Migrating the Internet to IPv6: 
An Exploration of the When and Why 

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Abstract—The paper documents and to some extent elucidates the progress of IPv6 across major Internet stakeholders since its introduction in the mid 90’s. IPv6 offered an early solution to a well-understood and well-documented problem IPv4 was expected to encounter. In spite of early standardization and awareness of the issue, the Internet’s march to IPv6 has been anything but smooth, even if recent data point to an improvement. The paper documents this progression for several key Internet stakeholders using available measurement data, and identifies changes in the IPv6 ecosystem that may be in part responsible for how it has unfolded. The paper also develops a stylized model of IPv6 adoption across those stakeholders, and validates its qualitative predictive ability by comparing it to measurement data.

I. INTRODUCTION

The Internet has grown far beyond what its original designers anticipated. As a result and even if the original 32-bit IPv4 addresses may have initially seemed an inexhaustible resource, we have run out of them. The need for a solution was recognized early on and led to the standardization of IPv6 in 1995 [11]. IPv6 boasts a 128-bit address field, and therefore this time a truly inexhaustible address space. However, even if IPv6 was standardized close to 20 years ago and the IPv4 address exhaustion is now a reality, the Internet’s migration to IPv6 has been anything but smooth, to the point that many have at times expressed doubts it would ever happen.

Migrating the Internet to IPv6 involves two dependent factors, the availability (and stability) of IPv6 solutions across the Internet infrastructure (from applications to network components), and the adoption (and use) of those solutions by Internet stakeholders. In that context, the goals of this paper are two-fold. It seeks, using empirical data gathered over time by us and others, to document and elucidate the progress of the availability and use of IPv6 across major Internet stakeholders (more on this below). It also aims to build and validate a simple model that captures some of the cause and effect relationships that produced major changes in those empirical observations.

Empirical data suggest an evolution that went through roughly three major phases since IPv6 was first introduced. The first phase, from IPv6 inception (circa 1995) until about 2009, is best characterized as stagnant, i.e., IPv6 usage experienced little or no growth even if IPv6 as a technology matured considerably during that time. As we argue later in the paper, the lack of maturity (compared to IPv4) of initial versions of IPv6 solutions likely contributed to IPv6 limited early appeal. A second phase followed from 2009 until early 2012, where while IPv6 usage remained mostly marginal, there were telltale signs of its emergence. A third phase started in late 2012, with IPv6 usage slowly accelerating, so that an eventual migration of the Internet to IPv6 now appears likely, albeit still distant.

The paper’s contributions are in documenting and to some extent revealing the stages IPv6 development and deployment went through across stakeholders. The paper also proposes a simple model to explicate the cause and effect relationships that have and are driving the Internet’s migration to IPv6, and offers qualitative evidence of the model’s predictive ability.

The rest of the paper is organized as follows. Section II briefly reviews relevant prior works. Section III introduces Internet stake-holders and their respective roles, and reports their use of IPv6 over time. Section IV identifies factors that likely affect the decisions of Internet stakeholders when it comes to IPv6, and discusses the impact that changes in these factors may have had. Section V introduces a simple model to capture these decision processes, and uses it to qualitatively reproduce the trends reported in the data of Section III. Section VI summarizes the paper’s contributions.

II. RELATED WORKS

The Internet’s transition to IPv6 has been extensively studied, and we only review a sample of representative works, some of which are detailed further in the next section. Most works fall in either one of two major categories: measurement (empirical) or modeling (analytical) studies.

Empirical studies have sought to measure IPv6 availability and performance at both an Internet-wide scale and by focusing on individual components. See for example [37] for a useful albeit slightly dated overview of the status of IPv6 across the Internet, or CAIDA [3], [12] that arguably offers one of the more comprehensive repository of related information. Other studies have focused on quantifying adoption across Autonomous Systems (ASes) [15], [39], among end-users [16], and in Operating Systems (OSes) [8], [21]. Performance issues in OSes have been explored in [34], [49], while investigations aimed at end-to-end performance have compared IPv4 and IPv6 using metrics such as path delay and packet loss [47].

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1IANA allocated its last large block of IPv4 addresses in February 2011, and the RIRs are rapidly following suit, i.e., see http://www.potaroo.net/tools/ipv4 for an up-to-date status.
On the modeling front, many studies have sought to formulate the IPv6 adoption question in the context of an economic framework, in an attempt to capture the many interacting factors affecting it [14, 18, 35, 42].

Finally, a recent comprehensive investigation of the status and progress of IPv6 prevalence across the Internet ecosystem was reported in [9]. It measured changes in address allocation, DNS readiness, routing, etc., and is closest in motivations to this paper. An important difference though is in our attempt to develop a model that can explain some of the measurement results on which we report. In particular, this paper combines measurements and models to not only document, but also to some extent explain the evolution of IPv6 adoption.

III. QUANTIFYING THE INTERNET’S MIGRATION TO IPv6

This section reports on the evolution of IPv6 “adoption” across Internet stakeholders. Those stakeholders are diverse and adopting IPv6 has very different meanings across them. Hence, it is useful to first describe them, together with what IPv6 adoption means for each. This is the goal of the next subsection, which also introduces how IPv6 adoption is measured.

A. Internet Stakeholders

There has been much interest for what drives the Internet’s growth and the roles its stakeholders play, e.g., as demonstrated by the creation of an OECD Working Group on Internet Governance[3]. A recent report [28] offers an initial taxonomy of Internet stakeholders that lists, among others, Internet Technology Developers (ITDs), Internet Service Providers (ISPs), Internet Content Providers (ICPs), and Internet (content) consumers or users. We focus on those, as they are the major actors in the Internet’s migration to IPv6, and review their roles and how to best quantify their migration to IPv6. This is followed by the presentation of measurement data, gathered by others and us, that offers a timeline for the Internet’s migration to IPv6.

1) ITDs: They build the technologies behind the Internet, and are, therefore, necessary precursors to any new Internet capability, including IPv6. In other words, they develop and release IPv6 versions of their products that are then deployed by other stakeholders to realize an IPv6 Internet. Hence, measuring IPv6 “adoption” among ITDs calls for tracking the availability and stability of IPv6-capable products (an IPv6 version may be available, but until it is as stable as its IPv4 counterpart, it is unlikely to be widely adopted).

2) ISPs: They provide (Internet) connectivity to users and ICPs through equipment purchased from ITDs. Their adoption of IPv6 is through upgrading their infrastructure to IPv6, i.e., by supporting routing and forwarding of IPv6 traffic. This adoption can be measured in a number of different ways, but we rely on two representative metrics: (i) the number of major transit Autonomous Systems (ASes) that advertise IPv6 capabilities; (ii) the number of (peering) links that exist between them. The first offers insight into the overall penetration of IPv6 among ISPs, while the latter captures the density of IPv6 connectivity (both affect end-to-end connectivity quality).

3) ICPs: They own the content that makes up for much of the Internet’s value (to users). For an ICP, IPv6 adoption implies native IPv6 access to its content. This requires upgrades to its local infrastructure (or that of its hosting provider), and advertising IPv6 accessibility (through DNS) to users. Measuring IPv6 accessibility among ICPs, therefore, calls for tracking which ICPs advertise IPv6 addresses. ICPs, like ISPs, are, however, diverse in size and popularity, and accounting for those differences can offer a more accurate perspective on IPv6 adoption. In the next section, we report measurements of both overall IPv6 adoption by ICPs, as well as based on their popularity. We use the latter to later estimate the volume of IPv6 traffic contributed by ICPs.

4) Users: Users derive “value” from accessing content, use of Internet services, etc. They are mostly oblivious to technology choices, but their expectations for the underlying technology have implications for IPv6: (i) IPv6 applications should be available and stable; (ii) IPv6 connectivity should be on par with IPv4; and (iii) content should be accessible over IPv6. Hence, using IPv6 addresses for new users once IPv4 addresses have been exhausted, is feasible only if those conditions are met. Because a comprehensive census of IPv6 users is not feasible, we measure IPv6 “adoption” among users using statistical estimates based on representative samples.

B. Assessing the Internet’s Migration to IPv6

This section presents empirical data on the evolution of IPv6 adoption among ITDs, ISPs, ICPs, and users. As mentioned before, the data points to a three-phase adoption:

Phase I [1995 – 2009]: Stagnation;
Phase II [2009 – 2011]: Emergence;
Phase III [2011–]: Acceleration.

