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Essays On The Market For Ipv4 Addresses

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Abstract

In this dissertation I study the market for IPv4 addresses - a multi-billion dollar market that is crucial for seamless internet communication. As this market has been understudied due to lack of accessible data, I collect data from various sources and create novel datasets that make this study possible.

In the chapter, ``Technology transition with frictions: Evidence from the market for IP addresses", I introduce IP addresses and the market for IPv4 addresses. Each IPv4 address is a durable, homogenous resource and has zero fundamental value once the standard changes from IPv4 to IPv6. Yet in the market prices have been continuously increasing. Understanding this pricing puzzle is not just interesting from a theoretical perspective, but also crucial for applied policy analysis.

To understand these and other empirical facts I explore the transition of firms from IPv4 to IPv6 in the presence of market frictions. The two key frictions in the market are switching costs and network effects. To substantiate this, I develop a dynamic model of firm behavior and calibrate the model to get a plausibly parametrized version of the model. This model can explain the striking increase in prices observed and the delay in IPv6 adoption.

In the parameterized version of the model I find that it would take 33 years to reach near complete IPv6 adoption. In counterfactual simulations, I examine the role of frictions and optimal adoption path by a social planner. A regulation that aims to shut down the market by a certain period leads to a coordination in IPv6 adoption and increase in producer surplus, thus making it in an effective policy tool to enable transition to IPv6. Thus, in the presence of market frictions, the market on its own could fail in efficiently transitioning to the next protocol.

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ESSAYS ON THE MARKET FOR IPV4 ADDRESSES

Dedicated to my family

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‘God’s plans for you are bigger than your plans for yourself’ - *Isaiah 55:8-9*

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ABSTRACT

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In this dissertation I study the market for IPv4 addresses - a multi-billion dollar market that is crucial for seamless internet communication. As this market has been understudied due to lack of accessible data, I collect data from various sources and create novel datasets that make this study possible.

In the chapter, "Technology transition with frictions: Evidence from the market for IP addresses", I introduce IP addresses and the market for IPv4 addresses. Each IPv4 address is a durable, homogenous resource and has zero fundamental value once the standard changes from IPv4 to IPv6. Yet in the market prices have been continuously increasing. Understanding this pricing puzzle is not just interesting from a theoretical perspective, but also crucial for applied policy analysis.

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1 Technology transition with frictions: Evidence from the market for IPv4 addresses

1.1 Introduction

A world without internet is unimaginable, with many tasks in our daily life increasingly coupled with the internet. An essential component for this exchange of data over the internet is an IP address. The first protocol - IPv4 had only a finite number of addresses available. Even with the development of the next protocol- IPv6, IPv4 continued to remain the dominant protocol.IPv4 and IPv6 addresses are not directly compatible, and 'translation' is needed for devices on different protocols to be able to communicate with each other. In 2008 a market for IPv4 addresses was created motivated by the slow pace of IPv6 transition. In 2021 this market was worth over $100 billion dollars. As in other similar markets used for technology transitions, market frictions could lead to an excessive delay in adoption of the new technology. The two key frictions in this market are network effects and switching costs. which could lead to a delay in IPv6 adoption and affect all firms in the internet ecosystem.

In this paper I develop and calibrate a model to measure the welfare effects from the frictions and evaluate policies that might take the market closer to the optimal equilibrium path. Towards this end, I collect novel data and describe the ecosystem. This is important as both the ecosystem and the dataset are both novel. Then I analyze the inefficiencies that arise from the decentralized transition from IPv4 to IPv6 addresses. I focus on the evolution of price, IPv6 adoption, and the welfare effect from the frictions.

My research approach has been data-collection, development of an empirical model, calibration of parameters and analyzing counterfactuals. I collect novel data including micro data from the IPv4 market, IPv4 and IPv6 allocations and firm features for three regions between 1984-2020. I complement this with a novel dataset from a brokerage firm that has about 20% of the market transfers along with the transfer price. Since there is no official data collected about price in the market, this provides information into the evolution of price over time.

Three striking patterns emerge from the data. First, price in the market has been rising continuously since mid-2015. Between 2015 and 2020 prices have more than doubled. This is contrary to the expectation in the model by Edelman & Schwarz (2015) that prices would decline. This is an empirical puzzle as the data diverges from the theoretical model. Second, IPv6 adoption has been slow with adoption rates varying across ISPs, content provider and enterprise firms. Third, I provide evidence that IPv4 addresses are not perfectly liquid assets in the market. This is based on the observation that firms sell their IPv4 address holdings over time in multiple transfers and also corroborated through interviews with sellers[1].

Motivated by the descriptive evidence, I develop a dynamic model of firms making decisions in the market for IPv4 addresses and IPv6 adoption decision. There are two sources of switching cost. First, it is costly to free IPv4 blocks that are currently in use to be made available for sale. Second, without a central marketplace finding a buyer/seller, completing the transfer proceedings is costly and is incurred for every single transfer. In addition to a fixed IPv6 adoption cost the current IPv4 holding of each firm affects their total cost of IPv6 adoption. The model also includes indirect network effects in this ecosystem - firms care about the number of users on either protocol as the value of holding address increases with the number of users in that protocol.

I use a dynamic model because IP addresses are durable goods and decisions

[1]This is included in section 2.7 of the appendix

made by a firm with respect to the IPv4 market and IPv6 adoption decision affect their future payoffs and choices. I abstract away from several features such as some firms also being users, the usage of NAT[2] and CGNAT[3] by ISPs that allow multiple devices to share one IPv4 address (only 17% of firms use it as measured by Richter (2017)).

I calibrate the parameters related to switching cost, adoption costs, size and production parameter to fit the data for the time period 2008-2020. Key calibration targets include number of buyer/sellers, fraction of firms adopting IPv6 (by role and size) and share of total addresses sold over time. The calibrated model when simulated forward shows rising prices till \$60 and takes 33 years to reach almost complete IPv6 adoption. I find that enterprise firms have 58% higher per-unit switching costs and content provider firms 24% higher compared to ISPs.

Using the parameterized model, I look at four counterfactual simulations. First, I evaluate the impact of eliminating switching costs on prices, IPv6 adoption and producer surplus. Prices are lower than in the baseline. Price increases upto \$50 and then starts declining reaching a minimum in the last period. IPv6 adoption permeates 20 years quicker than in the baseline. Thus, compared to the baseline model prices in the market start declining earlier and reaches the peak 10 years earlier. The producer surplus is 88% higher than in the baseline model.

Second, I evaluate the impact of having the same network effects on both the protocols. In this case, I find that the market adopts IPv6 almost immediately (within three years) with prices reaching a peak of \$60 and then dropping to below \$20. But due to the presence of switching costs firms sell their IPv4 holdings over time.

Thirdly, I look at the welfare-maximizing adoption path which leads to a much quicker adoption, 50% of firms adopting within 16 years. Producer surplus is 25%

[2]NAT -Network address translation
[3]CGNAT - Carrier grade network translation

higher than in the baseline. This indicates that market frictions have a significant effect on the transition towards IPv6 as well as total producer surplus. Lastly, I look at a policy that declares an end-period for the market for IPv4 addresses. This is an easy policy tool that regulators can use unlike calculating the optimal subsidy for IPv6/tax for IPv4. With this policy, all firms have the common knowledge that the market would shut down by a given year. With this common knowledge firms can coordinate IPv6 adoption and overcome the delay in IPv6 adoption. Thus, relying on the market alone for transition to IPv6 could lead to a loss in welfare due to delay in adoption of the new technology.

The many attempts by various countries to improve IPv6 adoption highlight the policy relevance of this transition. The Chinese government introduced additional regulations mandating 70% IPv6 adoption by end of 2025 which spurred IPv6 adoption by firms. The US military has established similar mandates to achieve 80% adoption. Thus, answers to these questions can help policy makers achieve transition to the next technology in the most efficient way.

1.2 Related Literature

This paper relates to and builds on several strands of literature. The seminal work in this market is a theoretical work by Edelman & Schwarz (2015) that predicted declining price paths for IPv4 addresses. This is based on the assumption that IPv4 addresses are durable assets that provide value until all firms transition to IPv6. There are N firms that received an initial IPv4 allocation and in every period these firms can trade addresses in a perfectly competitive market until the last period. The underlying assumption is that there is common knowledge about the last period when all firms move to IPv6 and IPv4 addresses have zero value.

Equilibrium price adjusts each period to ensure the market clears. Price each period is equal to its fundamental value plus its resale value which is equal to the price next period. Thus, given a finite horizon price each period can be calculated through backward induction, and it must be the case that price is non-increasing over time. This was the seminal paper to introduce the market and make a prediction regarding price. The model is agnostic about how the transition to IPv6 happens and how there is common knowledge among firms that by a given last period all firms have transitioned to IPv6.

Building on this work, my first contribution is including endogenous IPv6 adoption by firms. This makes the last period of an IPv4 address endogenous. With this addition I find that the model predicts prices to rise before reaching a threshold IPv6 adoption and drops from then on. I also include two important features from the ecosystem - network effects and switching costs. These features affect firms' decision to adopt IPv6 as well their decisions in the market. There has been no empirical analysis of the market yet. My second contribution is to bring together novel datasets that make empirical analysis of this market possible.

The second strand of literature is the work studying technology adoption with network effects. Empirical work has analyzed various industries. This includes Caoui (2019) estimating the costs of standardization in the movie industry, Dubé et al. (2010) studying tipping in the hardware industry with indirect software network effects and Ryan & Tucker (2012) studying network effects and heterogeneity in the adoption of a video conferencing technology within a firm.

Theoretical work include Farrell & Saloner (1985) studying the inefficient delay in adoption of a new standard with network effects, Sen et al. (2010) analyzing the role of converters in technology adoption (IPv6 included as an example without IPv4 market), Ostrovsky & Schwarz (2005) studying the effect of uncertainty on standardization and Guérin & Hosanagar (2010) analyzing IPv6 adoption across different types of firm based on quality of connection (without the market for IPv4 addresses).

In the spirit of the papers above, this paper is an application of technology adoption with network effects in the IP address technology. Unlike previous papers that have tried to study the market for IPv4 addresses or IPv6 adoption separately, I develop a model to study both aspects in a single framework. This work sets up the space for further work in areas such as adoption of electric vehicles and the regulatory credits program as well as the carbon trading markets. My contribution is to develop a dynamic model suited to firm decision-making in this ecosystem and demonstrate that a plausibly parametrized version of the model can quantitatively explain the empirical findings as arising from rational choices of firms transitioning from IPv4 to IPv6 in the presence of market frictions. I calibrate the model parameters and then study counterfactuals.

The third strand of literature is the economics of internet infrastructure. This is a growing area answering a variety of economic questions within the internet realm. Bauer & Latzer (2016) in their handbook study questions related to technology adoption (e.g. fixed and wireless networks have been constantly upgraded), internet search as a two-sided market supported by advertising, online entertainment (related to bundling, pricing, content differentiation by OTT services) and many more. Greenstein (2020) provides a basic overview of the internet infrastructure. While different examples of technology adoption in the internet infrastructure have been studied, this paper focusses on the transition from IPv4 to IPv6 addresses.

My work draws on the techniques developed by Weintraub et al. (2010) on nonstationary oblivious equilibrium. There is growing empirical application of nonstationary oblivious equilibrium: Qi (2013), Buchholz (2016) and Saeedi (2019). Given the large number of firms that are present in this ecosystem and therefore the large state space I make the assumption that each firm only keeps track of its own state and the aggregate state variables - price and number of users on either protocol. This assumption is used in oblivious equilirium. I set the firm problem in a dynamic general equilibrium setting based on previous work in the literature including Lee (2005), Lee & Wolpin (2006), Yoon (2017) and, Humlum (2019). Similar markets are increasingly common in other areas as well. Carbon trading markets have been popular in many places - Europe, Canada and China. These are used to encourage firms to transition to a low carbon economy through the price mechanism. Similarly, zero-emission vehicle credit transfer programs have been introduced in various states in the US to encourage firms to transition towards electric car production. Firms producing electric vehicles receive credit that they can sell to others in the market. There was a similar expectation with the creation of the market for IPv4 addresses - that it would allow firms with lower adoption cost to switch first. This was keeping with the spirit of the internet which grew largely outside the purview of strong regulation.

The rest of the paper is organized as follows. Section 1.3 lays out the institutional setting. Sections 1.4 describes the data and presents descriptive evidence. Sections 1.5 and 1.6 details the hypothesis, dynamic game, and equilibrium. Section 1.7 and 1.8 details the calibration, results, and sensitivity analyses. Section 1.9 analyzes the counterfactuals and section 1.10 concludes.

1.3 Institutional setting

This section will discuss the institutional settings related to IP addresses including a background, segments demanding IP addresses, market for IPv4 addresses and IPv6 adoption.

Background about IP addresses

IP address stands for Internet Protocol address and refers to the set of rules governing the format of data sent via the internet or local network. IP addresses are included in the packet header to indicate the source and the destination of each packet. Thus, every device connecting to the internet has an IP address. This allows devices to communicate with each other over the internet using data packets.

The initial standard of IP addresses - IPv4 was created in 1984. This was the de facto standard used by all firms. Under the IPv4 protocol approximately 4 billion addresses were available, and this could not be expanded. The initial allocation was given to firms at zero price.

THe quick growth in the number of internet users led to the development and deployment of the next version of the protocol :IPv6 in 1999 with approximately 3×10^{38} addresses.[4] The number of IPv6 addresses was much larger than the number of addresses available under IPv4. For practical purposes it can be considered unlimited compared to the 7 billion devices in use today. While IPv6 has some minor advantages in terms of additional security given the larger number of addresses available within that protocol, for most practical purposes they can be considered the same.

The two key features of an IP address within either protocol are homogeneity and durability. Within a protocol, every IP address is exactly the same and there is no product differentiation. IP addresses don't depreciate over time, hence can be considered a durable good.

Compatibility between IPv4 and an IPv6 device

'2001:0db8:85a3:0000:0000:8a2e:0370:7334' is an example of an IPv6 address. '172.16.254.1' is an example of an IPv4 address. The two protocols have different address formats. This also makes the packet headers of IPv4 and IPv6 addresses different and incompatible. Thus, a device with only an IPv4 address cannot communicate directly with a device with only IPv6. There are three main techniques

[4] IPv5 was an experimental protocol that was never formally adopted as a standard

used to overcome this compatibility issue:

- Translation - a device that translates IPv6 packets into IPv4 packets or vice versa
- Tunneling - encapsulating IPv6 packets within IPv4 packets
- Dual-stacking - devices are able to run IPv4 and IPv6 in parallel, allowing to simultaneously reach IPv4 and IPv6 content

Translation[5] and tunneling techniques are difficult to scale-up and lead to higher costs and increased latency. Dual-stacking requires firms to support both IPv4 and IPv6 leading to higher operational costs with all systems and applications running on both protocols. Hence these techniques are unlikely to be a permanent solution, thus ruling out the coexistence of IPv4 and IPv6 in the long run.

Dual-stacking was the most common strategy used by firms transitioning to IPv6 in the early years. This is because firms care about the number of users and content that is available on either protocol. It has been noted that by Force (2006) that in this ecosystem indirect network effects that exists between firms and number of users as more important than direct network effects that arise as an additional firm adopts IPv6. In case of indirect network effects as the number of users increase in either protocol the value of holding address in that protocol increases.

Due to the presence of these indirect network effects, firms adopting IPv6 don't immediately decrease their IPv4 holdings. Rather they hold onto their IPv4 addresses and decrease dependence over time. In the rest of the paper by IPv6 adoption I mean that firms are adding dual stacking capability. This is similar to 'dual-homing' seen in other industries. Dual stacking is associated with deployment costs and continued

[5] Also called Network Address Translation-Protocol Translation (NAT-PT)

higher operational costs as they need to support both the protocols in the interim. Higher operational costs include additional testing, troubleshooting etc. This makes it harder to be the first adopter as well as beneficial to be the last adopter.

The ISPs make the decision about how many users receive IPv4 addresses and how many IPv6 addresses to connect to the internet based on their translation costs. To make the problem tractable without losing the objective of short run transition of firms, I assume that the number of users on IPv6 is an increasing function in the share of firms with IPv6.

There is no empirical measure of how actively firms are using IPv6 (traffic data). Instead, I look at two measures of IPv6 capability that I use to have a sense of IPv6 adoption. First, I look at the firms that have received at least one IPv6 block from an RIR. Second, I look at the firms that have routed at least one of these IPv6 block that they received. Naturally the number of firms with an IPv6 block is higher that the number of firms that have routed at least one of these blocks. I include more details about the steps to check if a block is routed in the appendix 2.1.

Organizations in charge of IP addresses

The IP address space has been managed by IANA (Internet Assigned Numbers Authority) - a global organization overseeing IP address allocation. In the early days IANA directly allocated IP addresses to organizations in North America. During this time, each firm received 16,777,216 addresses with a total of 587 million addresses allocated to these 35 firms (18% of the total space). These allocations were made to corporations or government organizations like the USPS or the Department of Defense.

Later they established five regional RIRs (Regional internet Registries) that are currently in charge of allocation and maintenance of IP addresses. The five RIRs in charge of the regions of North America, Asia Pacific, Europe, Latin America, and

Africa respectively are:

- ARIN (American Registry for Internet Numbers)
- APNIC (Asia Pacific Network Information Centre)
- RIPE NCC (Réseaux IP Européens Network Coordination Centre)
- LACNIC (Latin America and Caribbean Network Information Centre)
- AFRINIC (African Network Information Centre)

IANA looked at the average usage in the last 6 months for an RIR and used this to project demand for the next 9 months. RIRs that fell short were given more addresses to allocate. The IANA ran out of addresses to allocate to the RIRs in 2011 and the RIRs ran out of addresses soon after[6].

In the figure below I look at the allocation of IP addresses by RIRs to firms. RIRs further allocated IP address blocks in smaller sizes to ISPs, content providers, schools, universities, banks, museums, factories, governments, and enterprise networks in standard contiguous sizes. The ISPs and other internet operators further allocate addresses to large and small users while deriving revenue from them.

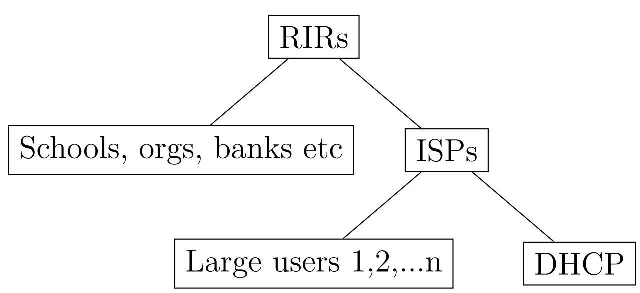


Figure 1: Allocation of addresses by regional internet registries

[6]APNIC:04/2011,ARIN:08/2015 and RIPE: 11/2019

The initial allocation was based on classful allocation where firms received addresses in three sizes: 16,777,216, 65,536 and 256 irrespective of their demand for addresses[7]. Later they moved to CIDR (Classless Inter-Domain Routing) blocks which allowed a finer granularity by allowing addresses to be allocated in sizes between 256 and 65536 (Class B and class C). The RIRs tried to allocate addresses in the closest size to a firm's projected demand.

I focus on the three RIRs - ARIN (North America), APNIC (Asia Pacific) and RIPE (Europe) as they allow IPv4 addresses to be transferred between themselves forming a common market for IPv4 addresses. The other two RIRs do not allow inter-RIR transfers. There is also limited information about price in these other two markets and is likely to be driven by local demand and supply. These three RIRs also accounts for majority of the addresses allocated to firms.

Address block sizes

IPv4 addresses are given out in standard sizes. Each block of address is represented by a 'slash notation' that captures the number of addresses in it. Blocks with more addresses have a smaller number in the slash notation compared to smaller blocks. Firms receiving IP addresses paid initial and annual fees to the RIRs as RIRs considered themselves the final owners of the IP addresses. Firms could use the address blocks as long as they paid the annual fees.

The fees/address fall in the number of blocks purchased and the fees charged is much smaller than its value or the price in the market. This is because the RIRs are nonprofit organizations largely motivated to ensure enough funds to cover operation costs. The table below shows a sample of block size and associated fees for IPv4 addresses from ARIN. Fees/address starts from less than \$1/block and is close to 0 for extremely large blocks. IPv6 has the same fee structure for its various block sizes.

[7]This was called Class A, class B and Class C respectively. There were two more classes, but these were not relevant for firm address allocation.

Initial Fee/ Annual Fee	IPv4 addresses	Fees/address	Slash Notation	Size
$250	256	0.977	/24	S
$1,000	4,096	0.244	/20	S
$2,000	16,384	0.122	/18	M
$8,000	262,144	0.030	/14	M
$64,000	16,777,216	0.004	/8	L
$128,000	67,108,864	0.002	/6	L

Table 1: ARIN latest fee schedule for certain sizes

Segments that demand IP addresses

Users are passive and care only about internet access (through their ISP) and not the IP version used. Hence, they are not agents in this ecosystem. Much of the internet technology developers (router/switch manufacturers, OS developers, internet applications) have already been IPv6 ready for many years thus allowing IPv4 and IPv6 addresses to be competing technologies. Hence, they are also not agents in this ecosystem.

Firms are the agents that demand IP addresses from the RIRs. They can choose between the two protocols: IPv4 and IPv6 as well as how many addresses to hold on each protocol. They are heterogenous in their role and size. The three main types of firms by role are ISPs, content firms and enterprise firms.

Examples of ISPs in the North America region include Comcast, Verizon etc. ISP firms provide internet access to residential users and business firms by providing IP addresses to allow them to connect to internet while deriving revenue from them. Large users are assigned specific addresses whereas the smaller users are part of a dynamic pool (DHCP - dynamic host control protocol) where they are assigned addresses when they arrive and relieve the addresses once they are done. They also receive revenue by routing[8] packets of data on the internet.

[8] Routing is the way packets of data on the internet travel from origin to the destination

Content providers usually have their own IP addresses and rely on an ISP firm for internet connection[9]. These firms provide content on the internet which is the main reason users and other firms access internet. Examples of content firms include Google, YouTube, Netflix etc.

Enterprise firms include organizations, universities and companies that are mostly users, rather than ISPs, or content. They typically have a local network in addition to accessing internet. Examples include big corporations such as HP, Xerox, and universities.

Firms further vary in size within these three roles. Size of the firm can be understood along two dimensions: cone size and number of users. Cone size is a metric used to measure the size and influence of a firm in the internet infrastructure measured as the number of firms with which a given firm peers. This also measures the number of firms that pay for routing data packets.

Since there is no other measure of traffic/revenue to measure the size of firms, I use this measure provided by CAIDA. Thus, it can differentiate firms based on the revenue it makes from routing packets on the internet. E.g., it can help differentiate between big firms that form the internet backbone from a tiny ISP. Thus, firms with larger cone size can get larger revenues with the same number of IP addresses. The number of users captures the number of customers from whom the firm gets revenue. The demand for IP addresses increases with cone size and users.

Market for IPv4 addresses

The market for IPv4 addresses was decentralized with no central marketplace for buyers and sellers. Even though the market was permitted in 2008, it started functioning with organized exchanges and brokerages only from 2011. Microsoft's $7.5 million purchase of 666,624 addresses in 2011 brought this market to the spotlight.

[9]Content firms typically use the lines laid by the ISP for internet connection

While firms buying addresses need to show projected demand to the RIRs to prevent speculative trade, there has been limited post-purchase verification. This further stimulated interest in the market to see how this market would develop, both from the perspective of mechanism design (to improve market efficiency) and evolution of prices in the market.

With finite number of IPv4 addresses, the constraint is binding and at the current price of $30/address the market capitalization is over $100 billion. While firms are more likely to feel this scarcity in the short run, this could eventually lead to price pass-through to their customers.

Who are the sellers?

Sellers in the market are firms that were allocated large blocks of addresses in the early years. These include large universities such as MIT, big corporations such as Northeast Technology solutions, Dupont, Msen, HP, Xerox etc. I include the firms that have sold the most number of addresses in the market and the total number of IPv4 addresses they sold in the table below. Between 2008 and 2020, the top four firms have sold over 10 million addresses and the largest sellers have sold over 3 million addresses.

IPv4 addresses sold	Top Sellers
21,400,000	E.I. du Pont de Nemours and Co
16,900,000	General Electric Company
16,600,000	Bell-Northern Research
15,900,000	Computer Sciences Corporation
10,100,000	Massachusetts Institute of Technology
9,699,328	Merck and Co.
9,437,184	Xerox Corporation
8,345,600	Merit Network
3,716,096	Ford Motor Corp

Table 2: Top sellers in the market

In the table below I compare the total addresses held by all firms and firms that have sold in the market. Sellers are firms that have received much bigger blocks with the median size being 3072 blocks. Firms from the top 25% based on total address allocation are the majority of the sellers in the market. At the same time some of the firms that have received the largest number of addresses have not participated in the market yet.

Size	Initial allocation	Market
count	70,878.0	6079.0
mean	46,820.7	143,530.9
std	1,094,258.4	9,033,987.0
min	256.0	256.0
25%	256.0	1,024.0
50%	1,024.0	3,072.0
75%	4,096.0	143,531.0
max	220,997,632.0	58,615,552.0

Table 3: Total IPV4 addresses held by firms

In the next figure I look at the distribution of the average years firms held onto the IPv4 addresses from the initial allocation before selling in the market. Compared to the distribution for all firms, for sellers there is a higher proportion of firms that received addresses 20-30 years ago. This higlights that sellers in the market received more IPv4 addresses and earlier.

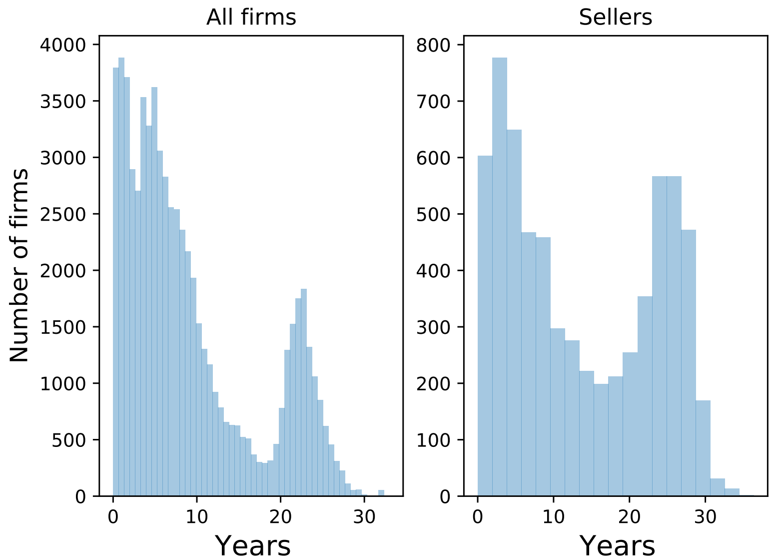


Figure 2: Average years of holding of all firms and sellers

Notes: In the left panel I look at the years of holding for all firms as of 06/2020. In the right panel I look at the years of holding for the subset of firms that have sold addresses in the market.

