple metrics. Domingues, Friacas, and Veiga (2007) used autonomous systems in BGP, RIR address allocations, Internet core peering, and IPv6-enabled top-level domains to assess IPv6 adoption on the Internet. They conducted latency experiments to measure IPv4 and IPv6 performance from a scientific network in Portugal to 28 globally distributed target websites. Their findings indicated that IPv6 was not yet broadly adopted. Another study by Nikkhah and Gurin (2016) assessed the evolution of IPv6 adoption by four key Internet stakeholders: service providers, Internet technology developers, content providers, and users. Findings indicated that IPv6 adoption progressed through three phases: stagnation, emergence, and acceleration (Nikkhah & Gurin, 2016). The authors developed a model to validate the relationship between the decisions of stakeholders to adopt IPv6 and utility functions that depend on the adoption decisions of other stakeholders.

Diffusion of innovation theory has also been applied to the study of IPv6 adoption. Hovav and Schuff (2005), defined factors that influence the timing of IPv6 adoption decisions by Internet Services Providers (ISP) through investigation of early and late adopters in several countries. They concluded that factors related to relative advantage had the most influence in the adoption decision of Internet stakeholders (Hovav & Schuff, 2005). Another study, conducted by Dell, Kwong, Syamsuar, Francois, and Choy (2007) also applied diffusion of innovation theory in a study of the attitudes and perceptions of Information Computer Technology (ICT) practitioners towards IPv6 in Indonesia, Mauritius, and Australia. The authors determined that prevalent information about IPv6 in each country was "scarce and inaccurate," contributing to the reluctance of organizations to adopt IPv6 (Dell et al., 2007).

Theoretical Framework

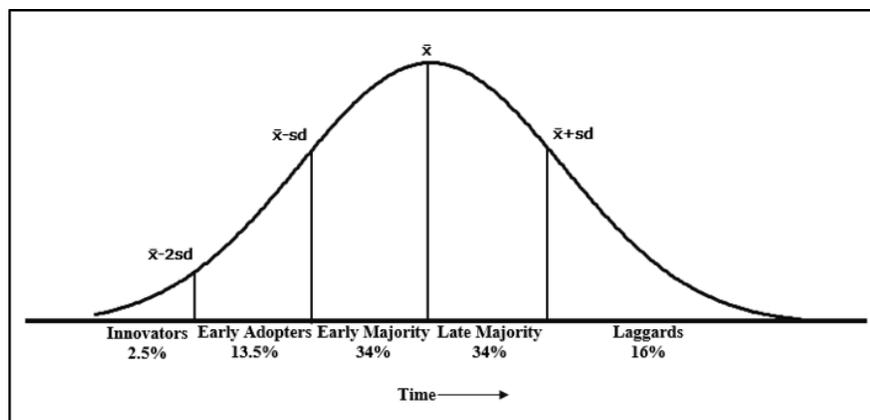
Research by Everett Rogers led to the establishment of a foundational theory on innovation diffusion through social systems (Rogers, 2003). He argued that organizations go through an innovation-decision process similar to that of individuals. Both begin with gaining initial knowledge of an innovation, then proceed through forming an attitude about the innovation, making a decision to adopt or reject the innovation, implementing the innovation, and finally confirming the decision. Because organizations do not all adopt an innovation at the same time but rather on the basis of their level of innovativeness, the adoption of an innovation usually follows a normal bell-shaped distribution curve plotted over time (Rogers, 2003).

Diffusion of innovations theory seeks to explain how and why new ideas, practices, and technology are adopted, and the rate in which they diffuse through the social system or marketplace (users/consumers) over time. The time element of the innovation diffusion process allows the classification of adopters into categories and the representation of the process with diffusion curves. Rogers popularized the theory by establishing an "innovativeness dimension" measured by time, using a cumulative distribution function to track an innovation from introduction to mass acceptance by classifying users. The first group of users is defined as "innovators," and subsequent groups are described by a sequence of "adopter" classifications, ending with a final group referred to as "laggards" (Rogers, 2003).

As shown in Figure 1, Rogers used the mean (\bar{x}) and the standard deviation (sd) to map adopter classifications onto the normal distribution curve to define a population's percentage of classification and their thresholds. The mean rate of adoption was established around a 50% marketplace share defined by the new technology's adoption. Vertical lines are drawn to mark off the standard deviations on either side of the mean to divide the normal distribution curve into five adopter categories: 1) innovators, 2) early adopters, 3) early majority, 4) late majority, and 5) laggards. The percentage of adopters in each category is based on the area under a normal distribution curve.

The first 2.5% of users to adopt a new technology are classified as "innovators" and occupy the extreme of the left tail of the normal curve, starting at a zero (introduction) point and extending approximately to minus 2 standard deviations below the mean. The next 13.5% of users are the "early adopters" and are included in the area between minus 2 and minus 1 standard deviations from the mean. The next 34% are the "early majority" of users and are included in the area between minus 1 standard deviation and the population mean. Once half of the marketplace/population has adopted, the next group to adopt is termed the "late majority," making up the next 34% of users between the mean and plus 1 standard deviation above the mean. The final 16% of adopters are classified as the "laggards", occupying the area starting 1 standard deviation from the mean and continuing on toward total user adoption (Rogers, 2003).