We provide next evidence in support of this conclusion.

1) ITDs: There are many technologies involved in delivering Internet connectivity. We focus on IPv6 progress for a representative subset, namely, routers/switches, Operating Systems (OSes), and applications.

a) Router/Switch Manufacturers: Support for IPv6 came in early in routers/switches, e.g., between 1998 to 2000, when Juniper introduced its first series of IPv6-capable routers [27]. Cisco quickly followed suit by introducing IPv6 capability in CISCO IOS routers and L3 switches. Early availability, however, did not equate quality/stability. In particular, a 2007 study [50] showed that IPv6 forwarding plane lagging behind its IPv4 counterpart, with routers/switches the primary culprits. Those early stability problems are, however, now over and a study we conducted in 2011 [36] showed that the IPv6 and IPv4 forwarding planes now perform similarly.

b) OS Developers: Support for IPv6 appeared first in Linux 2.1.8 (in 996), but remained in experimental status until around 2005. Microsoft Windows 2000 did support IPv6, but not by default, and Microsoft did not ship Windows OSES with default IPv6 support until 2007 (Windows Vista). Apple introduced IPv6 by default in 2003 in Mac OS X v10.3. As with routers, early IPv6 offerings were plagued by problems, e.g., [49]. Performance, however, improved over time across all operating systems, e.g., [34] showed in 2009 that IPv6 and
IPv4 performance were on par in Microsoft Windows Vista and in Linux Ubuntu. As of today, IPv6 is available in nearly all operating systems (Windows Phone 8 added support for IPv6 in 2011, and Android with its Lollipop release) with few if any remaining performance problems.

c) Internet Application: A comprehensive list of IPv6 capable applications (with their IPv6 launch date/version) is available at [22], [23]. In this subsection, we rely on a set of popular applications, to gauge the evolution of applications’ IPv6 readiness. Table 1 gives the launch date of the IPv6 version of applications in this target set (or NA when an IPv6 version is not yet available). The table indicates a slow but steady progress in adding IPv6 support from the late 1990’s onward, with IPv6 support not always synonymous with stability or quality. Consequently, many applications initially shipped with IPv6 disabled by default, and some still do (e.g., VMware vSphere ESX/ESXi had IPv6 disabled by default until v. 5.1 [46]).

In summary, after a relatively slow start, IPv6 support is now readily available across all major Internet technologies. Maturity and stability of those offerings is, however, relatively recent. The lack of stability in early versions may partially explain some of the findings on which we report next, namely, a relative stagnation of IPv6 adoption among other Internet stakeholders (ISPs, ICPs, and users) in IPv6 early years.

2) IPv6 status across ISPs: As ISPs upgrade their network to IPv6 and advertise it to other ISPs, they affect overall IPv6 Internet connectivity. To measure this impact, we focus on IPv6 adoption among “major transit ISPs” that carry a large share of Internet traffic. CAIDA has been conducting such a study since 2005 [3], tracking all major IPv4 and IPv6 transit ASes and their peering links. We summarize in Table II some of CAIDA’s more salient results, which illustrates the evolution of IPv6 adoption among major transit ASes.

CAIDA’s data show that by 2009 barely 500 or just over 2% of the major transit ASes were IPv6 capable. The next two years, 2009 – 2011, hint at the beginning of a transition with a doubling of this number to 1183, with IPv6 penetration itself also nearly doubling. This trend continued, and the number of IPv6 capable transit ASes again doubled by late 2013. This indicates that in spite of a slow start, a critical threshold seems to have been crossed, with IPv6 deployment now expanding rapidly. The progression of the number of IPv6 peering links/sessions (a measure of IPv6 connectivity) displays a similar trend (last three columns of Table II). Ripe Labs carried out a similar study [39] recording all ASes (from transit to edge, including content ISPs) advertising at least one IPv6 route, which yielded results consistent with the three-phase progression of CAIDA’s more focused data.

3) ICPs IPv6 Accessibility: Internet content is accessible (to users) in many different forms, but websites host the vast majority of it. Tracking IPv6 accessibility across public websites, therefore, offers a reasonable estimate of IPv6 deployment among content providers. Early (circa 2004) estimates [47] reported that barely 1,000 out of more than 51 millions websites (see [51]) were IPv6 accessible, i.e., a negligible fraction (less than 0.001%). This confirms the limited appeal of IPv6 in those initial years.

In 2009, we started an independent set of measurements, tracking IPv6 accessibility of Alexa’s top one million websites (see [http://www.alexa.com]). Alexa’s top one million websites span a broad range of categories (commercial, educational, entertainment, etc.) and popularity, and offer a representative sample of the now more than 1 billion websites in existence (as of September 2014 based on [www.internetlivestats.com]). The methodology behind our measurements is documented in [36], but essentially consists of three steps: (i) issuing DNS queries for websites in the list; (ii) downloading the homepage; (iii) time-stamping and recording the results in a database.

Fig. 1 reports the results of our measurements, showing that while IPv6 adoption remained low in the 2009 – 2011 period, it improved on its earlier marginal adoption (it grew from essentially 0 to about 0.2% by early 2011). A momentous change appears to have occurred in 2011, likely spurred by the “official” exhaustion of IANA’s IPv4 address pool in February 2011, and by a greater awareness contributed by events such as the World IPv6 Day [http://www.worldipv6day.org] that produced a large albeit somewhat transient increase in mid 2011. The temporary gains of the World IPv6 Day were eventually cemented after the World IPv6 Launch in mid 2012 [http://www.worldipv6launch.org], with IPv6 adoption transitioning to a faster pace (approximately doubling every

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2The list now includes over 8 millions websites, because of churn in Alexa’s top 1 million list and additions from local DNS caches.

3Websites accessible only over IPv6 represent only a minute fraction of monitored websites, and are, therefore, ignored in the measurements.
<table>
<thead>
<tr>
<th>Year</th>
<th># of ASes (IPv4)</th>
<th># of ASes (IPv6)</th>
<th>% of IPv6 ASes</th>
<th># of Peering Sessns. (IPv4)</th>
<th># of Peering Sessns. (IPv6)</th>
<th># of IPv6 Peering per 100 IPv4 Peering</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>23k</td>
<td>515</td>
<td>2.24%</td>
<td>50k</td>
<td>1904</td>
<td>3.8</td>
</tr>
<tr>
<td>2011</td>
<td>29k</td>
<td>1183</td>
<td>4.08%</td>
<td>78k</td>
<td>2738</td>
<td>3.51</td>
</tr>
<tr>
<td>2013</td>
<td>34k</td>
<td>2419</td>
<td>7.11%</td>
<td>109k</td>
<td>8881</td>
<td>8.15</td>
</tr>
</tbody>
</table>

TABLE II. INTERNET AS CORE EVOLUTION (DATA FROM CAIDA’S WEBSITE [3]).

![IPv6 Adoption among Alexa’s Top 1M Websites.](image1)

**Fig. 1.** IPv6 Adoption among Alexa’s Top 1M Websites.

![IPv6 Adoption among the Top 100, Top 1k, and Top 1M Websites.](image2)

**Fig. 2.** IPv6 Adoption among the Top 100, Top 1k, and Top 1M Websites.

year), and reaching a penetration close to 5% by mid 2014. This roughly mirrors the trend observed for ISPs.

Fig. 2 expands the view of Fig. 1 showing IPv6 accessibility as a function of a website’s popularity, i.e., it reports separately IPv6 accessibility for the top 100, top 1000 and top 1 million websites. The figure clearly illustrates that more popular websites are more likely to be IPv6 accessible (by as much as a factor 6), though all categories follow similar trends.

4) *Estimating the IPv6 User Base:* Evaluating the extent to which users have IPv6 connectivity is a challenging problem, not only because of the size of the user population, but also because of the diversity in how that connectivity is used when available, *e.g.*, many OSes are configured to prefer IPv4 over IPv6 when both are available [43]. Furthermore, changes usually happen at a coarse granularity, *e.g.*, because of an ISP’s conversion, large scale monitoring is important. For that purpose, we rely on data gathered by Google. Google sites see billions of accesses daily from across the globe, and can monitor how many were over IPv6 [16]. Google’s data may under-sample regions such as China where popular alternatives to its services exist, but it nevertheless offers a reasonable assessment of the evolution of the IPv6 user base worldwide.