Who are the buyers?

Much of the buyers in the market have been data centers, web hosting and transit, organizations etc. These include Amazon Technologies, Charter Communications, Cluster Logic, Microsoft etc. These firms spend millions in each transfer, upto 0.5% their annual revenues. In the table below I include the list of top buyers in the market and the number of IPv4 addresses bought. The biggest buyers in the market have bought over 1 million addresses, with the top two buyers - Amazon and Microsoft buying over 30 million addresses each.

IPv4 addresses bought	Top Buyers
68,020,512	Amazon Technologies Inc./Amazon.com
31,000,000	Microsoft Corporation
9,437,696	Google LLC/ Google Inc.
8,316,416	Charter communications
8,257,536	Alibaba.com
4,718,592	Frontier Communications Corporation
2,162,688	Reliance Jio Pvt Ltd
2,097,152	Google Fiber
1,179,648	Oracle Public cloud

Table 4: Top buyers in the market

IPv6 adoption decision by a firm

Here I look at an example of a firm trying to adopt IPv6 in the figure below. In the initial stages of IPv6 adoption a firm looks at its own IPv4 address holdings. Given the low number of users on IPv6 (and network effects from IPv6), if the firm has enough IPv4 addresses it will choose to delay IPv6 adoption. If the firm faces a shortage of IPv4 addresses it will compare the marginal benefit of an additional IPv4 address with its price (marginal cost) compared with marginal benefit of deploying IPv6 vs the marginal cost (which includes cost of deploying).

The marginal benefit of an IP address depends on the number of users on the protocol. As the number of users on IPv6 increases the marginal benefit from an additional IPv6 address increases. As the price of IPv4 addresses rises in the market it raises the marginal cost of an additional IPv4 address. Thus, more IPv6 users and higher prices drive firms to adopt IPv6.

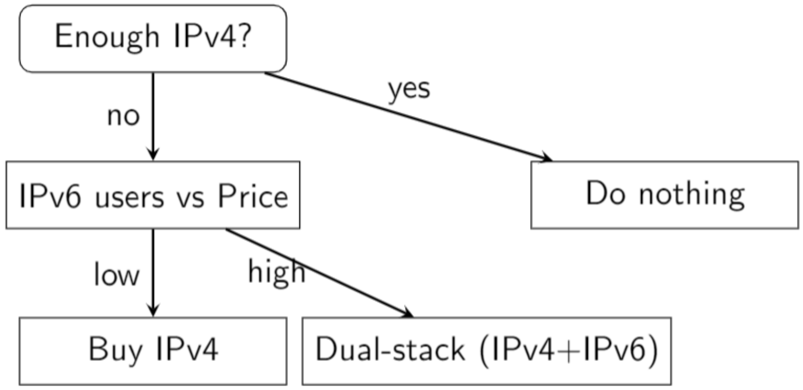


Figure 3: IPv6 adoption by a firm

This captures the main coordination challenge facing firms. It also brings to light the effect of initial IPv4 allocation (through switching cost) on IPv6 adoption. As IPv6 adoption reaches a certain threshold the strength of IPv4 network effects starts to weaken and firms (even those not facing IPv4 scarcity) start switching towards IPv6. Thus, the industry would tip from the current standard to the next.

Number of internet users

According to Statista (2021), as of 2020, the global internet penetration rate is 59.5 percent. Using data from Max Roser & Ortiz-Ospina (2015) in the figure below I look at the global evolution of internet penetration across the following countries: Afghanistan, China, India, United Kingdom and United States. While US, UK and Germany have seen very high levels of internet penetration, there are still large parts of the population that are still offline in countries such as Afghanistan, China and India. With easier access to computers, modernization and increased mobile connections more users are expected to go online.

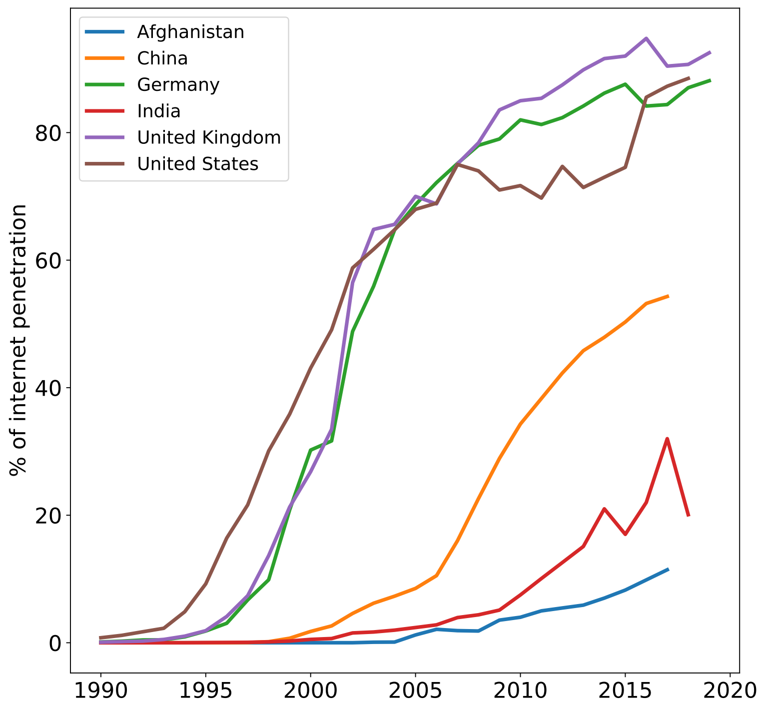


Figure 4: Internet penetration over time

Notes: This figure is based on data from Max Roser & Ortiz-Ospina (2015) which has information for most countries in the world. I plot the date for the selected countries: Afghanistan, China, Germany, India, United Kingdom and United States.

In the figure below I look at the trend in global internet users over time and it has been linearly increasing since 2008.

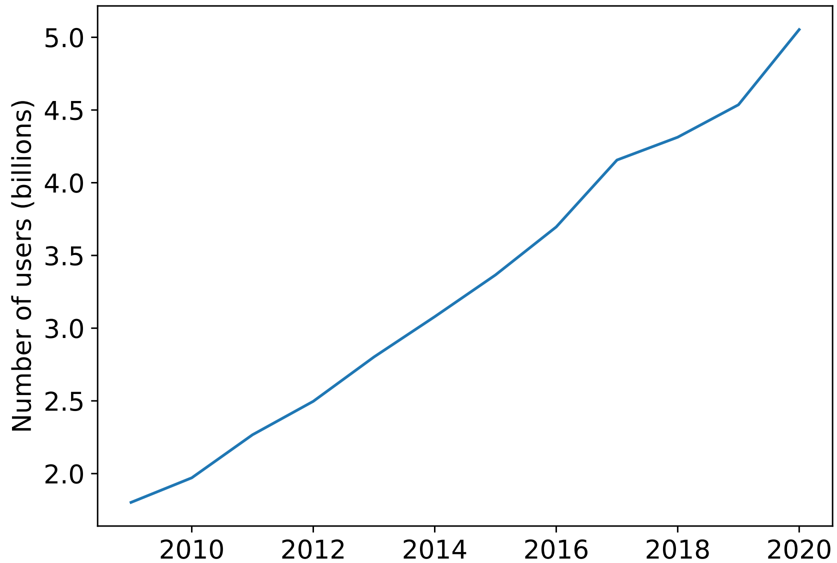


Figure 5: Internet users over time

Notes: This figure is based on data from *Internet Growth Statistics 1995 to 2021 - the Global Village Online* (n.d.)

1.4 Descriptive evidence

In this section I look at the key empirical features related to the market for IPv4 addresses, heterogeneity across firms, and IPv6 adoption.

Stylized fact 1: *Rising price in the market*

Price in the market is characterized by price/address: $\frac{\text{Purchase price}}{\text{Number of addresses}}$. In the figure below I look at the mean price/address over time across all sizes. The initial price/address varied between \$4.45 and \$15. The most striking fact of this market is the rising prices observed in this market since ARIN[10] exhaustion in late 2015. From 2015 to 2020 price/address increased from \$7.5 to over \$21, which is more than a 100% increase.

[10]North America RIR

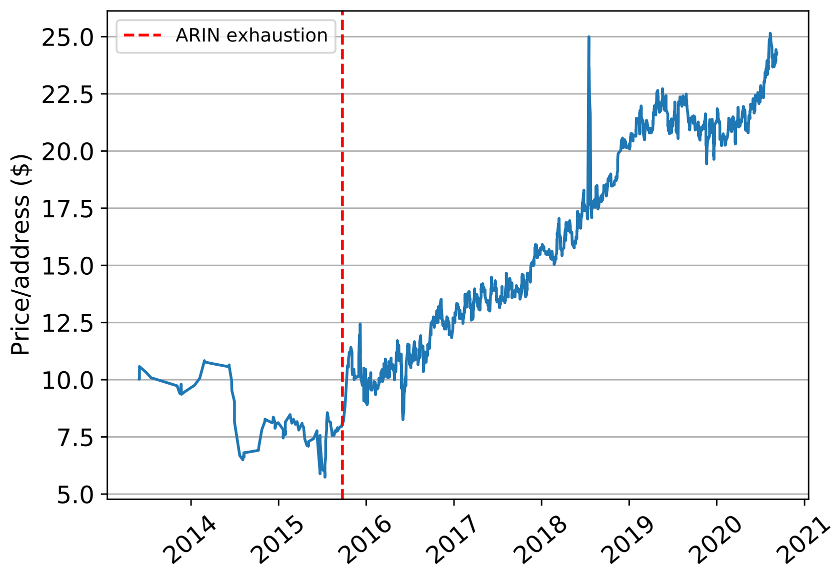


Figure 6: Price/address over time

Notes: This is based on average price using transfer data from the brokerage firm. The red dashed line represents IPv4 exhaustion by ARIN in 2015.

Price across different block sizes

A similar trend in price/address is observed across different sizes in the figure below. While there was more dispersion in price in the initial years across sizes, as the market picked up there is roughly linear pricing in the market. There is a single price/address and the total purchase price across different sizes is given by: purchase price = price/address × number of addresses in the block

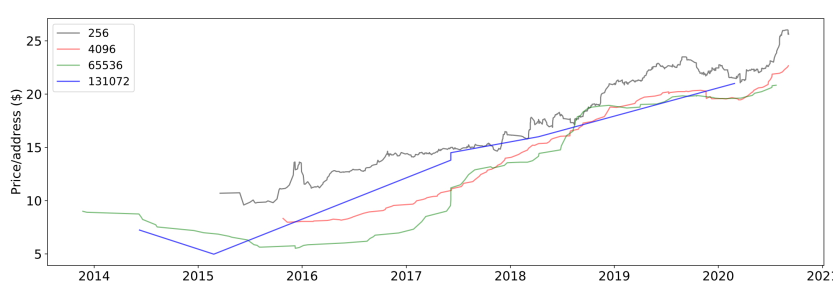


Figure 7: Price/address across different block sizes

Notes: I look at the price/address across four different sizes in the market: small (/24-256, /20 -4096), medium (/16 -65536) and large (/15- 131072) address blocks. These are the most commonly transferred sizes in the market.

Stylized fact 2: IPv6 adoption across firms

I lay out two patterns observed related to IPv6 adoption - pace of IPv6 adoption and variation of IPv6 adoption by firm size[11].

Slow pace of IPv6 adoption and variation across firm roles

In the figure below on the left panel, I look at the aggregate pace of IPv6 adoption. I look at the two measures of IPv6 adoption - the black line represents the percentage of firms that have received IPv6 address allocations, and the green line represents the percentage of firms that have routed at least one of these IPv6 addresses. Even though IPv6 has been around since 1999, the pace of firms adopting has been slow. Many factors such as NAT, market for IPv4 addresses affect the speed of IPv6 adoption. For the empirical analysis I use the second measure of IPv6 adoption.

On the right panel, I look at the pace of IPv6 adoption across firm roles using the second measure. IPv6 adoption varies within firm roles with content providers leading and enterprise firms lagging. To reiterate this is not a measure of traffic that is routed through IPv6 blocks for each firm.

[11] I include additional correlation oserved in appendix 2.8

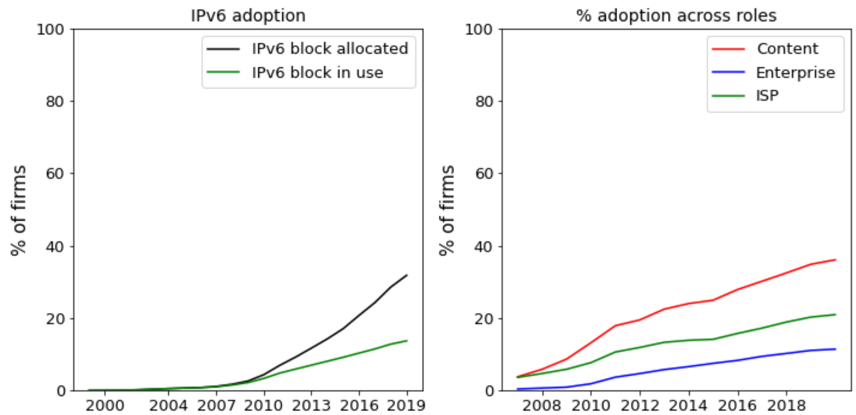


Figure 8: IPv6 adoption over time and across roles

Notes: In the left panel I show the rate of IPv6 adoption based on both the measures of IPv6 adoption - firms with IPv6 allocation and firms with routed IPv6 blocks. I use the second measure of IPv6 adoption for the right panel (which is based on firms with routed IPv6 blocks).

Larger firms adopt IPv6 earlier

In the figure below I look at the distribution of firm size (cone size on the left panel and users on the right panel) adopting IPv6 over three time periods: early, mid and late. Firms that adopted before 2012 are classified as early adopters, between 2012 and 2016 as mid adopters and those adopting after 2016 as late adopters. Looking at the figure it is clear that larger firms adopted IPv6 before smaller firms.

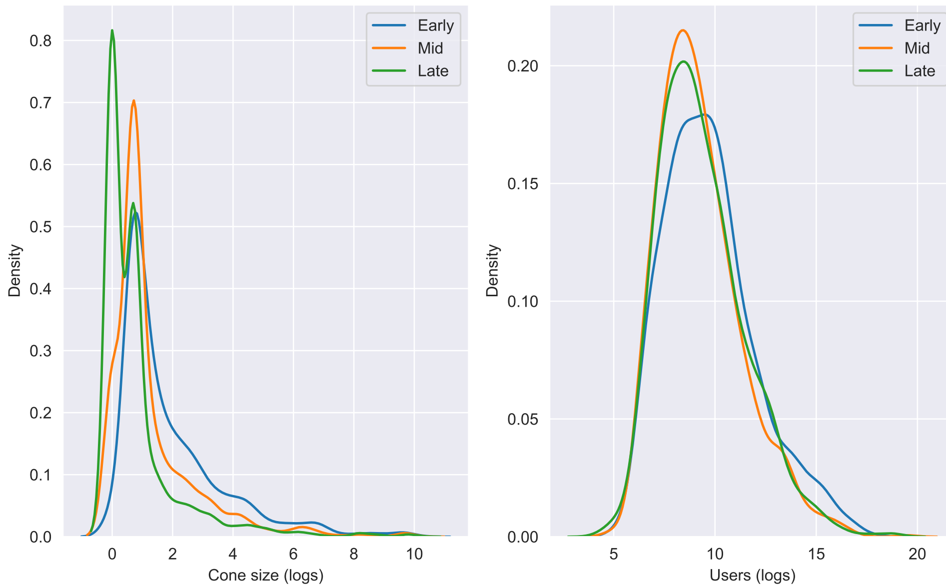


Figure 9: Firm size of IPv6 adopters over time

Notes: In the left panel I look at the distribution of cone size (in logs) across firms adopting IPv6 each period. In the right panel I look at the distribution of users (in logs) across firms adopting IPv6 each period. I restrict to the sample with number of users larger than 1. 10% of the firms have number of users (logs) less than 1.

Stylized fact 3: *Heterogeneity across firms by size and IPv4 holdings*

Even within roles firms vary in size across two dimensions: cone size and users. This heterogeneity affects their IPv6 adoption decisions and IPv4 market decisions. In the figure below I look at the histogram of users (logs) and cone size (logs) for firms across different roles. Firms vary in both cone size and number of users. For both cone size and users, ISP firms show the greatest variation, representing the difference in size across rural ISPs versus some of the biggest ISPs serving as the internet backbone. Enterprise firms have the lowest variation along both cone size and users.

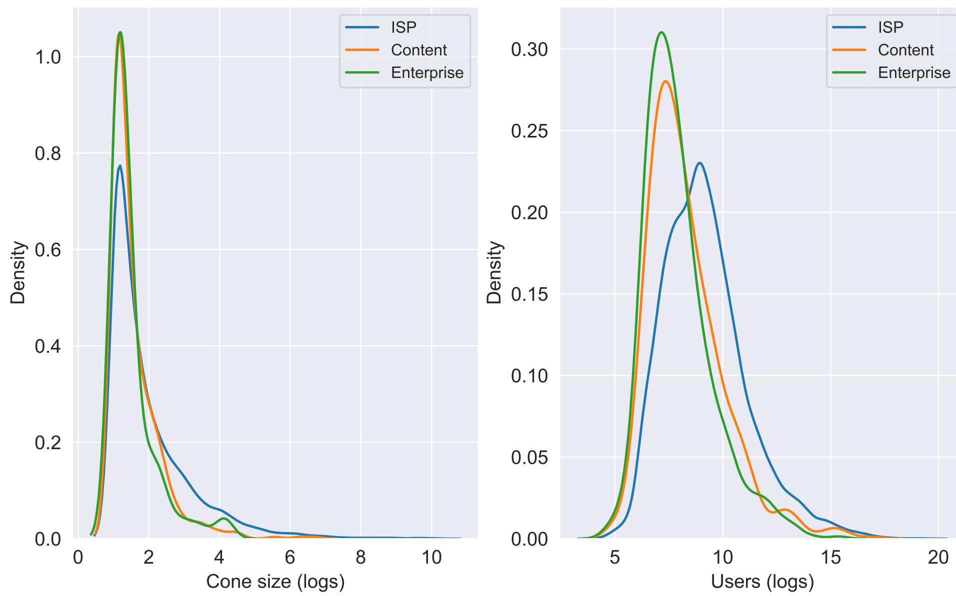


Figure 10: Distribution of firm heterogeneity across roles

Notes: In the left panel I look at the distribution of cone size (in logs) across firms. In the right panel I look at the distribution of users (in logs) across firms. In the figure I restrict to the sample with cone size (logs) larger than 1 and number of users larger than 1. 16% of the firms have cone size (equal to 1). 40% of the firms have number of users equal to 1.

Heterogeneity in IPv4 holdings across firms

Next, I look at the heterogeneity of IPv4 holdings across firms. I categorize firms into three groups of IPv4 ownership based on the total addresses held: small, medium, and large. Even within these groups there is great inequality in the total IPv4 blocks owned. While majority of the firms belong to the small group of owners, they hold less than 2% of total IPv4 addresses, majority of the address space is owned by firms in the medium category. There are only 44 firms in the large category and these firms hold about 37% of the total address space.

Statistic	Small	Medium	Large
count	55,364.0	15,470.0	44.0
mean	1,029.6	130,513.1	28,239,057.5
std	1,048.4	649,116.5	33,346,620.0
min	256.0	4,352.0	15,008,000.0
25%	256.0	8,448.0	16,777,664.0
50%	512.0	32,768.0	18,403,840.0
75%	1,024.0	65,536.0	25,660,992.0
max	4,096.0	14,680,064.0	220,997,600.0
Total firms	78.1%	21.8%	0.1%
Total addresses	1.6%	61%	37.4%

Table 5: Distribution of blocks across sizes

Stylized fact 4: ***Early firms received larger addresses/user***

Next, I provide evidence that early firms received larger IPv4 addresses/user which I define as total addresses/number of users. This is important to look at because firms with higher initial allocation could have higher costs of IPv6 adoption. For this I look at the cross-section across all firms as of 2016 and regress the addresses/user on the RIR, firm role, age of allocation and cone size. I convert users and cone size to log.

These variables explain upto 10% of the observed differences in addresses/user. Age has a significantly positive correlation whereas cone size has a significant negative correlation with addresses/user. ARIN has a significantly positive correlation with addresses/user. This is in line with the anecdotal experience and corroborates with the large number of sellers from ARIN in the market. Enterprise firms have a positive significant coefficient, suggesting a positive correlation between enterprise firms and addresses/user. Given that IPv6 adoption costs depend on the IPv4 holdings this could further delay IPv6 adoption among enterprise firms.

$$\text{Addresses/user}_j = \beta_0 + \beta_1 \text{RIR}_j + \beta_2 \text{Role}_j + \beta_3 \text{Age}_j + \beta_4 \text{Cone size}_j + \epsilon_j$$

Stylized fact 5: ***Repeated transfers among sellers in the market***

Table 6: Initial allocation of IP address/user

	Dependent variable:
	Addresses per user
Age	0.1*** (0.003)
Cone size	−0.3*** (0.01)
ARIN	1.1*** (0.1)
RIPE	0.5*** (0.1)
Content	−1.1*** (0.1)
Enterprise	−2.6*** (0.1)
ISP	0.2 (0.2)
Constant	5.8*** (0.1)
Observations	46,547
R^2	0.1
Adjusted R^2	0.1
Residual Std. Error	3.9 (df = 46539)
F Statistic	822.7*** (df = 7; 46539)
Note:	*p<0.1; **p<0.05; ***p<0.01

The last descriptive evidence I present is that firms sell addresses through multiple transfers in the market. A firm has repeated transfers if it has transferred addresses on multiple dates.[12]

While buyers having repeated transfers could signify demand as arriving over time, firms selling addresss over multiple transfers could signify illiquidity in the market. Thus, IPv4 addresses are not perfectly liquid assets. It is costly to repurpose and sell addresses that are currently in use. This is because it takes time and effort for network engineers to identify IPv4 addresses that are currently in use but could be freed-up for sale. This would require the devices currently using those IPv4 addresses to be moved to other addresses. This limits the number of addresses sold in a single transfer. Other than IPv6 adoption costs firms switching to IPv6 face additional costs due to this illiquidity which I include as part of the switching costs. As a result,

[12]Multiple address blocks transferred on the same day are considered part of the same transfer and not a multiple transfer

firms sell their addresses through multiple transfers. This also corroborates with the interviews with large sellers in the market indicating the presence of switching costs.[13]

In the figure below I further look at the histogram of the transfers made by sellers in the market based on IPv4 addresses held. I categorize firms into three categories: small, medium, and large. It is clear that firms with larger blocks have more transfers in the market compared to small and medium IPv4 ownership.

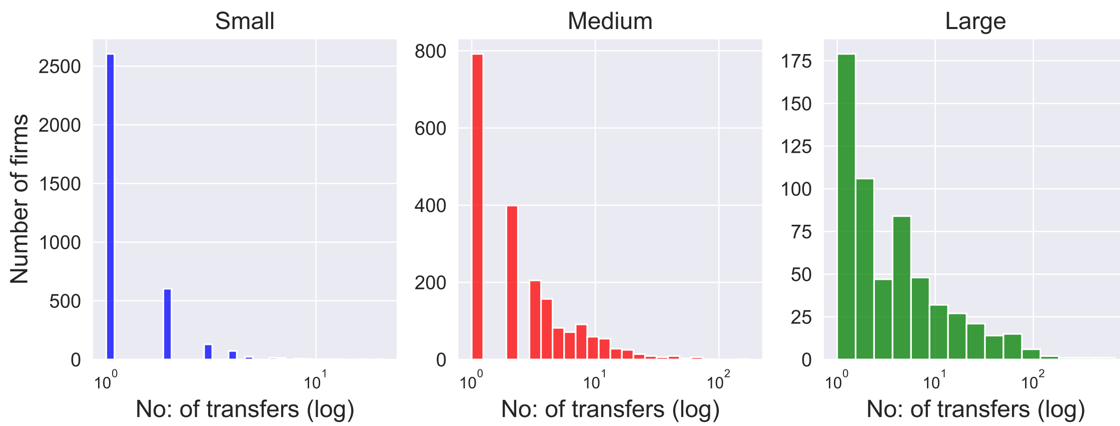


Figure 11: Histogram of the number of transfers by sellers

Notes: Small - less than 4096 addresses, Medium - between 4096 and 65536 addresses, large - greater than 65536 addresses

Other descriptive evidence that can help understand the market better such as number of transfers, market participation, rental market, resale and the effect of Covid-19 in the market as well as a qualitative survey of sellers are included in the appendix 2.4 and 2.6. To summarize, the key empirical features from this section are:

1. Price in the market has been continuously rising since late 2015

2. IPv6 adoption across firms

[13]Included in appendix 2.7

3. Heterogeneity across firms in size and IPv4 holdings
4. Early firms received larger addresses/user
5. Repeated transfers among sellers in the market

The rest of the paper is concerned with developing tools to study the impact of market frictions on prices and IPv6 adoption. This requires a model of firm decision making that includes the empirical features from above and also be able to generate a rising price trend and delay in IPv6 adoption. Towards this end I first develop a hypothesis for the observed empirical patterns. This inspires modeling choices made and is the topic of the next section.

1.5 Hypothesis

How should prices and IPv6 adoption evolve over time?

In the long run IPv6 is expected to become the de facto standard. At that time IPv4 addresses have zero fundamental value. In the short run it is observed that the market starts with a positive price and keeps rising over time. I look into the factors that cause prices to rise in the short run.

Firstly, even though IPv4 addresses have a finite life, it is unclear ex-ante which is the last period as this depends on the evolution of IPv6 adoption. Firms could have different information/expectation about the last period of IPv4 addresses and this creates a challenge of coordination. This prevents prices from falling over time. Rather the life of IPv4 addresses is tied to the pace of IPv6 adoption which is an endogenous choice of firms. In the dynamic model I look at an infinite period where firms make IPv4 market and IPv6 adoption decisions over time. Thus, the last period for IPv4 addresses is endogenous and a simple backward induction cannot be used to determine price in any period.

Secondly, there are strong network effects in this ecosystem. Firms prefer using the same version as the majority as these IP addresses aren't used in isolation. Firms adopting IPv6 in the initial years still hold onto their IPv4 addresses to maintain connectivity on both the protocols. Thus, IPv4 addresses become more valuable in the interim.

Thirdly, firms face switching costs. Switching costs prevent firms from selling all the desired addresses in the market leading to a scarcity of addresses in the market. This is due to difficulty in finding a buyer/seller as well as the costs associated with bringing IPv4 addresses that are in use to the market. Similarly, the generous allocation of IPv4 addresses in the initial years caused firms to prefer IPv4 over IPv6.

These frictions have slowed down IPv6 adoption and has subsequently led to a rise in demand for IPv4 addresses and hence the value for IPv4 addresses. Thus, prices rise in the market in the short run diverging from its long run fundamental value.

