Migrating to IPv6 - The Role of Basic Coordination*

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***Abstract*—The need for a larger Internet address space was acknowledged early on, and a solution (IPv6) standardized years ago. Its adoption has, however, been anything but easy and still faces significant challenges. The situation begs the questions of "why has it been so difficult?" and "what could have been (or still be) done to facilitate this migration?" There has been significant recent interest in those questions, and the paper builds on a line of work based on technology adoption models to explore them. The results confirm the impact of several known factors, but also provide new insight. In particular, they highlight the destabilizing effect of Internet Service Providers (ISPs) offering competing alternatives (to IPv6), and demonstrate the benefits of even minimum coordination among them in offering IPv6 as an option. The findings afford additional visibility into what affects technology transition in large systems with complex dependencies such as the Internet.**

Keywords*—*IPv6, adoption, Modeling, Two-sided Market

I. Introduction

IANA ran out of IPv4 addresses in February 2011 (see http://www.nro.net/news/ipv4-free-pool-depleted), and even if IPv4 addresses scarcity has not yet materialized everywhere, we are slowly but surely headed in that direction. IPv6 was designed to address this issue, but migrating from IPv4 to IPv6 remains rife with challenges. Those challenges are not (anymore) of a technical nature, and instead due in part to a lack of incentives for the current (IPv4) Internet to migrate to IPv6. The marginal migration of the IPv4 Internet to IPv6 together with the incompatibility of IPv6 and IPv4 are forcing the use of translation mechanisms [1], [2] to allow IPv6-only users access to the IPv4-only Internet. While necessary for a transition, the availability of those mechanisms itself further reduces the motivation for current IPv4 users to adopt IPv6.

The lack of strong incentives notwithstanding, there are significant commercial interests that should help drive the Internet's migration to IPv6. The lists of participants in events such as the 2011 World IPv6 Day[1] and the subsequent 2012 World IPv6 Launch[2] clearly demonstrate such a will. However, and in spite of this real desire, native end-to-end IPv6 connectivity remains spotty, *e.g.,* see http://mnlab-ipv6.seas.upenn.edu/fig1.

A goal of this paper is, therefore, to explore and explain what may be behind IPv6 ongoing struggle, and possibly suggest ways of mitigating it. Our initial intuition was that besides the role of IPv4 incumbency, the distributed structure of the Internet also had an impact. Specifically, the benefit of migrating to IPv6 depends to a large extent on what others in the Internet do. This is not an uncommon situation (*e.g.,* see [3] for a related discussion in the context of Internet security protocols), but uncertainty in the decisions of others can significantly delay the adoption of a new technology.

To better understand the extent to which this may be the case, several simple yet representative scenarios and models were developed. We acknowledge up-front the many simplifying assumptions they rely on (a necessity in most modeling efforts), and their lack of completeness. However, they incorporate major aspects of IPv6 adoption decisions, namely, they (i) heterogeneity in the Internet stake-holders making those decisions; (ii) a representative sample of available technology options; and (iii) the dependencies that exist across decisions.

An important finding from those scenarios and models is that in an uncoordinated (competitive) setting, it is difficult for ISPs to effectively decide how to choose between and price connectivity options, including IPv6[3]. The uncertainty this creates slows down decisions to migrate to a new technology such as IPv6, or at the very least create a more haphazard migration process, as has indeed been the case. More importantly, it makes planning for a successful migration strategy more difficult. Another finding of interest is that even minimal coordination among ISPs, *e.g.,* an Internet-level agreement to consistently offer IPv6 as an option, allows strategies to emerge that can eventually lead to a successful migration to IPv6. This does not mean that coordination alone is sufficient, but it affords an understanding of the role different factors play, and hence the opportunity for a more predictable outcome.

The paper's contributions are, therefore, two-fold:
(i) It illustrates how, in the presence of competing options to handle IPv4 address exhaustion, the distributed decision process of Internet stake-holders can make identifying "winning strategies" difficult and therefore contribute to continued difficulties in migrating to an IPv6 Internet; and
(ii) It demonstrates how the introduction of limited coordination among ISPs,while not in itself sufficient to ensure IPv6 success, affords greater insight into the impact of different parameters and, therefore, facilitates a smoother migration.

The rest of the paper is structured as follows. Section II introduces IPv6 adoption scenarios and models, including Internet stake-holders and the *utility* functions guiding their decisions. Sections III and IV explore uncoordinated and coordinated scenarios, respectively, and discuss the implications of the results. Section V briefly reviews related works, with Section VI summarizing the paper's findings and recommendations.

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[1]See http://internetsociety.org/ipv6/archive-2011-world-ipv6-day.
[2]See http://www.worldipv6launch.org.
[3]IPv6 slow uptake has resulted in other alternatives being considered.

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II. Scenarios and Models

Many factors arguably contribute to IPv6 adoption decisions, and any (tractable) model is unlikely to account for all of them and their variations across stake-holders. In this section, we introduce and motivate the different factors the models rely on, and the two-sided market approach used to capture dependencies and interactions between stake-holders.

A. Core IPv6 Adoption Factors

1) Internet stake-holders: We distinguish between *three* types of Internet stake-holders: Internet Service Providers (ISPs), Internet Content Providers (ICPs), and Internet Consumers (users). ISPs derive revenues from providing Internet connectivity to both ICPs and users, and are, therefore, concerned with the choices and costs of the technologies used to implement this connectivity. ICPs obtain the bulk of their revenues from users that connect to them over the Internet. Hence, their focus is on the quality of their connectivity to users and how it may affect revenues, as well as any cost they may incur to upgrade their existing infrastructure to support a new connectivity option, *e.g.,* IPv6. Finally, users purchase Internet connectivity from ISPs, and use it primarily to connect to ICPs (and to a lesser extent to each others). Hence, they are affected by the cost of Internet connectivity and by its quality.

2) Internet connectivity options: ISPs are the providers of Internet connectivity, and therefore control technology choices. We consider three representative technology options ISPs may choose from to accommodate customer growth.

The first is to simply continue using public IPv4 addresses. This has the advantage of full compatibility with the current Internet, but given the growing scarcity of public IPv4 addresses is likely to quickly involve added costs, *e.g.,* to purchase public IPv4 addresses from an address market such as Hilco Streambank IPv4 Address Marketplace.