Google’s data show that by 2009, barely 0.2% of users were accessing its services over IPv6. This grew to 0.3% over the next two years, after which growth started to accelerate to reach 3% by early 2014 (a ten-fold increase). This roughly matches the three phase growth pattern of ISPs and ICPs.

The next section seeks to develop a better understanding for the reasons behind this three-phase adoption pattern.

IV. IPV6 ECOSYSTEM

Explicating the evolution of the Internet’s migration to IPv6 calls for a better understanding of what drives Internet stakeholders to adopt IPv6 in the first place. In other words, what factors affect those decisions and how? Users are mostly oblivious to what technology is used to connect them to the Internet, *i.e.*, IPv4 or IPv6, and their choices are typically dependent on decisions made by ITDs, ISPs and ICPs. As a result, we focus on these latter three stakeholders.

All three are complex decision makers, so that modeling their decisions unavoidably involves simplifications. A common approach is to rely on an objective or utility function that (rational) decision makers then seek to maximize [32]. Utility functions vary across stake-holders, but typically incorporate factors such as cost and quality of a product, its value, how widely it is adopted, etc. In this section, we first posit a number of factors and their influence on the decisions of ITDs, ISPs, and ICPs. We then identify and characterize changes in those factors, and establish how they may have produced the three-phase migration process documented in the previous section.

A. Decision Factors

In identifying factors and their role in the (IPv6) “adoption” decisions of ITDs, ISPs and ICPs, we consider each separately.

1) *ITDs:* They develop IPv6 versions of their products based on expectations of demand for those products. As alluded in Section III-B1 this demand, however, depends on the availability of those very same products (IPv4 versions were, at least initially, a perfect substitute); in the process creating a chicken-and-egg problem that may have contributed to their slow maturation. The problem is compounded by the fact that availability alone is not sufficient. Because IPv4 serves as a benchmark to which IPv6 is compared, the quality and stability of IPv6 products affects demand; in particular by ICPs whose revenues are affected by the quality of users’ experience. Formalizing the impact of those dependencies in the context of a simple model is the subject of Section V.

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6See for example, T-Mobile’s recent announcement [41] to use only IPv6 for users with Android 4.4 KitKat phones.
2) ISPs: The growing scarcity of IPv4 addresses is the primary motivation for an ISP to adopt IPv6. This, however, calls for upgrading its network and operational practices. This one-time cost can result in an ISP deferring such a decision, especially since alternatives exist for dealing with IPv4 address shortages. Those include private IPv4 addresses, or securing additional public IPv4 addresses, e.g., through “markets” that are emerging to meet such a demand (see Section V-B2).

Large-scale use of private IPv4 addresses has many drawbacks, including the need to deploy “Carrier Grade NATs” (CGNs) or NAT444, and more importantly offers little long-term strategic value (see [26], for a related discussion). Purchasing (new) public IPv4 addresses avoids those problems, but has a cost of its own. One that will likely increase as the supply of available public IPv4 addresses dwindles. This is in part why ISPs such as CERNET2 in China, and Verizon Wireless and T-Mobile in the U.S., opted to start using IPv6. CERNET2 [48] (an academic network), already had over 400k IPv6-only users in 2009, and is expected to reach 3 millions by the end of 2015 (see [4], [5]). Similarly, Verizon Wireless and T-Mobile are now primarily relying on IPv6 addresses for new cell-phone subscribers [41], [44].

An ISP’s decision to adopt IPv6 and start assigning IPv6 addresses to its users will, therefore, largely depend on the tension between upgrade costs and the cost of procuring new public IPv4 addresses once it exhausts its current pool. The simple model of Section V seeks to capture this tension.

It should be noted though that adopting IPv6 has implications beyond allocating IPv6 addresses to new users. In particular, users not assigned a public IPv4 address need some form of “translation” service to connect to the public IPv4 Internet. For example, CERNET2 and T-Mobile use IPv6-to-IPv4 translation mechanisms called IIVI and 464XLAT, respectively. Verizon Wireless, on the other hand, assigns both private IPv4 and IPv6 addresses to users. A user’s IPv6 address is used to connect to IPv6 accessible destinations, while connectivity to the public IPv4 Internet is through the user’s private address and NAT444 devices. Translation requirements will, however, eventually disappear once the Internet is fully IPv6 accessible. Hence, while ISPs will incur translation costs after exhausting their public IPv4 addresses, these costs alone are unlikely to play a major role in their decision to upgrade to IPv6.

3) ICPs: They are mostly oblivious to how their content is accessed, i.e., whether over IPv4 or IPv6, and mostly concerned with how access may affect their revenue. ICPs derive revenues from users in a variety of ways [38], from a user’s number of clicks (e.g., Google), to a user’s purchasing a good (e.g., Amazon), to how much time a user spends consuming content (e.g., Facebook), etc. In spite of their diversity, these have in common that they are impacted by connectivity quality (see [2] for an investigation with a “per-click” revenue model, and [40] for a general study of how a site’s “speed” affects conversion rates). Performance of IPv6 users is well known to be negatively affected by translation [1], [6], [13], [31], which can then provide an ICP with the motivation to become IPv6 accessible. This is, however, predicated on IPv6 connectivity being of sufficient quality, and on the number of IPv6-only users being high enough to justify the change and its cost.

The former is well illustrated by the “white-listing” [17] that content providers such as Google rely on to control IPv6 connectivity to their content (IPv6 connectivity is allowed only if its quality is on par with that of IPv4). The latter depends on both the expected growth in the number of IPv6 users and on the cost of upgrading the ICP’s infrastructure and operational procedure (or those of its hosting provider) to IPv6. This cost is usually proportional to the size of the ICP.

There are clearly other factors that can contribute to an ICP’s decision to become IPv6 accessible, e.g., greater ease of obtaining Provider Independent (PI) IPv6 addresses [29]. However, improving connectivity quality, and consequently revenue, is one factor common to all ICPs. In contrast, the ability to, say, obtain a PI IPv6 address is attractive only to ICPs without a PI IPv4 address, and this is a relatively small fraction (a random sample of 100 websites in the top 1 million showed that about 80% of them already had a PI IPv4 address). Hence, we expect IPv6 connectivity quality and its impact on ICPs revenue to be a major factor in their decision to become IPv6 accessible.

B. Ecosystem changes

Section III documented changes over time in IPv6 adoption by Internet stakeholders, while Section IV-A put forward factors that are likely to shape their decisions. In this section, we investigate the extent to which those factors evolved over time, and whether those changes can explain the three phases migration pattern we observed.

As a prelude to this investigation and as a means to classify the impact of the different factors identified in Section IV-A we record them in Table III according to how increases (↗) in each one of them affect decision makers. The (⊕) and (⊖) symbols in the “Effect” columns indicate whether an increase has a positive or negative impact on a stakeholder’s utility. Conversely, an (×) symbol signals that the factor does not affect the stakeholder’s utility, while a ~ indicates that the factor should only have a marginal impact.

1) Demand for IPv6 Technologies: It is not easy to quantify the demand for IPv6 technologies. However, anecdotal evidence points to near-zero demand in 1995 (the birth of IPv6),

<table>
<thead>
<tr>
<th>Factors</th>
<th>ISPs</th>
<th>ICPs</th>
<th>TTDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand for IPv6 Tech.</td>
<td>X</td>
<td>X</td>
<td>⊕</td>
</tr>
<tr>
<td>IPv4 Address Cost</td>
<td>⊖</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Upgrade Costs</td>
<td>⊖</td>
<td>⊖</td>
<td>X</td>
</tr>
<tr>
<td>Translation Cost</td>
<td>~</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td># of IPv6 Users</td>
<td>~</td>
<td>⊖</td>
<td>~</td>
</tr>
<tr>
<td># of IPv6 ICPs</td>
<td>⊖</td>
<td>⊖</td>
<td>~</td>
</tr>
<tr>
<td>IPv6 Quality</td>
<td>X</td>
<td>⊖</td>
<td>⊖</td>
</tr>
</tbody>
</table>

TABLE III. EFFECT OF INCREASES IN IPV6 ADOPTION FACTORS.