1.6 Dynamic game

Building on the framework of Edelman & Schwarz (2015), this section introduces a dynamic model that is able to predict the observed stylized features and then defines the equilibrium. This model includes three novel features compared to Edelman & Schwarz (2015): studying the market and IPv6 adoption in a unified framework, endogenous IPv6 adoption, network effects and additional sources of heterogeneity.

Although some model details relate specifically to IP addresses it can be generalized to technology transition of any durable good with a secondary market. In the model, firms decide how many IPv4 and IPv6 addresses to hold each period, firms with only IPv4 decides whether to adopt IPv6 or not in that period. I use a dynamic model as IP addresses are durable goods and their decisions in one period affects their decisions and payoffs in later periods.

Time is discrete and infinite indexed by $t = 1, 2, ..\infty$ where t stands for each year. The model environment is not stationary because it tracks the short-run evolution of the industry. Agents are heterogenous firms. The number of firms is fixed and indexed by j. There are three main sources of heterogeneity among firms which are fixed throughout the game. This is captured by $\tau_j = (\eta_j, \lambda_j, \theta_j)$ representing role, cone size and users respectively. Firms based on their role can be of three types: ISP,content and enterprise, $\eta_j \in \{\text{ISP,content,enterprise}\}$. I categorize the cone size of firms into three types - small,medium and large, $\lambda_j \in \{\text{Small,Medium,Large}\}$. Lastly I categorize the number of users as low and high, $\theta_j \in \{L, H\}$.

In 2008 when the market started there were already firms that had received IPv6 addresses. So, I assume that there are two types of firms with respect to IPv6 adoption- firms that have already adopted IPv6 and firms that only have IPv4.

I model users as passive in this model - they don't make any decisions. Rather a summary measure of total users on IPv4 and IPv6 is used, denoted by N_t^4 and N_t^6 respectively. Total users in a period N_t is given as $N_t = N_t^4 + N_t^6$. N_t is assumed exogenous since the increase in number of internet users has nothing to do with the transition and increases both due to increase in the number of users going online for the first time and number of devices per user. In the initial period:$N_0^4 > N_0^6$. I include more details about the number of users in each protocol after noting the industry state.

IP addresses held by firm j in period t is represented by x_{jt} for IPv4 addresses and y_{jt} for IPv6 addresses. Being durable in nature a firm's IP holdings are available for use every period in the future unless it's changed by the firm in the market. No firm can sell more addresses than they hold in that period.

The sequence of actions available to a firm in period t is:

- First IPv4-only firms choose between {adopt IPv6,wait}
  - Firms adopting IPv6 receive $\bar{y}$ IPv6 addresses in that period
- Next firms can adjust their IP holdings
  - Firms can adjust their IPv4 holdings by buying/selling in the market. Firms can change their IPv6 holdings for zero price

I choose this sequence of actions to reflect observed firm behavior. Firms adopting IPv6 progressively increase their IPv6 usage. To capture this, I assume that all firms adopting start off with the same level of IPv6 addresses and can increase their IPv6 addresses over time. Similarly, all firms can adjust their IPv4 holdings each period in the market. This captures that IPv6 adoption doesn't automatically lead to decrease of all IPv4 holdings.

IPv6 adoption is assumed irreversible and dual stacking. IPv6 adoption cost is given by:

$$\mathrm{A} + \gamma_\eta x_{jt}$$

This includes a fixed adoption cost and a linearly increasing cost based on the IPv4 addresses held. The fixed cost captures costs associated with installation of new hardware, software and upgrading legacy applications(Paltridge (2014) and Tassey (2005)). The variable cost with IPv4 holdings captures the labor costs which includes training the IT staff to be proficient in IPv6 and troubleshooting. They would apply IPv6 configuration to routers, firewalls, computers, and many other systems. This effort is assumed proportional to the effort in managing IPv4 addresses. Firms with larger IPv4 holdings typically have larger network teams to manage their holdings.

This also captures the higher adopting costs that firms with larger initial IPv4 addresses have. I allow γ_η to vary across firm roles - ISP/content provider/enterprise. This is to capture differences in IPv6 adoption costs across firm roles which could lead to differences in IPv6 adoption across different roles.

There are three components to firm j's per period profit. This includes the value a firm gets in every period from holding IP addresses, the cost of holding IP addresses and the revenue change that results from buying/selling addresses in the IPv4 market. By holding x_{jt}, y_{jt} IPv4 and IPv6 addresses firm j get a value each period - which could represent revenue from customers, other firms or even implicit benefit:

$$R(x_t, y_t, \tau, N_t^4, N_t^6, P_t) = \underbrace{\lambda_j^\kappa \theta_j^{(1-\kappa)}}_{Size} \underbrace{(N_{4t}(\frac{x_{jt}}{\lambda_j^\kappa \theta_j^{(1-\kappa)}})^\alpha}_{\text{IPv4 benefit}} + \underbrace{N_{6t}(\frac{y_{jt}}{\lambda_j^\kappa \theta_j^{(1-\kappa)}})^\alpha)}_{\text{IPv6 benefit}}$$

Following Edelman & Schwarz (2015) IP addresses are considered inputs into production, with production function of the form: $f(x) = x^\alpha$, where $0 < \alpha < 1$ capturing non-negative and diminishing marginal value from holding IP addresses. To introduce network effects, this is scaled by the number of users available on either protocol. Thus, given the difference in the number of users on both the protocols, the marginal value of an IPv4 and an IPv6 address is no longer the same.

Lastly the value is scaled by both cone size and number of users to allow revenue to vary with firm size (cone size and number of users). This captures that firms with larger size get more value than smaller firms with the same number of addresses. In this environment it would make sense to consider constant returns to scale in size and IP address inputs. Hence I include coefficients on size that sum up to one and divide the production input by the size. Without adjusting for the size in the production input, a firm with double the cone size, users and IP addresses would have $2^{1+\alpha}$ times the revenue. Whereas by normalizing the input x by the (cone size and users), doubling the cone size, users and IPv4 addresses would result in double the revenue, signifying constant returns to scale in size of the firm. Given the nature of IP addresses as inputs for firms it is more realistic to assume constant returns to scale in size than increasing returns to scale.

Firms face a cost of holding addresses each period. This represents the annual fee/leasing costs paid by the firms to the registries for overseeing use of addresses. This cost is assumed linear in the number of addresses given by $c(x_{jt}, y_{jt}) = c(x_{jt}+y_{jt})$. I set c at a low value of \$0.01 in line with the actual leasing costs.

Firms can buy and sell IPv4 addresses in the market each period. The net benefit from changing addresses in the market in a given period is:

$$b(x_t, x_{t-1}) = -\underbrace{P_t(x_{jt} - x_{jt-1})}_{\text{IPv4 market revenue/cost}} - \underbrace{\phi(x_{jt} - x_{jt-1})^2 1(x_{jt} \leq x_{jt-1})}_{\text{Switching cost}} - \underbrace{F1(x_{jt} \neq x_{jt-1})}_{\text{Fixed switching cost}}$$

With a positive price/address firms selling addresses in the market get extra revenue based on the market price and firms buying in the market have to pay extra. P_t stands for the IPv4 price/address in period t. IPv6 addresses have zero price as there is no scarcity, firms only pay leasing costs for IPv6 addresses.

F stands for the fixed part of the switching cost in the market which captures the costs involved in arranging a suitable buyer/seller/brokerage firm and a clean address block (with no issues such as being blacklisted/hijacked). ϕ stands for the per-unit switching cost as network engineers must re-optimize their usage before selling. This is a per-unit cost assumed to be convex to capture the increasing costs associated with re-arranging more addresses in a single transfer. This cost is incurred only by sellers.

Combining all three parts the per-period profit can be summarized as:

$$\Pi(x_t, x_{t-1}, y_t, \tau, N_t^4, N_t^6) = \underbrace{R(x_{jt}, y_{jt}, \tau, N_t^4, N_t^6) - c(x_{jt}, y_{jt})}_{\text{Net benefit from holding addresses}} + \underbrace{b(x_{jt}, x_{jt-1})}_{\text{benefit/cost from market}} + \epsilon_{jt}$$

The error term ϵ_{jt} is an idiosyncratic shock that each firm has towards each action in that period. It is assumed to be independent and identically distributed (i.i.d) and follows a Type-I extreme valued distribution. I assume that the number of IPv4 (x) and IPv6 (y) addresses that a firm can hold lies on a grid uniformly between 1 and 10, i.e $x \in X, y \in Y$ where X and Y are both uniform grids between 1 and 10.

The state space of firm j is $k_{jt} = (x_{jt-1}, y_{jt-1}, \tau_j)$. The industry state is the vector of all players' state variables in time t and can be summarized as $k_t = (k_{1t}, k_{2t}, ..k_{Jt})$. There is no uncertainty in state transition. The initial distribution of firms across IPv4 and IPv4+ IPv6 is obtained from the data.

Number of users

I look at the total number of users in the world from *Internet Growth Statistics 1995 to 2021 - the Global Village Online* (n.d.) for the observed periods (2008-2020). To project total number of users for the future periods I primarily use a linear projection and exponential and log formulations as sensitivity analyses. In all three formulations till 2020 the number of users is equal to the observed number of users. To keep this in perspective, the world population is expected to be 9.2 billion by 2041 based on *Population Pyramids of the World from 1950 to 2100* (n.d.).

I assume that the number of users on either protocol is a function of the total number of users and the industry state of IPv6 adoption. $N_t^4 = h(N_t, k_t)$ and $N_t^6 = N_t - h(N_t, k_t)$. Here h is assumed to be increasing in both k and N. For the analysis I assume $h_t = N_t \times (\text{Fraction of firms with IPv6})_t$. This is increasing in both k and N. This captures the dependence between IPv6 adoption by firms (fraction of firms with non-zero IPv6 addresses) and the fraction of users that are on IPv6 the next period. As more firms adopt IPv6 the number of users on IPv6 increases, thus increasing the network benefit from adopting IPv6 and giving firms incentive to increase their IPv6 holdings. This is to capture the indirect network effects observed. All firms observe the number of users each period before taking actions.

In the figures below I look at the evolution of users, IPv4 users and IPv6 users. This is based on the assumption that the industry IPv6 adoption increases linearly over time. This is also the initial assumption for state I use for solving the model after which the state gets updated with each iteration based on actual firm IPv6 adoption choices.

First, I look at the number of users projected with a linear increase reaching 6.7 billion users by 2041. This is line with the current trend observed so far. This is a scenario where there would still be world population not yet connected to the internet even by 2041. Using the initial guess for state, I look at the evolution of IPv4 users and IPv6 users over time. Given complete IPv6 adoption by 2041 all users are on IPv6 by the last period. At the same time the number of IPv4 users fall to zero by the last period. I use this as the baseline assumption for the rest of the empirical analysis and include the other formulations to check for sensistivity.

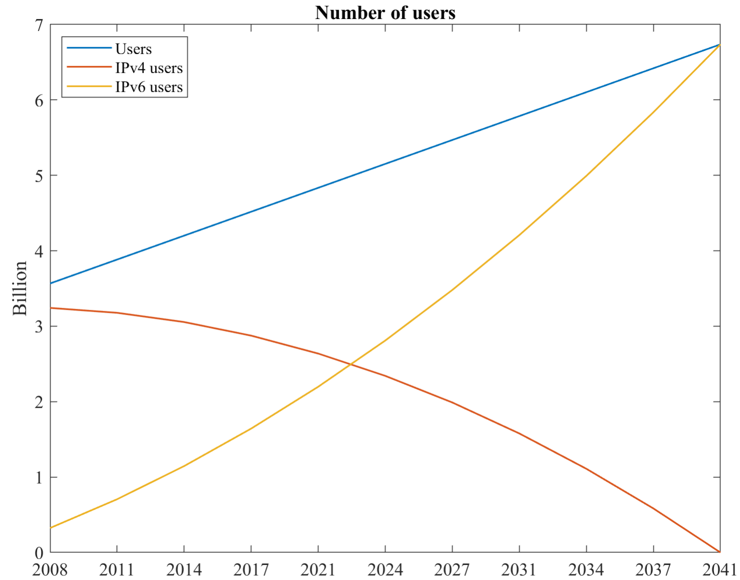


Figure 12: Linear projection of number of users over time

Equilibrium

Given the large state space, I use an assumption used in oblivious equilibrium. In an oblivious equilibrium each firm is assumed to make decisions based only on its own state, knowledge of the average industry state and ignore current information about competitors' states. I make a similar assumption regarding firm state space with each firm making decisions on own state, h_t and P_t. This reduces the dimensionality of the state space.

This is reasonable for two reasons. First, in this ecosystem there are close to 70,000 firms and thus each firm's individual decision in the IPv4 market and IPv6 adoption is unlikely to have a big effect on the industry state and the number of IPv6 users the next period. Second, it is also unlikely that each firm knows the exact state space of all the other firms in the industry.

Next, I define the nonstationary recursive competitive equilibrium for this model. I use a non-stationary equilibrium so as to approximate the short run dynamics of an industry starting from a given initial state and reaching a specific state, which in this case is complete IPv6 adoption. Equilibria can only be computed numerically. Computing a full rational expectation equilibria is not feasible. Instead I assume that firms have perfect foresight about future prices and share of users on either protocol $(P = (P_1, P_2, .., P_T), h = (h_1, h_2, .., h_T))$. Price in endogenous in each period such that the market clears in that period.

Strategies for IPv4-only firms include optimal adoption decision (a_{jt}) and optimal IP holding decisions in the market (x^4_{jt}). IPv4+IPv6 firms make optimal IP holding decisions in the market (x^6_{jt}, y^6_{jt}). I define the optimal ex-ante non-stationary value functions in period t for firm j as:

- for IPv4 firms in the market:

$$\tilde{V}^4_{\tau_j,t}(k_{jt}, P, h) = Max_{\{x^4_{jt}\}} E_{\epsilon_{jt}}\{\Pi(x^4_{jt}, 0, \tau_j, N_t, P_t, h_t) + \epsilon_{jt} + \beta\tilde{V}^4_{\tau_j,t+1}(k_{jt+1}, P, h)\} \tag{1}$$

- for IPv4+IPv6 firms in the market:

$$\tilde{V}^6_{\tau_j,t}(k_{jt}, P, h) = Max_{\{x^6_{jt}, y^6_{jt}\}} E_{\epsilon_{jt}}\{\Pi(x^6_{jt}, y^6_{jt}, \tau_j, N_t, P_t, h_t) + \epsilon_{jt} + \beta\tilde{V}^6_{\tau_j,t+1}(k_{jt+1}, P, h)\} \tag{2}$$

- for IPv4 firms adopting IPv6:

$$\tilde{V}^{4A}_{\tau_j,t}(k_{jt}, P, h) = Max_{\{a_{jt}\}} E_{\epsilon_{jt}}\{\Pi(x_{jt}, \bar{y}a_{jt}, \tau_j, N_t, P_t, h_t) + \epsilon_{jt} - Aa_{jt} + \beta\tilde{V}^{6a_{jt}+4(1-a_{jt})}_{\tau_j,t+1}(x_{jt}, \bar{y}a_{jt}, P, h)\} \tag{3}$$

Formally the nonstationary recursive competitive equilibrium in this model *is a sequence of price*$\{P\}_t^T$, *state* $\{h\}_t^T$, *strategies* (a_{jt}, x_{jt}^4) *for IPv4 firms and* (x_{jt}^6, y_{jt}^6) *for IPv4+IPv6 firms such that taking* $\{P\}_t^T, \{h\}_t^T$ *as given*

1. *for IPv4 firms :*
   - a_{jt} *maximizes* $\tilde{V}_{jt}^{4A}$ *for all states and time periods*
   - x_{jt}^4 *maximizes* $\tilde{V}_{jt}^4$ *for all states and time periods*
2. *for IPv4 + IPv6 firms:*
   - (x_{jt}^6, y_{jt}^6) *maximizes* $\tilde{V}_{jt}^6$ *for all states and time periods*
3. $\{P\}_{t=1}^T$ *clears the market each period (i.e. demand equals supply)*
4. *The evolution of* $\{h_t\}, \{P_t\}$ *is consistent with the strategy profile*

1.7 Calibration

In this section I present the assumptions and model primitives used in solving the model and describe the calibration procedure. I assume that the industry converges to a stationary equilibrium by period T with probability arbitrarily close to one. In the stationary equilibrium there is industry-wide adoption of IPv6 - all firms have adopted IPv6, all users are on IPv6: $N_T^4 = 0$,$N_T^6 = N_T$, firms don't hold IPv4 addresses $x_T^* = 0$, they hold a constant amount of IPv6 addresses - y_T^* is constant - and price in the market $P_T = 0$. This allows me to numerically simulate industry evolution until T after estimating the parameters.

I use T equal to 33 years for the main analysis - which means that it would take 33 years from the start of the market in 2008 for the industry to be fully on IPv6. Since the market converges in 33 years the results wouldn't change for T larger than

33 years. I also check for sensitivity to T by setting it to 24 and 42 years. I assume a time period to be three years. The annual discount factor is set to be $\beta = 0.95$. I assume that the number of IPv4 and IPv6 addresses that a firm can hold lies on a grid uniformly between 1 and 10. For prices I use a grid from \$1 to \$70 evenly spaced by \$1. There are 70,000 firms and in the first period I observe that 5000 of these firms are already dual-stacked. The list of parameters to be calibrated are market switching costs F and ϕ, per unit adoption costs for content: γ_c , enterprise: γ_e and ISP: γ_i, fixed IPv6 adoption cost: A, revenue parameters: α and size parameter: κ. I summarize all the parameters as $\theta = (F, \phi, \gamma_c, \gamma_e, \gamma_i, A, \alpha, \kappa)$.

To calibrate the parameters I use a GMM approach to maximize the fit of the model with respect to a set of data targets using two steps. In the inner loop I solve the model and in the outer loop I simulate the model to calculate moments. Solving the model can be understood in two steps. In the first step I solve the individual firm problem through backward induction for a given price and state. From period T the stationary equilibrium starts and so the optimal IPv6 holdings and value functions remain constant for a given state and so T can be considered the last period of the non-stationary equilibrium reducing the problem to a finite horizon. For period T using the assumptions from above I calculate the optimal IPv6 holdings for each state space (using FOC) and then calculate value function for the state space. Then I solve for the continuation values in T-1,T-2… back to the first period using backward solution.

In the second step I solve the equilibrium price that clears the market each period using a multiple shooting algorithm. I start by guessing a path of prices, then solving the dynamic problem of firms, simulating forward using the firm decisions and then look for the price that clears the market period-by-period. This algorithm is iterated until it converges in the price path and industry state. This algorithm is adapted from Lee (2005) and Humlum (2019). I relegate the algorithmic details of computing and simulating the model to section 2.9 and 2.10 appendix.

Data targets

For the most part, the model's parameter values are jointly determined as a function of the data targets. But some data targets play a much more important role in identifying a parameter. The key parameters in the model that capture switching costs that affect firm behavior in the market are : ϕ and F. This reflects the frictions in the market that arise due to switching costs. Similary IPv6 adoption cost is captured by the fixed and per-unit adoption cost across firm roles: $A, \gamma_c, \gamma_i, \gamma_e$.

The fixed switching cost F is identified primarily through the number of buyers and sellers in the market each period. Higher values of F lead to smaller participation and lower values lead to higher participation. I also match the observed prices to the price predicted by the model.

To identify the differential per-unit adoption cost parameter across different firm roles I include the fraction of firms of different roles adopting IPv6 each time period. As the per unit adoption cost increases IPv6 adoption for that firm role would decrease. As the fixed adoption cost increases the fraction of firms adopting IPv6 decreases. Thus, the fraction of firms adopting IPv6 along with the fraction of firms adopting IPv6 based on firms' role identifies the fixed and per-unit cost of adoption. κ which is a parameter for the size of the firm is identified from the participation of firms of different sizes in the market. The parameter affects firms' payoff from holding IP addresses and is identified together with the price target.

Overall, I calibrate the 8 parameters using a combination of data targets shown in the table below. I observe 10 values for most targets as its over time. For size of the firm, I observe 6 data points each period (cone size $\times$ users). Even though I simulate and solve the model for all 33 periods I construct moments from the first 10 periods that are observed in the data. In total I use the following 170 moments:

Moments	Number of moments
No: of buyers	1×10
No: of sellers	1×10
Share of total addresses sold	1×10
Price	1×10
Fraction of content w/ ipv6	1×10
Fraction of enterprise w/ ipv6	1×10
Fraction of isp w/ ipv6	1×10
Fraction of firms adopting ipv6	1×10
Fraction of content firm buyers	1×10
Fraction of enterprise firm buyers	1×10
Fraction of ISP firm buyers	1×10
IPv6 adoption by share of firms by size	6×10

Table 7: Moments used for calibration

I use a GMM approach to calibrate the parameters in the model. For each value of θ I solve the equilibrium and simulate the model 1000 times for 33 periods each from the initial state. I calibrate parameters to minimize the distance between the simulated moments from the model and the data targets. With the parameters calibrated, I calculate the producer surplus as the sum of the variable profits for each firm minus the fixed adoption cost and fixed switching cost fee over every time period.

Results

The results from the calibration exercise is included in the table below. Per-unit switching costs are large compared to the fixed switching cost and fixed IPv6 adoption cost. ISP firms have the lowest per-unit adoption cost, enterprise firms have almost 118% higher per-unit switching costs compared to ISP firms and content firms have 27% higher per-unit switching costs compared to ISP firms, thus able to quantify the observed differential IPv6 adoption across firm roles.

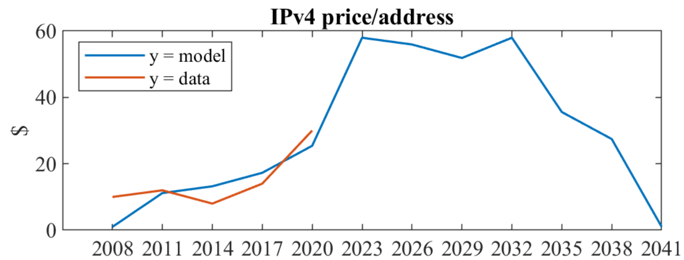
Parameter	Results
Fixed switching cost, F	10.0255
Switching cost, ϕ	0.1522
Aoption cost for content, γ_c	0.1639
Adoption cost for enterprise, γ_e	0.2809
Adoption cost for ISP, γ_i	0.1284
Fixed IPv6 adoption cost, A	34.1527
Revenue parameter, α	0.2564
Size parameter, κ	0.3046

Table 8: Results

Next, I simulate the model till T using the parameters and look at the model's fit.

Simulation results using calibrated parameters

Here I plot the evolution of prices and IPv6 adoption using the parameters calibrated compared with that observed in the data. The red line represents the actual data, and the blue line shows the model prediction. In the figure below I look at the simulated results from the linear projection of number of users.



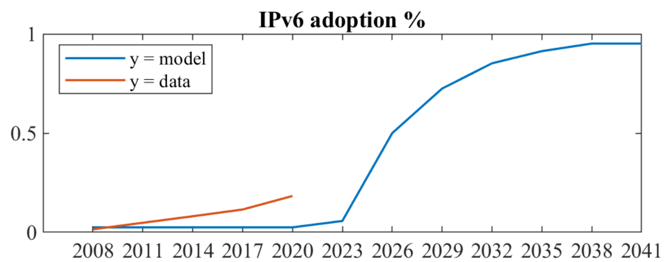


Figure 13: Model fit using linear projection for users

The price pattern in the initial years has been close to the actual prices observed so far. Based on this price is expected to increase reaching a peak of $60, but only slowly come down even with rising IPv6 adoption, reaching its minimum only by the last period. It takes almost 33 years for almost complete IPv6 adoption. The model is unable to capture the gradual increase in IPv6 adoption. Rather in the model IPv6 adoption stays relatively flat before starting to increase. By 2021 the model and the data predict similar percentage of IPv6 adoption. In the linear projection of number of users I calculate the total producer surplus to be $34 million.

1.8 Sensitivity Analyses

In this subsection I look at the robustness of the results to changes in parameters - the last period: T, prediction for number of internet users as well as key model parameters.

Effect of changing T

First, I look at the impact on model fit of changing T that determines the time period it takes for complete IPv6 adoption. I consider two cases: increasing T to 42 years and decreasing T to 24 years. In the figure below, I look at the effect of increasing T to 42 years and find that by 30 years there is almost complete IPv6 adoption.

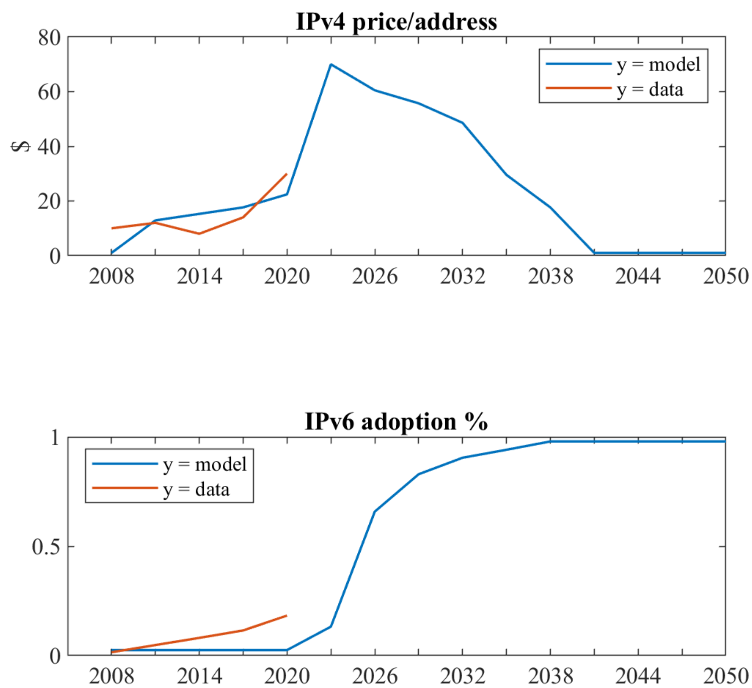
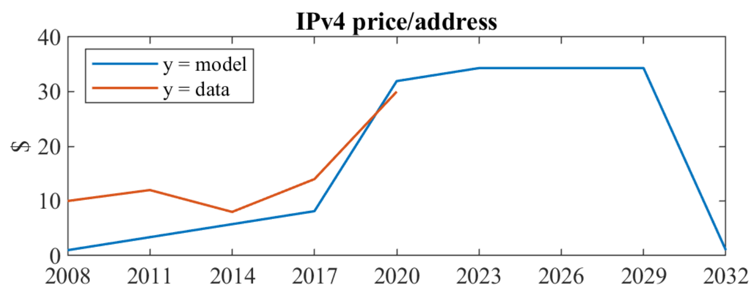


Figure 14: Increasing T to 42 years

Thus, it can be concluded that extending T beyond 33 would imply firms transition to IPv6 before T. Thus, in the case of looking at 42 years, transition to IPv6 happens almost 10 years earlier. Price in the market has a similar pattern, with prices dropping to zero by 2043 (before T).