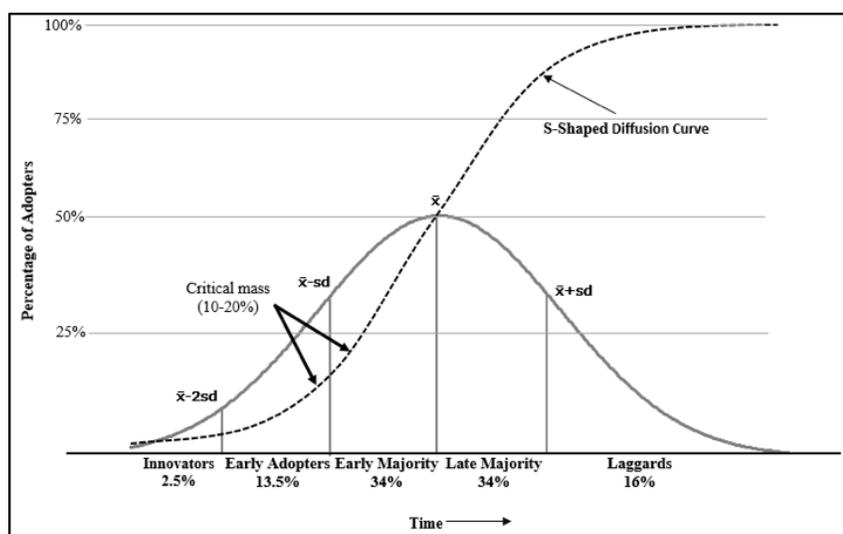
Figure 1. The adopter distribution normal curve partitioned into Rogers' five adopter categories.



When the cumulative number of adopters over time is plotted, the result is an S-shaped curve as shown in Figure 2. Diffusion studies have shown that when the cumulative number of adopters reaches a certain point, known as critical mass, further adoption becomes self-sustaining. Critical mass represents a tipping point at which the rate of adoption rapidly increases and the S-shaped diffusion curve takes off. The tipping point of critical mass is unique to each technology but occurs at about 10 to 20% adoption, which is at the transition point between the early adopters and early majority on the distribution curve (Rogers, 2003). The S-shaped adopter cumulative function curve rises slowly at first with the innovators and early adopters, followed by a rapid rise (rapid adoption) through the early majority and late majority categories of adopters. This accelerating increase occurs once a critical mass

of adopters is reached, typically at the early majority threshold of around 10 to 20%. The adoption rate of increase gradually slows as a smaller pool of users is available to adopt the innovation (Rogers, 2003). The intersection of the S-shaped cumulative function curve with the adopter distribution normal curve in Figure 2 occurs at the mean (50% adoption) which is the transition point between the early majority and late majority of adopters. This is also the inflection point of the growth curve, translating it into an S-shaped cumulative diffusion curve, whereby growth begins to slow but continues to be driven by late majority adopters and technology laggards. According to Rogers (2003), the S-curve is innovation-specific and system-specific, and a normal S-shaped diffusion curve occurs only in cases where innovation is successful and spreads to almost all potential adopters.

Figure 2. -shaped diffusion curve representing the cumulative number of adopters over time overlaid with the bell-shaped distribution frequency curve.



Methodology

The transition of the Internet infrastructure from IPv4 to IPv6 offers a unique opportunity to observe innovation diffusion applied to an Internet protocol as it unfolds on a global scale. To understand the diffusion of IPv6 empirically and provide insight into this transition, diffusion of innovation theory was applied to six metrics of IPv6 adoption collected from four datasets over a period of eight years. Each metric views IPv6 adoption from a different perspective as summarized in Table 1. Each perspective is a look into the level of adoption by various types of Internet stakeholders: Internet Service Providers (ISPs), Internet Content Providers (ICPs), and Internet Users. The data collected were from January 2009 to January 2017 for each metric with the exception of the IPv6 AAAA records of the Alexa top 25,000 websites, which only had data going back to June 2009. Each metric is discussed in detail in the following sections.

Table 1. Summary of datasets and related IPv6 adoption metrics.