An exhaustive census is challenging, as accurately verifying address ownership is complex and involves manually cross-checking multiple databases.
followed by government mandates providing some initial impetus in the late 90’s, before the looming scarcity of IPv4 addresses became more apparent and resulted in a substantial demand today, e.g., in 2014 Verizon Wireless proceeded to allocate IPv6 addresses to over 45% of its approximately 90 millions subscribers [45]. ITDs likely responded to or anticipated those changes, which may explain the progressive maturation of IPv6 core technologies in the 1990’s, followed by the rapid expansion of IPv6 enabled end-devices and applications in the late 2000’s.

2) IPv4 Address Cost: As mentioned earlier, although IANA and most RIRs have run out of IPv4 address blocks to allocate, this does not mean that all public IPv4 addresses are in use. As a matter of fact, recent studies [10], [19] estimate that of the order of about 30% of all public IPv4 addresses are still available (unused). As a result, mechanisms, e.g., markets, have started to appear to facilitate access to those unused addresses. Specifically, following the purchase in 2011 of Nortel’s IPv4 addresses by Microsoft at a cost of about $11 per address (http://goo.gl/ZIA18), several private markets have emerged such as the IPv4 Market Group (http://ipv4marketgroup.com) and IPv4Auctions.com. Both report a steady stream of IPv4 addresses sales at prices ranging from $7 to $18 in 2013 and 2014, with larger blocks, i.e., /15’s and /16’s having typically lower per address costs than smaller block.

The role of those markets in facilitating the exchange of IPv4 addresses notwithstanding, their biggest impact is likely to signal to ISPs that IPv4 addresses are not free anymore. As mentioned earlier, although IANA and most RIRs have run out of IPv4 address blocks to allocate, this does not mean that all public IPv4 addresses are in use. As a matter of fact, recent studies [10], [19] estimate that of the order of about 30% of all public IPv4 addresses are still available (unused). As a result, mechanisms, e.g., markets, have started to appear to facilitate access to those unused addresses. Specifically, following the purchase in 2011 of Nortel’s IPv4 addresses by Microsoft at a cost of about $11 per address (http://goo.gl/ZIA18), several private markets have emerged such as the IPv4 Market Group (http://ipv4marketgroup.com) and IPv4Auctions.com. Both report a steady stream of IPv4 addresses sales at prices ranging from $7 to $18 in 2013 and 2014, with larger blocks, i.e., /15’s and /16’s having typically lower per address costs than smaller block.

The results are in Fig. 3 and assume that all users request the particular type of request. The figure shows that even if recent growth in the number of IPv6-only users contributed to an increase in translation traffic, this volume remains small (less than 0.4% of Verizon Wireless traffic).

5) Number of IPv6 Users: As seen in the Google data of Section III, the number of IPv6 users has been steadily increasing. This trend is echoed in various public reports pointing to faster IPv6 growth, especially in the Asia-Pacific region, where the scarcity of public IPv4 addresses is more severe. A larger IPv6 user base should entice more ICPs to become IPv6 accessible, which would reduce the need for translation and in the process make IPv6 more attractive to ISPs. These positive dependencies could trigger a virtuous cycle.

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Footnotes:


[9] Those users do not have a public IPv4 address.

adoption spiral of the kind we appear to be witnessing in what we termed Phase III. The model of Section V offers a possible option for formalizing these dependencies.

6) Number of IPv6-accessible ICPs: The measurement results of Section III indicate a strong recent uptick in the number of IPv6 accessible ICPs, which, if the trend persist, should further strengthen IPv6 momentum.

7) IPv6 connectivity quality: This is the last and possibly most important change in the IPv6 ecosystem, namely, the coming of age of IPv6 when it comes to technology maturity. This maturity manifests itself through improvements in both stability and performance; improvements that finally allowed IPv6 to be on par with IPv4 and in some cases better. We illustrate this in Fig. 4 that reports the results of a measurement study started in 2009 (see [36] for details). The study compares IPv6 and IPv4 web download speeds from several vantage points for a large set of websites (including all top 1M sites).

Fig. 4 displays the fraction of web servers accessible over both IPv6 and IPv4 for which IPv6 download speed was equal or higher than with IPv4. The figure shows a period of continuous improvement until early 2013, at which point IPv6 was at least as good as IPv4 90% of the time. The remaining gap of 20% is comparable to that of IPv4, which also lags behind IPv6 for 20% of websites. This is not unexpected when comparing two (now) mostly equivalent technologies, where small configuration or load differences can easily result in one outperforming the other. This hypothesis was confirmed by verifying that when IPv6 is strictly better than IPv4, and vice-versa, the difference in performance is small, i.e., in the range 5 to 10 kbytes/sec.

The results demonstrate that, as of 2013, IPv6 and IPv4 are mostly on par performance-wise. This is undoubtedly the product of improvements made by ITDs. However and interestingly, greater technology maturity is not the only factor behind this change; adoption decisions by ISPs also played a role. In order to better understand this, it is useful to take a closer look at the different components that affect connectivity quality. Specifically, end-to-end connectivity is affected by both end-systems and the network. We proceed next to drill down on each one of these components.

![Fraction of websites with better or equal IPv6 connectivity than IPv4.](image)

Fig. 4. Fraction of websites with better or equal IPv6 connectivity than IPv4.

a) End-Systems: IPv6 support in end-systems is dominated by decisions from ITDs, i.e., when do they first make it available and how quickly do they ensure that the new software is stable. As reported in Section III-B1, IPv6 availability was uneven across OSes with support and improvement across many platforms happening as late as 2009. However, IPv6 support is now stable across all OSes, so that their IPv6 performance is not of concern anymore.

b) The Network: IPv6 network performance depends on both routers’ ability to forward IPv6 packets (the data plane), as well as how the path connecting the source to the destination is chosen (the control plane). The first factor depends solely on decisions by ITDs, i.e., their ability to release product upgrades that deliver identical packet forwarding performance in IPv6 and IPv4. The second factor, although clearly affected by ITDs’ decisions, is also, as we discuss below, very much dependent on adoption decisions made by ISPs.

There is no denying that IPv6 data plane performance was initially lagging behind that of IPv4. A 2007 study [50] identified a non-trivial gap in end-to-end performance between IPv6 and IPv4, and assigned most of the blame to the data plane. In 2009, we started an independent measurement study aimed at assessing the extent to which this performance gap still existed, and what contributed the most to it. The study involved multiple sources (clients) geographically distributed around the world, which continuously probed over a million websites (including Alexa’s top 1M) for IPv6 access, and for those accessible over both IPv4 and IPv6 measured their respective web access performance (download speeds). The study’s methodology and its results are documented in [36]. It showed that while as of 2011 a performance gap remained, it was not anymore caused by differences in data plane performance. Instead, control plane factors, i.e., routing and peering decisions affecting IPv6 paths, were the main contributors.

The determination that the IPv6 data plane had finally achieved performance parity, and conversely that control plane factors were now primarily responsible for the remaining performance gap, involved a two step analysis of the available measurement data:

| Same Path Destinations | Top 100K Sites | 94% | Top 1M Sites | 90% |
| Diff. Paths Destinations | 70% | 74% |

**TABLE IV. IPv6 Better or Equal to IPv4 Between 2009-2011.**

**Step 1** focused on instances of end-to-end connectivity for which IPv4 and IPv6 made identical control plane decisions, i.e., IPv4 and IPv6 packets are forwarded along the same path. This isolates the data plane as the main source of (network) performance differences. The first row of Table IV shows nearly identical performance, which established the parity of the IPv4 and IPv6 data planes.

**Step 2** considered cases for which IPv4 and IPv6 control plane decisions differ, i.e., the paths chosen by IPv4 and IPv6 routing are different. Note that such differences arise primarily because of adoption (or lack thereof) decisions. Specifically, instead of following the optimized IPv4 path, IPv6 routing is required to detour (or tunnel) around routing domains (ISPs) that have either not deployed IPv6 or opted not to establish
IPv6 peering sessions with their neighbors. Measurement data revealed that a substantial performance gap remained in those cases (second row of Table VIII). Hence, establishing the control plane, and therefore ISP's adoption decisions, as the main contributor to IPv6 continuing performance lag.