Next, in the figure below, I look at the effect of decreasing T to 24 years. With this timeline, firms start adopting IPv6 from 2017 reaching a peak slightly over 60% by 2021. By reducing the timeline complete transition to IPv6 is not achieved. Prices in the market reach a peak of $33 and plateaus there before falling to zero in the last period (by construction).



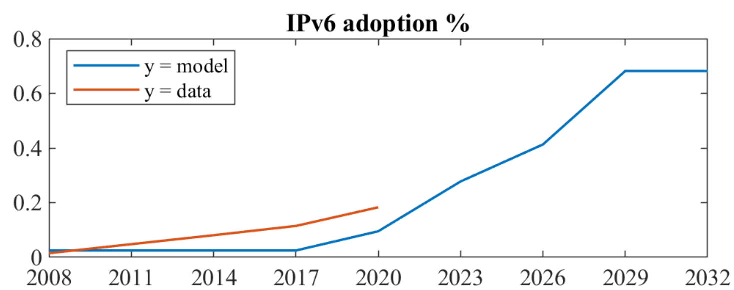


Figure 15: Decreasing T to 24 years

Thus, in this environment setting T equal to 33 is appropriate as it ensures complete transition to IPv6 by then.

Effect of changing formulation for number of users

Next, I look at two alternate formulations that predict the number of users in the future. First, I look at an exponential prediction and then a log prediction. I simulate the model using the parameters calibrated earlier. In the figure below I look at the model fit from the exponential projection of number of users, followed by the log prediction. Next, in the figure below I look at the more optimistic projected increase in number of users with an exponential increase reaching 16.2 billion users by 2041. This could represent an over optimistic projection of both world population as well as number of internet users.

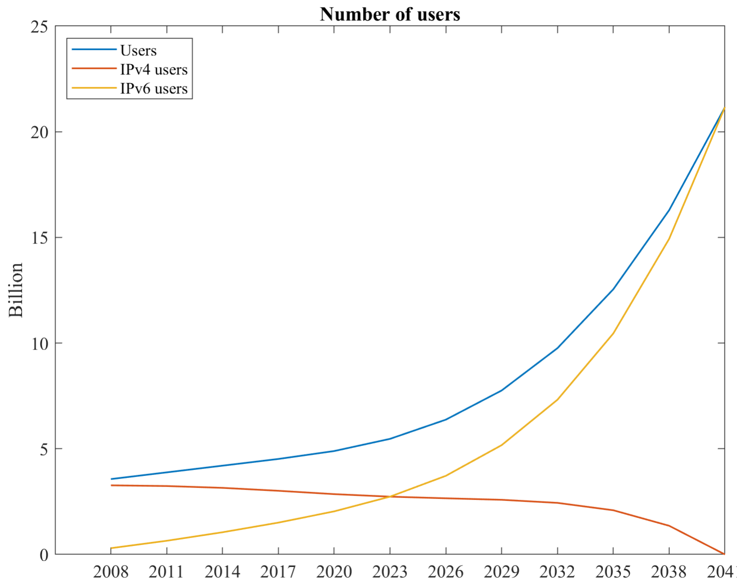


Figure 16: Exponential projection of number of users over time

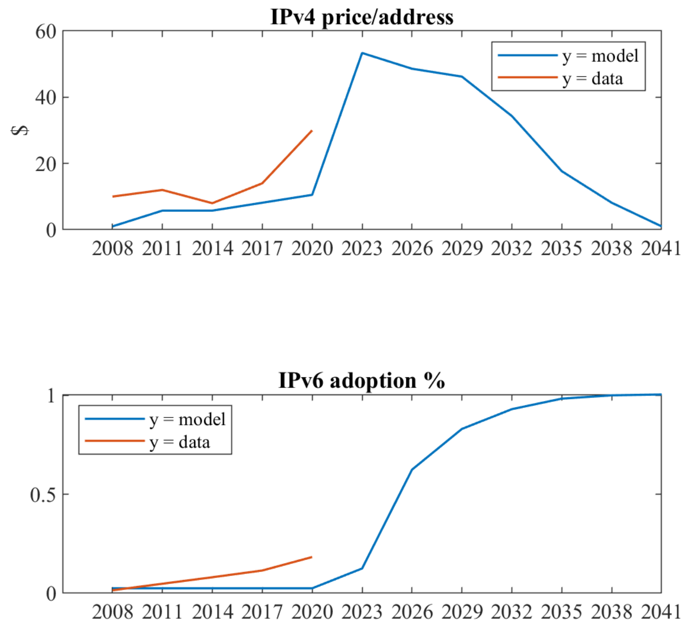


Figure 17: Exponential prediction of the number of users

Next, in the figure below I look at a more conservative projected increase in number of users projected with a log increase reaching 5.5 billion users by 2041.

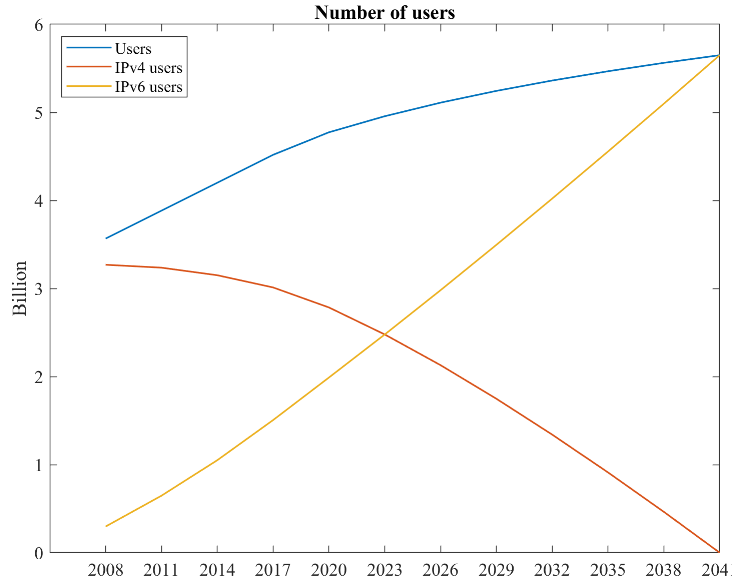


Figure 18: Log projection of number of users over time

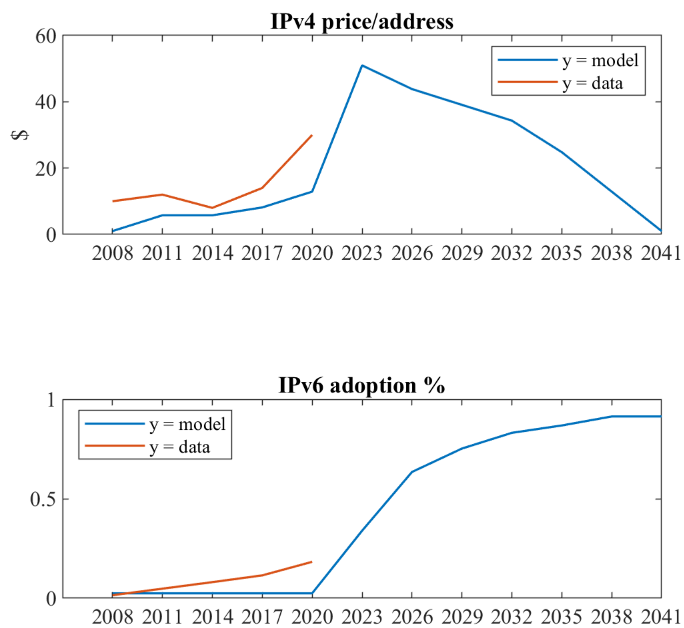


Figure 19: Log prediction of the number of users

Looking across the two formulations it is clear that both market and IPv6 adoption are affected by assumptions regarding the total number of internet users - which in turn affects the number of users on IPv4 and IPv6. This is in turn affects the pace of IPv6 adoption. With an exponential growth in the number of users there is complete IPv6 adoption by 2037 which is 3 years faster than that in the linear case (which is only close to complete IPv6 adoption). Whereas in the log prediction scenario the pace of adoption is slower with adoption falling short by a few firms even in 2041 (even more than in the linear case). There is a period of delay in IPv6 adoption in all three cases.

In all three scenarios, price in the market is similar - it reaches a peak and then gradually comes down by the last period. This is due to the presence of switching costs which prevent prices from dropping immediately even as IPv6 adoption increases. In the exponential scenario the price rise is steeper and in the log case the price rise is more gradual (reaching a peak slightly less than $60).

Changes in parameters

In this subsection I check the robustness of the results to changes in key parameters. First I study the effect of increasing the per-unit switching cost parameter:ϕ. Small increments in the switching cost parameter raises prices in the market and speeds up IPv6 adoption. This could be because an increase in switching cost would lead to fewer units of IPv4 addresses sold in the market leading to higher prices and this price effect leading to a faster adoption of IPv6 as well.

If switching costs are too high the market, I find that the market doesn't take-off in a big way and IPv6 adoption happens almost immediately. On the other hand, an increase in the fixed switching cost:F keeps prices high making it longer for prices to drop to zero.

Increasing the fixed adoption cost (A) and per-unit adoption cost ($\gamma_c, \gamma_e, \gamma_i$) decreases the pace of IPv6 adoption, taking longer time for firms to adopt IPv6. This is in line with the expectation that increase in IPv6 adoption costs lead to slower adoption. Small increments in the revenue parameter:α lead to increase in prices in the market.

1.9 Counterfactual Analyses

In this section I contrast the parameterized model with the following four exercises. The first is to study the evolution of price and IPv6 adoption without any switching cost. The second is to study the evolution of price and IPV6 adoption when IPv4 and IPv6 addresses have the same network effects. The third is to study the optimal IPv6 adoption path by a social planner. Lastly, I consider a policy to see if it would lead to a faster transition towards IPv6. For the number of users, I use the linear extrapolation of number of users for the future.

How would prices and IPv6 adoption evolve without switching costs?

With the calibrated parameters I approach the main question of the paper: What is the effect of market frictions on prices and IPv6 adoption? To answer this, I set one of the main source of friction - switching costs - to be zero in the market. This means that firms can sell excess IPv4 blocks without any per unit or fixed switching cost in the market.

As a result, more firms sell in the market leading to lower prices overall. At the same time without switching costs more firms can adopt IPv6 earlier, leading to overall faster adoption. Thus, prices increase reaching a peak of $60 and then fall to zero by 2023. Since network effects are still present it takes about 16 years for IPv6 adoption to permeate. Thus, IPv6 adoption happens 18 years faster than that predicted in the baseline. Calculating the producer surplus, I find it to be 64 million dollars, which is 88% higher than the initial prediction.

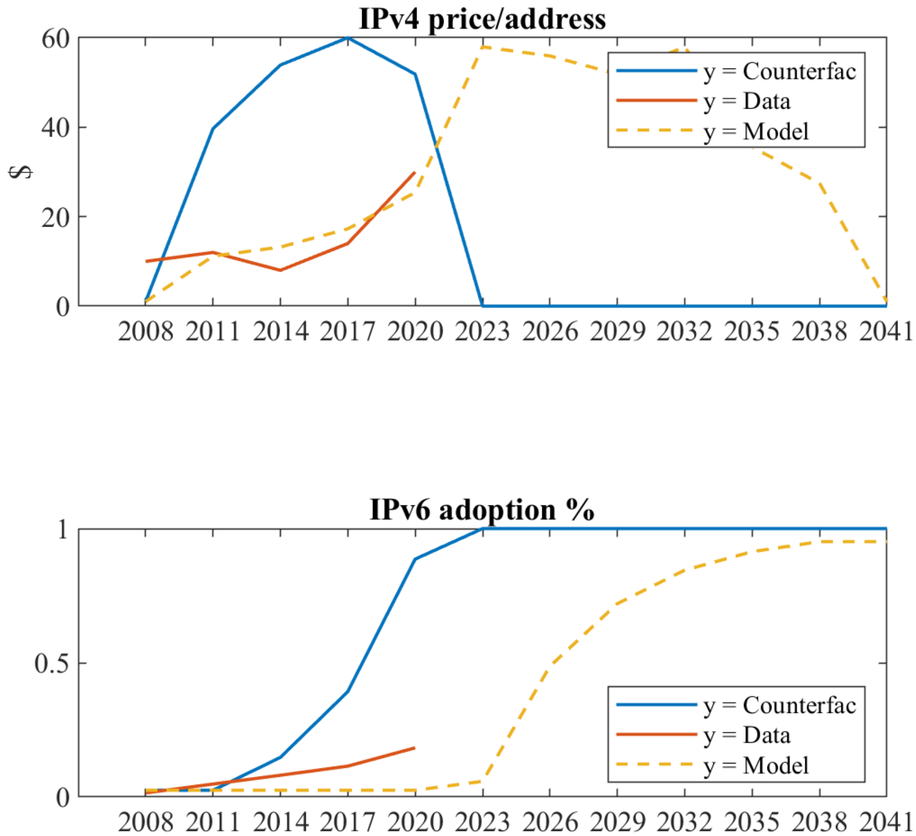


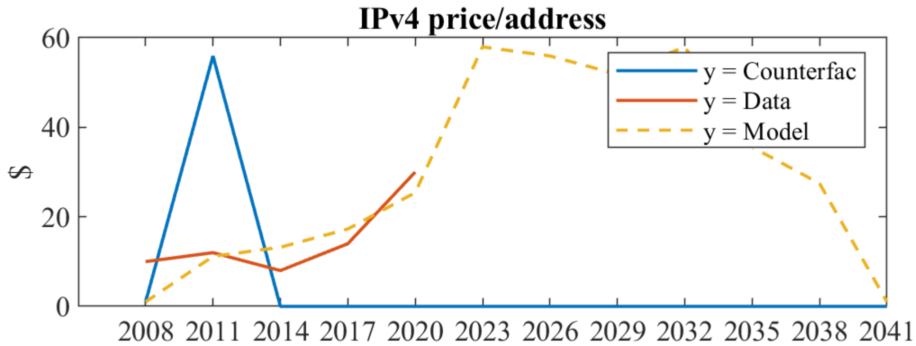
Figure 20: Counterfactual: Without switching costs

How would prices and IPv6 adoption evolve with inter-operable network effects?

In the second counterfactual I let the network benefits that firms receive from both IPv4 and IPv6 addresses to be the same, while still allowing there to be all other frictions such as switching costs. This counterfactual represents the scenario if an

IPv6 address had been compatible with an IPv4 address in which case both addresses would have network effects which depend on the total number of users in each period.

I do this by replacing the number of users on each protocol in profit function with the number of users each period. Unlike in the baseline model where the network effects from that protocol was available only within that protocol based on the number of users in that protocol, now I assume that firms can get the same network effects (based on the total number of users) from having either address.



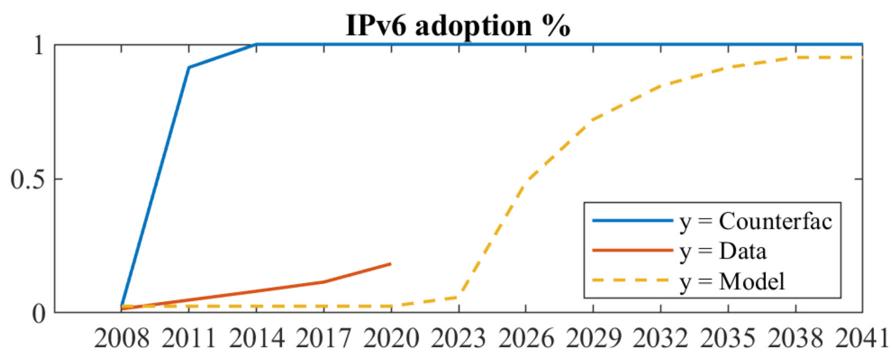


Figure 21: Counterfactual: Inter-operable network effects

In this case I find that majority of the IPv6 adoption happens within six years. This implies that network effects play a strong role in preventing the take-up of IPv6. Prices reach a peak of \$50 and then come down as IPv6 adoption permeates across all firms. Calculating the producer surplus, I find it to be \$35 million dollars. This is 1% higher than the one in the baseline.

How does the decentralized adoption compare to the optimal adoption path?

To find the optimal adoption path I look at a social planner maximizing aggregate producer surplus taking as given the evolution of number of users. By adopting IPv6, firms increase the number of users on IPv6. This increased number of users on IPv6 is a positive externality on other firms. The increased number of IPv6 users raises the option value from IPv6. This increased profits and option values are not internalized by firms adopting in a given period and thus industry profits are not maximized under the decentralized outcome.

In this benchmark, the social planner chooses a sequence of adoption decisions and IPv4, IPv6 holdings for each firm to maximize the producer surplus. This is a computationally hard problem to solve because of the large number of players in the industry. Since the objective of interest is aggregate producer surplus and the aggregate adoption path, I search for the highest aggregate producer surplus over the space of various adoption paths. For this, I search over the space of random adoption paths and select the path that maximizes the aggregate producer surplus. The paths are simulated by adding firm specific perturbations to their IPv4 adoption decisions. Each path lengths is 33 years. I draw 15,000 perturbations and average over the perturbations.

Figure 21 shows the set of simulated paths of adoption and figure 22 shows a comparison of optimal adoption path by the social planner and the pace of IPv6 adoption predicted in the baseline. The aggregate producer surplus is 25% higher than in the baseline. The optimal adoption path is faster than that observed in the data. In the optimal adoption path - within 16 years, more than 50% of the firms have adopted IPv6.

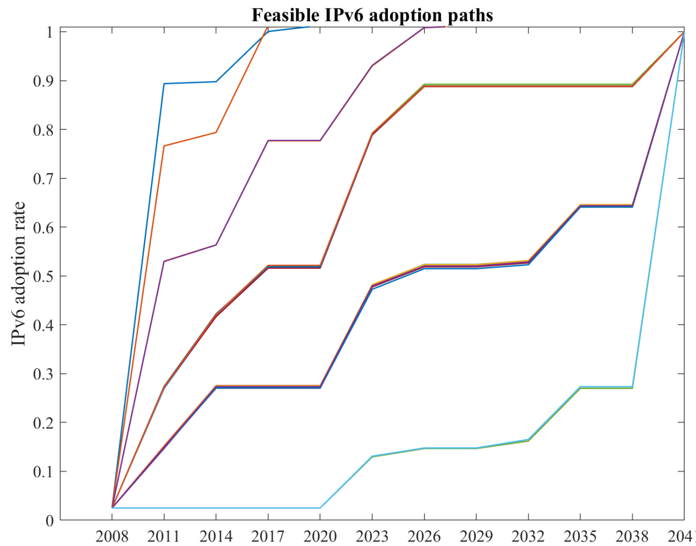


Figure 22: Feasible adoption paths

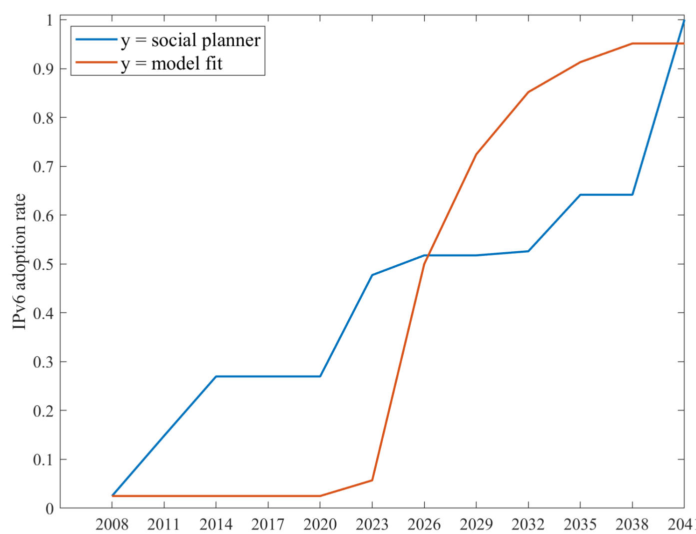


Figure 23: Social planner IPv6 adoption path

The main takeaways are that switching costs, along with network effects can significantly delay IPv6 adoption leading to lower total producer surplus overall. This opens the discussion regarding the importance of policies that could lead to quicker

IPv6 adoption by firms. Next, I look at one such policy that could lead to a quicker transition towards IPv6.

How does the welfare compare if IPv4 addresses were phased out?

In this counterfactual I look at the welfare if firms knew that IPv4 addresses were phased out by 2025 - this is equivalent to shutting down the market by 2025. This is in keeping with the spirit of the regulations by various countries that have tried to regulate IPv6 adoption by setting IPv6 adoption goals. To implement this I assume from 2025 that all users are on IPv6 and there are zero users on IPv4.

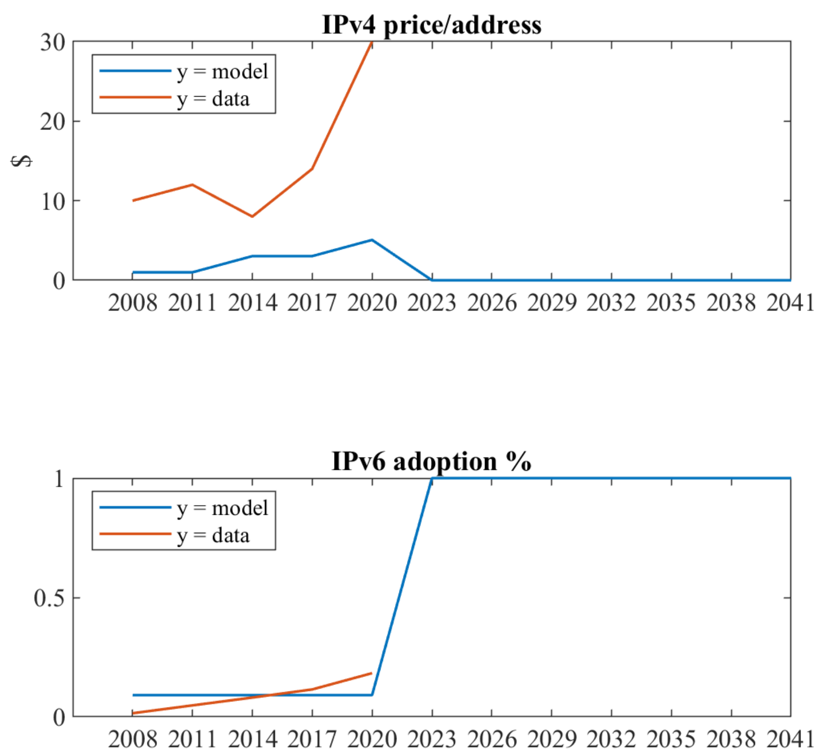


Figure 24: Counterfactual: Market shut down from 2025

With this assumption it is common knowledge among firms that there is a last period for IPv4 - which in this case is assumed to be 2025. As a result, firms coordinate in their IPv6 adoption. Majority of the firms adopt IPv6 between 2021 and 2024. Thus by choosing the appropriate shut down date for the market it is possible to overcome the delay in IPv6 adoption currently observed in the market. Price in the market retains the trend seen in the baseline but is much lower- reaching a peak of $10 by 2021 and then starts to taper down to zero. Thus rising prices in the market are endogenous as transition happens in the presence of market frictions. Total producer surplus is $75.37 million, which is more than twice the surplus in the baseline. This could be an effective policy in achieving transition to the next protocol-IPv6 by enabling coordination between firms in IPv6 adoption. Currently there has been no coordination among different countries in trying to push for IPv6 adoption, rather this is a policy that could be achieved at the internet registries level.

1.10 Conclusion

While markets seem to be gaining importance for technology transition through a price mechanism, the market is unable to solve the transition problem necessarily on its own in all cases. The aim of this paper was to study such a market - the market for IPv4 addresses. This is a multi-billion dollar market used by firms to purchase or sell IPv4 addresses given exhaustion of the initial IPv4 allocation.

In this paper I introduce novel datasets that can be used to study this market. One caveat of the dataset is the lack of information related to traffic through different IP address blocks. If such data could be collected it could help clarify the intensity of usage of IP address blocks.

Next, I provide descriptive evidence to understand the internet ecosystem better. To understand the empirical features I develop a dynamic model to study technology adoption in the presence of a secondary market. Using a plausibly parametrized version of the model I simulate the model and find prices rising as firms transition to the next protocol in the presence of market frictions such as switching cost and network effects.

Looking at counterfactual simulations I find that switching costs lead to higher prices and prevent prices from falling until complete IPv6 adoption and delaying IPv6 adoption by 20 years. With inter-operable network effects majority of the IPv6 adoption happens within six years, thus playing a big role in the delay of IPv6 adoption. Analyzing a policy that would shut down the market in a pre-specified period, I find that this brings about coordination in IPv6 adoption among firms. Thus, the model suggests that it is not necessary that a free market improves transition outcomes in the presence of frictions in the market. This raises the importance of policy tools in this market and other similar markets that could lead to a more efficient technology transition.

There are two caveats related to this analysis. The first caveat is that I ignore NAT6 and CGNAT - services that allow multiple devices to connect using the same IP address (thereby extending the life of IPv4 addresses). I ignore this aspect as this is a band-aid solution and cannot be scaled-up without negatively affecting the quality of the internet connection. A similar argument follows for ignoring 'translation/tunneling' techniques that allow IPv4 and IPv6 devices to inter-operate.

The second caveat is that I have not examined the possibility of a price bubble in this market. Experimental studies have found evidence of price bubble in a finitely lived durable asset. Theoretical work has laid the necessary conditions for a price bubble which hold true for this market as well. While it would be interesting to test for the presence of a price bubble, confidently testing for a price bubble remains challenging and outside the scope of this paper.

2 APPENDIX

2.1 Data sources

In this section I look at the various data sources and how to merge them.

Market transfers dataset

I create this dataset by tapping the transfer statistics published daily on the RIR's website for ARIN, RIPE and APNIC. The websites are:

1. https://ftp.arin.net/pub/stats/arin/transfers/ for ARIN,
2. https://www.ripe.net/manage-ips-and-asns/resource-transfers-and-mergers/transfer-statistics/within-ripe-ncc-service-region/ipv4-transfer-statistics (allocated and assigned) for RIPE and
3. https://ftp.apnic.net/transfers/apnic/ for APNIC.

The data is at the level of the address block transferred and includes the buyer and seller names, the specific block transferred, RIR information (from and to) and transfer date.

The structure of the data and format varies across the RIRs. For example, ARIN has its data in json format which I convert into csv files. I use only the data categorized as 'RESOURCE TRANSFER' as this captures the market based transfers. For ARIN each address transferred is shown by the starting and ending IPv4 addresses instead of the CIDR blocks (unlike the other registries). These starting and ending addresses are not in the standard IP address format(e.g '122.012.022' instead of '122.12.22' as it includes a 0 in place of missing number). I write Python functions (along with the netaddr package) to first convert the starting and ending IP address into a standard format and then convert the starting and ending IP into a CIDR block. Based on this I convert the number of addresses using standard size definitions using Koishigawa (2021).

