When Wells Run Dry: The 2020 IPv4 Address Market

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ABSTRACT

With the recent IPv4 address exhaustion, many networks can no longer rely on requesting additional IPv4 addresses space. They resort to new ways to obtain addresses: buying and leasing. In this paper, we first shed light on the recent economic trends of the IPv4 buying market by augmenting transfer statistics with public and private pricing information from four large IPv4 brokers. We infer the size of the IPv4 leasing market through two different data sources: routing information observed from BGP collectors and RDAP databases operated by the Regional Internet Registries. We find that neither of those sources alone is capable of estimating the full market size. We relate our findings to discussions with 13 IPv4 brokers and summarize how networks handle their demand for obtaining IPv4 addresses in 2020.

CCS CONCEPTS

• **Networks → Naming and addressing**; **Network management**;

KEYWORDS

IPv4 Address Market, IP Address Distribution, Network management, IPv4 shortage, Address shortage

ACM Reference Format:
Lars Prehn, Franziska Lichtblau, and Anja Feldmann. 2020. When Wells Run Dry: The 2020 IPv4 Address Market. In *The 16th International Conference on emerging Networking EXperiments and Technologies (CoNEXT '20), December 1–4, 2020, Barcelona, Spain.* ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/3386367.3431301

1 INTRODUCTION

As of today, the world has almost run out of unallocated IPv4 addresses to satisfy the ever-growing demand for new addresses [64]. Three RIRs, namely ARIN, LACNIC, and RIPE NCC, have depleted their pool of unallocated IPv4 addresses, and the last two RIRs, APNIC and AFRINIC, currently allocate from their last /10 and /11 address block, respectively. Thus, all have changed their IPv4 allocation policies to shortage management [7, 15, 63, 68]. As part of those policies, all RIRs have reduced the size of the IPv4 blocks a new member can receive (e.g., the RIPE NCC only allocates /24 IPv4 prefixes [81]), and most of them instantiated a waiting list for already approved but not fulfilled requests. Since their pools contain no more unallocated addresses, depleted RIRs have to rely on organizations to return some of their allocated resources; thus, the amount of time a request stays on the waiting list is unpredictable. As a result, networks may need to use alternative ways to acquire IPv4 address space: leasing and buying.

The Internet standardization and governance community already foresaw the exhaustion of IPv4 address space some 20 years ago and introduced IPv6[36]. In the past, networks got a decently sized address block upon becoming an RIR member and could request additional resources as needed. Today, this only holds for IPv6. Despite increasing IPv6 adoption (especially by end-users [31]), many popular services are still not reachable via IPv6 [25]. Thus, many networks—even in 2020—prefer (or may need) new or additional IPv4 addresses over IPv6 addresses [60]. While techniques such as carrier-grade NAT (CGN) [79] reduce the need for public IP addresses, they do not eliminate it.

Motivated by the fact that the RIPE NCC allocated its last IPv4 address block on 25th Nov 2019, we study how networks satisfy their demand for IPv4 addresses in 2020. We highlight the challenges and the costs that IPv4 dependent networks face by analyzing the IPv4 address markets that emerged as a result of the address shortage. We do not only study allocations and address transfers within the RIRs but also the emerged leasing and buying markets for IPv4 address space. Accordingly, the contributions of this paper are:

- For each RIR, we summarize the IPv4 exhaustion status, address allocation policy, and waiting list status in §2.
- To understand the IPv4 address transfer market, we use the RIR transfer statistics as well as pricing data from four large brokers, see §3. We find that prices have doubled since 2016, yet they are significantly lower than expected given predictions from a previous study [56]. Today, the average market price per IPv4 address, regardless of the RIR, lies around \$22.50 with little variance.
- To get a glimpse of the IPv4 leasing market, we revisit the concept of address space delegation using publicly available BGP data as well as data from RIPE's RDAP database. We observe that, for the RIPE region, the amount of delegated IPv4 address space visible in BGP heavily underestimates the actual market size. We further find that current leasing prices vary significantly—\$0.3 to \$2.4 per address per month—based on the leasing provider, see §4.

We outline how our work extends existing literature in §5 and discuss the interplay of our findings combined with insights from discussions with 13 IP brokers in §6. We, finally, point out that due to the huge range of leasing prices the amortization time for buying IPv4 address space can range from less than a year to 36 years.