The second option relies on private IPv4 addresses together with Carrier-Grade NATs (CGNs). Unlike public IPv4 addresses, private IPv4 addresses can be reused and so are not scarce. CGNs are required to allow connectivity to the public Internet, but the technology behind CGNs is mature. Private IPv4 addresses also have the benefit of letting ISPs defer a potentially expensive upgrade of their network to IPv6. The main disadvantage (to the ISP) is the cost of CGNs, which grows as more users are assigned private IPv4 addresses.

IPv6 is the third option. IPv6 addresses are not scarce, but like private IPv4 addresses will require some form of "translation," *e.g.,* NAT64 [1] or DSLite [2], to allow IPv6 users to communicate with the IPv4 Internet. IPv6$\leftrightarrow$IPv4 translation is less mature than that for private IPv4 addresses, and may therefore be initially more expensive. On the flip side, even if the exact time-frame remains unclear, the need for translation, and therefore its cost, should disappear as the Internet eventually migrates to IPv6.

3) Technology adoption dependencies: As alluded to, although ISPs choose Internet technologies, their decisions, including *pricing*, depend heavily on users and ICPs. For example, an ISP offering both IPv6 and (public) IPv4 connectivity can offer a discount for IPv6, thereby attracting users to that option and lowering the need for (expensive) public IPv4 addresses. However, more IPv6 users also means higher translation costs, unless this entices more ICPs to become IPv6 accessible thereby lessening the need for translation. This creates a complex web of dependencies, whose impact is amplified by the distributed decision process that prevails in the Internet. As we shall see, this can make devising sound (profit maximizing) strategies difficult if not impossible.

B. Adoption Scenarios

IPv6 adoption decisions are obviously affected by many other factors, and our goal is not to devise an all inclusive model. Instead, we seek to incorporate some of the main dependencies that connect the decisions of Internet stake-holders. As we shall see next, even accounting only for those aspects gives rise to complex models and a broad range of possible scenarios. We describe next representative configurations we use to explore this space, and shed some light on the type of outcomes that can emerge.

For normalization, all scenarios start with an Internet user population of unit size, *i.e.,* the size of the current Internet. This population is then increased in discrete steps of δ users. At each step, new and existing users evaluate the Internet connectivity choices available to them through their local ISP(s)[4], and select[5] the one with the highest *utility*. We define a user's utility in Section II-C1, but it depends primarily on the cost and quality of her Internet connectivity. Users are assumed heterogeneous, but primarily in their sensitivity to connectivity quality[6]. We further assume (see [5] for a related discussion) that address translation devices, if used, are the main contributors to degradation in connectivity quality/functionality.

Because ICPs are part of the current Internet, they already have a public IPv4 address, and their only decision is whether or not to become IPv6 accessible. They incur a cost when doing so (upgrading their existing IPv4 infrastructure and/or update of operational processes), but unlike users that can change their decisions, an ICP's decision to become IPv6 accessible is irreversible (once incurring the upgrade cost).

The goal behind the adoption scenarios we describe next is to span a representative combination of connectivity offerings. The first two assume a competitive environment with ISPs offering different connectivity options and setting prices so as to maximize their own profit. The third scenario assumes some coordination. ISPs do not compete on the basis of connectivity, *i.e.,* all offer identical connectivity options, including IPv6. Connectivity options still compete for users, but now internally to each ISP.

[4] According to http://www.broadbandmap.gov/summarize/nationwide, over 99% of the U.S. population can choose from two or more ISPs, while this figure is 90% in Europe (see http://goo.gl/MjTPJ6).

[5] We acknowledge that allowing users to re-evaluate their decision at every time step ignores many factors that introduce inertia in those decisions, *e.g.,* contractual agreements. However, as discussed in [4] for a related system, while such factors have a quantitative impact, they typically do not qualitatively change the outcome.

[6] Coarser grain heterogeneity is also possible, *e.g.,* between, say, residential and enterprise users, but adds significant complexity to the model. Similarly, heterogeneity in price sensitivity can also be included, but with again a cost in terms of complexity.

1) **IPv6 vs. Public IPv4:** Given that the main competition that IPv6 faces is the incumbent IPv4 Internet, the first scenario considers the case of two ISPs, one having embraced IPv6 as the technology of choice for its new customers, while the other has decided to defer any migration and to simply acquire additional public IPv4 addresses to accommodate new customers. The first ISP needs to deploy address translation devices to allow its new (IPv6) customers to connect to the legacy IPv4 Internet. This cost grows with the number of users that choose IPv6, and decreases as more ICPs become IPv6 accessible[7]. Conversely, while the second ISP does not incur translation costs, it needs to purchase public IPv4 addresses for its new customers. Those costs are expected to rise as public IPv4 addresses become scarcer.

2) **IPv6 vs. private IPv4 and CGN:** In this scenario, no ISP wants to incur the cost of purchasing more public IPv4 addresses (or those addresses are unavailable for purchase). ISPs that defer upgrading to IPv6 would then rely on private IPv4 addresses. Offerings based on either IPv6 or private IPv4 addresses both require translation (CGNs) to connect to the public IPv4 Internet. Translation costs for private IPv4 are likely to be lower than for IPv6, if only because of more mature technology and/or greater operational familiarity and compatibility with the current Internet. On the flip side, translation costs for private IPv4 keep increasing as more users join, independent of how many ICPs become IPv6 accessible.

3) **IPv6 <u>and</u> public IPv4:** On the technology choice front, this scenario is identical to the first one, namely, both IPv6 and public IPv4 are available as connectivity options. The main difference is that the two options are now systematically offered by all ISPs, and therefore priced internally to maximize their own profit, as opposed to competitively. This is equivalent to having a monopolistic ISP that sets the price of both options.

C. Decision Processes

We capture the interactions and decision dependencies of ISPs, ICPs and users through a two-sided market model [6]. The ISP is the market maker through its offering of connectivity options, while users and ICPs are the two sides of the market that derive value from each other through the market.