APNIC has its transfers in a text format, it also has information on ASN[14] transfers that I drop. I include only 'resource_type' which are IPv4, which are the market based IPv4 transfers. RIPE also has the data in a json format. RIPE includes information about both transfers and transfers that are due to mergers and acquisitions. I drop the transfers due to mergers and acquisitions because these are not transfers through the market, but internal transfers between firms due to change of ownership. Market based transfers have the transfer type set equal to 'POLICY'.

To avoid double counting of transfers across RIRs, I collate all the transfers from ARIN, transfers of IP addresses within RIPE and APNIC and transfers coming into RIPE and APNIC to create the transfers dataset. I collect this data for the period: 2009-2020. I additionally collect this set of data for the time period: January 2021 - May 2021 to study the impact of Covid-19 on the market.

[14] Autonomous system numbers - numbers part of the routing internet architecture

IPv4 and IPv6 allocation dataset

This is a snapshot of the IPv4 and IPv6 allocations at the IP address block level as of a given date.

This data is available at the following website: [ftp://ftp.x.net/pub/stats/x/2016/ where x belongs to ARIN/RIPE/APNIC].

This data is available for each RIR for each day. I collect this for various time periods. For IPv4 addresses, for summary statistics of the initial allocation I use the one recorded on February 9, 2016. This is the earliest period for which there is information about the org_id (firm identifier) for all RIRs. While ARIN and APNIC have org_id for earlier periods, this is the period from which RIPE has org_id information. Aggregating over all the blocks a firm owns I get the total IPv4 addresses held by each firm as of early 2016. I call this the allocation dataset.

The identifier in this dataset is 'org_id'. It is important to keep in mind that the 'org_id' while consistent within a dataset is not consistent across datasets (i.e. on different dates). While the dataset is available for different dates, the org_id cannot be used to identify the same firm over different dates. But within a dataset for firms with multiple allocations the org_id stays the same.

For each IPv4 block in the transfer dataset (market) I look up the firm that was allocated that block in the allocation dataset. Often this is a smaller IPv4 address block than the initial allocation and so I write a function to check if it lies within each block in the initial allocation and sum the total addresses held by that firm in the initial allocation. This gives the total address blocks that each firm selling in the market was allocated initially.

For IPv6 allocation I use the data available on June 28, 2020 to get the most upto date IPv6 allocation. Similar to IPv4 allocation there are instances of multiple allocation over time for IPv6 as well. To avoid double counting of firms for IPv6 adoption I look at the first date of allocation for each firm. For IPv6 blocks allocated I check the routing status and the date of first usage using https://stat.ripe.net/. An IP address block that has been used atleast once would show up in the global routing table. For a block that has been routed the earliest date it showed up in the routing table is also included. This is the first step towards usage of an IP address. This is date that I record for first usage.

While this is not a perfect measure as it doesn't measure real time usage or the intensity of usage, it helps distinguish between IPv6 blocks that have not been used at all and those which have been routed. Since I need this information for every IPv6 block that has been allocated, I write a program in Python that automatically gets the information about the IPv6 block routing status and if it has been routed the first date it was observed.

Firm features

I collect information about the role (ISP/content/enteprise) of a firm from the CAIDA website: (https://www.caida.org/).

The information is available at the AS number level. AS refers to group of IP networks operated by one or more network operators that has a single and clearly defined external routing policy. Some common examples are networks connected to two or more upstream service providers or networks peering locally at exchange points. There is an almost 1:1 relationship between an AS number and a org_id, except for certain cases where it is a slightly broader ownership than the org_id found in the allocation datasets.

CAIDA website also has a page about the cone size of the firms: https://asrank.caida.org/. This information is also at the AS number level. This information is a table that is spread over multiple pages on the website, I scrape the website using Python to collect this data and convert it into a dataset. I collect information about the number of users from the APNIC site (https://stats.labs.apnic.net/aspop). This information is available at the AS number level.

I also use information at a more detailed level about firm roles from IP2Location (https://www.ip2location.com/database/ip2location). Firm roles are as follows: COM - commerical, ORG - Organization, GOV - Government, EDU - University/College/School, ISP - Fixed Line ISP, MOB - Mobile ISP, DCH - Data Center/Web Hosting/Transit). This is an online website that provides information about IP addresses using individual query and bulk queries. I used a combination of individual and bulk queries to get information about the usage type of each IPv4 address transferred in the market and each IPv6 address. Given the sheer number of IPv4 addresses in the initial allocation and because this data is current, I'm not able to look at the usage type of IPv4 addresses from the initial allocation.

2.2 Merging the datasets

It is clear that the different datasets available have different identifiers and cannot be easily be merged. Thus merging the separate datasets is a challenge. While firm features are at the AS level, the IPv4 and IPv6 data from the RIRs use an org_id and the transfers data use the name of the buyer and seller. I use an online database (www.BGPlookingglass.com) which has information on the AS level and firm name to connect the firm level features with the transfer dataset. While majority of the names matched exactly, the rest were merged manually.

I also use data from Geolite2: https://dev.maxmind.com/geoip/geolite2-free-geolocation-data?lang=en. This has information about the most recent AS number associated with an IP address. Using this I'm able to find the AS number for the IPv6 allocations and buyers in the market. I'm able to connect the sellers in the market and their initial allocation as mentioned before.

In a given time period the org_id within an IPv4 and IPv6 allocation is consistent. Using the org_id for the initial allocation I merge the latest IPv6 allocation using the IPv6 block to get the current IPv6 holdings of firms in the initial allocation. I can do this because the org_id for IPv4 and IPv6 is consistent on a given date and IPv6 allocation blocks don't change over time. This also helps me to identify the AS number for a subset of firms in the initial IPv4 allocations. By this process, this allows me to study the whole picture rather than just look at individual slices of the data.

2.3 Initial IPv4 allocation

In this section I look at the following features from the initial IPv4 allocation:

1. IPv4 allocation over time and across RIRs
2. Allocation size and number of allocations over time
3. Distribution of IPv4 holdings across firms

The initial IPv4 allocation refers to the allocation at zero price made by RIRs to the firms. In the figure below I look at the cumulative number of addresses allocated across the 3 RIRs. It is clear that the market was permitted when the RIRs had already allocated majority of the addresses. Compared to the total number of IPv4 addresses available globally (approx. 4 billion), it is clear that the three RIRs account for the majority of the IPv4 addresses allocated.

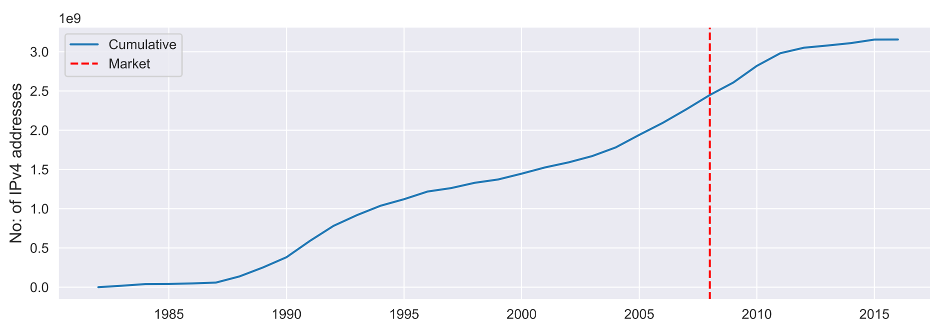


Figure 25: Cumulative IPv4 address allocation over time

Notes: The blue line captures the cumulative sum of IPv4 addresses allocated across the three RIRs. I calculate this by adding the number of blocks allocated to firms across the three RIRs over each year. The red dashed line represents the time the market for IPv4 addresses was permitted in 2009.

In the next figure I look at IPv4 address allocation across the three RIRs over time. ARIN allocated more addresses than the other two, allocating more than twice the number of addresses as RIPE. By the early 2000's, ARIN allocated close to 70% of its total addresses much earlier than the other two RIRs.

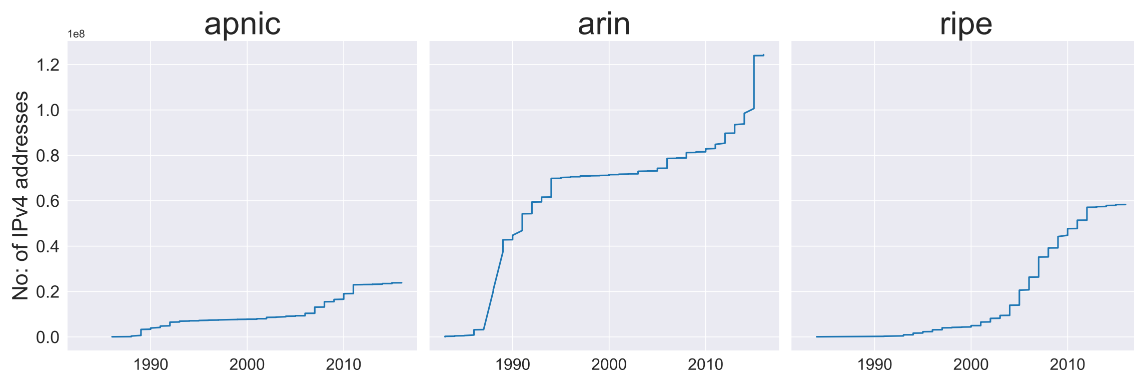


Figure 26: Cumulative IPv4 allocation across RIRs

Notes: I look at the cumulative sum of IPv4 addresses allocated by each of the three RIRs. APNIC - Asia Pacific, ARIN - North America and RIPE - Europe. I calculate this by adding the number of blocks allocated to firms for each RIR over each year.

In the figure below I look at the average number of addresses allocated per firm $= \frac{\text{Total addresses}}{\text{Number of firms}}$ across the three RIRs. Across all the three RIRs it is clear that early firms received addresses larger blocks compared to later firms. This was due to both technical reasons (related to classful address allocation), zero price as well as desire to promote the use of internet which was a new technology in the 1980's.

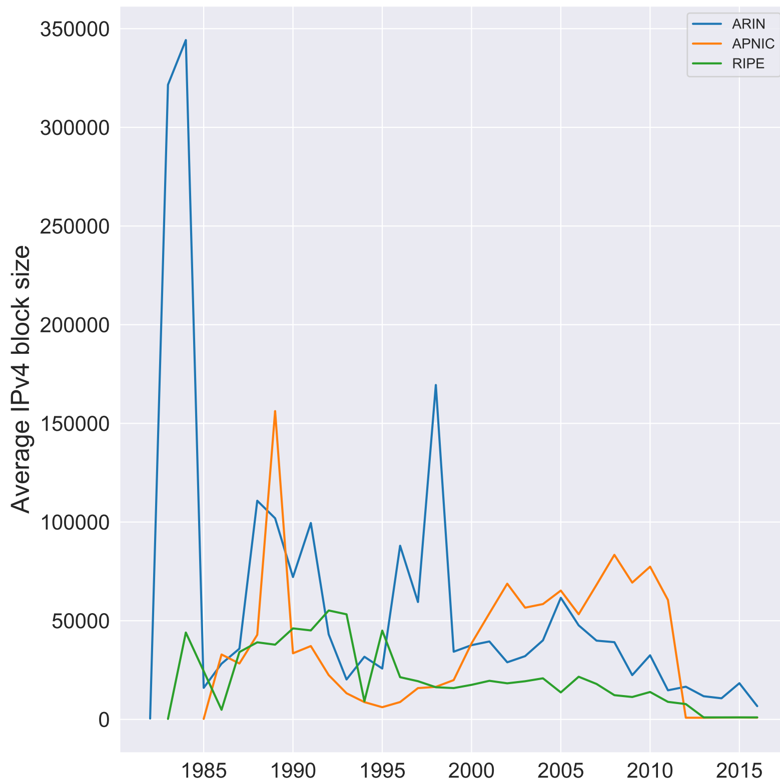


Figure 27: Average IPv4 address block size over time

Next, I look at the summary statistics of the block size and the number of allocations across each firm. Block size represents the size of the address block allocated. Number of allocations per firm refers to the total number of allocations a firm has received from the RIR until early 2016. Due to data limitations, I choose this period and this is further explained in the appendix. In the first two columns I look at the block size, block size among the top 25 percentile and in the next two columns I include the number of allocations per firm and that among the top 25 percentile.

Statistic	Block size	Top 25% percentile	No: of allocations	Top 25% percentile
count	130,573.00	33,956.00	67,638.00	15,718.00
mean	26,259.33	97,189.05	7.52	28.36
std	307,421.73	597,178.03	49.03	98.90
min	8.00	4,352.00	1.00	3.00
25%	512.00	8,192.00	1.00	3.00
50%	1,024.00	32,768.00	1.00	5.00
75%	8,192.00	65,536.00	2.00	11.00
max	16,777,216.00	16,777,216.00	1,083.00	1,083.00

Table 9: Summary statistics for allocation size and number of allocations

A number of these allocations are the smaller sized allocations. The maximum size of 16,777,220 represents the 35 legacy allocations. In comparison the median allocation size was 1024 blocks and the mean allocation was 26,259 blocks. I find that half the firms have at the most 1 or two allocations, in the top 25% there are firms with over 1000 allocations. The mean number of allocations for this group is much higher at 7.9.

Over time some firms have accumulated IPv4 blocks and thus to understand the total IPv4 holdings of a firm at a given point in time total addresses from all the allocations have to be aggregated.

Next, I calculate total IPv4 addresses held by a firm in the initial allocation by aggregating the number of addresses for each firm. I divide firms into three categories of total IPv4 ownership: small, medium and large. Less than 0.1% of the firms hold as much as 37% of the total allocated space. Whereas 78% of the firms own as little as 1.6% of total blocks allocated.

Total addresses held: x	No: of firms with Initial allocation	% Total addresses	% Total firms
$x \leq 4096$	55,364	1.6	78.1
$4096 < x < 15$Mn	15,470	61.0	21.8
$x \geq 15$Mn	44	37.4	0.1

Table 10: Distribution of firms across sizes based on total IPv4 holdings

Next, I look at the summary statistics of total blocks held by firms within the three groups of ownership - small, medium and large. It is clear that there is great inequality in the total IPv4 blocks owned even within a group.

Statistic	Small Holdings	Medium Holdings	Large Holdings
count	55,364.0	15,470.0	44.0
mean	1,029.6	130,513.1	28,239,057.5
std	1,048.4	649,116.5	33,346,620.0
min	256.0	4,352.0	15,008,000.0
25%	256.0	8,448.0	16,777,664.0
50%	512.0	32,768.0	18,403,840.0
75%	1,024.0	65,536.0	25,660,992.0
max	4,096.0	14,680,064.0	220,997,600.0

Table 11: Summary statistics of IPv4 holdings across categories

In the table below I look at three features across **all** firms (not just firms selling in the market). I look at the distribution of total blocks held, cone size and users.

Statistic	Total IPv4 addresses	Cone size	Users
N	67,638	77,468	77,468
Mean	1,206,383	5	39,695
St. Dev.	6,782,475	170	1,439,894
Min	256	1	1
Pctl(25)	1,024	1	1
Pctl(75)	65,792	2	1
Max	182,560,256	26,012	292,944,972

Table 12: Summary statistics of firm features

Notes: This is a cross-section comparison of all firms as of early 2016.

The large standard deviation for the total IPv4 blocks held by the firms indicate the difference in the total blocks held by firms. Similarly, the number of users has a lot of variation - it varies from 1 to close to 300 million users. Similarly cone size[15] of the firm varies between 1 and 26,012 with a mean of 5.

[15] which is a measure of the revenue derived from routing data

Accumulation through multiple allocations

In the figure below I look at the total number of addresses allocated to firms with different number of allocations over the years - 2013,2014,2015 and 2016. On the y-axis I have the total number of addresses allocated to firms and on the x-axis I have the corresponding number of allocations. Allocations more than 32 are categorized together in a single category. It is clear that there are firms with more than 1 allocation and ranging all the way up to more than 32 allocations per firm. In the initial years majority of the total addresses allocated to firms belonged to the single allocation. By 2016 almost as much addresses were allocated to firms with a single allocation as firms with 32+ allocations.

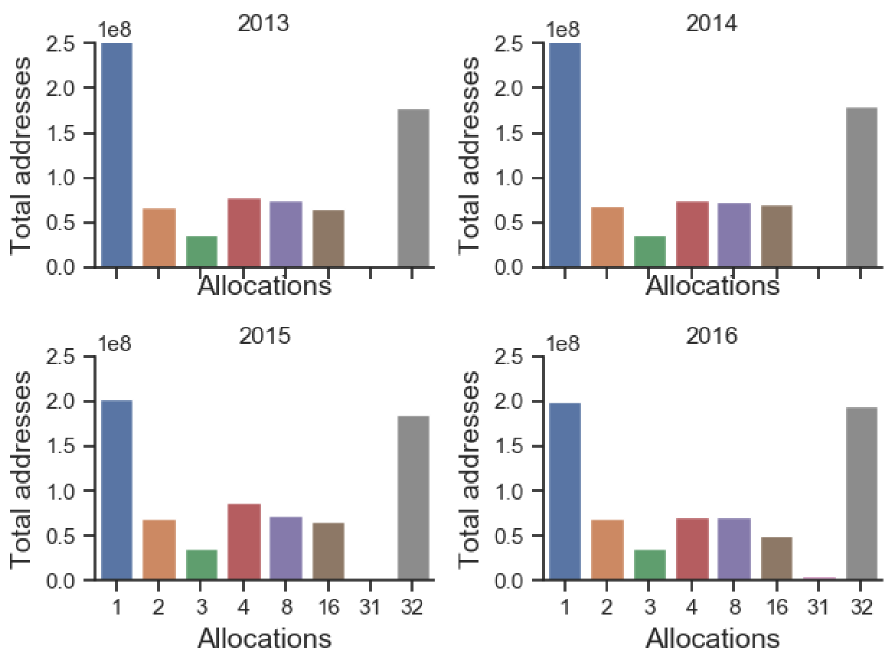


Figure 28: Accumulation of addresses through multiple allocations

For this figure I use the data from IPv4 allocations for the years 2013, 2014, 2015 and 2016 (for the date March 3rd for each of the year).

2.4 Market for IPv4 addresses

In this section I look at some additional empirical features from the market for IPv4 addresses.

Number of transfers and volume of transfers

In the figure below, on the left I look at the number of transfers and on the right volume of addresses (total sum of addresses transferred across all firms) transferred in the market for IPv4 addresses. In the initial period the number of transfers in a month were limited between 0 and 3 transfers per month. But this quickly picks up and there are between 200-400 transfers each month from 2015. Next, I look at the volume of addresses transferred in the market each month over time. There is a similar pattern as the number of transfers.

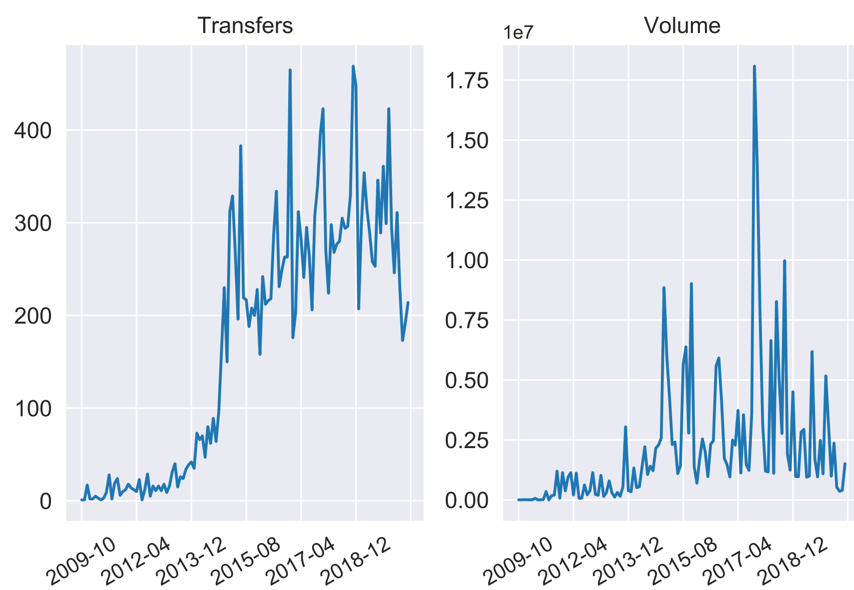


Figure 29: Number of transfers and volume per month over time

In the table below I look at the distribution of number and volume of transfers within the three sizes of total IPv4 ownership (small, medium and large). It is clear that the largest number of transfers happen among the smallest blocks, followed by the medium sized blocks . In 2015 and 2017 there is an unusually large number of transfers among the largest blocks. In terms of the volume of addresses transferred, the majority of the transfers are in the medium to large blocks.

Year	Transfers			Volume(%)		
	Small	**Medium**	**Large**	**Small**	**Medium**	**Large**
2009	19	-	-	100	-	-
2010	4	-	-	100	-	-
2011	92	28	2	3	32	65
2012	107	58	2	1	66	32
2013	190	113	2	5	66	29
2014	794	279	3	8	73	18
2015	2544	336	18	5	36	59
2016	2607	527	4	10	67	23
2017	2864	564	16	6	46	49
2018	3160	592	8	8	54	38
2019	3218	472	3	13	64	23
2020	1456	203	2	17	61	23

Table 13: Transfers and volume across sizes

Market participation

In the figure below I look at participation by buyers and sellers in every month in the market. Apart from the rising trend over time, from late 2015 there is a rising gap between the number of buyers and sellers in this market.

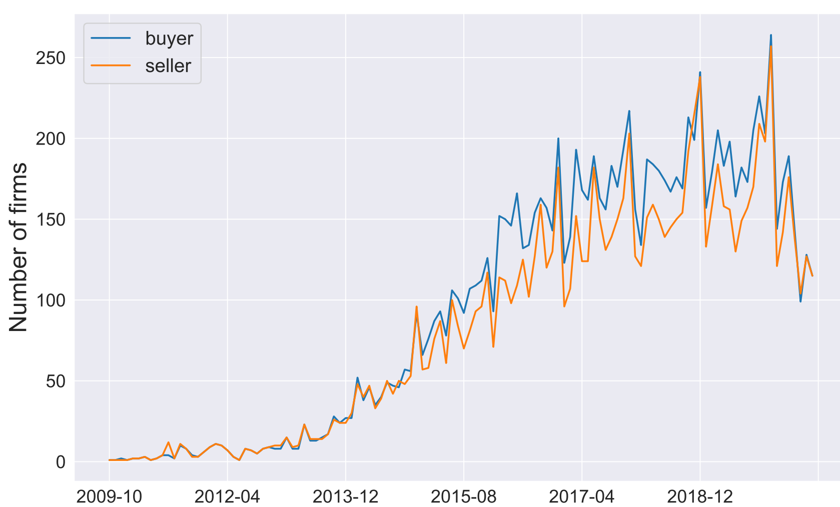


Figure 30: Number of sellers and buyers in the market

In the table below I look at buyer and seller participation in the market from different sizes of IPv4 ownership. In the last column I compare the distribution of all firms across each size category. It is clear that the majority of buyers and sellers come from the smallest category, followed by the medium category. There are limited number of buyers and sellers in the largest category. Comparing this to the number of firms within each size category it is clear that there is limited participation in the market. This could be because of failure to realize the worth of this asset or anticipation of higher price or use value in the future. Thus even while there has been a lot of unused addresses that could be transferred in the market, the number of addresses that make it to the market is still limited.

Block size	No: of buyers	No: of sellers	Firm distribution
Small	9188	7729	55,364
Medium	1705	1838	15,470
Large	24	26	44

Table 14: Participation in the market

Rental market

There has been no formal rental market for the IPv4 addresses due to various reasons including possible IP space hijacking. From 2015 there is some evidence[16] of two firms leasing out IPv4 addreses. With rising prices this market has gained some traction as firms are reluctant to sell their address blocks but eager to make some money out of it. Rental rates/block per year charged by these two firms are driven largely by the firm's bottom-line. Rental rates offered by these firms vary between $5-9 per block per year. But the rental market is yet to take-off in a big way to influence prices in the market.

Resale in the market

[16] scraped using Wayback machine (https://archive.org/web/)

Looking at all transfers in the market I find that only 0.3% of the addresses picked up in the market are resold again in the market. With rising prices we could see more cases where firms resell the blocks they picked up. At the same time if these firms are expecting higher prices they might hold on to the addresses and delay selling. Thus for now, I can treat firms that are buying IPv4 addresses separate from firms that are selling IPv4 addresses.

Share of addresses sold in the market

In the table and figure below I look at the fraction of addresses sold by sellers in each transfer. At the median, in each transfer firms sell 30% of the blocks they own.

count	9,234.00
mean	0.44
std	0.39
min	0.00
25%	0.08
50%	0.31
75%	1.00
max	1.00

Table 15: Fraction of blocks sold

Multiple transfers in the market

Sellers have an average of 3.23 transfers and buyers have an average of 2.67 transfers in the market. In the top 25% sellers and buyers have 10.58 and 8.43 transfers respectively.

	Seller	Buyer	Top 25%	Top 25%
count	6,288.00	7,533.00	1,348.00	1,526.00
mean	3.23	2.67	10.58	8.43
std	20.80	6.71	44.15	13.42
min	1.00	1.00	3.00	3.00
25%	1.00	1.00	3.00	3.00
50%	1.00	1.00	5.00	4.00
75%	2.00	2.00	8.00	8.00
max	1,278.00	199.00	1,278.00	199.00

Table 16: Number of transfers by buyers and sellers

Next, I look at the number of repeated transfers among sellers with different IPv4 blocks holdings. I categorize IPv4 holdings into three categories: small, medium and large. The columns represent the total number of transfers by a firm in the market, starting from 1. Since there is a long tail, I group 8 or more transfers into a single category - '8+'. In each cell I record the number of firms that belong to each category. In the small category majority of the firms sell their addresses in a single transfer. Majority of the firms with medium and large blocks have more than one transfer.

IPv4 holdings	1	2	3	4	5	6	7	8+
Small	2604	603	129	73	23	15	13	22
Medium	967	501	252	208	113	89	71	376
Large	4	4	0	1	1	1	0	8

Table 17: Number of transfers by seller vs IPv4 addresses owned

IPv4 address purchase in the market by firm roles

In the figure below I look at the total IPv4 blocks purchased in the market across firm roles over time. ISP and content firms have been leading total purchases in the market, but this is also because of the distribution of firm roles (majority of the firms are ISP firms, followed by content firms and enterprise firms).