Metric	Description	Dataset
1 IPv6 users	IPv6 users	1 Google IPv6 statistics
2 Active BGP Entries	IPv6 prefix announcements in BGP	2 Route Views AS6447
3 RIR IPv6 Allocations	RIR IPv6 prefix assignments	3 Prefix assignments by each RIR
4 Unique IPv6 AS Count	Unique IPv6 autonomous system (AS)	4 Route Views AS6447
5 Unique IPv6 AS Paths	Unique IPv6 autonomous system paths	
6 AAAA from Top 25K	IPv6 AAAA records	5 Alexa Top 25k web sites

IPv6 users

The first metric is a measure of the number of users who are accessing Internet content over IPv6. As the size of the IPv6 user base increases, it has a positive effect on Internet content provider IPv6 adoption, which in turn has a positive effect on Internet service provider adoption, creating a positive upward spiral of adoption. The data source for capturing the size of IPv6 user base was Google's IPv6 Statistics ("Google IPv6 Statistics," n.d.). Google measures client IPv6 use by adding a measurement JavaScript to a random sample of visits to various Google properties. The measurement JavaScript uses HTTP to fetch a URL from an IPv4-only hostname and a URL from a dual-stack hostname in random order. The percentage of users connecting to Google using IPv6 increased 6,665% from 0.23% to 15.56% between January 2009 and January 2017.

Each of these six metrics was included in a correlation analysis using SAS JMP Pro 12 for the purpose of identifying if a single metric could best represent an overall window into the current level of global IPv6 adoption. Subsequently, the single metric would serve as a proxy of the metric pool to allow a trend-fit analysis to develop a best case and worse case time projection of IPv6 adoption along Rogers' innovation diffusion timeline.

Active BGP Entries (IPv6 prefix announcements in BGP)

The second metric is the number of IPv6 prefixes found in the global Border Gateway Protocol (BGP) routing table. In order for IPv6 prefixes assigned to an organization to be used on the Internet, those prefixes must be advertised in the global BGP routing tables. For this metric, data were obtained from the IPv6 BGP table report from Geoff Huston (2017) which uses the University of Oregon Route Views Project to capture IPv6 BGP announcements. The University of Oregon Route Views Project maintains Autonomous System (AS) 6447 for multi-hop BGP sessions to peer with backbones and other ASes at various Internet locations for the purpose of collecting BGP data ("Route Views," n.d.). Active BGP entries were collected by Router Views for each month from January 2009 through January 2017. IPv6 prefix advertisements in BGP increased 2,263% from 1,585 to 37,460 during this time frame.

RIR IPv6 Allocations (RIR IPv6 prefix assignments)

The third metric is the number of IPv6 prefixes assigned by the RIRs to ISPs or very large enterprise organizations and represents the demand for IPv6 address space. Each RIR updates this information daily and makes it publicly available for download (Czyz et al.,

2014). Note that demand does not equal use since organizations may demand and obtain IPv6 address space long before the addresses are put to any actual use. The address allocation datasets from January 2009 through January 2017 for each RIR were downloaded and analyzed ("ARIN Stats Index," n.d.). The prefixes from each RIR were then aggregated into one single metric of RIR IPv6 prefix assignments. The aggregated IPv6 prefix assignments increased 940% from 3,090 to 32,123 between January 2009 and January 2017.

Unique IPv6 AS Count and Unique IPv6 AS Paths (autonomous systems and system paths)

The fourth and fifth metrics are concerned with the maturity of IPv6 adoption on the Internet in terms of the number of unique IPv6 Autonomous Systems and unique Autonomous System paths. Routing paths on the Internet are through and between Autonomous Systems. The number of Autonomous Systems that are announced through IPv6 is suggestive of support for IPv6 on the Internet, while the number of unique IPv6 Autonomous System paths is an indicator of maturing IPv6 connectivity between autonomous systems. Taken together, these two metrics give an indication of overall IPv6 Internet connectivity. To capture this metric, data were again obtained from Huston (2017) which uses raw data obtained from AS 6447 maintained by the University of Oregon Route Views Project ("Route Views," n.d.). The number of unique IPv6 AS paths increased 3,669% from 11,433 to 430,900 between January 2009 and January 2017. The number of IPv6 unique ASes increased 948% from 1,225 to 12,838 in the same time period.

AAAA from Top 25K (IPv6 enabled websites)

The final metric is the number of the Alexa top 25,000 websites that have IPv6 AAAA records advertised in the global Domain Naming System (DNS) ("AAAA and IPv6 Connectivity," n.d.). This metric captures the use of IPv6 by Internet Content Providers (ICPs). In order for ICPs to make their content, such as websites, accessible over IPv6, not only do the content servers need to be reachable over IPv6 but the Fully Qualified Domain Name (FQDN) used to reach the content must be resolvable to an IPv6 address. This is accomplished by advertising the FQDN in DNS with an IPv6 AAAA resource record. The percentage the Alexa top 25,000 websites with AAAA records in DNS increased from 0.3% to 19.06% between June 2009 and January 2017, an increase of 6,252%.

FINDINGS

As previously stated, there are three goals to this paper: 1) to offer a comprehensive assessment of the current level of IPv6 adoption on the Internet from the perspective of six adoption metrics, 2) to offer a predictive model of the diffusion of IPv6 on the Internet, and 3) to assess how Rogers' diffusion model translates from its "innovation" foundation to "technology advancement" as applied to the large scale diffusion of protocols on the Internet. The first two goals are discussed in this section, and the third goal is discussed in the discussion and conclusion section.

