Migrating to IPv6
The Role of Basic Coordination

M. Nikhah
Dept. Elec. & Sys. Eng.
University of Pennsylvania

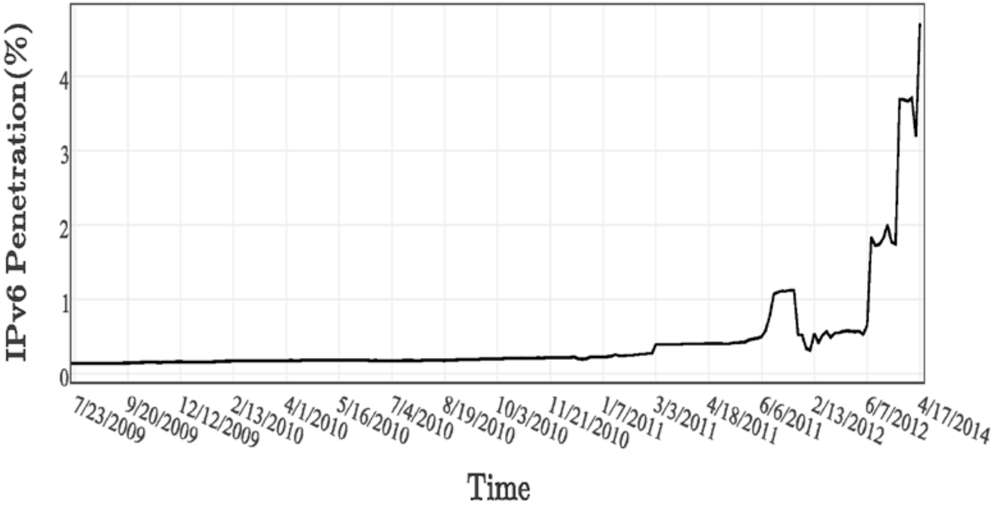
R. Guérin
Dept. Comp. Sci. & Eng.
Washington U. in St. Louis

Outline

- Background and Motivations
- Approach
  - Stakeholders and adoption factors
- Models
  - Scenarios
  - Capturing interactions and dependencies
  - Stakeholders utility functions
- Solution methods and results
- Summary of findings

Background and Motivations

- IPv4 addresses are slowly but surely becoming scarcer
  - IANA allocated its last block in February 2011
  - Many RIRs have exhausted their address pool
- The problem has been forecast for about 20 years
  - IPv6 was standardized circa 1998 to address it
- IPv6 has by all accounts been struggling to gain a foothold



- In this paper, we highlight one of (many) things we should avoid to not further derail IPv6 adoption (and conversely, may want to do to foster continued IPv6 adoption)
  - Uncertainty in the IPv6 market and the availability of competing alternatives

Approach

- Classify drivers for IPv6 adoption and adoption decisions?
  - Stakeholders and major adoption factors
- Identify representative evolution scenarios
  - What are plausible alternatives to IPv6, and how do they interact/compete?
- Develop (reasonable) models to capture the likely decision process of stakeholders
- Explore solutions to those models and the types of outcomes they give rise to
- Offer insight into what factors affect the outcome and why

Stakeholders and Adoption Factors

- Three main interacting players in the IPv6 adoption decision process
  1. Internet Service Providers (ISPs) decide what connectivity options to offer, including IPv6
  2. Internet users acquire connectivity from ISPs, and may choose between competing options if offered
  3. Internet Content Providers (ICPs) seek access to users through the connectivity that ISPs offer

  4. Technology makers, *e.g.*, router & OS vendors, clearly play a role, but are not (directly) involved in adoption decisions

- Each stakeholder is influenced by different though not necessarily independent factors
  - ISPs are primarily concerned about costs and revenues
  - Users are sensitive to what they pay for connectivity and its quality
  - ICPs are mostly interested in maximizing the revenue they derive from users

  and they interact

IPv6 Alternatives (Competitors)