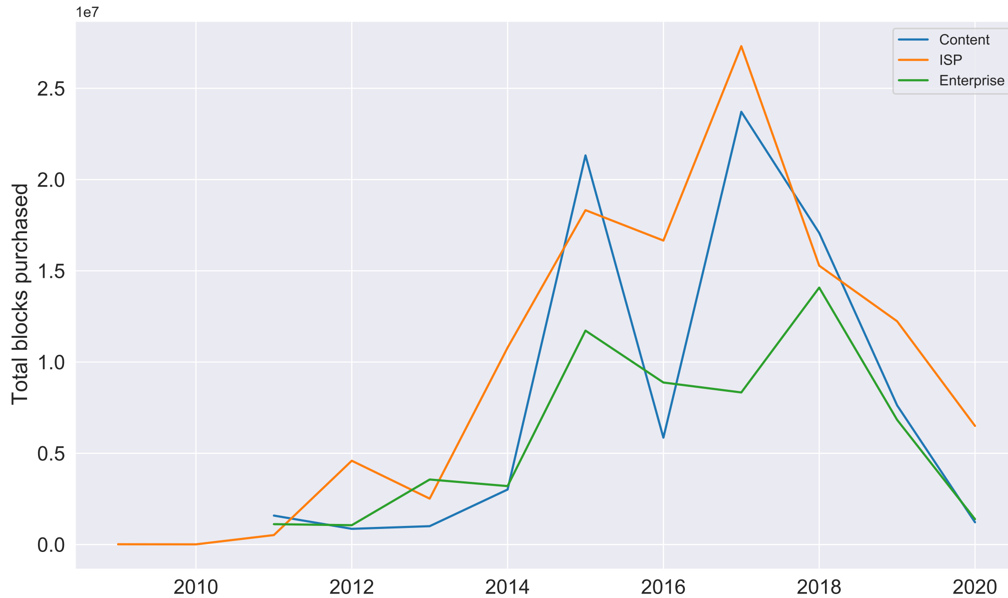


Figure 31: Total IPv4 addresses purchased in the market

In the figure below I look at the average IPv4 address block size purchased across firm roles over time. Enterprise firms have been purchasing larger blocks on an average compared to the other two firm roles.

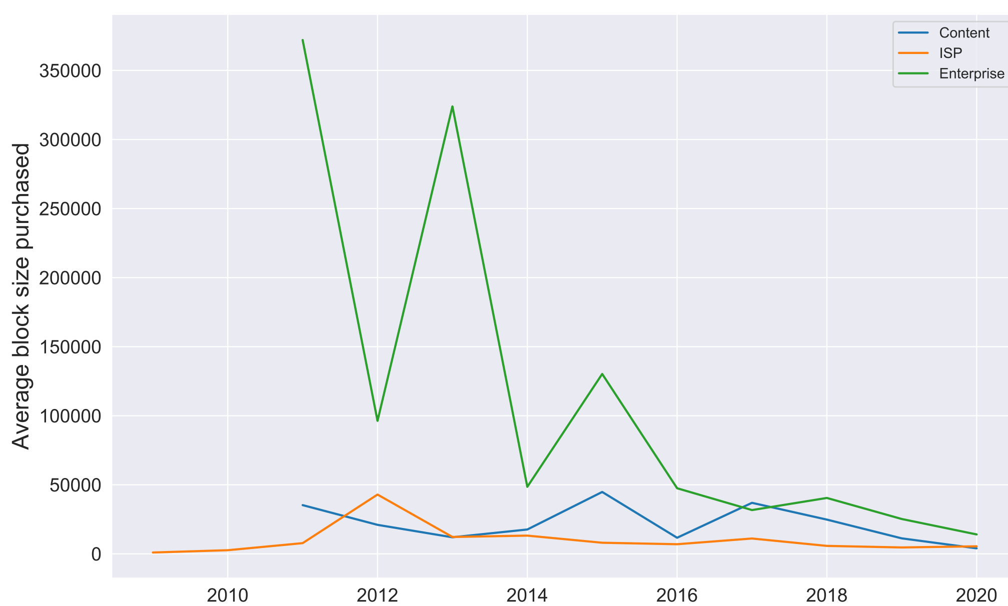


Figure 32: Average block size purchased in the market

Buyers in the market by detailed firm roles

In the figure below I look at the firm role of buyers. Datacenters and Web hosting centers are the main buyers in the market followed by commercial firms and ISP firms.

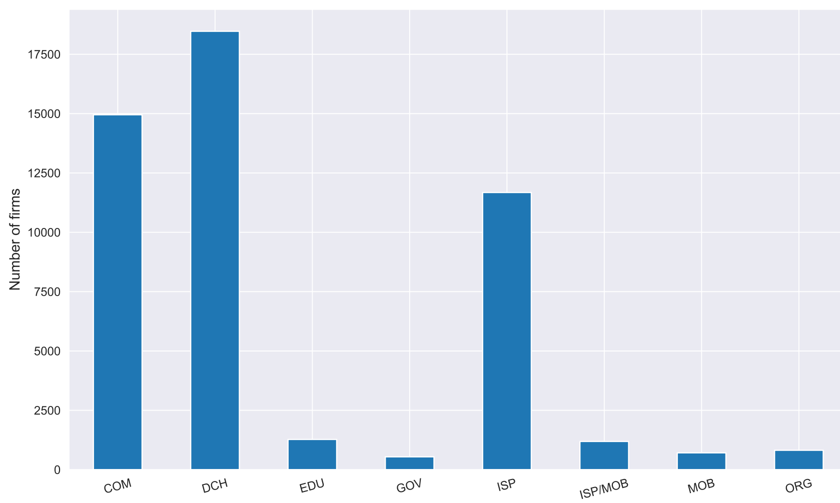


Figure 33: Number of firms buying in the market by role

Notes: This is based on the IP2Location dataset with following category names. COM - commerical, ORG - Organization, GOV - Government, EDU - University/College/School, ISP - Fixed Line ISP, MOB - Mobile ISP, DCH - Data Center/Web Hosting/Transit

In the figure below I look at the total addresses purchased in the market by firm roles. Datacenters and Web hosting centers together bought close to 120 million addresses which is almost four times as much as the total purchases by the next biggest buyer: ISP firms.

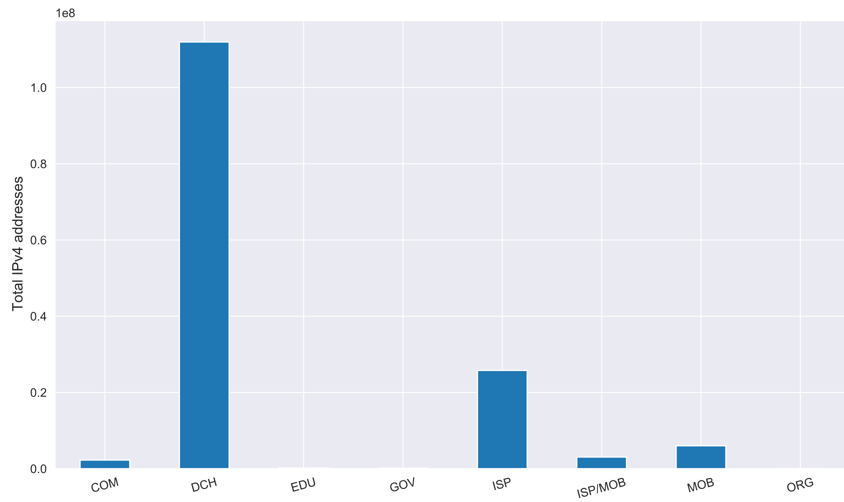


Figure 34: Total IPv4 addresses bought by firms in the market by role

Notes: This is based on the IP2Location dataset. EDU, GOV and ORG have much smaller scale of total IPv4 address purchases compared to the other categories, so appear close to zero.

In this figure I look at the number of transactions of firm buying IPv4 addresses in the market by role over time. Datacenters/webhosting/transit, ISP, commercial firms are leading demand for IPv4 addresses in the market. There is a spike in demand from late 2014. This is also close to IPv4 address exhaustion ARIN, which was the major RIR IPv4 exhaustion.

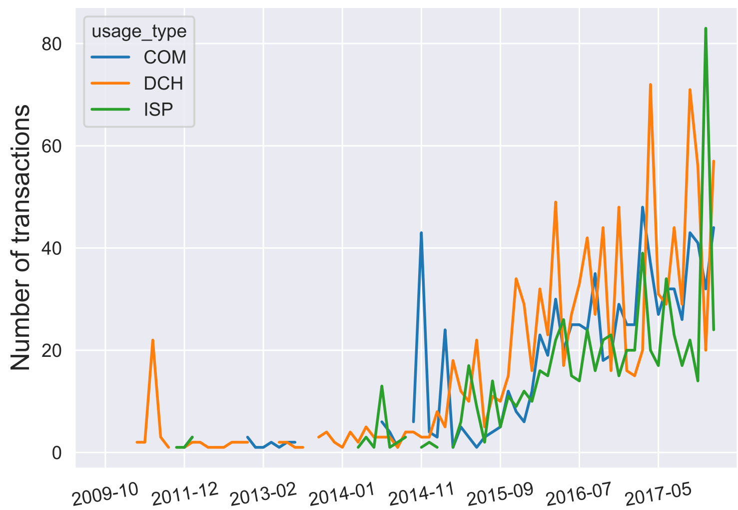


Figure 35: Usage type of transfers

Notes: This is based on the IP2Location dataset with following category names. COM - commerical, ISP - Fixed Line ISP, MOB - Mobile ISP, DCH - Data Center/Web Hosting/Transit

Effect of blocks owned on number of transfers by a seller

A 1% increase in the total number of addresses held by a firm leads to 10.1 additional transfers on an average. This effect is significant and accounts for 34% of the difference in the number of transfers observed.

Positive significant effect of total blocks owned on total blocks sold and explains 30% of the variation in total blocks sold.

Effect of transfers on number of addresses sold/bought

In the figue below I look at the correlation between the number of transfers by a seller and the total addresses sold by the firm in the market. There is a positive correlation between the number of transfers by a seller and the total addresses sold by that firm.

Table 18: Effect of blocks owned on number of transfers by sellers

	Dependent variable:
	No: of transfers
Intercept	6.0*** (0.8)
Total Blocks owned	−26.8*** (7.3)
Observations	7,114
R^2	0.01
Adjusted R^2	0.01
Residual Std. Error	150.7 (df = 7112)
F Statistic	55.4*** (df = 1; 7112)
Note:	*p<0.1; **p<0.05; ***p<0.01

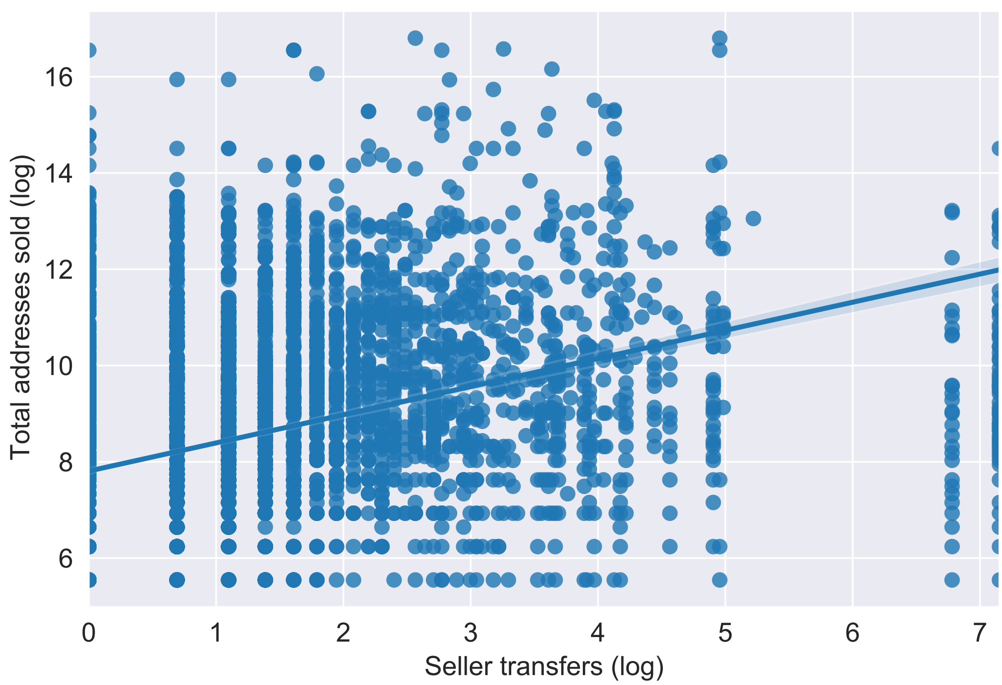


Figure 36: Transfers and total addresses sold

In the figure below I look at the correlation between buyer transfers and total addresses purchased in the market. There is a positive correlation between the number of transfers by a buyer and the total addresses bought by that firm.

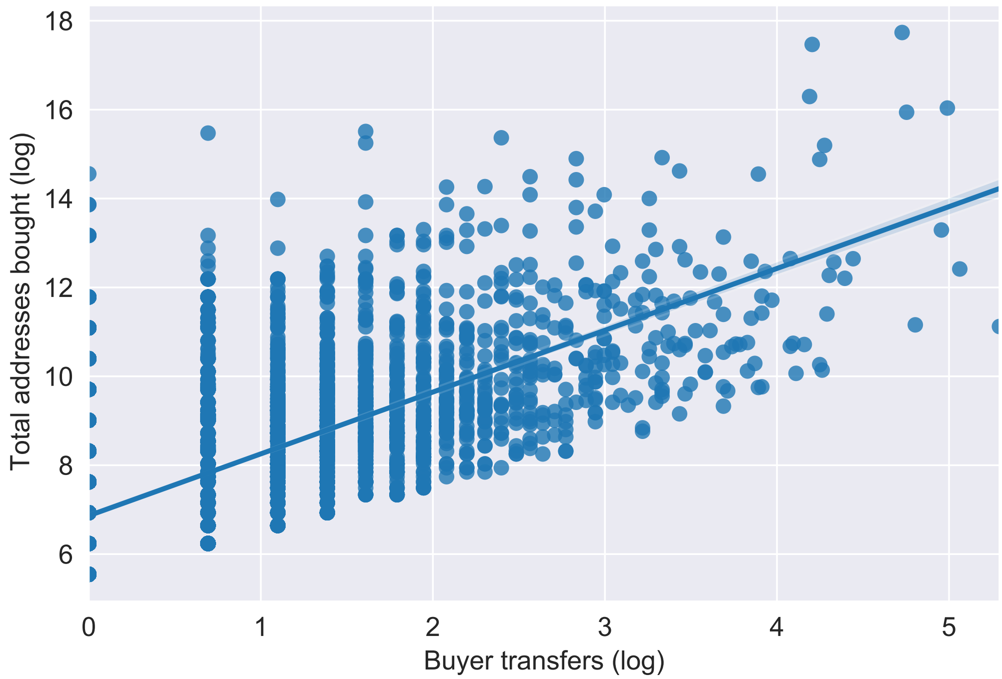
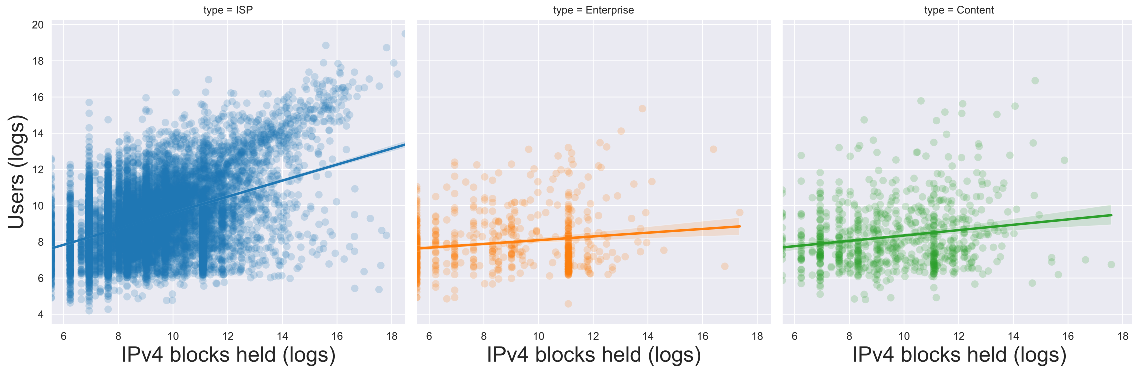


Figure 37: Transfers and total addresses bought

Evidence of NAT

NAT - Network Address Translation was introduced in 1994. This is a feature observed in the internet ecosystem by firms allowing less than 4 billion IPv4 addresses to support over 20 billion devices. Using the NAT a single address could be used to connect an entire network, extending the life of IPv4 addresses in the short run. For the analysis in chapter 1 and 2, I ignore the possibility of NAT.

There exists no empirical measure to verify how many firms use NAT from the IP allocation data. In the figure below I look at the scatterplot of number of users and number of IPv4 addresses held by each firm across different firm roles (Content/ISP/Enterprise). Firms supporting much more users than the number of blocks must be using some NAT technology to allow all their users to connect to the internet. While there exists firms that support more users than the number of addresses they hold across all the; more ISP firms support this compared to Enterprise and Content firms.



Largest initial IPv4 owners and participation in the market

Looking closer at the top 25th percentile of total addresses held by firms in the initial allocation, a small number of firms own large blocks of addresses in the initial allocation and there is limited sale across these large firms.

Total addresses (x):	Total no: of firms	% of addresses	Firms in market	% of total firms
$x \geq 21,759$	1747	96.2	133	7.6
$x \geq 65,535$	2802	94.2	308	11.0
$x \geq 100,000$	1328	84.5	102	7.7
$x \geq 500,000$	363	76.2	34	9.3
$x \geq 1,500,000$	203	66.5	18	2.3
$x \geq 9,000,000$	53	45.3	14	26.4
$x > 25,000,000$	13	20.4	3	23.1

Table 19: Distribution of firms across sizes in the initial allocation and market

Purchase price across sizes over time

In the figure below I look at the purchase price which is defined as:

$$\frac{\text{Price}}{\text{address}} \times \text{Number of addresses}$$

Looking at the larger sized blocks it is clear that for the larger sizes the total purchase price easily runs into millions of dollars

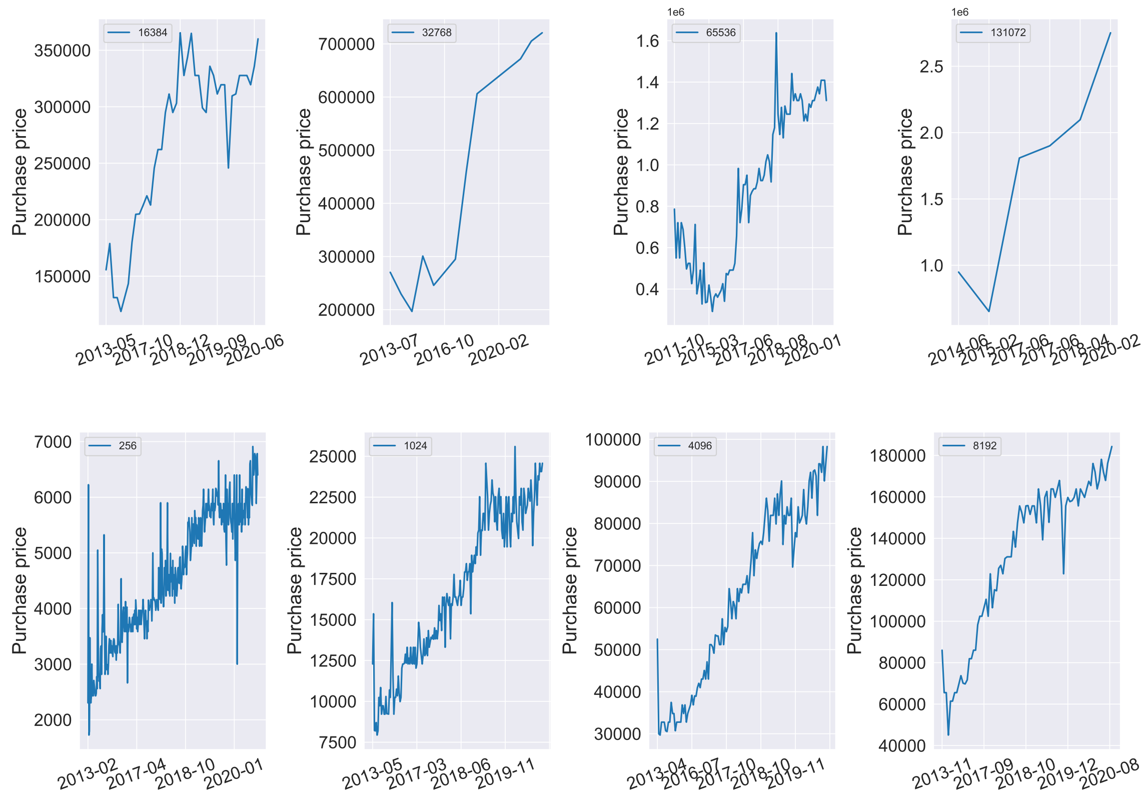


Figure 38: Purchase price across sizes

Distribution of price/address over time

Next, I look at the distribution of price/address across all transfers for a given year. Looking at the price/address for each year, there is greater dispersion in price in the initial years. But over time this dispersion reduces and price in the market converges.

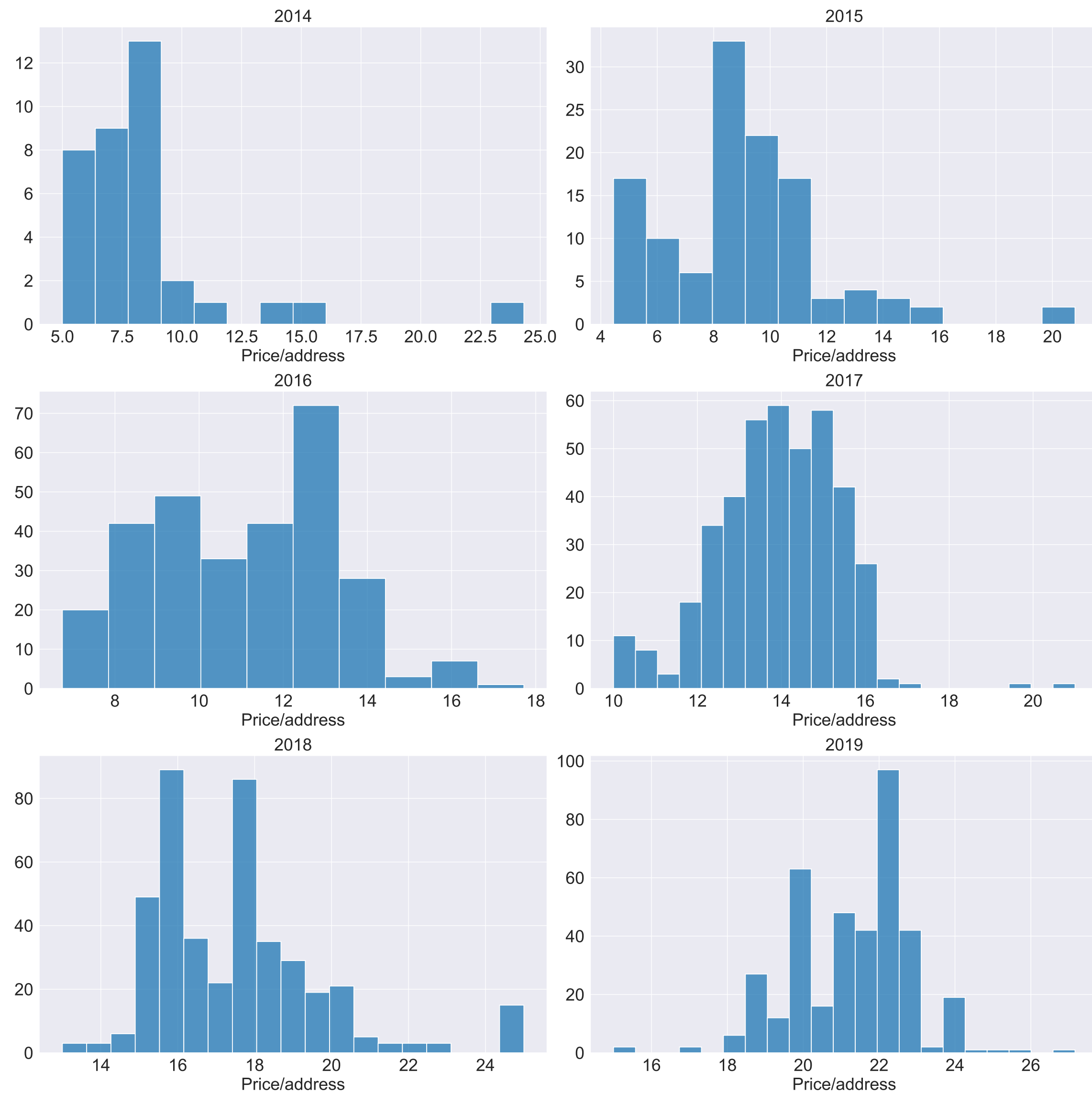


Figure 39: Price dispersion

Comparing 256 sized-block with 65536 sized-block

The bigger blocks initially had a bigger discount compared to the smaller block, but over time this gap converges.

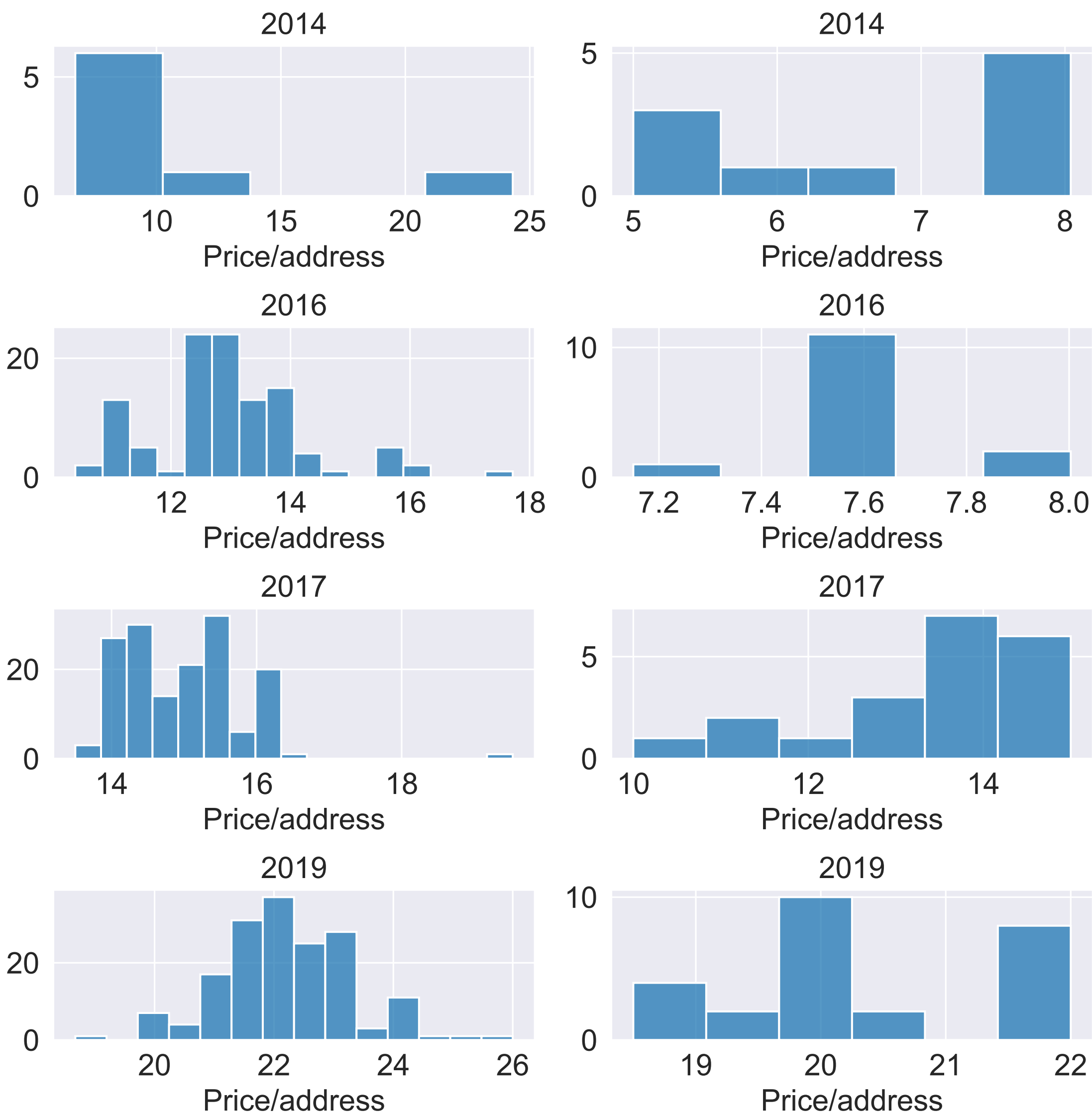


Figure 40: Price dispersion across the smallest and large size

Price trend

Here I look at the price trend - the price/block rises 1 cent everyday.