Current level of IPv6 adoption

The adoption of IPv6 on the Internet was assessed using six metrics from data spanning an eight-year period from January 2009 through January 2017. The data show evidence of accelerating IPv6 adoption across all metrics as summarized in Table 2.

Table 2. Percentage increase of IPv6 adoption metrics

Metric	Jan 2009	Jan 2017	Percent Change
IPv6 users	0.23%	15.56%	+ 6,665
Active BGP Entries	1,585	37,460	+ 2,263
RIR IPv6 Allocations	3,090	32,123	+ 940
Unique IPv6 AS Count	1,225	12,838	+ 948
Unique IPv6 AS Paths	11,433	430,900	+ 3,669
AAAA from Top 25K	0.30%	19.06%	+ 6,252

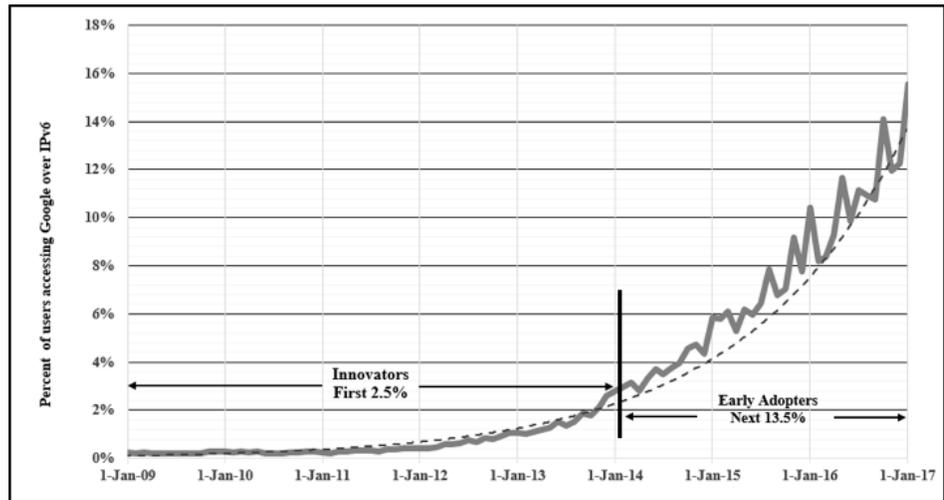
A key factor in the analysis is that user access to Internet content over IPv6 is dependent on the IPv6 adoption decisions made by ISPs and ICPs. This allows the assumption that the size of the IPv6 user base can be used as a proxy for overall IPv6 adoption. To provide a degree of confidence that IPv6 users is a valid reference point, correlation analysis was conducted for other IPv6 adoption metrics as shown in Table 3. IPv6 users as a measurement metric most closely correlates to Active BGP Entries and Unique IPv6 AS Paths, but shows a strong correlation to all metrics studied. Therefore, it was determined that the metric of IPv6 users from the Google IPv6 Statistics data is a suitable proxy for global IPv6 adoption (Colitti et al., 2010).

Table 3. Correlation matrix of IPv6 adoption metrics.

IPv6 Adoption Metric	IPv6 Users	Active BGP Entries	RIR IPv6 Allocations	Unique IPv6 AS Count	Unique IPv6 AS Paths	AAAA from Top 25 K
IPv6 users	1.0000					
Active BGP Entries	0.9512	1.0000				
RIR IPv6 Allocations	0.9174	0.9917	1.0000			
Unique IPv6 AS Count	0.8845	0.9808	0.9941	1.0000		
Unique IPv6 AS Paths	0.9792	0.9788	0.8545	0.9348	1.0000	
AAAA from Top 25K	0.9317	0.9673	0.9509	0.9365	0.9411	1.0000

Applying the percentage of users accessing Google over IPv6 data to Rogers’ categories of adopters, IPv6 was in the Innovator’s phase for almost 20 years from its 1995 standardization as an Internet protocol. The historical curve of Google utilization in Figure 3 shows that IPv6 adoption took nearly five years from January 2009 to 2013 for the innovators to reach the Early Adopter threshold at 2.5%. The dashed line in the figure shows a trend line representing users over IPv6 from January 2009 to January 2017. Both the actual data and trend line indicate that IPv6 is about to reach the end of the Early Adopter phase, which occurs at the cumulative utilization of the Innovators 2.5% plus the Early Adopters 13.5%, or 16 % total. The authors posit that IPv6 adoption is at the cusp of transitioning from Early Adopters to the Early Majority of adoption. This is supported by the trend line and actual 2017 first quarter data showing that as of March 2017 the number of IPv6 users stands at 15.6%. This indicates that IPv6 adoption is about to reach the tipping point of critical mass as previously described in Figure 2. Further, using Rogers’ diffusion curve, the rate of adoption is about to accelerate to the 50% point of adopters which is discussed in the next section.

Figure 3. Percentage of users accessing Google over IPv6.