1) **Users utility:** Users derive a unit value from Internet connectivity, with price and quality affecting their overall utility. Recall that quality is assumed to be primarily affected by (the presence of) translation devices. A user's utility is then captured through the following expression:

$$U_{\text{user}}(\sigma) = 1 - p_R - \sigma a_R \gamma_R \,, \tag{1}$$

where R indexes connectivity options, p_R is the price of type R connectivity ($p_{\text{pub. IPv4}} > p_{\text{IPv6}} > p_{\text{priv. IPv4}}$), $a_R \in [0,1]$ quantifies quality (translation) impairments for connectivity option R, if any (a_R is 0 for public IPv4 and positive for both private IPv4 and IPv6), γ_R is the fraction of the Internet (ICPs) affected by those impairments, and $\sigma \in [0,1]$ denotes a user sensitivity to impairments[8].

[7]Translation costs are assumed proportional to the volume of traffic that needs to be translated, *i.e.,* higher capacity devices are needed.

[8]σ captures users' heterogeneity and, as commonly done for analytical tractability, is assumed uniformly distributed in $[0,1]$ (the results typically also hold for distributions with increasing hazard rates [7]).

2) **ICPs utility:** ICPs derive revenues from users, and those revenues can be affected by connectivity quality [8]. A major factor in an ICP's decision to become IPv6 accessible[9] is, therefore, the impact this decision can have on the revenue it generates from IPv6 users, and how this compares to the cost of upgrading to IPv6 (or convincing its hosting provider to upgrade). Revenue improvements depend on the number of IPv6 users and how they are affected by the ICP's adoption of IPv6. In particular, and as shown in [9], IPv6 and IPv4 connectivity are now mostly on par, so that the main benefit of native IPv6 access is to eliminate the need for translation.

The cost of upgrading to IPv6 is largely a function of the "size" of the ICP's infrastructure. For simplicity, this size is assumed proportional to the Internet user-base (the traffic volume an ICP sees grows with the Internet). The net utility in(de)crease an ICP derives from becoming IPv6 accessible can, therefore, be captured as follows:

$$\Delta_6(\text{ICP}) = n_6 a_6 - S_{\text{infra}} \theta c_6 \tag{2}$$

where n_6 is the number of IPv6 users, a_6 the per-user revenue gain from eliminating translation, and θc_6 the per-user upgrade cost of the ICP's infrastructure (of size S_{infra}). θ captures heterogeneity in cost structure across ICPs, and as with users' heterogeneity, *i.e.,* σ, is assumed uniformly distributed in $[0,1]$.

There are obviously many simplifying assumptions behind Eq. (2). In particular, it assumes that ICPs are homogeneous in revenue and traffic, with their IPv6 adoption having, therefore, equal weight in the eyes of users (clearly, Google becoming IPv6 accessible has a bigger impact than when a smaller ICP does). Nevertheless, it captures heterogeneity in ICPs' decisions and that they are affected by costs and revenues.

Last, we note that the decision process behind Eq. (2) is "myopic," *i.e.,* it compares *near-term* revenue improvements ($n_6 a_6$) and upgrade costs ($S_{infra}\theta c_6$). Strategic decisions that account for *future* revenues and the fact that upgrade costs grow with the ICP's user-base (assuming c_6 stays constant) are a natural extension. We discuss its impact in [10].

3) **ISP utility:** An ISP's utility (profit) depends on revenues derived from users[10] and costs. Given our aim of assessing the impact of offering different connectivity options, we focus on their cost contributions and ignore other cost components. As costs differ across connectivity options, we introduce the ISP's utility function separately for each.

Public IPv4 only

An ISP that only offers public IPv4 connectivity has a utility function of the form:

$$\Pi_{\text{pub. 4}} = n_4 p_4 - C(n_4 - 1)_+^2 \tag{3}$$

n_4 is the number of users willing to pay p_4 for public IPv4 connectivity, while $C(n_4 - 1)_+^2 = C\max(0, n_4 - 1)^2$ is the acquisition cost of the $(n_4 - 1)$ additional public IPv4 addresses

[9]As participation in events such "World IPv6 Launch Day" demonstrates, there are obviously many other possible reasons for an ICP to become IPv6 accessible. However, even when those other motivations prevail, the importance of preserving connectivity quality remains, *e.g.,* through the enforcement of some form of "white-listing."

[10]We ignore revenues from ICPs, as they are mostly independent from an ISP's connectivity choices.

the ISP needs beyond the "unit" block it already owns (to accommodate its existing users). The quadratic function used for address acquisition costs (C is a normalization constant) seeks to capture that public IPv4 addresses will grow progressively more expensive as they become scarcer.

IPv6 only (and IPv6↔IPv4 translation)

An ISP offering IPv6 connectivity has a utility of the form:

$$\Pi_6 = n_6 p_6 - D_6 n_6 \gamma_6 \,, \tag{4}$$

with n_6 the number of users choosing IPv6 connectivity at a price of p_6, and $D_6 n_6 \gamma_6$ the translation cost for those users. Each user generates 1 unit of traffic distributed uniformly across ICPs, so that if γ_6 ICPs are not IPv6 accessible, $n_6\gamma_6$ units of traffic must be translated at a unit cost of D_6.

Private IPv4 (and Private IPv4↔Public IPv4 translation)

The utility function of an ISP offering private IPv4 addresses is similar to Eq. (4), albeit with all traffic requiring translation, namely,

$$\Pi_{\text{p4}} = n_{p4} p_{p4} - D_4 n_{p4} \gamma_{\text{p4}} \,, \tag{5}$$

where $\gamma_{\text{p4}} = 1$, and as alluded to earlier, we expect $D_4 < D_6$.

III. The Impact of (Connectivity) Competition

This section considers scenarios II-B1 and II-B2. They involve (two) ISPs competing for users and offering different connectivity options. One ISP relies on IPv6, but the other has deferred upgrading to IPv6. Instead, it chooses to either incur the (growing) cost of acquiring public IPv4 addresses (II-B1), or to assign private IPv4 address to new users and rely on translation (CGNs) to connect them to the public Internet (II-B2). ISPs compete for users based on price and connectivity quality, with prices endogenously set to maximize profit.

Specifically, we assume *rational* and *myopic* ISPs that engage in a repeated multi-stage game played each time the Internet increases by $\delta < 1$ new users. ISPs first announce a price for connectivity (see below), with users then choosing a connectivity option in a best response manner, *i.e.,* they select the option that maximizes their utility.