Table 20: Trend in price

	Dependent variable:
	Price per address
t	0.01*** (0.000)
Constant	8.9*** (0.1)
Observations	1,000
R^2	0.9
Adjusted R^2	0.9
Residual Std. Error	1.7 (df = 998)
F Statistic	7,337.5*** (df = 1; 998)
Note:	*p<0.1; **p<0.05; ***p<0.01

Effect of number of transfers on transfer size

In the table below I look at a regression of the number of transfers on the size of the IP address block transferred in the market. This explains 30% of the variation observed in the size of the address transferred.

Table 21: Effect of number of transfers on transfer size

	Transaction size
	(1)
Intercept	-315326.62371*** (12438.62835)
Total IPv4 blocks	35441.55043*** (1222.54129)
Number of transfers	-1211.0871*** (70.42561)
Observations	6187.0
R2	0.11966
Adjusted R2	0.11937
Residual Std. Error	199307.94633(df = 6184.0)
F Statistic	420.26461*** (df = 2.0; 6184.0)
Note:	*p<0.1; **p<0.05; ***p<0.01

Controlling for the blocks owned, I find that each additional transaction reduces the transaction size by 1211 blocks on an average (which is also close to the median transaction size in the secondary market). Thus firms that are selling more often are selling smaller blocks.

Speculative demand

I check the usage status of each CIDR transacted in the market based on its routing status.[17] As a conservative estimate I assume the entire block is in use even if a sub-block is only being routed. In the figure below I look at the total address block bought in a given year and how many of these have been routed. The units on the y-axis are 10MN address blocks. Hence even a small gap converts to 1MN to 3MN address blocks being bought but not being used, which is around 2.5% of the number of addresses transacted in a year. This gap starts from 2016 and seems to be expanding. The observed gaps in 2019 and 2020 transactions could also be attributed to the turn around time in putting the transferred blocks into use.

[17] as of 06/28/2020

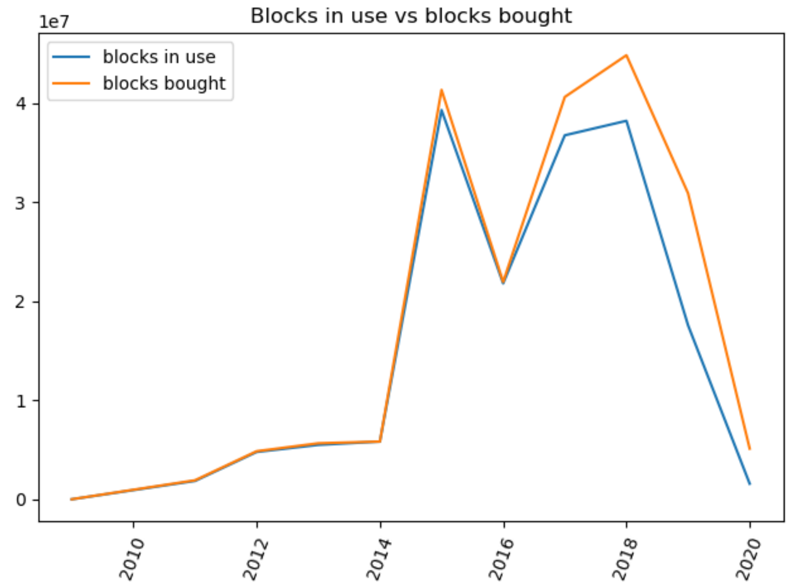


Figure 41: Speculative demand in the market

2.5 Brokerage firm details

The data related to price comes from one of the oldest and largest brokerage firms in ARIN. For the smaller sizes they conduct online auctions. For the larger sizes (/16 and larger) they conduct private negotiations. For the auction data I see information related to the number of bidders, number of bids, starting price, winning bid and second highest bid.

The brokerage firm conducted daily online auctions for the smaller sizes -/24(256 addresses) to /16 (65536) addresses. In the auctions sellers set a minimum opening bid price with incremental bidding until auction ends. Buyers are allowed to bid using the minimum allowable bid. Buyers are shown a message if the bid is high enough to become current high bid or if not it can increase the bid. If a bid placed in the last 5 minutes, then auction is extended for another 2 minutes. Firms can also use ”proxy” bids. In case of a tie, the first bidder wins the object.

Effect of size and number of bidders on price/address

In the regression I look at the effect of size, number of bidders on the price of an IPv4 address. After controlling for a linear trend in price, size doesn’t have an effect on price and the number of bidders has a positive correlation with the price/address.

Table 22: Effect of size and number of bidders on price/address

	Dependent variable:
	Price/Address
t	0.016
	(0.0002)***
size	−0.0001
	(0.00001)***
unique_bidders	0.373
	(0.127)***
Constant	8.083
	(0.176)***
Observations	1,568
R^2	0.878
Adjusted R^2	0.877
Residual Std. Error	1.513 (df = 1564)
F Statistic	3,742.564*** (df = 3; 1564)
Note:	*p<0.1; **p<0.05; ***p<0.01

Ratio of winning bid and second highest bid over time

In the figure below I look at the ratio of winning bid/second highest bid in the auctions over time. Since a number of the auctions have limited competition there is limited data related to the second highest bid. This gap can be used to study "money left on the table".

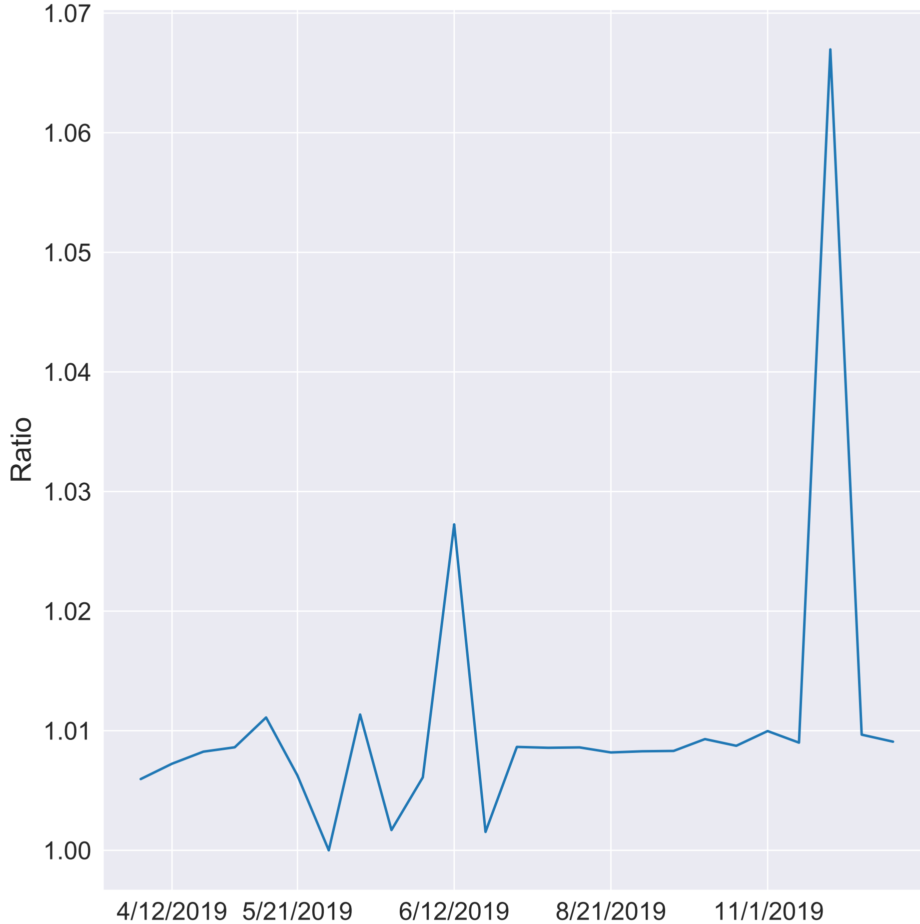


Figure 42: Ratio of winning to second highest bid

Number of bidders

To get a sense of competition in the market I look at the number of bidders and bids in the auctions conducted by brokerage firm. In the figure below I look at the average number of bidders in a month. I find limited competition in the daily auction market.

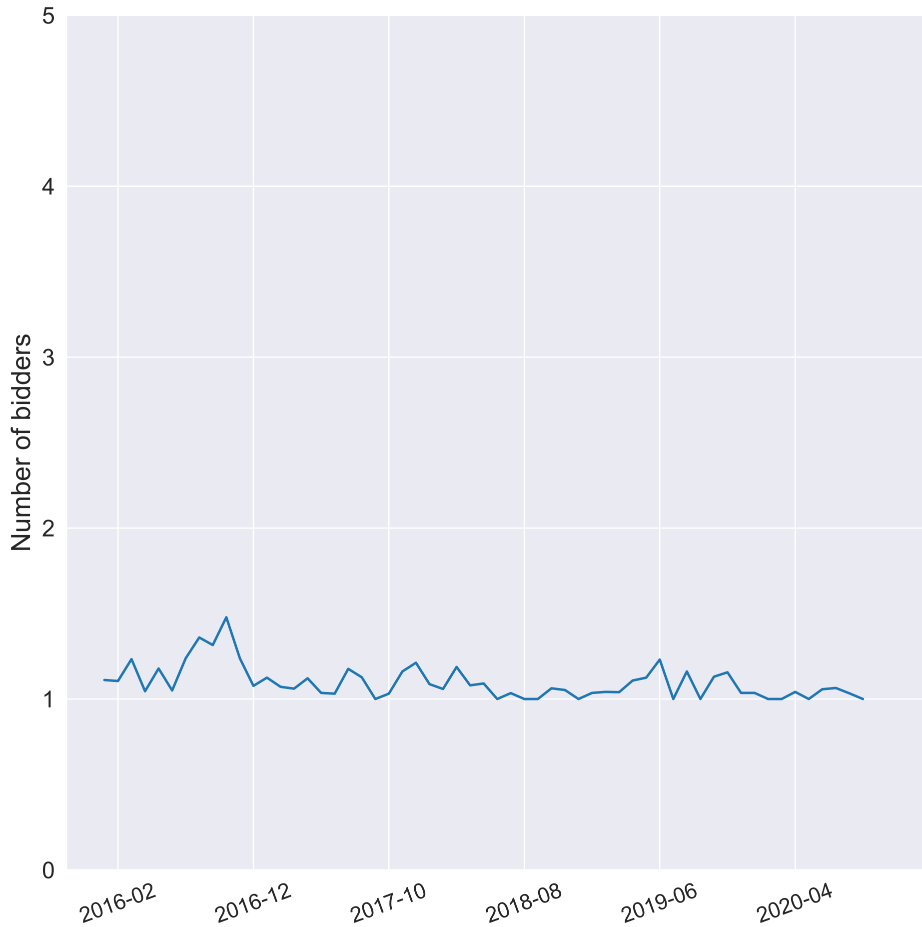


Figure 43: Number of bidders over time

Number of bids

Looking at the average number of bids across auctions in a month, it is clear there is an increase in bidding competition from late 2018. I include more description and evidence based on auctions in the appendix.

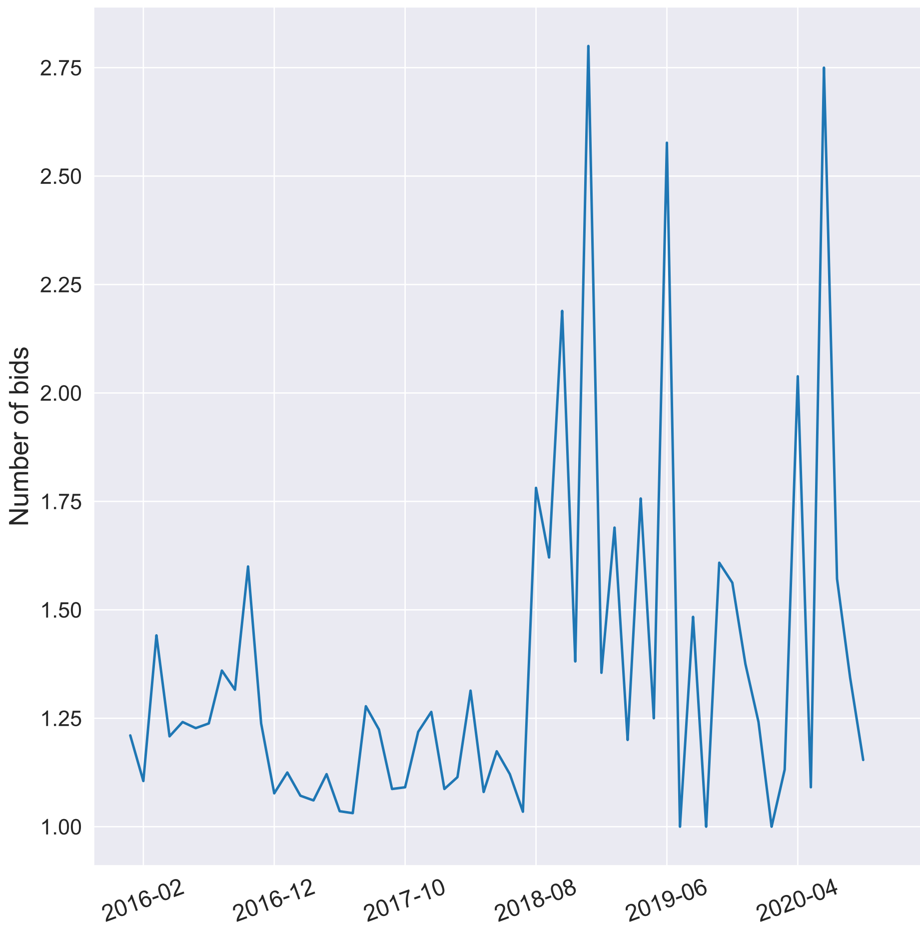


Figure 44: Number of bids over time

2.6 Effect of Covid-19 in the market

In this section I look at the effect of the Covid-19 pandemic on the market for IPv4 addresses. This was was an exogenous shock to the market. Many firms moved their employees to work from home, leading to an increase in demand for IP addresses. I look at the effect of this shock on prices, volume, number of transfers and average size of transfer in the market. I analyze the trend from January 2019 which was the pre-pandemic period until June 2021. I note the beginning of Covid-19 as March 2020 as this was when much of North America moved to work from home measures.

Volume of transfers

In the figure below I look at the volume of addresses transferred in the market before and during the Covid-19 pandemic. On the left panel I look at the volume each month among the larger sizes and on the right panel among the smaller sizes.

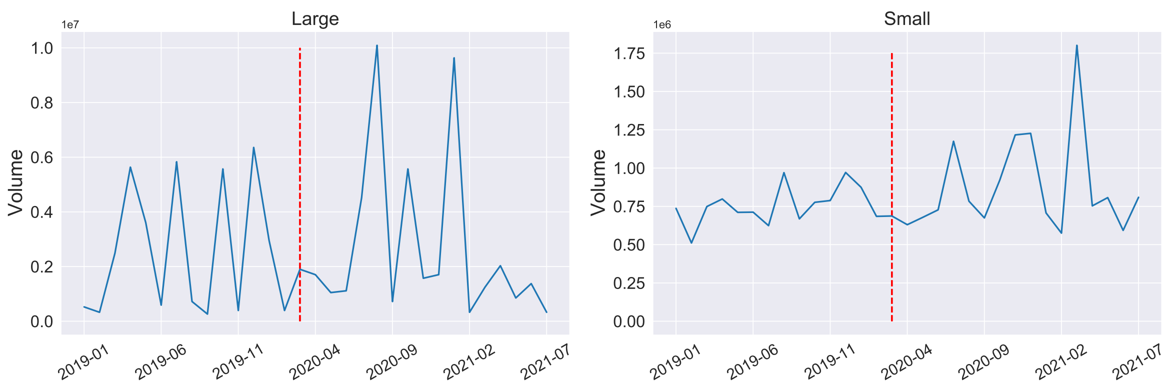


Figure 45: Volume of transfers each month

Notes: In the large category I include all sizes larger or equal to 65536 ($\geq /16$)and in the small category all sizes less than 65536 (< 16). The red dashed line stands for March 2020 the start of the Covid-19 pandemic.

It is clear that there has been an increase in volume of transfers in both categories immediately with the onset of the pandemic.

Number of transfers

In the figure below I look at the number of transfers in the market before and during the Covid-19 pandemic. On the left panel I look at the transfers each month among the larger sizes and on the right panel among the smaller sizes.

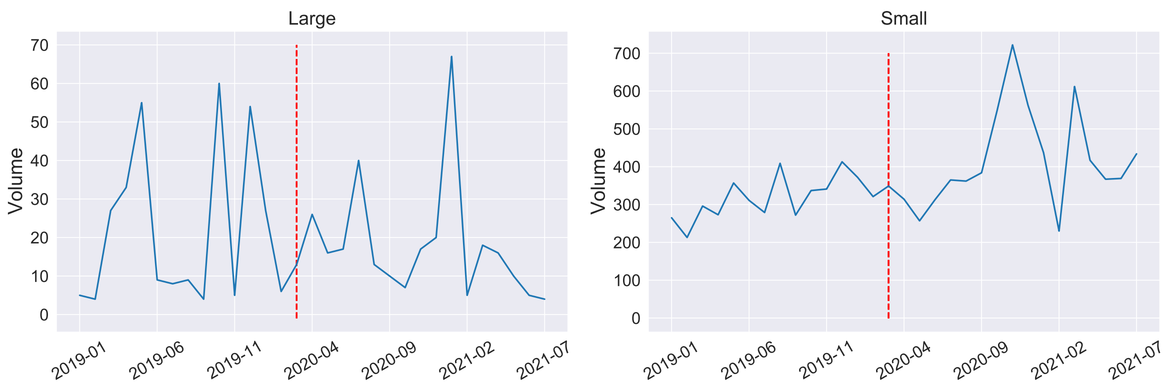


Figure 46: Number of transfers each month

It is clear that there has been an increase in number of transfers in both categories (especially among the smaller sizes) immediately with the onset of the pandemic.

Average block size

In the figure below I look at the average size of addresses transferred in the market before and during the Covid-19 pandemic. On the left panel, I look at the average size each month among the larger sizes and on the right panel among the smaller sizes.

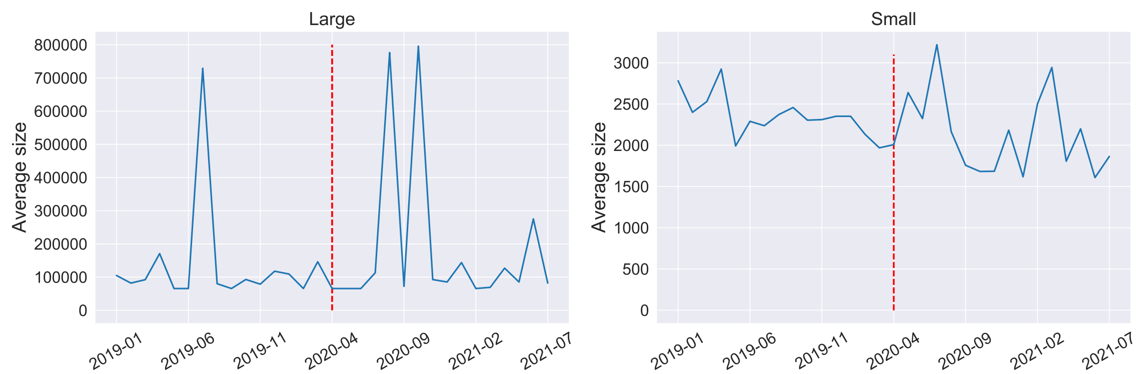


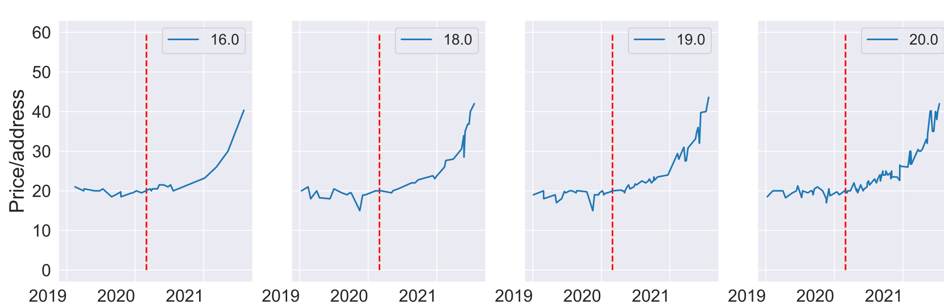
Figure 47: Average block size each month

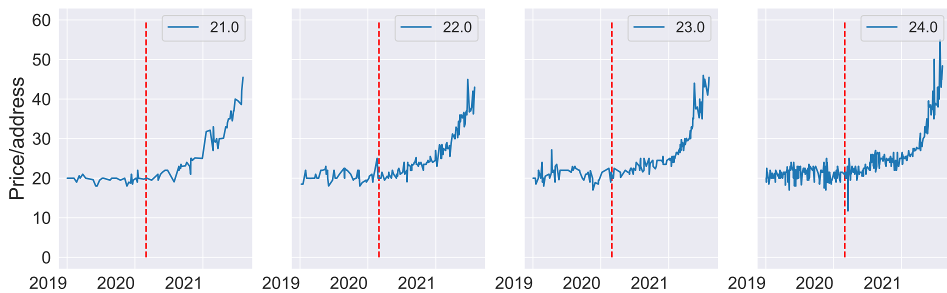
It is clear that there has been an increase in size of the transfers in both categories immediately with the onset of the pandemic.

Price/address

In the figure below I look at the effect on price/address across different sizes. While prices remain the same for first few months, it starts rising quickly and by August 2021 price/address has doubled. While the pre-pandemic prediction was that it would take five years for price/address to double, with the exogenous shock prices double in less than a year.

Thus prices are responding to changes in the market. It is interesting to watch what would happen to this market once the demand slackens and see if price responds to that change in demand. Thus we need to continue to track this market over time.





During the pandemic of Covid-19, there was an exogenous increase in the demand for IPv4 addresses as many firms allowed their employees to work from home. Compared to the pre-pandemic period, I find that the price, number of transfers and volume of addresses transferred in the market increases. Thus the prices in the market seem to be responding to increase in demand in the market.

2.7 Survey of sellers in the market

In this section I present a summary of the results from a survey conducted among five sellers selling IPv4 addresses in the market. These are some of the largest enterprise firms and universities selling in the market. Insights from these conversations inspired modeling choices in chapter 2.

Knowledge about IPv4 blocks for sale

Some of the firms were contacted four-five years ago by brokers (on the phone/conferences such as NANOG) telling them that IPv4 addresses are valuable assets and if they would be interested in selling/leasing their addresses. Often this was the first time firms realized the worth of these addresses.

Firms then reached out to their network team to identify addresses they could start freeing. While some other firms knew the worth of these addresses but decided to sell only due to financial struggles.

Sale of addreses

After a brokerage firm contacted a firm there was a strong push to sell the addresses from the upper management. Firms initially never checked with multiple brokers, just went ahead with one broker. More recent firms identified a good broker and enquired about the process, fees, expected sales price and references of past customers.

The brokerage firms connected the sellers to buyers. Firms chose their brokers based on NDAs, promptness of contracts, higher customer experience, expected sales price and fees. Some of the brokers have put together – automatic online selling patterns – which are helpful for the smaller sizes.

Share of addresses sold

Some of the early firms sold all their addresses (except few small ones) to avoid fragmentation, while more recent firms did only part sales. The IT departments were often confused about many to keep/how much to sell. Rising prices was a minor factor compared to switching costs in deciding the number of addresses to sell.

Proceeds used for

Some firms used the funds for general purposes, while some of the colleges were using it for IPv6 transition, network upgrades etc.

IPv6 transitioning status

While the question of IPv6 transitioning is often brought up, the big sellers were still considering the costs and the number of older equipment they have. It was harder for the larger firms to find motivation given the vast number of IPv4 addresses they have.

Broker fees

Brokers charge a hefty fee ranging from 4%-10%. One firm found a brokerage firm that started from 15% commission and was willing to go down to whatever would work for them.

Benefit of working with a broker

Advantage working with a broker is that they take care of every aspect of the transfer - change in registration, ARIN requirements, ESCROW (a security for the smaller firms) etc. For the smaller firms the initial transfers were difficult and they had to rely on brokers, but subsequent transfers became easier.

Technical knowledge really varied across brokers, ranging from no network knowledge to full-fledged network features (able to advice efficient use of their space, esp for small firms). Brokerage firms had the right connections - to bring a buyer who wants the size they are looking to sell. Brokerage firms have an almost insatiable demand – with lots of customers. These have reduced the market frictions that some of these firms faced in the market initially.

Some of the bigger firms used brokers early on in the market when it was hard to find buyers. Some other bigger firms preferred finding a reputable buyer on their own to prevent misuse of the block for spamming/other illegal activities and avoid paying a commission.

Brokerage competition has gone up extensively. A number of them were very new into the business, "hoping to make a quick buck" and in a number of cases this was not even their main line of business.

Big buyers

The number of big buyers are few and most sellers know the big buyers. They have significant needs (especially when setting up datacenters) for a long period of time and often contract upfront for different sizes to be delivered over time. The sellers then reorganize their address usage and deliver the addresses.