- IPv6 is only one of several options available to address the growing scarcity of public IPv4 addresses
  - In its favor, it solves the problem once and for all, but
  - It requires a technology upgrade, and more importantly still mandates "translation" to reach most of the current Internet, hence imposing an added cost and affecting connectivity quality (or functionality)
- ISPs opting not to deploy IPv6 can choose from at least two alternatives
  1. Keep using public IPv4 addresses
     - They are getting scarcer but remain available, *e.g.*, through emerging "markets"
     - This preserves the status quo, but at a cost that will likely grow
  2. Rely on private IPv4 addresses
     - A mature and well understood technology
     - Like IPv6, communication with the public Internet requires translation

Three Sample Connectivity Scenarios

High-level goal: Contrast scenarios with and without consensus on IPv6 as the solution to IPv4 address scarcity

1. ISPs offer competing connectivity options
   - Public IPv4 **versus** IPv6
   - Private IPv4 **versus** IPv6
2. All ISPs offer the same connectivity options, which still compete but now internally to each ISP
   - Public IPv4 **and** IPv6

Q: What IPv6 adoption outcomes arise in each scenario?

Outline of Adoption Decisions
(Modeling the Interactions' Cycle)

Assuming a growing Internet, for each connectivity scenario:

- After an increase δ in demand, ***ISPs*** set the price of the option(s) they offer so as to maximize their expected revenue
- ***Users*** choose connectivity based on its price and quality (accounting for the impact of translation)
  - Users are heterogeneous in their sensitivity to connectivity quality
- ***ICPs*** decide whether to become IPv6 accessible based on the trade-off between upgrade cost and higher revenues from IPv6 users
  - ICPs are heterogeneous in their upgrade costs

Model

- The system is essentially a two-sided market
  - ISPs as the market makers
  - Users and ICPs as the two sides of the market
- ISPs announce prices and the two sides of the market make adoption decisions accordingly
  - Users and ICPs make decisions that maximize their "*utility*"
  - ISPs set prices to maximize their revenue
    - When ISPs compete, the setting of prices is essentially the outcome of a *game* where each seeks to maximize its revenue

Utility Functions

- **Users**: value – price – translation impairments*
  - Users vary in their sensitivity to impairments, and therefore choice of connectivity option
- **ICPs**: revenue from users – upgrade cost*
  - Revenues are affected by connectivity quality
  - Upgrade costs vary across ICPs, which can therefore lead to different upgrade choices
- **ISPs**: revenue from users – translation costs* – address costs*
  - Revenues depend on price & number of users
  - Translation costs depend on number of users and destinations (ICPs) that need translation (different for IPv6 and private IPv4)
  - Address costs are only applicable to public IPv4 addresses and depend on overall demand

* *When applicable*

Outline of Solution Method

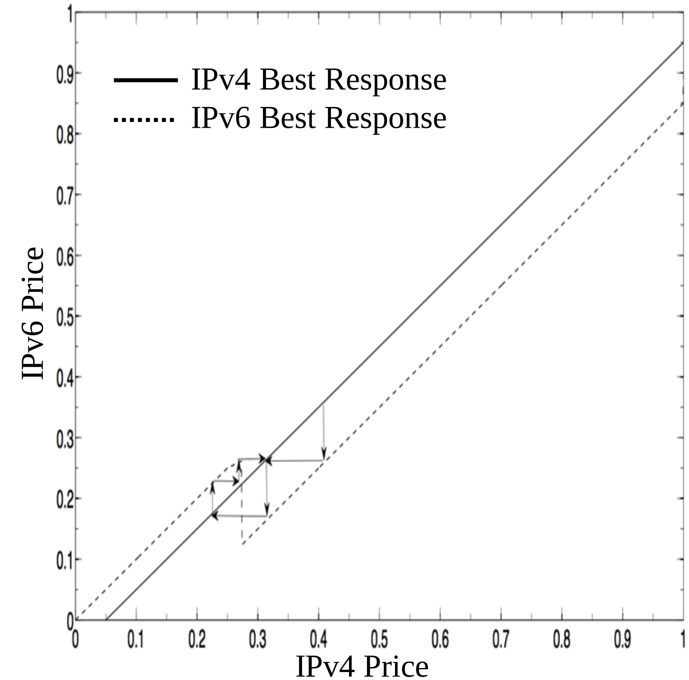
- Consider an ISP offering connectivity option *i* (to accommodate an increase of size δ in Internet demand/users)
  - Its goal is to maximize it profit Π
  - $\Pi = f_{\mathrm{ISP}}(p_i, p_j, users, ICPs)$
    - p_i and p_j are prices of connectivity options *i* and *j* (offered by ISP and/or its competitors)
    - *users* denotes how many users choose which option
    - *ICPs* identifies the # of ICPs natively accessible over each connectivity option
- Given p_i, p_j, and *ICPs*, we can obtain
  - $users = f_{\mathrm{users}}(p_i, p_j, ICPs)$
- Given *users*, ICPs decisions can be determined
  - $ICPs = f_{\mathrm{ICP}}(users)$
- So that $\Pi = f_{\mathrm{ISP}}\big(p_i, p_j, f_{\mathrm{users}}(p_i, p_j, f_{\mathrm{ICP}}(users)), f_{\mathrm{ICP}}(users)\big)$