As per Eq. (1), users' utility depends on price (p_R), quality of connectivity (a_R), and the fraction γ_R of ICPs affected by quality impairment associated with connectivity option R. γ_R is assumed known to users, and in the case of IPv6 depends on the outcome of the previous round of the game, *i.e.,* how many ICPs have become natively accessible. ICPs decide whether or not to become IPv6 accessible in the third and last stage of the game, again in a best response manner and based on the number of users that have chosen IPv6. ISPs are assumed aware of the rationale and economic incentives guiding users and ICPs decisions, *e.g.,* based on surveys of users and ICPs. Hence, they set prices that maximize their own profit, *i.e.,* by solving the above sequential decision process in reverse order.

An alternate game would have users and ICPs aware of each others decisions, deciding simultaneously rather than sequentially. This assumes that users are able to predict how ICPs will respond to their decisions and vice versa, and makes for a more complex and possibly less realistic game (neither users nor ICPs may have access to the necessary information). More importantly, the outcomes are similar to those of the simpler sequential game. As a result, we focus on the latter.

A. *IPv6 vs. Public IPv4 – Scenario II-B1*

In this scenario, one ISP offers IPv6 and the other stays with public IPv4 connectivity. Public IPv4 has an edge when it comes to connectivity quality ($a_6 > 0$), but that edge is present only for the fraction γ_6 of ICPs that require translation. Conversely, the disadvantage of public IPv4 is the likely cost of acquiring additional public IPv4 addresses.

1) **Decision Mechanism & Solution:** In round i of the game and assuming IPv6 and public IPv4 announced prices of p_6 and p_4, users and ICPs decisions proceed as follows.

Based on Eq. (1), a user with quality sensitivity σ chooses[11] IPv6 if, $1 - p_6 - \sigma a_6 \gamma_6^{(i-1)} \geq 1 - p_4$, where $\gamma_6^{(i-1)}$ denotes the fraction of ICPs not yet IPv6 accessible after round $(i-1)$ (this information is available after each round, with $\gamma_6^{(0)} = 0$ for completeness). Hence, the fraction $\sigma_6^{(i)}$ of (new and existing) users choosing IPv6 in round i satisfies

$$\Rightarrow \sigma_6^{(i)} = \begin{cases} 0 & \text{if } p_4 - p_6 < 0 \\ \frac{p_4 - p_6}{a_6 \gamma_6^{(i-1)}} & \text{if } 0 \leq p_4 - p_6 \leq a_6 \gamma_6^{(i-1)} \\ 1 & \text{if } p_4 - p_6 > a_6 \gamma_6^{(i-1)} \end{cases} , \tag{6}$$

The dependency on the price differential $p_4 - p_6$ is intuitive. For example, when the discount for IPv6 is larger than the quality penalty perceived by the most quality sensitive user ($\sigma = 1$), then all users select IPv6.

ICPs decide to become IPv6 accessible once knowing users choices. From Eq. (2), they do if the difference between the added revenue $n_6 a_6$ this generates and the upgrade cost $S_{\text{infra}} \theta c_6$ is positive. The latter depends on the current size of the ICP's infrastructure, S_{infra}, which as mentioned earlier is proportional to the Internet user-base in round $(i-1)$, *i.e.,* $1 + (i-1)\delta$. Conversely, the revenue increase created by becoming IPv6 accessible is proportional to the number of users choosing IPv6 in round i, *i.e.,* $n_6^{(i)} = (1 + i\delta)\sigma_6^{(i)}$. Assuming θ is uniformly distributed in $[0, 1]$, ICPs for which becoming IPv6 accessible yields a positive profit in round i are those with $\theta \leq \theta_6^{(i)}$ (conversely, the fraction of IPv6 accessible ICPs after round i is $\gamma_6^{(i)} = 1 - \theta_6^{(i)}$), where

$$\theta_6^{(i)} = \begin{cases} \frac{k a_6}{c_6} & \text{if } p_4 - p_6 > a_6 \gamma_6^{(i-1)} \\ \frac{k a_6 \sigma_6}{c_6} & \text{if } \frac{\gamma_6^{(i-1)}(1-\gamma_6^{(i-1)})c_6}{k} \leq p_4 - p_6 \leq a_6 \gamma_6^{(i-1)} \\ 1 - \gamma_6^{(i-1)} & \text{Otherwise} \end{cases} \tag{7}$$

where for notation simplicity $k = \frac{1+i\delta}{1+(i-1)\delta}$ is the relative growth in user population between rounds $(i-1)$ and i.

The first expression of Eq. (7) corresponds to all users selecting IPv6, *i.e.,* $\sigma_6^{(i)} = 1$, which yields the maximum possible adoption of IPv6 among ICPs. IPv6 adoption progressively

[11] Recall that users are heterogeneous in how they value connectivity quality, with σ uniformly distributed in $[0, 1]$.

decreases as fewer users select IPv6 (second expression), down to no less than $1 - \gamma_6^{(i-1)}$, which reflects the fact that ICPs that upgraded to IPv6 in an earlier round cannot revert.

Eqs. (6) and (7) are known to the two competing ISPs, which use them to optimize their own utility functions, as expressed in Eqs. (3) and (4). This yields the following expressions for optimal prices, where for simplicity we omit the index i and use $\gamma_6 = 1 - \theta_6$.

$$
\begin{aligned}
p_4^* = &\operatorname*{argmax}_{p_4}\{(1+i\delta)(1-\sigma_6)p_4 - \\
&C(((1+i\delta)(1-\sigma_6)) - 1)_+^2\} \qquad (8)\\
p_6^* = &\operatorname*{argmax}_{p_6}\{(1+i\delta)\sigma_6 p_6 - D_6\sigma_6(1+i\delta)\gamma_6\} \qquad (9)
\end{aligned}
$$

The two equations are coupled through Eqs. (6) and (7).

Explicitly solving this joint optimization is difficult[12]. It can be formulated as the solution of a best response game between the ISPs, each successively announcing and reacting to the other's price. In general, the game does not have a Nash Equilibrium to which prices would converge. In particular and as illustrated in the next section, instances of "cycles" in the ISPs' search for optimal prices arise in many cases. In other words, competition between ISPs on the basis of connectivity makes identifying rational operating (pricing) points difficult.

Interestingly but not surprisingly, dependencies between Internet stake-holders' decisions are largely responsible for this. In particular, if ICPs' decisions were independent of those of users (or proceeded at a much slower pace), the game would typically admit a unique Nash Equilibrium [10].