A predictive model based on Rogers’ Technology Adoption Curve

Table 4 represents quadratic formulas to model the trend of the data collected by Google on a continual basis about IPv6 adoption on the Internet; 97 data points were available, representing January 2009 as the earliest through January 2017. Note that the January 2009 point was used as a start point as it matched the earliest data of all other metrics in the correlation analysis. The data were imported into SAS JMP 12 Pro to conduct statistical analysis on fitting a curve to determine the growth rate of the adoption. An initial graphical review easily established a non-linear best fit line would be required. Both exponential and quadratic formula approaches were applied, and while both provided statistically significant results, the quadratic formula best represented the curve.

Table 4 both serves as a predictive model and demonstrates that the data show accelerating adoption based on the time frame of data analyzed. Regarding the first point, each quadratic formula in the table represents values from January of the “Data Start” column extending to January 2017. Therefore, the data starting in 2009 used all 97 data points available, data starting in 2010 used the most recent 85 data points, and so on. Data starting in 2014 used the most recent 37 data points, and this was the most recent starting point to yield statistically significant results.

Using all the available data, starting with January 2009, and the quadratic formula established by the best-fit line, the utilization at the end of January 2017 was approximately 15.6%. Referring back to Figure 1, Roger’s 1962 Diffusion of Innovation Curve established 2.5% as the upper boundary for technology innovators and 13.5% as the threshold to be considered the Early Adopter phase. Subsequently, 50% IPv6 adoption is projected to occur during October 2022, with the late majority adopter phasing into the laggards with 84% adoption in March 2026.

Table 4 Google Utilization Projections from Various Starting Points*.

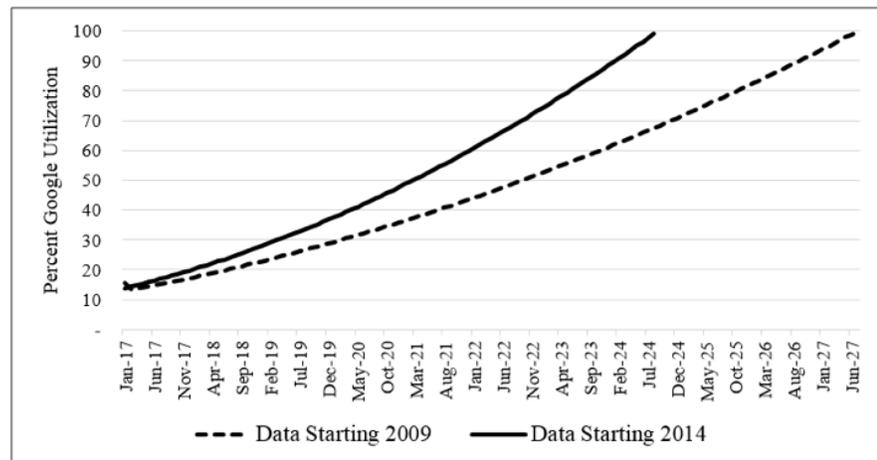
Data Start	IPv6 User Base	Start Early Majority (16%)	Start Late Majority (50%)	Laggards (84%)
2009	$0.00257(X_{2009} - 102.5)^2 + 0.395X_{2009} - 25.590$	2017 Oct	2022 Oct	2026 Mar
2010	$0.00304(X_{2010} - 96.5)^2 + 0.470X_{2010} - 27.177$	2017 Aug	2022 Apr	2025 Jun
2011	$0.00349(X_{2011} - 90.5)^2 + 0.550X_{2011} - 27.791$	2017 Jul	2021 Nov	2024 Nov
2012	$0.00383(X_{2012} - 84.5)^2 + 0.627X_{2012} - 26.733$	2017 Jul	2021 Sep	2024 Jul
2013	$0.00393(X_{2013} - 78.5)^2 + 0.683X_{2013} - 23.253$	2017 Jul	2021 Aug	2024 Jun
2014	$0.00497(X_{2014} - 72.5)^2 + 0.837X_{2014} - 23.451$	2017 Jun	2021 Mar	2023 Sep

* subscript on variable denotes data start January of the calendar year represented

However, as for the second purpose of the table and consideration that the rate of technology change is accelerating, Table 4 segments the data by calendar year starting points with the intention of assessing growth rates based on more near term data starting points. Thus, the data were parsed and evaluated using January of the years 2009 through 2014 as a starting point to calculate a quadratic growth curve. The theory behind this approach recognizes that irrespective of the data starting point, IPv6 is beyond the 2.5% utilization threshold of the Early Adopters but not quite at the Early Majority phase. This allowed calculations of best fit plots using data starting in January of the years 2009 through 2014. Data beginning January 2015 and January 2016 did not reveal statistically significant results and were therefore excluded from Table 4.