In summary, as of 2011 IPv6 was finally on par with IPv4 technology-wise, but while the performance gap had narrowed, it had not disappeared. Limited adoption (among ISPs), which IPv6 initial technical immaturity had contributed to, was still preventing parity by forcing the use of less efficient paths. In other words, IPv6 low adoption among ISPs was potentially slowing its future adoption by perpetuating a performance gap with IPv4. This begged the question of what adoption level was needed to, if not close, at least make this gap less perceptible.

As Fig. 4 demonstrates, the performance gap between IPv4 and IPv6 had essentially disappeared by 2013 (they perform identically about 80% of the time, and each outperforms the other for the remaining 20%). The hypothesis is that IPv6 adoption, at least in the core of the Internet, is now sufficient to ensure that even when IPv4 and IPv6 control plane decisions differ, the detours IPv6 may still have to make now have a negligible impact. Tables V and VII offer data in support of this conclusion. Table V shows that after 2011, not only did destinations with identical IPv4 and IPv6 paths continue to see mostly comparable performance (confirming performance parity), an increasing number of destinations accessible over different IPv6 and IPv4 paths also achieved parity. As Table VII suggests, this can be attributed to “shorter detours” taken by IPv6 paths because of the greater density of IPv6 ISPs in the core of the Internet. To further assess the extent to which this was the case, we compared IPv6 (AS) path lengths in 2011 and 2012 and found that 72% of them experienced a decrease. This is in contrast to only 18% of IPv4 paths experiencing a decrease in the same period.

In summary, by 2013 IPv6 had achieved not only technology, but also performance parity with IPv4. The latter was primarily due to higher IPv6 adoption in the core of the Internet. This contributed to decreasing the number and length of IPv6 detours, which all but eliminated differences in latency between IPv6 and IPv4 paths.

<table>
<thead>
<tr>
<th>Same Path Destinations</th>
<th>Top 100K Sites</th>
<th>Top 1M Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100%</td>
<td>94%</td>
</tr>
<tr>
<td>Diff. Paths Destinations</td>
<td>79%</td>
<td>84%</td>
</tr>
</tbody>
</table>

**TABLE V. IPv6 better or equal to IPv4 after 2011.**

<table>
<thead>
<tr>
<th></th>
<th>IPv4 Transit ASes</th>
<th>IPv6 Transit ASes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>216</td>
<td>134</td>
</tr>
<tr>
<td>2012</td>
<td>229</td>
<td>147</td>
</tr>
<tr>
<td>Growth</td>
<td>6%</td>
<td>10%</td>
</tr>
</tbody>
</table>

**TABLE VI. Transit ASes sampled in our measurements.**

Another category of websites of potential interest is that of sites associated with different destination ASes in IPv6 and IPv4, with Table VII showing how they fared performance-wise. There are various possible reasons for why IPv6 and IPv4 queries for a given webpage are sent to different locations. One of them is clearly the use of CDNs, especially since until 2012 very few CDN providers offered IPv6 service. We were, however, only able to confirm the use of CDNs for a few such websites. Irrespective of the reason behind the difference in destination ASes for IPv6 and IPv4 queries, Table VII shows that IPv6 performance also improved for this category of sites. This is again likely due to the overall improvement in IPv6 connectivity that made IPv6 paths more efficient.

<table>
<thead>
<tr>
<th></th>
<th>Top 100K Sites</th>
<th>Top 1M Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009–2011</td>
<td>67%</td>
<td>70%</td>
</tr>
<tr>
<td>2012–Present</td>
<td>80%</td>
<td>78%</td>
</tr>
</tbody>
</table>

**TABLE VII. IPv6 better or equal to IPv4 – Different ASes.**

**TABLE VIII. Evolution of Key IPv6 Adoption Factors.**

In summary, IPv6 lack of technology maturity initially resulted in poor performance, which likely contributed to slow adoption by ISPs. This in turn ensured a persisting performance gap, even after IPv6 achieved technology parity. This appears to have changed around early 2012, with IPv6 finally achieving parity with IPv4. This should, hopefully, further facilitate IPv6 continuing adoption.

### C. Closing the loop: positing cause and effect relationships

In this last section, we attempt to correlate the three phases of the IPv6 migration observed in Section III-B to changes in the different factors identified in the previous section. For convenience, we summarize those changes in Table VIII.

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12This is consistent with CAIDA's measurements summarized in Table II, which showed an increased density of IPv6 in the core of the Internet.

13See http://www.cdn-advisor.com/tag/ipv6/.

14Among 100 randomly chosen such websites, only 42 could be directly linked with a well-known CDN service provider such as Akamai, Biggravity, NTT, Bankinform, Cloudflare, Edgecast, Amazon, Google, Softlayer, Tata, etc. For the remaining 58 sites, we could neither confirm a well-known CDN service, nor could we rule out reliance on a lesser-known CDN provider, or some form of load-balancing mechanism.
The discussion is followed in Section [V] by the introduction of a simple model based on the parameters of Table VIII. The model seeks to capture the complex dependencies and interactions that exist between those parameters, and their effect on IPv6 adoption. The primary purpose is to qualitatively validate the causal relationships posited in this section between IPv6 adoption and changes in these parameters. In other words, given an evolution of the IPv6 ecosystem similar to that of Table VIII does the model yield changes in IPv6 adoption consistent with the observations of Section III-B. The goal is not to precisely reproduce those changes, but instead to confirm the cause and effect intuition we articulate next.

During Phase I (before 2009), IPv4 addresses were still plentiful and their exhaustion far in the future, so that demand for IPv6 products was low and limited mainly to a few forward-looking ISPs. This ensured a relatively low initial investment in the development of IPv6 technology by ITDs. This combination of limited investment and few users to test the technology likely contributed to the slow maturation of IPv6 technology. This in turn kept demand low and perpetuated the status quo. There does not appear to have been a single landmark event that triggered a sudden increase in ITDs investment in the development of IPv6 technologies. Instead a slow but steady rise in awareness, in part brought about by various government programs and mandates, e.g., see [7], resulted in IPv6 technologies being progressively brought on par with their IPv4 counterpart. By 2009, most key Internet technologies supported IPv6, and did so at a level of quality and stability close to that of IPv4.

Near technology parity paved the way for the emergence of IPv6 that started in Phase II. Technical parity was, however, by itself not sufficient to trigger mass adoption. IPv6 still lacked a strong enough incentive to overcome the adoption cost it imposed on both ISPs and ICPs. This remaining barrier was further strengthened by dependencies between stake-holders: ICPs had little incentive to become IPv6 accessible without a critical mass of IPv6 users, and ISPs where hesitant to invest in assigning IPv6 addresses, when IPv4 addresses were still available and most ICPs were not reachable over IPv6. Hence, in spite of the growing incentive to adopt IPv6 created by the steady decline in free IPv4 addresses and the steady improvements in quality of IPv4, progress remained slow. Several additional changes were required to usher in the acceleration of IPv6 adoption that started in Phase III. The reality of IPv4 address scarcity finally settled in with IANA’s allocation of its last block, and a sequence of high-profile events such as World IPv6 Day and World IPv6 Launch further contributed to this realization. In addition, the level of IPv6 adoption in the core of the Internet eventually reached sufficient critical mass to ensure that the quality of IPv6 connectivity was on par with that of IPv4, i.e., did not involve costly detours. As illustrated in Fig. [1] this together with the potential for faster growth in the IPv6 user base, made it easier for ICPs to opt to become IPv6 accessible. Anecdotal, this can also be seen when comparing the results of the IPv6 World Day (June 2011) and IPv6 World Launch (June 2012) (see again Fig. [1]). Many ICPs that “tried” IPv6 during IPv6 World Day reverted to IPv4 after the event, while most IPv6 trials converted to permanent status after IPv6 World Launch.

In the next section, we introduce a simple model that seeks to connect more formally the parameters and patterns identified in Table VIII to the three-phase adoption of Section III.

