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Maintaining the progress of IPv6 adoption☆,☆☆

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ABSTRACT

Even though IPv6 adoption has accelerated in recent years, the complete migration of the Internet still faces many challenges. There are multiple factors that can potentially affect, negatively or positively, the future adoption of IPv6 by various Internet stakeholders. This situation begs the question of "what could be done to avoid derailing the IPv6 adoption progress?" and "how different factors can help maintain its acceleration?" There has been significant interest in those questions, and the paper proposes a series of models to investigate and shed light on them. The results confirm the effect of a number of known factors, while also providing new insight. Particularly, they highlight the destabilizing impact of disagreement across Internet Service Providers (ISPs) on immediate migration to IPv6, and show the benefits of minimal coordination among them in offering IPv6 as an option. They also show what affects technology transition in a large network with complex dependencies such as the Internet. Using robustness analyses, the findings are shown to hold in the presence of different assumptions and scenarios.

1. Introduction

IANA announced in February 2011 that the free pool of IPv4 addresses is 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, and even though recent studies show its adoption is accelerating, there are hurdles that can impede or slow down its progress in the future. Although these hurdles are not (anymore) of a technical nature, years of technology disparity between IPv4 and IPv6 caused a marginal adoption of IPv6 across major Internet stakeholders [2], which in addition to incompatibility of the two technologies forced the use of translation mechanisms to allow IPv6-only users access to the IPv4-only Internet. These translation mechanisms are widely used today by ISPs such as CERNET2 in China, and Verizon Wireless and T-Mobile in the U.S. CERNET2 [3] (an academic network), already had over 400k *IPv6-only* users in 2009, is expected to reach 3 million by the end of 2015 (see [4,5]), and uses "IVI", which translates IPv4 traffic to IPv6 and vice versa. Similarly, Verizon Wireless and T-Mobile are now primarily relying on IPv6 addresses for new cell-phone subscribers [6,7], and use "NAT444" and "464XLAT" as their translation mechanisms, respectively. While necessary for a transition, the quality degradation those mechanisms introduce [8–11] reduces motivation for the new users to adopt IPv6. This is an instance of hurdles in front of the progression of IPv6 adoption in the future. Our initial intuition was that besides the above instance, the distributed structure of the Internet can also affect the progression of IPv6 adoption. 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 [12] for a related discussion in the context of Internet security protocols), but uncertainty in

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the decisions of others can significantly delay the adoption of a new technology.

A goal of this paper is, therefore, to explore and explain strategies that can derail or speed up the current progress of IPv6 adoption. These strategies require careful assessments as we are dealing with a highly decentralized system (the Internet). To better understand the extent to which these strategies can affect IPv6 adoption, several simple yet representative scenarios and models were developed. The focus of these models is on the decision making process of independent and decentralized stakeholders across the Internet, and how those decisions can affect IPv6 adoption. We acknowledge up-front the many simplifying assumptions these models rely on (a necessity in most modeling efforts), and their lack of completeness. However, they incorporate major aspects of IPv6 adoption decisions, namely, (i) heterogeneity in the Internet stakeholders making decisions; (ii) a representative sample of available technology options; and (iii) the dependencies that exist across decisions.

Our findings from these models indicate that independent decision making process of ISPs can negatively affect IPv6 adoption. In other words, disagreement between ISPs on connectivity option offerings, adds uncertainty to the factors that affect IPv6 adoption decisions of the Internet stakeholders, and makes it hard to identify winning strategies. As a result of this uncertainty, migration to IPv6 slows down, or at the very least becomes haphazard. Another finding of the models is that even minimal coordination among ISPs in offering connectivity options, *e.g.,*an Internet-wide consensus on offering IPv6 as one of the connectivity options, can significantly improve our abilities to identify strategies that hasten the IPv6 migration process. Although consensus alone is not sufficient, it makes it easier for the Internet stakeholders to identify winning strategies that can, at the same time, speed up the migration of the Internet to IPv6.

The paper's contributions are, therefore, two-fold:

(i) It shows how distributed decision making of the Internet stakeholders, in the presence of competing solutions to the problem of IPv4 address scarcity, can negatively affect identifying winning strategies, and therefore, linger the (current) uncertainty in IPv6 adoption; and
(ii) It illustrates how the introduction of limited coordination among ISPs, which is not in itself enough for IPv6 success, can help determine the impact of different parameters on IPv6 adoption, and hence, facilitate a smoother migration process.

The rest of the paper is structured as follows. Section 2 discusses the framework of the problem, including the Internet stakeholders, connectivity options, and scenarios. Section 3 introduces the models in two categories of disagreement and consensus. Sections 4 and 5 explore the outcome of the models with a certain set of assumptions, and provide the key findings. Section 6 investigates the robustness of our findings to different modeling assumptions and extensions. Section 7 briefly reviews related works, with Section 8 summarizing the paper's findings and recommendations.

There are too many differences between this paper and its preliminary version [1], and therefore, we only list the major changes, namely, generalized models, extended range of numerical analyses, and robustness analyses section.

2. Problem framework

There are many factors that arguably affect the adoption of IPv6, and any (tractable) model is unlikely to account for all of them and their variations across stakeholders. Our models operate within a certain framework, and this section specifies the outline of that framework by introducing the Internet stakeholders, their connectivity options, the inter-dependencies between their decisions, and the scenarios in which they interact.

2.1. Internet stakeholders

We distinguish between *three* types of Internet stakeholders: Internet Service Providers (ISPs), Internet Content Providers (ICPs), and Internet Content 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. They make the ultimate decision to offer IPv6 connectivity to the other two stakeholders, hence, they play the most significant role in IPv6 adoption across the Internet. ICPs obtain the bulk of their revenues from users that connect to them through ISPs. Hence, their focus is on the quality of their connectivity to users and how it may affect their 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.

2.2. ISP's connectivity options

ISPs are the providers of Internet connectivity, and therefore control technology choices. Although IPv6 adoption is on the verge of happening, implicit to our modeling effort lies the fact that IPv6 still faces competing solutions. Among those available technology choices ISPs may choose from to accommodate customer growth, we consider three representatives.

The first choice an ISP can make 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 an ISP can rely on is to use 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