2) **The Impact of Competition:** ISPs' inability to converge to jointly optimal prices is primarily because the coupling between users and ICPs' decisions introduces two distinct strategies for the IPv6 ISP, and correspondingly a discontinuity in its utility function. When the price of public IPv4 connectivity is high enough, it is best for the IPv6 ISP to heavily discount its connectivity to attract many users and in turn convince many ICPs to become IPv6 accessible, which lowers translation costs. This, however, triggers a price decrease from the public IPv4 ISP to recoup part of its lost user-base, and then forces the IPv6 ISP to itself lowers its price to maintain a sufficiently attractive discount. This eventually results in a public IPv4 price that is too low to allow the IPv6 ISP to give a large enough discount. The better strategy for the IPv6 ISP is then to reduce its discount and attract fewer users. Each user generates a higher revenue, and because there are few of them, translation costs are low. This pattern is shown in Fig. 1 that plots each ISPs' best-responses as a function of the other's price, and includes an instance of a pricing cycle.

Cycles occur when the utility gap between the two strategies of the IPv6 ISP is large enough to ensure that its best-response function and that of the IPv4 ISP do not intersect. Fig. 2 explores how often this arises across a reasonable range of configurations. The price of IPv4 addresses is chosen to have a normalization constant $C = 1$, so that the quadratic cost function for IPv4 addresses yields a value of 1 when the number of IPv4 Internet users reaches $n_4 = 2$, *i.e.,* doubles.

[12]Analytical solutions can be obtained, but are mostly negative results, *e.g.,* the absence of a Nash Equilibrium, which do not shed insight into the problem. Hence, we resort to numerical investigations to explore the solution space.

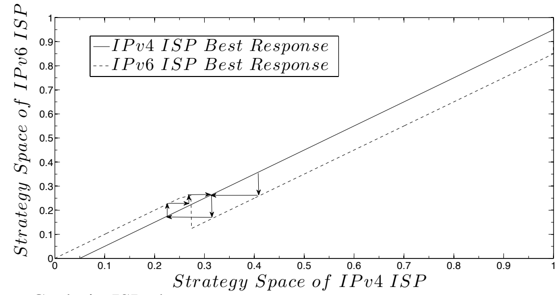

Fig. 1. Cycle in ISPs best response game

In other words, doubling the size of the current IPv4 Internet yields a public IPv4 address price equal to the value of Internet connectivity itself. This choice reflects the fact that according to current statistics there were about 2 billions Internet users by the end of 2012, and given the $\approx 50-75\%$ utilization of the address space, a doubling of IPv4 users is then still possible. A value of $a_6 = 0.08$ was also assumed, which corresponds to a relatively small (8%) degradation in connectivity quality.

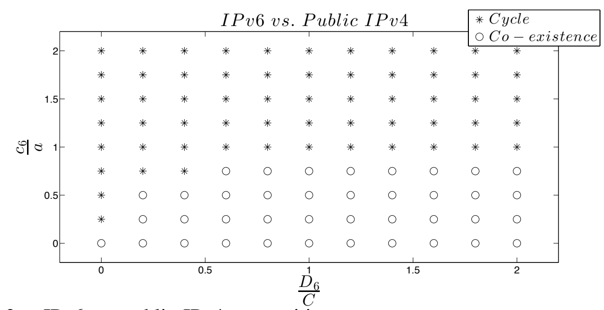

Fig. 2. IPv6 vs. public IPv4 competition

Fig. 2 shows the outcome of the game played by the two ISPs as a function of unit translation costs, D_6, and the maximum per user IPv6 conversion cost an ICP incurs, c_6. Both are varied from a few percent to more than ten percent of the base value of Internet connectivity. The figure illustrates the presence of cycles in a wide range of configurations, and in particular as soon as the cost of IPv6 conversion slightly exceeds the added revenue it can generate.

B. IPv6 vs. Private IPv4 – Scenario II-B2

In this scenario, one ISP offers IPv6 addresses to new users, while the other relies on private IPv4 addresses. Both require translation (IPv6↔IPv4 and Private IPv4↔Public IPv4) to communicate with the public IPv4 Internet. Both types of translation equally affect connectivity quality, as measured by a common parameter, a. The greater maturity of Private to Public IPv4 translation benefits a Private IPv4 solution, since $D_4 \leq D_6$. On the flip side, IPv6 users incur translation penalties only for the fraction γ_6 of ICPs not yet IPv6 accessible.

As with the previous scenario, we describe next the decision process of users and ICPs, and how the two ISPs select their prices. For simplicity, we assume that only new users decide on which connectivity option to choose. Allowing existing (public IPv4) users to make such a choice requires pricing a third option (public IPv4), which adds significant complexity without qualitatively affecting the results.

1) **Decision Mechanism & Solution:** After the two ISPs announce prices of p_6 and p_{p4}, (new) users choose an ISP as per Eqs. (10) and (11), where $\sigma_6^{(i)}$ and $\sigma_4^{(i)}$ denote the fraction of users choosing IPv6 or private IPv4 addresses in round i, respectively. In particular, a user with quality sensitivity σ prefers IPv6 over private IPv4 if $1-p_6-\sigma a\gamma_i^{(i-1)} \geq 1-p_{p4}-\sigma a$. Note that since $\gamma_6^{(i-1)} \leq 1$, this implies that prices verify $p_{p4} \leq p_6$. Note also, that it is possible that there exists a value σ_{NA} such that for $\sigma \geq \sigma_{\text{NA}}, 1-p_6-\sigma a\gamma_i^{(i-1)} \leq 0$, *i.e.,* users that are very sensitive to connectivity impairment will altogether opt out of connecting to the Internet. This can also arise in the previous scenario, albeit much more rarely as the availability of the public IPv4 option typically ensures that high σ users have access to a suitable alternative[13].