V. A SIMPLE VALIDATION

Our goal in this section is to offer a simple validation of the causal relationships put forward in the previous section, between changes in the IPv6 ecosystem and the IPv6 adoption pattern observed in Section III-B. For that purpose, we develop a model that captures interactions between the parameters of Table VIII and their effect on IPv6 adoption. We then vary those parameters in a manner consistent with Table VIII and show that the model produces changes in IPv6 adoption that are qualitatively consistent with the trends reported in Section III-B. We note that a more quantitative validation is challenging, as accurately estimating both exact changes in the parameters of Table VIII and their relative weights in the model is at best difficult. Furthermore, the specialized nature of the IPv6 adoption problem and its many unique parameters, make it unlikely that a more precise model formulation would have value that extends to other settings and technology adoption scenarios. Instead, the model developed in this section offers a broad confirmation of the cause-and-effect relationships posited in the previous section. As we illustrate later, it also enables coarse “what-if” investigations, which can highlight the importance of certain parameters in keeping IPv6 adoption on track.

A. Model Overview

The model involves the three major decision makers of Section IV, namely, ITDs, ISPs, and ICPs. As alluded to earlier, users are mostly passive, with their “adoption” of IPv6 largely a consequence of decisions made by others. Stake-holder’s decisions to adopt IPv6 are based on utility functions that depend on multiple factors, including the adoption decisions of other stake-holders. Stake-holders revisit their decisions at discrete epochs indexed by i, to account for changes in both the Internet ecosystem, e.g., a decrease in the number of available public IPv4 addresses or growth in the number of Internet users (the Internet user-base is assumed to grow at a rate of q in each epoch), and the decisions of other stake-holders. For simplicity and in keeping with practice, IPv6 adoption decisions are assumed irreversible (once their cost has been incurred, there is little benefit to reverting). ITDs, ISPs and ICPs boast different utility functions, and the model allows for heterogeneity in their individual decisions as well as limited competition (for ITDs).

In the next two sub-sections, we introduce expressions for the utility functions of ITDs, ISPs, and ICPs, and describe their use in making adoption decisions. The last sub-section is devoted to evaluating the model’s outcome under combinations of parameters that mimic the progression of Table VIII.

B. Utility Functions

1) ITDs: They provide Internet technologies to other Internet stakeholders, and their (IPv6) utility is expressed through
the revenues they generate from their IPv6 products. Revenues depend on demand (i.e., market size), which grows as more of the Internet migrates to IPv6. ITDs periodically assess the IPv6 market size, denoted as $M(i)$ at epoch $i$. For simplicity, the model does not endogenize the relationship between $M(i)$ and the level of ISP and ICP adoption. Instead, it couples them exogenously in its numerical evaluation.

ITDs are split into different market segments, e.g., router vendors, OS developers, etc., with segment $j$ assigned a share $\delta_j$ of the overall IPv6 market. Within a segment, the model includes two ITDs to incorporate the effect of competition. Market size determines whether an ITD invests in developing IPv6 technology and at what level, with a higher level of investment corresponding to higher product quality. Quality varies between 0 and 1, with 0 denoting no product offering and 1 corresponding to parity with IPv4. The quality of an ITD’s offering determines how it shares its market segment with its competitor. A product’s quality is taken to be proportional to the ITD’s cumulative investment in developing the product, and therefore of the form:

$$Q_j(i) = \sum_{l=1}^{i} c_l,$$

where $Q_j(i)$ denotes the quality of the IPv6 offering of a type $j$ ITD at epoch $i$, and $c_l$ is the investment it made at epoch $l$. The model further assumes that at each epoch, type $j$ ITDs play a best response game with their competitor to determine their investment. The utility function of an ITD of type $j$ at epoch $i$ is, therefore, of the form:

$$U_{ITD}(i, j) = \frac{Q_j(i)}{Q_j(i) + Q_{j_{\text{comp}}}(i)} \delta_j M(i) - c_i,$$

where $Q_{j_{\text{comp}}}(i)$ is the quality of the ITD’s competitor(s) at epoch $i$. Eq. (2) captures the relationship between the investment an ITD makes and the revenue it generates from investing in its IPv6 products. Note that Eq. (2) assumes a symmetric decision process by the competing ITDs in market segment $j$. This is for analytical tractability, but does not qualitatively affect the model’s outcome.

Eq. (2) also reflects two important aspects of IPv6 investments by ITDs: (i) they are demand-driven, i.e., if there is no demand ($M(i) \sim 0$), ITDs do not invest in IPv6, and conversely, growth in $M(i)$ fuels investments; and (ii) improving the quality of IPv6 products is in part driven by competition (see Section V-C for details).

2) ISPs: They all eventually need IPv6 to grow (keep adding new users), but upgrading their network to IPv6 involves a cost. The cost of upgrading an ISP’s network depends on network size and a “unit” upgrade cost. The size of an ISP’s network is assumed proportional to its user base, and the model allows heterogeneity in ISP sizes. The initial size of the $m^{th}$ ISP is denoted as $n_m$, and is assumed to grow at a constant rate of $q$. The unit cost of upgrading an ISP’s network to IPv6 depends on the availability and quality of versions of ITDs’ technologies. For simplicity, the model assumes that it is inversely proportional to a parameter $\phi(i)$ that tracks availability and quality of IPv6 technologies at epoch $i$ ($\phi(i)$ takes values in $[0,1]$ —see Eq. (5)—, with 0 corresponding to no IPv6 version of a technology, and 1 to quality that is on par with that of IPv4). The need to acquire more IPv4 addresses is the main counterpart to the cost of upgrading one’s network, and the model assumes that ISPs are heterogeneous in the number of IPv4 addresses they initially have at their disposal. This number is denoted as $k_m$ for ISP $m$ at epoch $i$.

The unit cost of upgrading an ISP’s network to IPv6 until epoch $i$ for the $m^{th}$ ISP is, therefore, of the form:

$$C_m^{UP}(i) = \frac{1}{\phi(i)} n_m (1 + iq) + \frac{1}{\phi(i)} C_{IPv4}^{UP}(i) - C_{IPv4}^{UP}(i),$$

The first term is the cost of upgrading an infrastructure that has grown to a size of $n_m (1 + iq)$ by epoch $i$ given a unit upgrade cost of $1/\phi(i)$, where $C_{IPv4}^{UP}(i) = C_{IPv4}^{UP}(i) = C_{IPv4} \max(0, ((i - 1)n_m q - k_m)^2)$. The cost of acquiring IPv4 addresses up to epoch $i - 1$ (this cost remains 0 until the ISP exhausts its initial IPv4 address pool of size $k_m$). Note that $n_m (1 + iq)$ grows over time, while $1/\phi(i)$ decreases as IPv6 technology improves. As we shall see in Section V-C2, ISPs seek to identify the epoch that minimizes upgrade costs.

Once an ISP has upgraded its network to IPv6, the model assumes that it allocates both IPv6 and IPv4 addresses to new users until it runs out of the latter. Once this happens, it must either purchase more IPv4 addresses, or deploy translation devices to enable IPv6-only users to access the IPv4 Internet. The choice is based on cost, and given that, as discussed in Section V-B, translation costs are expected to decline, we further simplify the model by assuming that translation is the solution of choice. The main impact of this assumption is in increasing the number of IPv6-only users, which, as we shall see next, positively influences ISPs’ decisions.

3) ICPs: Their revenue depends in part on the quality with which they deliver content to users. ICPs that are not IPv6 accessible must rely on translation to access IPv6 users, and as the IPv6 user base grows, the connectivity impairment this imposes on those users (see again [11]) translates into an increasing penalty (revenue loss). ICPs, therefore, weigh this loss against the cost of becoming IPv6 accessible. This cost is primarily an infrastructure upgrade cost, similar in nature to that of ISPs. It depends on the availability of IPv6 technologies and the size of the ICP’s infrastructure. An ICP decides to become IPv6 accessible once the cost of doing so is lower than the revenue gain the change will generate. This decision process is captured in Eq. (4) that also incorporates heterogeneity among ICPs based on their popularity. More popular ICPs are assumed to generate higher revenues from

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15In Section V-D both $n_m$ and $k_m$ are taken to be uniform in $[0,1]$.