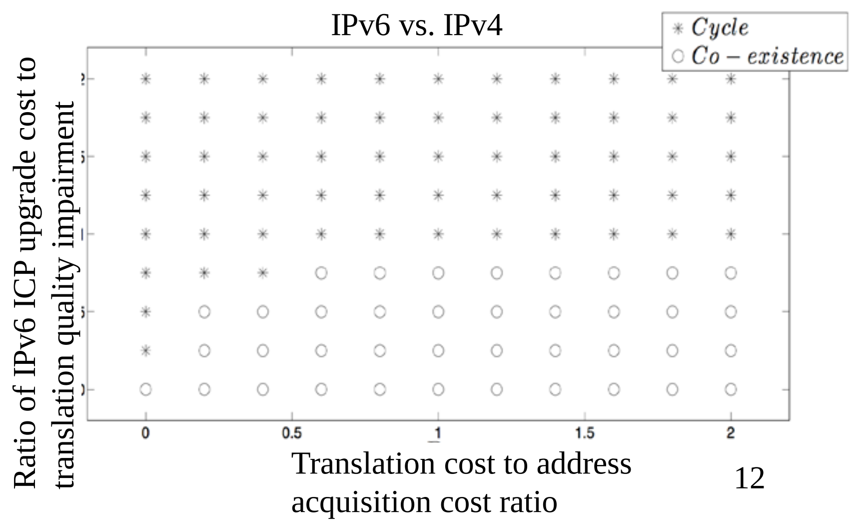
- It is then possible for the ISP(s) to solve for p_i, p_j, either directly or through a best response game
- The main question is whether and when a solution exists, and what its characteristics are?

Findings (1)

- When connectivity competition is externalized, *i.e.*, across ISPs, it can have a destabilizing effect (non-converging pricing strategies)
  - This arises for both IPv6 vs. public IPv4 and IPv6 vs. private IPv4 scenarios
  - Not an unusual outcome

- The main culprit is the coupling that exists between users and ICPs decisions in response to price announcements by competing ISPs
  - This introduces two distinct strategies for an ISP offering IPv6:
    - High & low discounts and correspondingly large and small customer bases
    - This can give rises to price cycles