$$\sigma_{p4}^{(i)} = \begin{cases} \frac{(p_6-p_{p4})}{a(1-\gamma_6^{(i-1)})} & \text{if } p_{p4} > \frac{p_6-1+\gamma_6^{(i-1)}}{\gamma_6^{(i-1)}} \\ \frac{(1-p_{p4})}{a} & \text{if } p_{p4} < \frac{p_6-1+\gamma_6^{(i-1)}}{\gamma_6^{(i-1)}} \end{cases} \tag{10}$$

$$\sigma_6^{(i)} = \begin{cases} \frac{a(1-\gamma_6^{(i-1)})-(p_6-p_{p4})}{a(1-\gamma_6^{(i-1)})} & \text{if } p_{p4} > \frac{p_6-1+\gamma_6^{(i-1)}}{\gamma_6^{(i-1)}} \\ & \& \, p_6 < 1-a\gamma_6^{(i-1)} \\ \frac{(1-p_6)}{a\gamma_6^{(i-1)}} - \frac{(p_6-p_{p4})}{a(1-\gamma_6^{(i-1)})} & \text{if } p_{p4} > \frac{p_6-1+\gamma_6^{(i-1)}}{\gamma_6^{(i-1)}} \\ & \& \, p_6 > 1-a\gamma_6^{(i-1)} \\ 0 & \text{if } p_{p4} < \frac{p_6-1+\gamma_6^{(i-1)}}{\gamma_6^{(i-1)}} \end{cases} \tag{11}$$

Once users have selected their connectivity option, ICPs proceed with their decisions as in the previous section. The process followed by ISPs to select prices also parallels that of the previous section, albeit with more complex expressions. We refer the reader to [10] for more details, but the more important aspect is that, as illustrated in the next section, pricing cycles again frequently arise.

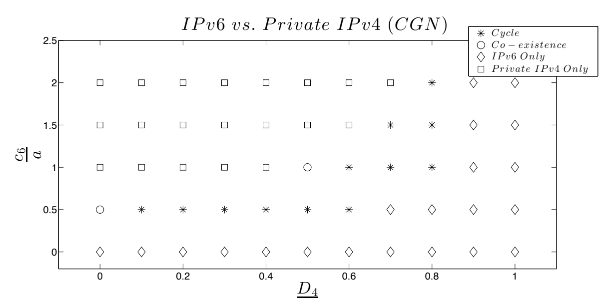

Fig. 3. IPv6 vs. private IPv4 competition

2) **The Impact of Competition:** Fig. 3 offers a perspective similar to that of Fig. 2, and reports the outcome of the ISPs' price selection process for a range of configurations. There are some differences, *e.g.,* coexistence arises rarely, but there is nevertheless a broad range of parameters for which cycle are present. As argued earlier, this makes devising pricing strategies difficult and is likely to contribute continued uncertainty in deciding how to settle on a migration strategy.

[13]It arises only for combinations of large C and D_6 values, *i.e.,* very high acquisition costs for public IPv4 addresses and very high translation costs.

The next section explores how a consensus among ISPs in what connectivity options to offer fosters better visibility into migration strategies to an IPv6 Internet.

IV. The Benefit of Connectivity Consensus

The previous section illustrated the difficulty of devising effective strategies, when ISPs tackle public IPv4 address shortage with competing connectivity options. The intent of this section is not argue that to migrate to an IPv6 Internet, we need to forfeit competition among ISPs. This would be neither realistic nor meaningful. Instead, we want to argue for shifting competition away from connectivity choices, *i.e.,* have a consistent offering of connectivity choices among ISPs. Choices need to be preserved, as users (and ICPs) are likely to remain heterogeneous in their willingness to accept a migration to IPv6. However, connectivity options should not be the basis on which ISPs compete.

Specifically, we consider a scenario where all ISPs offer Internet users the choice between IPv6 connectivity and traditional public IPv4 connectivity. Those two options continue to compete for users, but now *internally* to each ISP. This move from external to internal competition is by itself not sufficient to ensure IPv6 success (the lack of clear incentives and the complex dependencies that exist between stake-holders decisions remain). However and most importantly, it offers the opportunity for more direct visibility into how various parameters affect IPv6 adoption. This in turn can allow the formulation of recommendations on how to affect a faster migration to an IPv6 Internet.

In the rest of this section, we first describe how an ISP prices public IPv4 and IPv6 connectivity, and next explore the outcomes it gives rise to. The results help identify the roles of different parameters, and in particular which changes might be most effective in migrating to an IPv6 Internet.

A. IPv6 and Public IPv4

Consider an ISP offering its users (new and existing) the choice between traditional public IPv4 connectivity and IPv6 connectivity at prices of p_4 and p_6, respectively. As in the previous sections, users that opt for IPv6 must undergo translation when connecting to the γ_6 fraction of ICPs that are not yet IPv6 accessible. As before, translation introduces impairments of relative magnitude a. Similarly, the ISP incurs a cost of D_6 per unit of traffic that needs translation. The ISP has an existing user-base of unit size, and therefore owns a unit-size block of public IPv4 addresses. If it needs additional public IPv4 addresses, it acquires them at a cost that, again as before, grows quadratically, *i.e.,* based on Eq. (3). ICPs decide to become IPv6 accessible following the same process as that of Section II-C2. We describe next how the ISP selects the prices p_4 and p_6 that maximize its profit.

B. Decision Mechanism & Solution

Growth in the Internet user population again proceeds in steps of size δ that coincide with epochs where the ISP adjusts its prices p_4 and p_6. Choosing optimal prices involves solving the following optimization problem

$$
\begin{aligned}
(p_4, p_6) = \underset{(p_4,p_6)}{\operatorname{argmax}} \Bigg\{ & \\
& (1+i\delta)\left(1-\frac{p_4-p_6}{a\gamma_6^{(i-1)}}\right)p_4 - \\
& C\left(\left((1+i\delta)\left(1-\frac{p_4-p_6}{a\gamma_6^{(i-1)}}\right)\right)-1\right)_+^2 \\
& (1+i\delta)\left(\frac{p_4-p_6}{a\gamma_6^{(i-1)}}\right)p_6 \\
& -D_6(1+i\delta)\left(\frac{p_4-p_6}{a\gamma_6^{(i-1)}}\right)(1-\theta_6^{(i)})\Bigg\}, \qquad (12)
\end{aligned}
$$

where $\gamma_6^{(i-1)} = 1 - \theta_6^{(i-1)}$ is known, while $\theta_6^{(i)}$ needs to be replaced by its expression from Eq. (7). Note that different expressions must be used for $\theta_6^{(i)}$ depending on the value of $p_4 - p_6$. It is the need to consider those different cases that makes solving Eq. (12) cumbersome though not impossible.