16Other cost functions can be chosen, e.g., constant, and while they quantitatively affect the results, the outcome remains qualitatively similar.
their users, as well as incur lower upgrade costs (because of economies of scale). As expected, this translates into more popular ICPs adopting earlier, consistent with Fig. 2

\[ \Delta_{ICP}(i) = N_0(i) \beta a_6(i) \]

\[ -[N_6(i) \beta a_6(i)] + S_{infra(i)} \left( 2 - \beta \frac{1}{\phi(i)} \right) \]

**per user upgrade cost**

\[ \Delta_{ICP}(i) \]

measures the impact on the ICP’s revenue of becoming IPv6 accessible at epoch \( i \). The first term in Eq. (4) represents the gain associated with IPv6 accessibility, with \( N_0(i) \) the size of the IPv6 user base at epoch \( i \), \( \beta \) the ICP’s popularity factor\(^{17} \) and \( a_6(i) \) the per user revenue gain from native IPv6 connectivity at epoch \( i \) (it increases over time as the quality of IPv6 technology improves). Note that Eq. (4) highlights that when native IPv6 connectivity is (quality-wise) worse than what is achievable through translation devices, \( a_6(i) \leq 0 \), ICPs have little to no incentives to become IPv6 accessible (because \( \Delta_{ICP}(i) \leq 0 \)). The second term in Eq. (4) includes both a potential revenue loss associated with becoming IPv6 accessible, and the cost of upgrading the ICP’s infrastructure to IPv6.

The potential revenue loss associated with IPv6 accessibility is in the term \( N_6(i) \beta a_6(i) \). It accounts for the fact that dual-stack users (there are \( N_6(i) \) of them) often access IPv6 accessible ICPs over IPv6 and not IPv4, which may result in lower connectivity quality. This is captured through \( a_6(i) \) that denotes the per user revenue loss at epoch \( i \) from IPv6 connectivity relative to IPv4 connectivity. Finally, the term \( S_{infra(i)}(2 - \beta \phi(i)) \) represents the ICP’s IPv6 upgrade cost that is proportional to the size of its infrastructure at epoch \( i \), \( S_{infra(i)} \), and, as with ISPs, is inversely proportional to the availability and quality of IPv6 technology as measured through \( \phi(i) \). The factor \( (2 - \beta) \) reflects the economies of scale assumed available to more popular ICPs (the less popular ICPs have upgrade costs twice those of more popular ICPs).

An ICP re-evaluates the benefit of IPv6 accessibility at each epoch to account for changes in the parameters of Eq. (4). Factors that contribute to making IPv6 more attractive include growth in \( N_6(i) \), the number of IPv6-only users and improvements in IPv6 quality that contribute to both increasing \( a_6(i) \), the revenue gain afforded by native connectivity for IPv6-only users, and decreasing the revenue loss \( a(i) \) incurred for dual-stack users. On the other hand, the ICP’s infrastructure size, \( S_{infra(i)} \), keeps growing, so that upgrade costs may increase, unless the per user cost of upgrading to IPv6, \( (2 - \beta) \phi(i) \), decreases commensurately. To assess the overall impact of these different factors, the model uses the following expressions for estimating changes in \( a_6(i) \) and \( a(i) \):

\[ a_6(i) \sim \phi(i) \mu(i) + I_{CDN} \]

\[ a(i) \sim 1 - \frac{\phi(i) \mu(i) + I_{CDN}}{2} \]

where as in Eq. (3), \( \phi(i) \) measures the availability and quality of IPv6 technology, \( I_{CDN} \) denotes the fraction of CDN providers that support IPv6 (they can have a strong impact on IPv6 quality), and the product \( \phi(i) \mu(i) \) captures the dual impact of the network data plane (\( \phi(i) \)) and control plane (\( \mu(i) \)) on the overall quality of IPv6. As discussed earlier, \( \phi(i) \) depends on the maturity of IPv6 technology, while \( \mu(i) \) increases as more ISPs adopt IPv6 (detours around IPv4 only islands become shorter). In the next section, we formalize the evolution of those parameters and their dependencies.

### C. Decision Mechanisms & Solution Method

This section reviews the decision process that the utility functions of the previous section give rise to under the assumption that stake-holders make decisions that maximize their utility. In other words, they are rational.

1) **ITDs:** ITDs’ decisions are when and how much to invest in developing IPv6 versions of their technology. We assume that to be viable IPv6 products must meet a minimum quality threshold \( 0 < Q_{min} < 1 \). Hence, an ITD of type \( j \) first invests in IPv6 at epoch \( i \) if the cost (of meeting the minimum quality threshold) is less than the revenue potential of the IPv6 market, as defined in Eq. (2). The decision, therefore, depends on the ITD’s type, \( \delta_j \), the estimated size of the IPv6 market at epoch \( i \), \( M(i) \) (an increasing quantity), and the quality of its competitor’s technology at epoch \( i \), \( Q_{Comp.(i)} \). The first two parameters are exogenous, while the ITD needs to anticipate \( Q_{Comp.(i)} \). Given the assumption of a symmetric decision process (more on this below), the two competing ITDs (in market segment \( j \)) make consistent decisions, \( i.e. \), they invest to offer products of comparable quality so that \( Q_j(i) = Q_{Comp.(i)} \).

This competition between ITDs can be modeled as a best response game at each epoch. The actions of both players are their level of investment in IPv6, which in turns determines the quality of their offering. Both players in segment \( j \) account for the decision process of their competitor, so that their best response decisions are in the form of an investment that at epoch \( i \) yields a cumulative quality \( Q_j(i) \) for their technology of the form

\[ Q_j(i) = \sqrt{Q_{Comp.(i)} M(i) \delta_j - Q_{Comp.(i)}} \]

The symmetric nature of the two ITD competitors in market segment \( j \) produces a Nash equilibrium where they split the market equally with a cumulative quality \( Q_j(i) \) of the form:

\[ Q_j(i) = \max \left\{ \frac{M(i) \delta_j}{4}, 1 \right\} \]

Note that Eq. (3) implies that ITDs won’t invest in IPv6 versions of their technologies until \( \delta_j M(i) > 2Q_{min} \), \( i.e. \), the IPv6 market size exceeds a certain threshold. Conversely, as \( M(i) \) grows, ITDs’ technologies investment ultimately results in (quality) parity between the IPv4 and IPv6 versions of their technologies. This in turn yields the following expression for the parameter \( \phi(i) \) that measures the overall availability and

\(^{17} \beta \) is distributed in \([0, 1]\), with 1 the highest popularity.
quality of IPv6 technologies at epoch $i$:

$$\phi(i) = \frac{1}{\sum_{j} Q_j(i) \delta_j} \frac{M(i)}{4} \sum_{j} \delta^2_j,$$  \hspace{1cm} (9)

where the summation is over all market segments.

2) ISPs: An ISP’s goal is to find the epoch at which the cumulative cost of upgrading its network to IPv6 is “minimal.” Upgrade costs are initially high because IPv6 quality, $\phi(i)$, is low. As per Eq. \ref{eq:x}, this leads some ISPs to defer upgrading until quality improves. As IPv6 quality improves and approaches parity with IPv4, upgrade costs eventually increase driven by growth in an ISP’s user base. Predicting the exact crossover point is complex, and our goal is not to offer precise guidelines. Instead we seek to capture the inherent tension between those two factors in an ISP’s decision. For that purpose, we assume that ISPs rely on a myopic decision process and simply evaluate whether the rate of increase of upgrade costs is higher than in the previous period, and upgrade as soon as it is.

In other words, the $m^{th}$ ISP adopts IPv6 at epoch $i_m$ if $C_{m}^{IP}(i_m) - C_{m}^{IP}(i_m - 1) > C_{m}^{IP}(i_m - 1) - C_{m}^{IP}(i_m - 2)$, where $C_{m}^{IP}(i)$ is as per Eq. \ref{eq:x}. With ISPs decisions known, the fraction $\mu(i)$ of ISPs that have upgraded to IPv6 by epoch $i$ can then be readily obtained, and therefore used to determine its impact on IPv6 connectivity quality as per Eqs. \ref{eq:z} and \ref{eq:z}. Recall that the latter play a role in ICPs decisions, and capturing those interactions is one of the model’s goals.