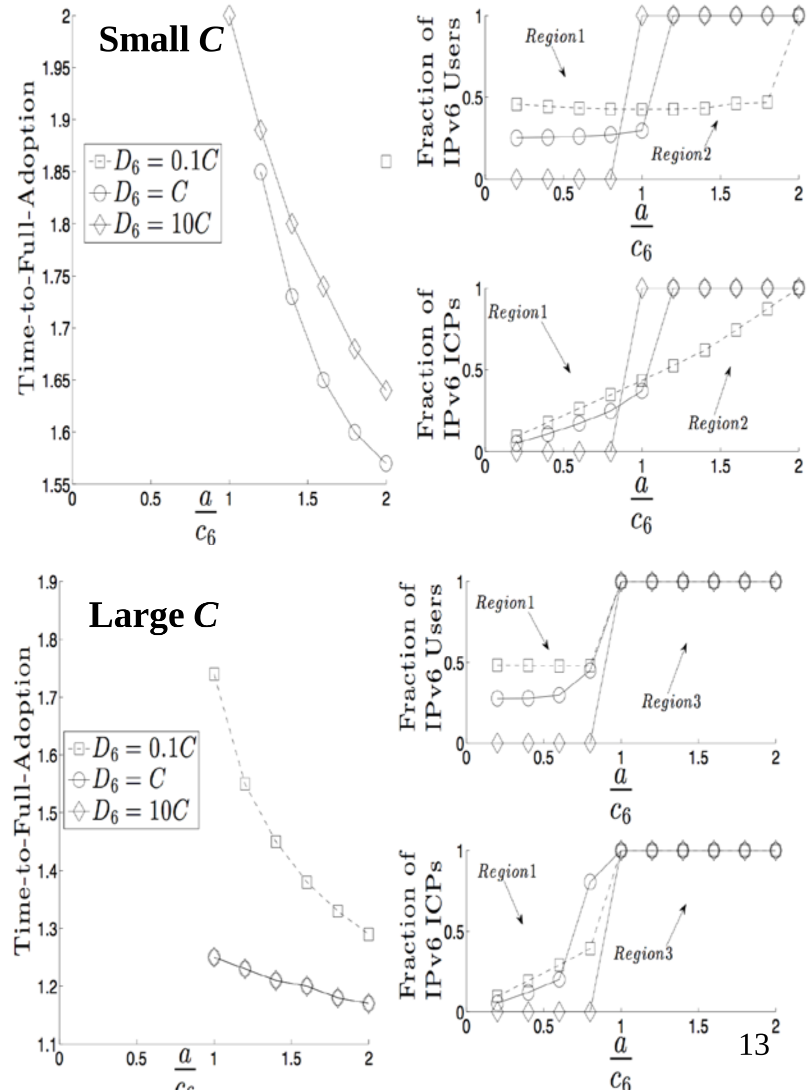


C: Acquisition cost factor for IPv4 addresses
D_6: Translation cost of one unit of traffic
c_6: Per user ICP IPv6 upgrade cost
a: Quality impairment from translation

Findings (2)

- When connectivity competition is internal, *i.e.*, a singe ISP offering multiple connectivity options to accommodate customers' demands, pricing instabilities are eliminated
- This does not mean though that IPv6 adoption is a sure thing!
- Several factors affect the outcome (overall IPv6 adoption and time† to full adoption by ICPs, when feasible)
  - Ratio a/c_6 (quality vs. upgrade cost)
    - The role of c_6 is clear (the lower, the better), but that of a is more ambiguous
    - A bigger a motivates more ICPs to adopt, but can make matters worse for users
  - Ratio D_6/C (translation vs. address costs)
    - Different regimes depending on the relative magnitude of C

† Measured in steps of 1% in Internet population increases



Model Limitations and Extensions

- There are obviously more limitations and simplifying assumptions in the model than there is room to list on this slide…
  - Homogeneity of ICPs in revenue and traffic they attract
  - User’s ability to change their connectivity option
  - Use of pricing as differentiator between connectivity options
- Some low-hanging and potentially useful extensions
  - Strategic vs. myopic decision makers, especially for ISPs and ICPs
    - Strategic decisions speed-up adoption in most scenarios, but do not qualitatively change outcomes or impact of parameters

Summary

- The difficulties faced by IPv6, in spite of the fact that it was identified early on as a solution to a serious problem the Internet faced, raises a range of interesting questions
  – There are clearly many factors behind the slow adoption of IPv6 as the “next generation” Internet protocol, and
  – Much of its current troubles could have been averted, if the original intent of parallel deployment had become a reality from the beginning
- Hopefully, we can avoid repeating the current situation, but it is still of interest to better understand what we should and should not do to further foster IPv6 adoption now that it finally seems on the mend
  – A two-sided market model is a natural option to explore this question
  – There are many possible configurations and combinations, but the models do help reveal a few interesting factors
    - Competition on the basis of connectivity creates uncertainty that can have a negative impact
    - The quality degradation imposed by translation (a) can have a somewhat ambiguous effect, but in general making translation too good is not helping…