Referring back to Figure 2, Roger’s 1962 Diffusion of Innovation Curve establishes 50% utilization as a transition between the early and late majority adopters. From the best fit quadratic formulas, the 50% utilization point predicted with data starting in January 2009 was determined to be October 2022. However, as more near term starting points are analyzed, it is evident that there is an accelerating technology change. The 50% utilization gets closer and closer with each early starting point. The most recent and statistically significant data are based on a January 2014 starting point and show the 50% utilization occurring in March 2021. These results are depicted graphically in Figure 4.

Figure 4. Accelerating adoption of IPv6 using various data ranges.



IMPLICATIONS AND DISCUSSION

IPv6 has the qualities of what Rogers calls a “preventive innovation,” or one that lowers the probability of some future negative event that may, or may not, happen. In the case of IPv6, that future event is the possibility of running out of IPv4 addresses. Rogers argued that preventive innovations have a particularly slow rate of adoption because potential adopters have a difficult time perceiving any relative advantage of the innovation. This lack of a relative advantage may explain the reluctance of organizations to adopt IPv6. For the past 20 years, IPv6 adoption has been mostly limited to what Rogers’ diffusion of innovations theory refers to as innovators, and only in the past three years included those considered as the early adopters.

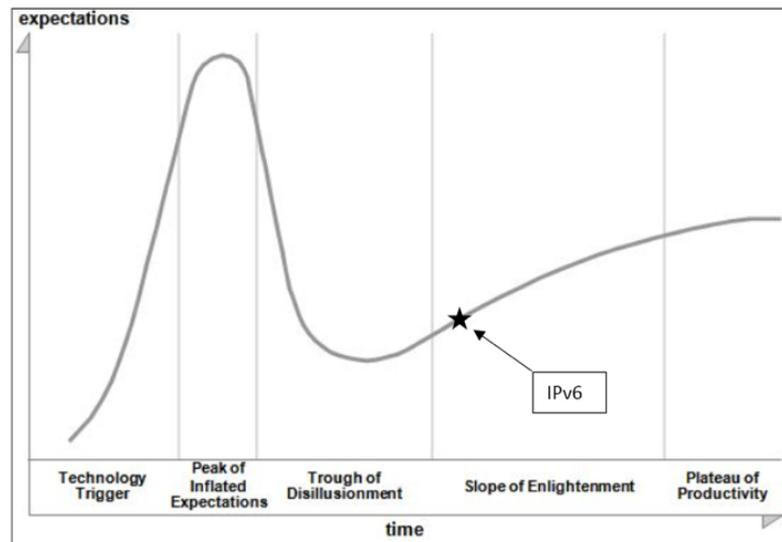
However, the slow rate of adoption is also explained by the fact that new communication technologies, such as IPv6, create an interdependence among adopters. Because IPv6 is not backward compatible with IPv4, it is of little use to an adopter to change communication protocol unless others also adopt. The typical analogy is the introduction of the telephone. The earliest adopters had a limited number of people to call, and not until mass adoption occurred did the technology flourish. For this reason, a critical mass of users must adopt IPv6 before it has much industrial utility. Thus, it is only after the point of critical mass is reached that the adoption of new communications technologies really accelerates.

Applying this concept to IPv6, the value is external to the adopter and relates to the size of the IPv6 community. Forecasting the size of the community at critical mass and forecasting the diffusion of the technology is a measure of the strength of network effects (Baraldi, 2012). In other words, until there is a critical mass of adopters and adoption of the technology becomes self-sustaining and rapidly accelerates, IPv6 has little advantage and considerable disadvantages for an individual adopter even though it is technologically superior to its predecessor, IPv4. While Rogers (2003) is careful to note that the exact point of critical mass is unknown and varies with different innovations and technologies, it usually occurs around the 10% to 20% adoption level. On a normal curve, this occurs at approximately one standard deviation below the mean or the 16% adoption level.

A final consideration is the confluence of a preventative innovation meeting rapid technology advances. At issue is the slow rate of IPv6 adoption and unforeseen technology advances that may leapfrog this Internet protocol with a superior approach before critical mass is reached. Predicting “unknown unknowns” is not possible, but one theory considered was the Gartner Hype Cycle. Research by Gartner, Inc., an information technology research and advisory company, produced a graphical representation for technology innovation’s expectations over time. While Rogers’ theory espouses eventual adoption, the Gartner hype cycle considers that not all technologies become commercially successful and/or live up to their potential (hype). Figure 5 shows the Gartner Hype Cycle and its phases starting with an “innovation trigger” which is similar to Rogers. However, the two theories diverge from this point as some technology takes on the persona of inflated expectations followed by disillusionment and a period of recovery to an eventual plateau, which would fall well below the Rogers’ adoption curve. Interpreted through the Gartner Hype Cycle, IPv6’s 20-year history has taken it through the technology trigger, up to a peak of inflated expectations, and has now climbed out of the trough of disillusionment into the “slope of enlightenment” and is in an “early mainstream” position. However, Gartner research states that “enabling IPv6 on the enterprise public Internet presence is now becoming critical” (Ramamoorthy, 2016, p.40). Because an expanding part of the internet’s population will be natively IPv6 - especially

in Asia, the developing world and 3G/4G mobile networks - public-facing services (such as websites) should be on the list to migrate to IPv6 now." (Ramamoorthy, 2016, p. 40).