Once an ISP has upgraded its network to IPv6, it faces another decision, namely, how to continue to provide new users with access to the IPv4 Internet. This is an easy decision as long as the ISP still has IPv4 addresses, i.e., until epoch $i = k_m/n_m\phi$ for the $m^{th}$ ISP, as new users can be assigned both IPv4 and IPv6 addresses. Once an ISP runs out of IPv4 addresses, it must then decide between acquiring more IPv4 addresses and deploying translation mechanisms, as discussed in Section \ref{sec:41}. The model can be readily adapted to allow for such a decision, i.e., select the lowest cost option. However, we assume in our evaluation (Section \ref{sec:42}) that ISPs are “strategic” and opt to handle IPv4 connectivity (for new IPv6 users) solely through translation mechanisms. The primary motivation is, as outlined next, that this offers additional incentives for ICPs to become IPv6 accessible earlier. Hence, hastening the Internet’s migration to IPv6, and ultimately lowering ISPs costs.

3) ICPs: An ICP’s goal is to maximize the revenue it derives from having Internet users. For that purpose, it re-evaluates $\Delta_{ICP}(i)$ (Eq. \ref{eq:z}) at each epoch, and becomes IPv6 accessible at the first epoch $i$ for which $\Delta_{ICP}(i) > 0$. Under the assumption that ICPs’ popularity $\beta$ is uniformly distributed in $[0, 1]$, this yields the following expression for the fraction $\gamma_0(i)$ of ICPs that are IPv6 accessible at epoch $i$:

$$\gamma_0(i) = \frac{N_0(i)a_0(i) - N_{46}(i)\phi(i) - S_{mfr}(i)/\phi(i)}{N_0(i)a_6(i) - N_{46}(i)\alpha(i) + S_{mfr}(i)/\phi(i)},$$  \hspace{1cm} (10)

$^{18}$Heterogeneity in decisions arises from differences in both ISPs’ size and in the number of IPv4 addresses they own.

Using Eq. \ref{eq:z}, it is easy to establish the following intuitive statements that highlight the dependencies that exist between ICPs decisions and those of ISPs and ITDs:

The fraction of ICPs natively accessible over IPv6 increases as either the number of IPv6 users increases, or the quality of IPv6 increases ($a_0(i)$ increases, $\alpha(i)$ decreases). In addition, once the IPv6 user base is large enough ($N_0(i)a_0(i) > N_{46}(i)\alpha(i)$), decreases in upgrade costs contribute to increasing the number of IPv6 accessible ICPs. Conversely, increases in the number of dual-stack users can delay increases in the number of IPv6 accessible ICPs.

D. Model’s Evaluation

The goal of this section is to explore the extent to which the progression of IPv6 adoption documented in Section \ref{sec:3} can be reproduced using the arguably stylized model that was just presented. For that purpose, we consider “configurations” associated with different combinations of the model’s exogenous parameters, and characterize the evolution of IPv6 “adoption” across stake-holders as the Internet’s user base increases. Specifically, we numerically evaluate the model’s outcome for three different sets of exogenous parameters that mimic the three right columns of Table \ref{tab:4}.

The first configuration emulates IPv6 early years. Demand for IPv6 versions of Internet technologies was initially non-existent ($M(i) \sim 0$). As a result, development incentives were low even in segments with large market shares $\delta_j$, e.g., router and OS vendors. The outcome predicted by Eq. \ref{eq:x} is marginal availability of IPv6 technologies, i.e., $\phi(i) \sim 0$, and consequently large upgrade costs ($1/\phi(i) \gg 0$). This in turn translates into a negligible fraction of ISPs upgrading their network to IPv6 ($\mu(i) \sim 0$) and similarly very few ICPs opting to become IPv6 accessible ($\gamma_0(i) \sim 0$). Initiatives aimed at promoting support for IPv6, e.g., government mandates, helped change the situation and create some early demand for IPv6 technologies ($M(i) > 0$) even in the absence of a real driver (the exhaustion of IPv4 addresses was still far away). This in turn triggered some initial investments on the part of ITDs (see again Eq. \ref{eq:x}), so that early releases of IPv6 products became available, i.e., $\phi(i) > 0$. This lowered upgrade costs ($1/\phi(i)$), but ultimately had little effect on IPv6 adoption by either ISPs or ICPs, i.e., $\mu(i) \gtrsim 0$, and $\gamma_0(i) \gtrsim 0$. The reason, consistent with Eqs. \ref{eq:z} and \ref{eq:z}, is that while demand for and availability of IPv6 technology improved, IPv6 quality/stability remained below that of IPv4 ($a_{46}(i)$ was still small), endemic problems continued to plague dual-stack users ($\alpha(i)$ stayed large), and IPv4 address exhaustion was nowhere near.

The second configuration seeks to capture the second phase of IPv6 adoption in Section \ref{sec:3}. During that phase, demand for IPv6 products increased to a point where most of the ITDs supported IPv6 in their products at a level of stability/quality on par with that of IPv4, i.e., $\phi(i) \sim 1$. This was sufficient to incentivize some ISPs to adopt IPv6. Most of those ISPs, however, still owned IPv4 addresses, so that new users were primarily dual-stack (as opposed to IPv6 only), i.e., $N_0(i)$ stayed small while $N_{46}(i)$ grew. This offered little motivation for ICPs to consider becoming IPv6 accessible, especially
since IPv6 connectivity quality was still lagging behind IPv4 (because many ISPs had not yet upgraded to IPv6). This is consistent with Eq. (10) that produces only small increases in $\gamma_0(i)$ under those configurations.

The third configuration maps to phase three of Section III. ISPs are increasingly running out of IPv4 addresses, and because IPv6 technology is stable and on par with IPv4, upgrading to IPv6 now makes sense for many of them. The larger number of IPv6 ISPs together with the greater availability of IPv6 versions of services such as CDNs result in IPv6 connectivity quality being now equals that of IPv4 ($\alpha_0(i) \sim 1$ and $\alpha(i) \sim 0$). This eliminates the quality penalty that IPv6 users suffer compared to IPv4 users. When combined with a growing number of IPv6-only users ($N_0(t)$), this is enough to entice an increasingly large number of ICPs to become IPv6 accessible; a phenomenon that Eq. (10) again captures.

IPv6 adoption under those three configurations is shown in Fig. 5 for ICPs. The outcome is qualitatively similar to Fig. 1. This is obviously no “proof” of the model’s validity. However, it offers a level of validation for the causal relationships put forward in Section IV-A, connecting changes in the IPv6 ecosystem and the observed evolution of IPv6 adoption.

The model can also be used for coarse “what-if” analyses exploring the potential impact of changes in the IPv6 ecosystem. Those can prove useful to avoid missteps, which could, if not derailed, at least slow down IPv6 adoption and in the process increase its overall cost. We illustrate this through a simple example that considers a scenario where ISPs that migrated to IPv6 proceed to sell their IPv4 addresses on open markets such as those of Section IV-B2. The resulting influx of new IPv4 addresses would likely stabilize or even reduce IPv4 address costs. This would in turn make it easier for ISPs that have not yet migrated to IPv6 to defer this decision; in the process slowing down the growth of the IPv6 user base. The impact on ICPs is less clear since there would be fewer IPv6 users overall, more of those users would now be IPv6-only. The former is a disincentive to becoming IPv6 accessible, while the latter acts as an incentive.

The model offers the opportunity to investigate the impact of such a change, with the results shown in Fig. 6. The figure demonstrates that the slower growth in the total number of IPv6 users produced by lower acquisition costs for IPv4 addresses is the dominant factor. It results in ICPs delaying their decision to become IPv6 accessible. The insight that emerges from this “what-if” scenario is that although ISPs that migrated to IPv6 stand to derive short-term benefits from selling their IPv4 addresses, those benefits are likely to be offset by the higher cost they will incur from the Internet’s slower migration to IPv6, e.g., through higher translation costs.

**VI. Conclusion**

The paper reports on measurements capturing the evolution of IPv6 adoption across Internet stakeholders, and identifies factors likely to have influenced adoption decisions. It posits, and to some extent documents, changes in those factors as possible causes for transitions in IPv6 adoption patterns observed in the measurements. The paper also develops a simple model connecting those changes to their impact on IPv6 adoption, and uses it to qualitatively validate its hypotheses. The investigation identifies the coupling between low initial demand for IPv6 products and their lower quality compared to their IPv4 counterpart as an important contributor to IPv6 early adoption challenges. In particular, it appears largely responsible for the initial reluctance of service and content providers to adopt IPv6, which in turn deterred users and contributed to prolonging the Internet’s migration to IPv6.

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**References**