Except for the fact that the optimal price for public IPv4 always satisfies $p_4 = 1$ (actually just below 1 to ensure positive utility), the expression for an explicit solution for Eq. (12) sheds little light on the role of different parameters, the reader is again referred to [10] for details, and we instead rely on numerical examples to explore the range of outcomes.

C. What Affects the Outcome and How?

Unsurprisingly, IPv6 adoption and the ISP's pricing strategy are directly affected by C, the normalization constant for the cost of acquiring additional public IPv4 addresses, and D_6, the translation cost of one unit of traffic. In addition, two other parameters indirectly affect the ISP's strategy because of how they influence users and ICPs decisions, namely, c_6, the per-user cost of upgrading the ICP infrastructure to IPv6, and a, the relative magnitude of the impairment that translation causes and consequently the loss in quality-of-experience for users and the related revenue loss for the ICPs.

It is possible to scope the ranges some of those parameters can span, *e.g.,* $C \leq 1$, but a complete sampling of this four-dimensional space is impractical. We rely instead on several figures to report how the outcome changes as some parameters vary, while others remain fixed. The figures help identify parameters that have a significant effect on IPv6 adoption by both users and ICPs; hence suggesting possible strategies.

Figs. 4 and 5 plot three quantities as a function of the ratio $\frac{a}{c_6}$. The left hand-side of the figures gives the time to full IPv6 adoption by ICPs (by how much the Internet user population needs to increase to convince ICPs to become IPv6 accessible[14]). The right hand-sides of the figures give, after doubling the size of the Internet user population, the (final) fractions of users that have opted for IPv6, and of ICPs that have become IPv6 accessible. The figures report the results for two different configurations, namely, small and large values of C, and for each configuration consider different ratios between

[14]Note that full adoption need not always be feasible.

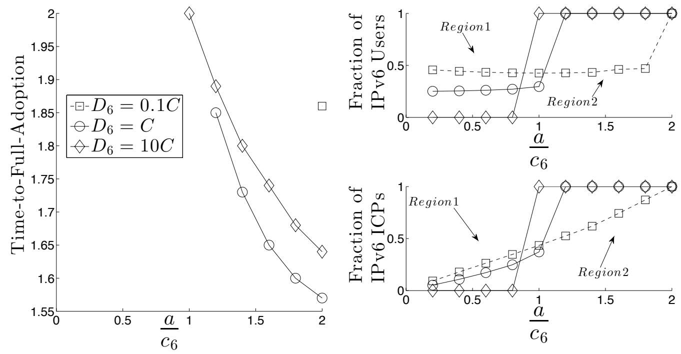

Fig. 4. Time-to-full-adoption population & adoption levels for small C

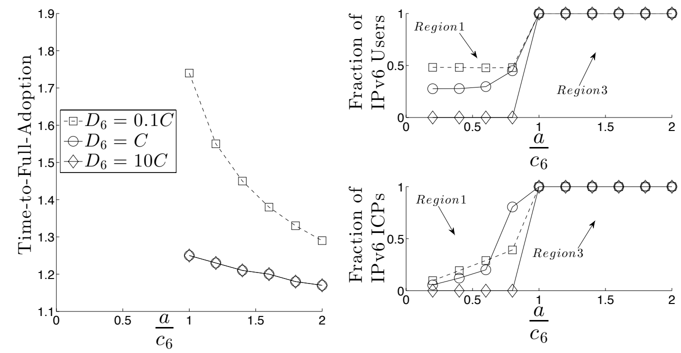

Fig. 5. Time-to-full-adoption population & adoption levels for large C

translation costs and IPv4 address acquisition costs, *i.e.,* $\frac{D_6}{C}$ takes values 0.1, 1 and 10.

The figures illustrate a number of intuitive outcomes, and in the process offer some level of "sanity checking" of the model. For example, they confirm the expected positive impact on ICP adoption of decreasing their upgrade cost, c_6. But they also reveal less obvious behaviors such as, for example, the effect of a, which as we discuss next can have an ambiguous effect. They also identify (combination of) parameters that have a systematic effect on IPv6 adoption, *i.e.,* the ratio $\frac{a}{c_6}$.

Consider first the effect of a decrease in the level of impairment, a, that translation imposes. Such a decrease can (initially) make IPv6 more attractive to users by lowering the penalty they incur when accessing ICPs that are not yet IPv6 accessible. This can increase the number of users that choose IPv6, which can in turn entice more ICPs to become IPv6 accessible; possibly starting a positive feedback loop in IPv6 adoption. On the flip side, a lower a value also decreases the potential revenue gain ICPs derive from becoming IPv6 accessible. This makes it more likely that revenue increases won't offset adoption costs; hence reducing ICPs' adoption of IPv6. This would in turn make IPv6 less attractive to users, and having fewer users opting for IPv6 would further reduce its attractiveness to ICPs. As we can see, the role of changes in a on IPv6 adoption is unclear, and the figures help elucidate under which conditions changes in a improve IPv6 adoption.

First, the figures illustrate that an increase in the ratio $\frac{a}{c_6}$ systematically results in higher IPv6 adoption by ICPs and to a lesser extent users. In the case of ICPs, $\frac{a}{c_6}$ represents the ICP's return on IPv6 adoption from a single user. An increase in this return motivates more ICPs to make such an adoption choice. When this increase is through an increase in a (rather than a decrease in c_6 that is trivially beneficial to both ICPs and users), the greater number of ICPs that opt to become IPv6 accessible offsets the larger penalty that users suffer when accessing ICPs that are not IPv6 accessible. In other words, users experience greater impairments when accessing ICPs that still require translation, but because there are fewer such ICPs, the impact is mitigated. Consequently, the number of users that choose IPv6 is not overly affected even if differences exist. In general, while both Figs. 4 and 5 establish that a larger ratio $\frac{a}{c_6}$ benefits IPv6 adoption by both ICPs and users, ensuring a complete migration to an IPv6 Internet requires a large enough value. How large this value needs to be depends on a number of factors, and in particular C and D_6, which as we discuss next introduce some interesting behaviors in their own right.