Figure 5. Adapted from Gartner Hype Cycle. (Ramamoorthy, 2016)



CONCLUSION

Comparing the current IPv6 Gartner status with the Rogers' S-curve projections, the authors conclude that if the bottom of the disillusionment trough is taken as a starting point, one of two future paths will be realized. Either the Rogers' projections, per Table 4 and Figure 4, will continue, or if Gartner's hype-curve prevails, market penetration will flatten at 20% - 50% of the marketplace. Rogers' theory is based on critical mass and self-sustaining growth, and therefore does not delve into the particulars of any technology. However, the authors draw a distinction between "enabling technologies" and "technology applications" when considering which model, Rogers or the Gartner hype-curve, to follow. Since IPv6 is an enabling technology for communication, this research and findings support using Rogers' diffusion model for innovation adoption. In support, Gartner unequivocally states that IPv6 is needed for enterprise public Internet presence and go on to state "although we do not recommend migrating to IPv6 for all internal systems, by now, enterprises should have progressed with their planning, such as understanding what systems and equipment are IPv6-ready and which are not, as well as establishing a transition roadmap." (Ramamoorthy, 2016, p. 40).

As IPv6 is an enabling protocol and does not generate revenue, the slow pace of IPv6 adoption has also been attributed to the reluctance of organizations to expend resources and funds to deploy the protocol without a compelling return on investment (Beeharry & Nowbutsing, 2016; Domingues, Friacas, & Veiga, 2007; Nikkhah & Guerin, 2016). However, the authors conclude the logic behind "wait-and-see" is misguided. With the global IPv4 address pool virtually exhausted, organizations that have not already begun the process of adopting IPv6 risk accessibility problems with their websites and other Internet-connected services that are only reachable over IPv4.

The over-arching conclusion from this research is that IPv6 adoption, as measured by the Google user base, is nearing a point of critical mass which will cause adoption to accelerate

rapidly to a self-sustaining rate and achieve Rogers' Early Majority phase between July and August of 2017. Further, the projection is that IPv6 adoption will meet the 50% point to begin the Late Majority phase between March of 2021 and October 2022.

Therefore, the recommendations stemming from this research is provided for two distinct industries, Internet-based, consumer-facing commercial enterprises, and higher education institutions. All commercial enterprises, regardless of their business model, should begin planning to deploy IPv6 in order to protect and enhance market share. Higher education institutions with technology management, industrial technology, and/or information and communication technology degree programs that do not already incorporate IPv6 into a computer networking curriculum are already behind the curve. These universities should develop content that will give students the knowledge and skills to implement and support IPv6 in the industrial-commercial world.

This research is limited by the data sources used for correlation and predictive analysis. These datasets are considered to be representative of IPv6 adoption, but there may always be additional sources given with width and breadth of global use of the internet. That said, future research will continue this work as a longitudinal study, updating the metric bi-annually in order to validate both the researcher's prediction and future the case for using Rogers' diffusion of innovation model for enabling technologies.

REFERENCES

- AAAA and IPv6 connectivity statistics of top websites. (n.d.). Retrieved from <http://www.employees.org/~dwing/aaaa-stats/>
- ARIN Stats Index. (n.d.). Retrieved from <ftp://ftp.arin.net/pub/stats>
- Baraldi, A. L. (2012). The size of the critical mass as a function of the strength of network externalities: A mobile telephone estimation. *Economics of Innovation and New Technology*, 21(4), 373-396. doi:10.1080/10438599.2011.595920
- Beeharry, J., & Nowbutsing, B. (2016, August). Forecasting IPv4 exhaustion and IPv6 migration. In *Emerging Technologies and Innovative Business Practices for the Transformation of Societies (EmergiTech)*, IEEE International Conference on (pp. 336-340). IEEE.
- Classe, A. (2003). Don't panic, but be ready to adopt IPv6. *ComputerWeekly.Com*, Retrieved from <http://www.computerweekly.com/news/2240050520/Dont-panic-but-be-ready-to-adopt-IPv6>
- Coffman, K. G., & Odlyzko, A. M. (2002). Growth of the internet. *Optical Fiber Telecommunications IV B: Systems and Impairments, IP Kaminow and T. Li, eds*, 17(56).
- Coleman, L. (2014). Next generation internet policy in Japan, China and India. *Asia & the Pacific Policy Studies*, 1(3), 497-512.
- Colitti, L., Gunderson, S., Kline, E., & Refice, T. (2010). *Evaluating IPv6 adoption in the Internet. Passive and Active Measurement* (pp. 141-150). Springer Berlin Heidelberg. doi:10.1007/978-3-642-12334-4_15
- Czyz, J., Allman, M., Zhang, J., Iekel-Johnson, S., Osterweil, E., & Bailey, M. (2015). Measuring ipv6 adoption. *ACM SIGCOMM Computer Communication Review*, 44(4), 87-98.
- Deering, S., & Hinden, R. (1998). Internet protocol, version 6 (IPv6) specification.