Information about prices in the market

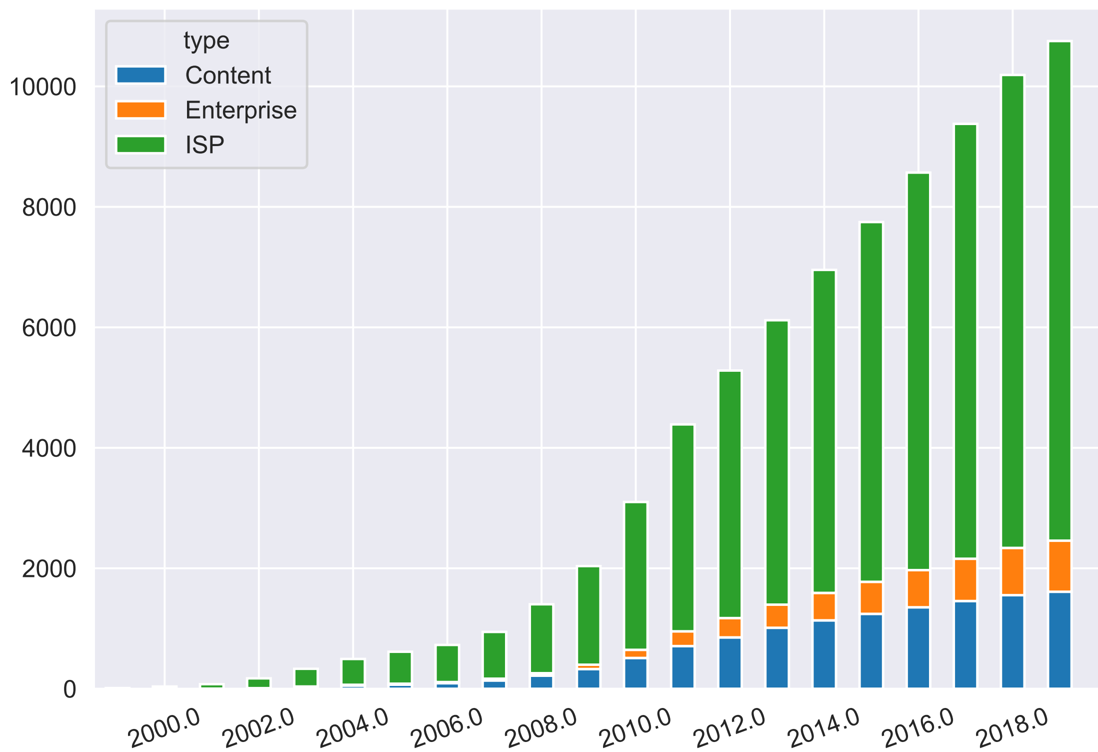
Most firms received information about the range of prices from a brokerage firm and used this as a benchmark even when they were trying to find a buyer on their own. Firms that have been selling multiple times insisted that they sold their addresses to a broker who has brought a higher price than their previous transfer. Firms who didn't use a broker found greater room for negotiation when dealing directly with the buyers.

Beliefs about prices in the market for IPv4 addresses

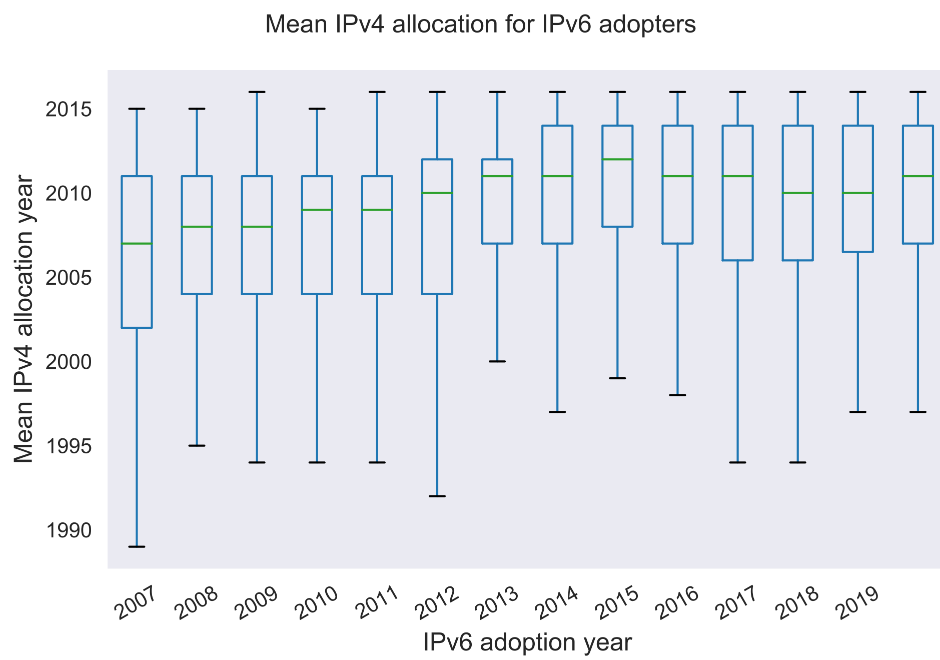
In the initial years firms didn't expect prices to rise. Currently there is a lot of difference in expectation about price. Some brokers say they are going to be in this market for another 10-20 years as there is still strong demand. There are others that say this market will lose interest in 2 years and price is going to drop rapidly. Plus any policy changes on inter-RIR transfers (US government supply) could bring a pool of addresses to the market dropping prices, even to the mid-teen levels. While other believe it would last 4-5 years. Thus the beliefs about the market varies across sellers depending on the beliefs with respect to IPv6 adoption.

2.8 IPv6 adoption

In the figure below I look at the composition of firms adopting IPv6 over time by role. It is clear that the initial adopters are the ISP firms. Content firms start adopting from 2010 followed by enterprise firms in 2011.



In the figure below I look at a boxplot of the average year of IPv4 allocation for firms adopting IPv6 in each year. It is clear that the median year of IPv4 allocation is over 2005, meaning that firms with more recent allocations are the ones that are moving to IPv6. Even in 2021 there are firms that received IPv4 allocations in 1999 receiving their first IPv6 allocation.



$ I look at the number of firms of different types that have been adopting IPv6. I find that datacenters/hosting sites (DCH) followed by ISPs and commerical firms are leading IPv6 adoption.

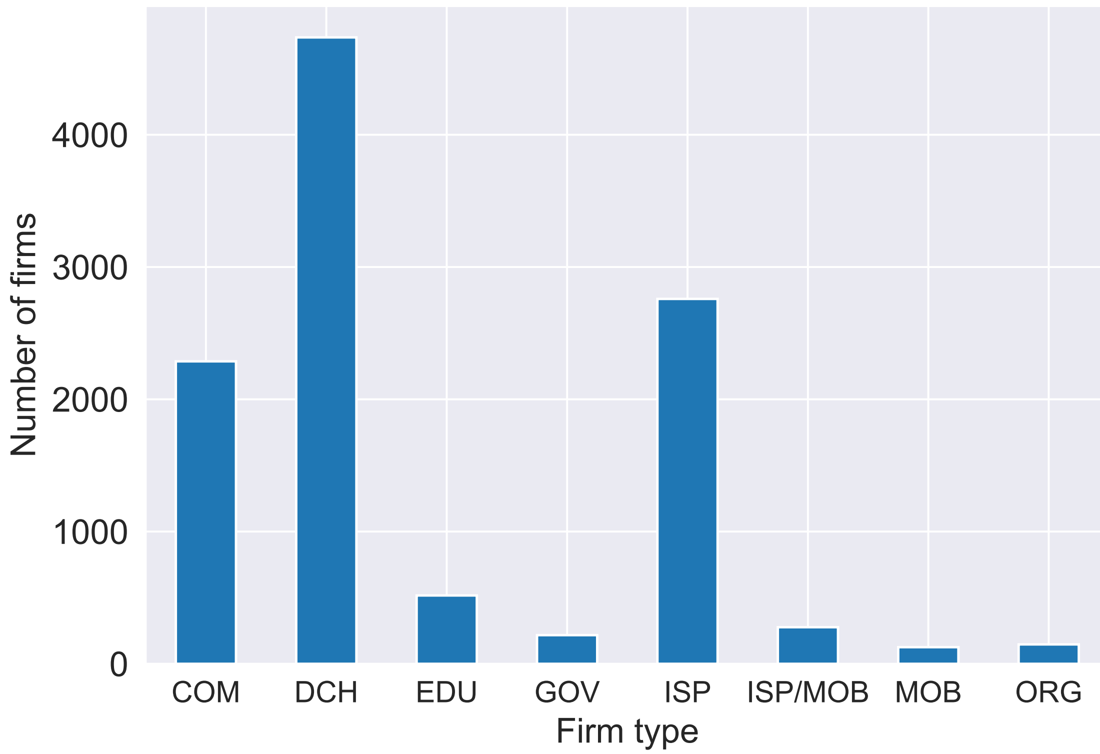
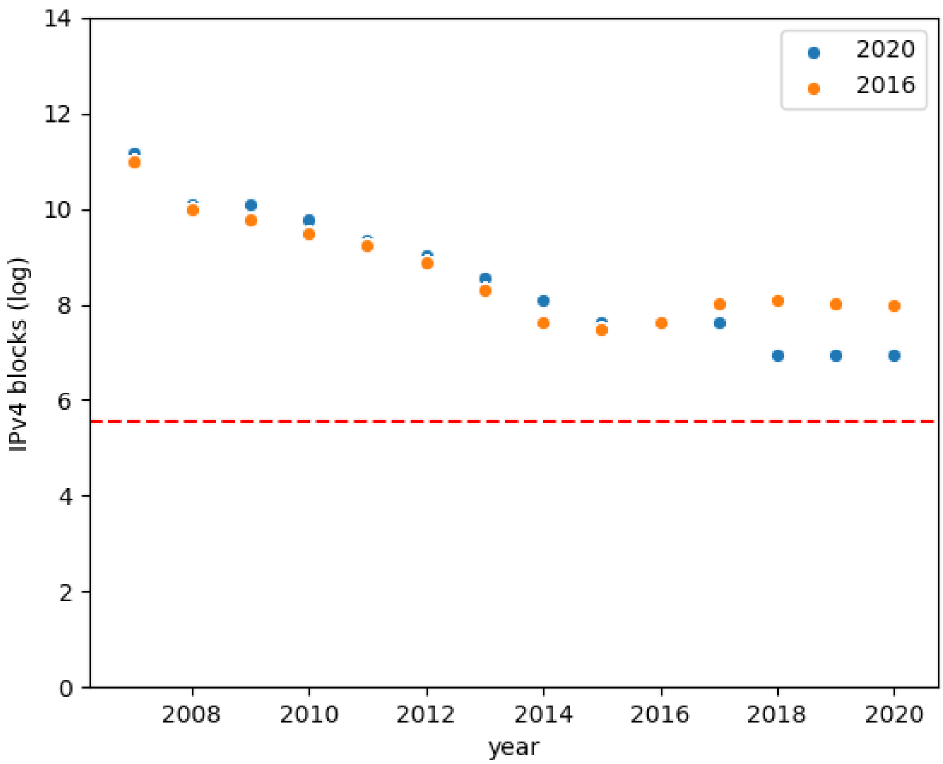


Figure 48: IPv6 adoption by firm role

Notes: This is based on the IP2Location dataset. COM - commerical, ORG - Organization, GOV - Government, EDU - University/College/School, ISP - Fixed Line ISP, MOB - Mobile ISP, DCH - Data Center/Web Hosting/Transit

Early IPv6 adopters still hold IPv4 addresses

In the figure below I compare the IPv4 holdings of firms adopting IPv6 over time in 2016 and 2020. Many of the initial adopters haven't really changed their IPv4 holdings much, whereas firms adopting IPv6 beyond 2015 have reduced their IPv4 holdings much more. Still the present holdings are still belong to the top 25 percentile of holdings in the initial allocation. Thus IPv6 adoption is not a substitute for IPv4 addresses. Firms are rather dual-stacking by holding both IPv4 and IPv6 addresses.



IPv6 adoption by cohort of IPv4 allocation

In the figure below I look at the percentage of IPv6 adoption across firms by their cohort of IPv4 allocation. There seems to an inertia in IPv6 adoption especially among firms that received IP addresses early, especially those firms that received addresses between 1990-1995.

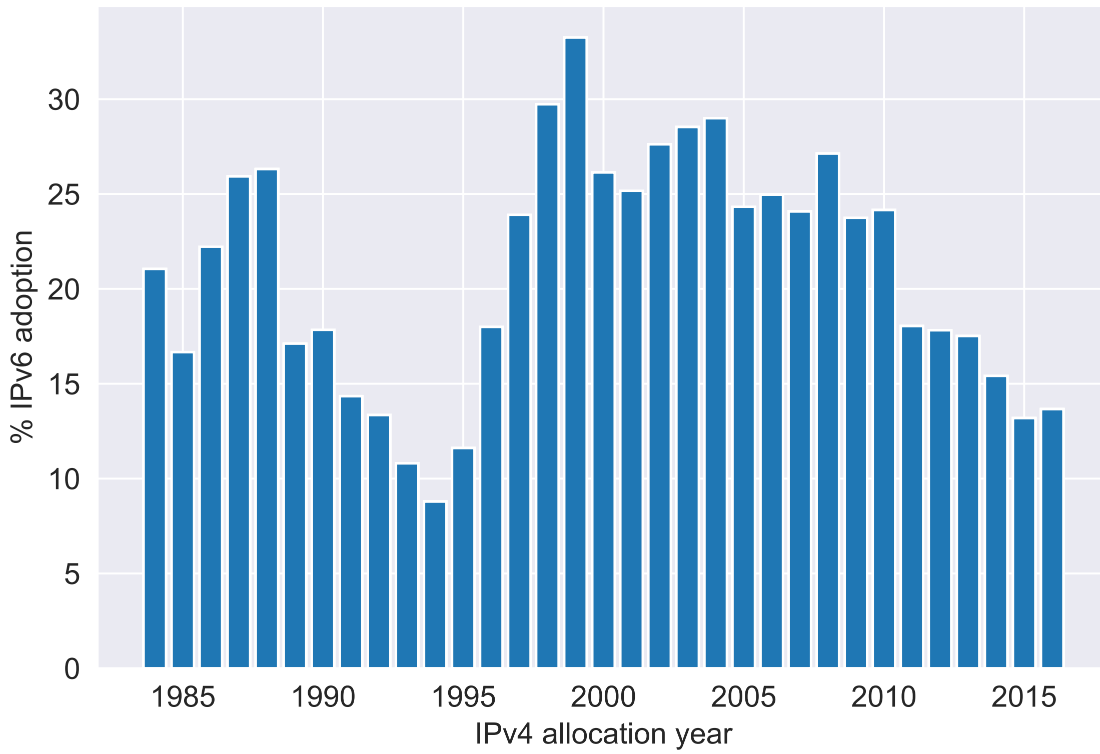


Figure 49: IPv6 adoption by cohort of IPv4 allocation

IPv6 adoption by cohort of IPv4 allocation by firm roles

Next I look at the same graph across different firm roles. I look at the percentage of firms with IPv6 adoption based on their cohort of IPv4 allocation across roles. The x-axis looks at the year of IPv4 allocation and the y-axis looks at the percentage of firms with IPv6 adoption in that cohort.

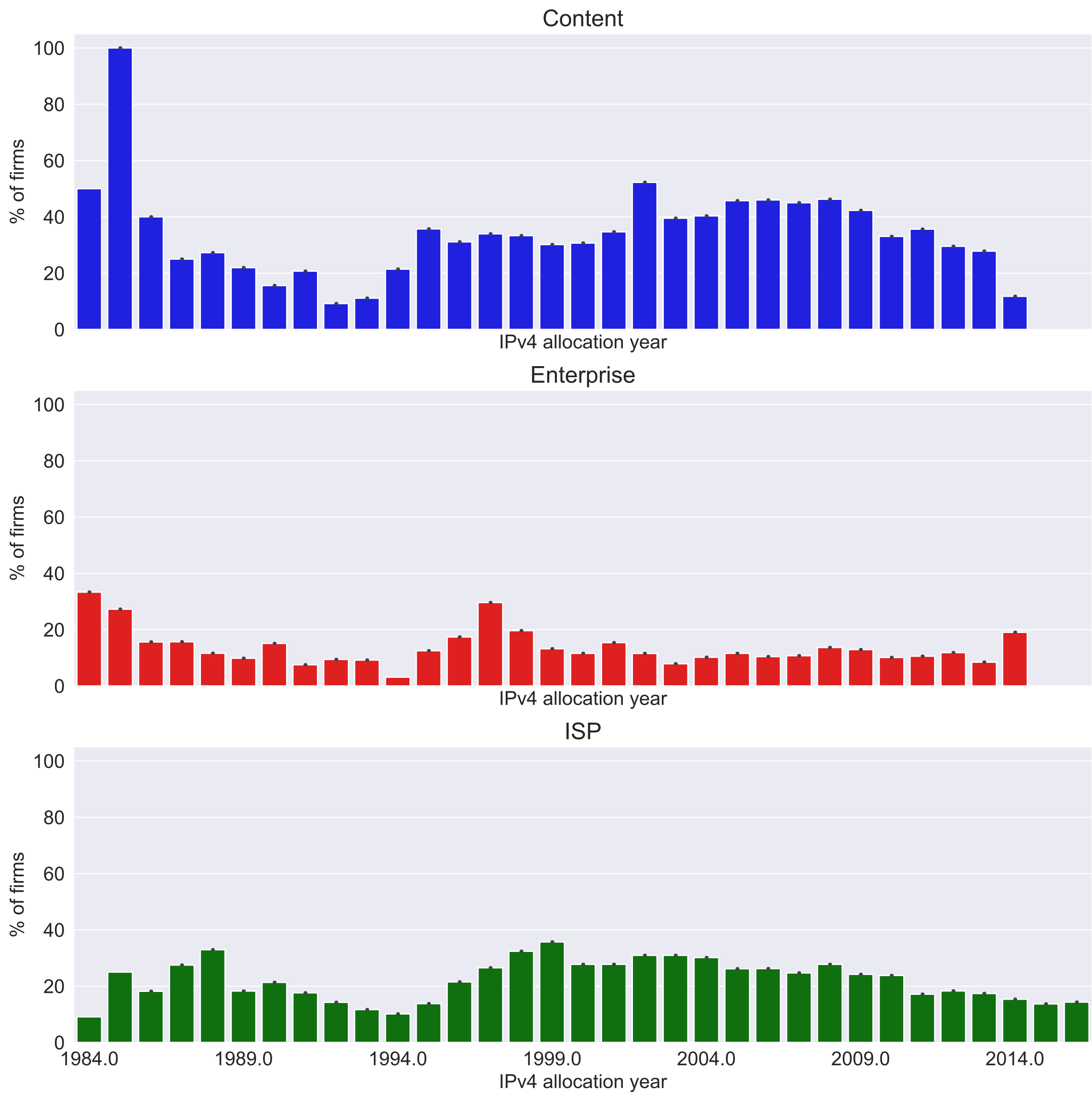


Figure 50: IPv6 adoption by IPv4 allocation cohort by firm roles

Across the three firm roles, early firms have lower IPv6 adoption. There seems to an inertia in IPv6 adoption especially among firms that received IP addresses early. This inertia varies across the three firm roles with lower levels of adoption among enterprise firms.

IPv6 adoption costs depend on current IPv4 holdings

Next, I look at the correlation between IPv4 holdings and IPv6 adoption status of a firm. IPv6 adoption status takes the value 1 if a firm has adopted IPv6 and 0 otherwise. I include the firm role, number of users and cone size in logs and an interaction between firm role and total IPv4 addresses held. I include the interaction term to capture any differences in IPv6 adoption across roles based on their IPv4 holdings. Age refers to the years of holding the IPv4 allocation. I run the following Probit regression:

$$Pr(\text{IPv6 adoption status}_j = 1) = \Phi(\beta_0 + \beta_1\text{Role}_j + \beta_2\text{Role}_j \times \text{ IPv4 addresses}_j$$
$$+\beta_3\text{Users}_j + \beta_4\text{Cone size}_j + \beta_5\text{Age}_j)$$

Table 23: Probit regression of IPv6 adoption

	Dependent variable:
	Adopted IPv6
Enterprise	-0.2^{***} (0.02)
ISP	-0.2^{***} (0.02)
IPv4 addresses	0.04^{***} (0.002)
Users	0.004^{***} (0.000)
Cone size	0.1^{***} (0.001)
Age	-0.004^{***} (0.000)
Enterprise x IPv4 addresses	-0.005^{**} (0.002)
ISP x IPv4 addresses	0.001 (0.002)
(Intercept)	0.1^{***} (0.02)
Observations	107,204
R^2	0.2
Adjusted R^2	0.2
Residual Std. Error	0.4 (df = 107195)
F Statistic	$4,457.2^{***}$ (df = 8; 107195)
Note:	*p<0.1; **p<0.05; ***p<0.01

I find that these variables explain upto 20% of the variation in IPv6 adoption status and most covariates are significant. Age has a negative coefficient, size (users, cone size and IPv4 addresses held) has a positive coefficient and content firms have larger coefficients than ISP or enterprise firms. The positive correlation between size of IPv4 addresses and IPv6 adoption could be capturing the size effect - that larger firms are more likely to adopt IPv6. For an enterprise firm having an additional IPv4 address is associated with a negative correlation of IPv6 adoption, whereas for an ISP firm there is a positive but not significant correlation. This could be indicative of adoption costs that varies across firm roles based on their holdings of IPv4 addresses.

2.9 Algorithm for solving the firm problem

The algorithm for solving the firm problem is as follows:

1. Set T at a sufficiently far time in the future when IPv6 would be the standard that all firms use. I use T=33 years, meaning by 2041 there would be complete IPv6 adoption.

2. In period T, I solve the stationary infinite horizon problem by solving for the optimal IPv6 holdings for each firm based on the first-order condition.

3. Solve for ex-ante value function using backward recursion from T-1 to the intial period t_0.

4. From the initial year, simulate firms forward using policy functions to verify that adoption is 1 at time T.

I assume firms have perfect foresight about price path and state.

2.10 Solving the dynamic general equilibrium

I use a fixed-point shooting algorithm that solves the price path that clears the market each period. The algorithm is as follows:

1. Guess a path of prices $p_t^{(0)}$,$h_t^{(0)}$
2. Solve for firm continuation values
3. Simulate firm states forward using continuation values
4. Find price that clears the market for each period by finding the price (from a grid) that minimizes the aggregate excess demand.
5. Update prices
6. Iterate until converge in price and industry state

With an initial guess for state and price I compute value functions for each state and t via backwards induction, beginning at period T and stepping backwards to period 1, updating continuation values in each step. Using the value functions, I compute choice - specific value functions and optimal policies. Using the computed policy functions and, starting at time t = 1 at h_0 I forward simulate the optimal transition paths and update the state for t = 2,. . . ,T resulting in a new guess of the state. With the new guess I update value functions. This process repeats until value and policy functions converge

3 Bibliography

Bauer, J. M. & Latzer, M. (2016), 'The economics of the internet: an overview', *Handbook on the Economics of the Internet* .

Buchholz, N. (2016), 'Spatial equilibrium, search frictions and efficient regulation in the taxi industry.(2016)', *URL https://scholar. princeton. edu/sites/default/files/nbuchholz/files/taxi_draft. pdf* .

Caoui, E. H. (2019), 'Estimating the costs of standardization: Evidence from the movie industry'.

Dubé, J.-P. H., Hitsch, G. J. & Chintagunta, P. K. (2010), 'Tipping and concentration in markets with indirect network effects', *Marketing Science* **29**(2), 216–249.

Edelman, B. & Schwarz, M. (2015), 'Pricing and efficiency in the market for ip addresses', *American Economic Journal: Microeconomics* **7**(3), 1–23.

Farrell, J. & Saloner, G. (1985), 'Standardization, compatibility, and innovation', *the RAND Journal of Economics* pp. 70–83.

Force, I. T. (2006), 'Technical and economic assessment of internet protocol version 6 (ipv6)', *White Paper, US Department of Commerce, National Institute of Standards and Technology, National Telecommunications and Information Administration* **20**, 21.

Greenstein, S. (2020), 'The basic economics of internet infrastructure', *Journal of Economic Perspectives* **34**(2), 192–214.

Guérin, R. & Hosanagar, K. (2010), 'Fostering ipv6 migration through network quality differentials', *ACM SIGCOMM Computer Communication Review* **40**(3), 17–25.

Humlum, A. (2019), 'Robot adoption and labor market dynamics', *Princeton University* .

Internet Growth Statistics 1995 to 2021 - the Global Village Online (n.d.).
URL: *https://www.internetworldstats.com/emarketing.htm*

Koishigawa, K. (2021), 'Subnet cheat sheet – 24 subnet mask, 30, 26, 27, 29, and other ip address cidr network references'.
URL: *https://www.freecodecamp.org/news/subnet-cheat-sheet-24-subnet-mask-30-26-27-29-and-other-ip-address-cidr-network-references/*

Lee, D. (2005), 'An estimable dynamic general equilibrium model of work, schooling, and occupational choice', *International Economic Review* **46**(1), 1–34.

Lee, D. & Wolpin, K. I. (2006), 'Intersectoral labor mobility and the growth of the service sector', *Econometrica* **74**(1), 1–46.

Max Roser, H. R. & Ortiz-Ospina, E. (2015), 'Internet', *Our World in Data* . https://ourworldindata.org/internet.

Ostrovsky, M. & Schwarz, M. (2005), 'Adoption of standards under uncertainty', *RAND Journal of Economics* pp. 816–832.

Paltridge, S. (2014), 'Unclassified dsti/iccp/cisp (2014) 3/final'.

Population Pyramids of the World from 1950 to 2100 (n.d.).
URL: *https://www.populationpyramid.net/world/2041/*

Qi, S. (2013), 'The impact of advertising regulation on industry: The cigarette advertising ban of 1971', *The RAND Journal of Economics* **44**(2), 215–248.

Richter, P. (2017), 'Empirical analysis of the effects and the mitigation of ipv4 address exhaustion'.

Ryan, S. P. & Tucker, C. (2012), ‘Heterogeneity and the dynamics of technology adoption’, *Quantitative Marketing and Economics* **10**(1), 63–109.

Saeedi, M. (2019), ‘Reputation and adverse selection: theory and evidence from ebay’, *The RAND Journal of Economics* **50**(4), 822–853.

Sen, S., Jin, Y., Guérin, R. & Hosanagar, K. (2010), ‘Modeling the dynamics of network technology adoption and the role of converters’, *IEEE/ACM Transactions on Networking* **18**(6), 1793–1805.

Statista (2021), ‘Number of internet users worldwide from 2005 to 2019’.

Tassey, G. C. (2005), ‘Planning report 05-2: Ipv6 economic impact assessment’.

Weintraub, G. Y., Benkard, C. L., Jeziorski, P. & Van Roy, B. (2010), Nonstationary oblivious equilibrium, Technical report, working paper.

Yoon, C. (2017), ‘Estimating a dynamic spatial equilibrium model to evaluate the welfare implications of regional adjustment processes: The decline of the rust belt’, *International Economic Review* **58**(2), 473–497.