Specifically, consider scenarios associated with *Region* 1 in Figs. 4 and 5, for which the ICPs' return on IPv6 adoption ($\frac{a}{c_6}$) is low, *i.e.,* the ICPs have limited incentives for becoming IPv6 accessible. In such a regime, low translations costs[15], D_6, afford the ISP enough leeway to price IPv6 competitively and convince some users, and consequently ICPs, to adopt IPv6. This is reflected in the higher adoption levels of both users and ICPs as D_6 decreases. Interestingly, increasing the ICPs' return on IPv6 adoption $\frac{a}{c_6}$ has little effect on the number of users that adopt IPv6, though it affects (increases) the number of ICPs that elect to become IPv6 accessible. As alluded to earlier, this is because while there may be more ICPs that can be accessed natively over IPv6, this benefit is offset by the greater impairments users experience when accessing the remaining ICPs.

Further increases in the ICPs' return on IPv6 adoption ($\frac{a}{c_6}$) eventually trigger a shift in adoption, with all users and ICPs adopting IPv6. When and how this shift happens is, however, affected by the relative magnitude of IPv4 address acquisition costs, C, and IPv6 address translation costs, D_6.

When IPv4 address acquisition costs are high (*Region* 3 of Fig. 5), the shift is abrupt. This is because the high cost of IPv4 addresses entices the ISP to aggressively discount IPv6 early on to quickly convince ICPs and users alike to adopt IPv6. This can be seen by comparing the left hand-side plots of Figs. 4 and 5 that report time to full IPv6 adoption[16] by ICPs, and which show that it is reached much faster when the cost of IPv4 addresses is high. In contrast, when IPv4 addresses costs are relatively low (*Region* 2 of Fig. 4), the transition to full adoption is more progressive and dependent on the relative magnitude of translation costs. In particular, when translation costs are low, the ISP may initially offer only a limited discount for IPv6, which can prevent full IPv6 adoption and prolong the coexistence of IPv4-only and IPv6-only Internets (as the Internet user-base grows, so do the benefits for ICPs of becoming IPv6 accessible, but unfortunately so do their upgrade costs). In other words, if IPv4 addresses remain cheap for an extended period of time, it not only prolongs the transition to an IPv6 Internet, it may also make it significantly more expensive by deterring many ICPs from migrating early; hence, incurring higher conversion costs later on (they will need to migrate a bigger infrastructure).

The above discussion highlights a potential shortcoming of the model, namely, the myopic decision process used by both ISPs and ICPs. More strategic ISPs and ICPs could foresee the impact of continued growth in the Internet user-base and make early (IPv6) pricing and adoption decisions accordingly. This would likely result in improved adoption outcomes in a number of scenarios. We have explored (numerically) the impact of introducing a more strategic decision making process for ISPs and ICPs. As expected, it did lead to faster and more optimistic adoption outcomes, but did not significantly affect the roles of different parameters as identified in this section. Details of the investigation can be found in [10].

[15]Note that changes in translation costs are chosen proportional to C, which explains in part the similarity of Figs. 4 and 5.

[16]Note that the low translation cost scenario ($D_6 = 0.1C$) of Fig. 4 allows full adoption only when $\frac{a}{c_6} = 2$, while in Fig. 5 the scenarios $D_6 = C$ and $D_6 = 10C$ yield identical times to full IPv6 adoption.

V. Related Works

Explaining the slow progress of IPv6 adoption has been the focus of much prior work (see [11] for a recent overview). Earlier works focused on identifying technical issues that created initial adoption hurdles [12]–[15], but as those were eventually addressed, the attention shifted towards measuring IPv6 adoption progress [9], [16]–[21], as well as exploring the role that economic forces may be playing [22]–[28].

Those latter works bear the most direct relevance to the investigation presented in this paper, with [22] echoing many of the same themes we identify, including the importance of coordination, albeit without analytical support. Casting IPv6 adoption as a game was proposed in [28], but one with Autonomous Systems as the sole players, *i.e.,* it did not account for either users or ICPs. The use of two-sided markets to capture dependencies between the decisions of Internet stake-holders was suggested in [25], but used simply to assess the impact of changing certain parameters, *i.e.,* it did not explore the possibility or competition between ISPs nor how the presence of coordinated revenue maximization by ISPs would influence the outcome.

There is also a vast literature on two-sided markets, and the reader is referred to [29], [30] for recent surveys. The most relevant works deal with competing platforms [6], [31], *e.g.,* IPv4 and IPv6, but the absence of pricing for one side of the market (the ICPs) in our context makes for a very different (and simpler) focus.

VI. Conclusion

This paper's motivation is to develop a better understanding of the reasons behind IPv6 ongoing struggle in convincing Internet stakeholders to adopt it, and if possible suggest ways to mitigate it. The paper develops models that explicitly incorporate the dependencies that exist between the decisions of Internet stake-holders, and explores how these dependencies affect IPv6 adoption decisions under different scenarios. A first set of scenarios involved ISPs that respond to IPv4 address scarcity differently, namely, by using different connectivity options. The ISPs then compete on the basis of their differences in those connectivity options. The scenarios helped demonstrate why, in the presence of such competition, devising effective IPv6 adoption strategies may be difficult.

The paper then explored an alternative scenario that preserves the ability to offer different connectivity options, but does so assuming that connectivity choices are not anymore a matter of competition between ISPs, *e.g.,* there is a consensus to offer similar options. While this is by itself not a sufficient condition to ensure a rapid or even certain migration to an IPv6 Internet, it affords a more predictable look at how different parameters can affect the outcome. In particular, it helped identify the return on IPv6 adoption, $\frac{a}{c_6}$, as a major factor affecting IPv6 adoption by ICPs and users alike, *i.e.,* larger values of this ratio systematically help foster a more rapid and complete migration to IPv6. The model also helped identify the role that both IPv4 address acquisition costs, C, and translation costs, D_6, play. In particular, it showed that if IPv4 address costs remain low, low translation costs can be detrimental and delay an eventual migration to an IPv6 Internet. The latter is to some extent a result of the model's assumption of a myopic decisions process by ISPs and ICPs, but while this can to some extent be alleviated by allowing more strategic decisions, the general behavior remains.

The models on which this paper's investigation is based have numerous obvious limitations, and clearly fail to capture many of the factors that play a role in IPv6 adoption decisions. However, they capture the interplay and roles of the different Internet stake-holders and their decisions. As such the results offer some insight into the potential causes behind the difficulty of migrating to an IPv6 Internet, and point to possible remedies to hasten it, *e.g.,* by ensuring that ISPs offer users and ICPs consistent connectivity choices and by focusing on increasing the ICPs' return on IPv6 adoption $\frac{a}{c_6}$.

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