- Dell, P., Kwong, C., Syamsuar, D., Francois, S., & Choy, K. (2007). A comparison of attitudes to IPv6 in three countries. In *Conference proceedings-corporate strategy and the path to a new economy*. Curtin University of Technology.
- Dhamdhere, A., Luckie, M., Huffaker, B., Elmokashfi, A., & Aben, E. (2012). Measuring the deployment of IPv6: Topology, routing and performance. *Proceedings of the 2012 ACM Conference on Internet Measurement Conference*, 537-550. ACM
- Domingues, M., Friacas, C., & Veiga, P. (2007). Is global IPv6 deployment on track? *Internet Research: Electronic Networking Applications and Policy*, 17(5), 505-518.
- Doyle, J. (2008). European Union plans widespread IPv6 deployment by 2010. *NetworkWorld.com*, Retrieved from <http://www.networkworld.com/article/2344470/cisco-subnet/european-union-plans-widespread-ipv6-deployment-by-2010.html>
- Droms, R. (1997). *Dynamic host configuration protocol*. (No. RFC 2131).
- Egevang, K., & Francis, P. (1994). *The IP network address translator (NAT)* (No. RFC 1631).
- Fuller, V., Li, T., Yu, J., & Varadhan, K. (1993). *Classless inter-domain routing (CIDR): an address assignment and aggregation strategy* (No. RFC 1519).
- Garretson, C. (2005, Aug 1.). Federal mandate to boost IPv6, but- *NetworkWorld.com*, Retrieved from <http://www.networkworld.com/article/2312998/lan-wan/federal-mandate-to-boost-ipv6-but----.html>
- Google IPv6 statistics (n.d.). Retrieved from <https://www.google.com/intl/en/ipv6/statistics.html>
- Hovav, A., & Schuff, D. (2005). Global diffusion of the internet V - the changing dynamic of the internet: Early and late adopters of the IPv6 standard. *Communications of the Association for Information Systems*, 15, (1). 14
- Hubbard, K., Koster, M., Conrad, D., Karrenberg, D., & Postel, J. (1996). *Internet registry ip allocation guidelines* (No. RFC 2050).
- Huston, G. (2017a). Retrieved April 9, 2017, from the IPv4 Address Report: <https://ipv4.potaroo.net/>
- Huston, G. (2017b). Retrieved January 17, 2016, from the CIDR Report: <http://www.cidr-report.org/as2.0/>
- Internet Society (n.d.). Retrieved from <http://www.internetsociety.org/ipv6/archive-2011-world-ipv6-day>
- Khan, R., & Sindi, H. F. (2012, June). Necessity to migrate to IPv6. In *Information Society (i-Society), 2012 International Conference* (pp. 210-215). IEEE.
- Kleinrock, L. (2010). An early history of the internet [History of Communications], *IEEE Communications Magazine*, vol. 48, no. 8, pp. 26-36, August 2010. doi: 10.1109/MCOM.2010.5534584
- Ladid, L. (2009, June). IPv6 - The next big bail-out: Will IPv6 save the Internet? In *Proceedings of the International Conference on Computer Systems and Technologies and Workshop for PhD Students in Computing*, p.2. ACM

- Nikkhah, M., & Gurin, R. (2015). Migrating the internet to IPv6: An exploration of the when and why. *IEEE/ACM Transactions on Networking*, 24(4), 2291-2304.
- Nikkhah, M., Gurin, R., Lee, Y., & Woundy, R. (2011, December). Assessing IPv6 through web access a measurement study and its findings. In *Proceedings of the Seventh Conference on Emerging Networking Experiments and Technologies*, p. 26. ACM
- Nordrum, A. (2016). Popular internet of things forecast of 50 billion devices by 2020 is outdated. *IEEE Spectrum*, 18. Retrieved from <https://spectrum.ieee.org/tech-talk/telecom/internet>
- Popoviciu, C., & Dini, P. (2006, August). IPv6 as a practical solution to network management challenges. In *Computing in the Global Information Technology, 2006. ICCGI'06. International Multi-Conference on* (pp. 5-5). IEEE.
- Postal, J. (1978). Internet protocol specification. Information Sciences Institute, University of Southern California.
- Ramamoorthy, G. (2016). *Hype cycle for IoT standards and protocols, 2016*. Gartner, Inc.
- Rogers, E. (2003). *Diffusion of Innovations (5th ed.)*. New York, N.Y.: Simon & Schuster, Inc.
- Route Views Project (n.d.). Retrieved from <http://www.routeviews.org/>
- World IPv6 Launch (n.d.). Retrieved from <http://www.worldipv6launch.org/>
- Wu, J., Wang, J., & Yang, J. (2011). CNGI-CERNET2: An IPv6 deployment in China. *ACM SIGCOMM Computer Communication Review*, 41(2), 48-52.