2 GETTING IP RESOURCES

To actively participate in the Internet's BGP routing ecosystem, organizations need IP resources. Initially, Jon Postel manually assigned IP resources. This process was formalized later in the 1990s, see RFC 7020 [38]. The Internet Assigned Numbers Authority (IANA)

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CoNEXT '20, December 1–4, 2020, Barcelona, Spain

ACM ISBN 978-1-4503-7948-9/20/12.
https://doi.org/10.1145/3386367.3431301

RIR	Down to last /8	Start of Recovery
AFRINIC	03/31/2017 [1]	— (last /11, 01/13/2020 [4])
APNIC	04/15/2011 [6]	07/27/2014 [8] (still /10 available)
ARIN	04/23/2014 [69]	09/24/2015 [24]
LACNIC	02/15/2017 [53]	08/19/2020 [50]
RIPE NCC	09/14/2012[89]	11/25/2019 [81]

Table 1: IPv4 exhaustion timeline for the five RIRs.

manages hierarchical allocations of IP addresses and AS numbers to the five Regional Internet Registries (RIRs). Those RIRs, namely AFRINIC (African region), APNIC (Asia Pacific region), ARIN (American region), LACNIC (Latin American region), and the RIPE NCC (European and Middle Eastern region), are responsible for address assignment, bookkeeping, and community support. Some of the IPs that Jon Postel assigned are still not managed by the RIR framework and, hence, are called "legacy" addresses. There are three options to obtain new IPv4 resources: *(i)* joining an RIR as a member and requesting new address space; *ii)* joining an RIR and buying address space; and *iii)* leasing address space.

RIR membership. RIRs are membership-based organizations: If an organization receives address space from an RIR, it typically becomes a member of that RIR—a Local Internet Registry (LIR). Membership status is not necessarily bound to address space allocation but rather implies participating in the Internet governance effort. RIRs develop their operational policies through engaging discussions among their members. LIRs can (e.g., by voting for board members or (dis)approving financial decisions) influence the policies of their RIR. To become and stay an LIR, an organization has to pay an annual membership fee plus fees depending on the number of requested resources. Yet all five RIRs differ in their exact pricing model. [3, 10, 12, 52, 86]. In October 2020 the RIPE NCC handled a first time incident where the "Right to Registration of IPv4 Addresses" was auctioned to recover money in a legal case [65]. case.

Towards IPv4 exhaustion. All RIRs maintain IPv4 and IPv6 address pools. They receive addresses from IANA, other RIRs, or organizations that no longer need their allocated IPs. The IPv4 address pools decreased drastically over time. Since IANA allocated its last remaining IPv4 address blocks to APNIC on 31st January 2011, the RIR pools can no longer receive reserved IPv4 addresses. As a result, the RIRs soon reached their last /8 (see Table 1). To distribute the remaining resources fairly, all RIRs soon established more restrictive assignment policies—this phase is also known as "soft-landing".

IPv4 exhaustion. ARIN, LACNIC, and the RIPE NCC completely depleted their address pools in 2015, 2020, and 2019, respectively. Now, those RIRs have to recover unused IPv4 address space before they can fulfill any requests. APNIC and AFRINIC combined still have less then the equivalent of a /9 of IPv4 addresses left. Currently all RIRs recover IP address space if an organization closes down or the original criteria for the initial assignment are no longer satisfied [71]. APNIC actively contacts members who have received delegations that are not at least partially visible in the global routing system [68]. Upon recovering IP address space and removing the associated objects from the database most RIRs put the blocks into a six month quarantine period before redistributing it again [62]. As a result, assignment policies became more restrictive, and most RIRs introduced waiting lists.

Today, AFRINIC [4], ARIN [13], and LACNIC [49] limit the assignable address space per organization to a /22. For APNIC [10] it is a /23 and for RIPE [81] a /24. That does not mean that the RIRs force organizations to return address space if they previously received a larger address block. To highlight the impact of IPv4 address exhaustion, we point out that the waiting lists of ARIN, LACNIC, and RIPE held up to 202, 275, and 110 approved requests, respectively [19, 54]. For Arin, this corresponds to waiting times of up to 130 days.

Since November 2019 RIPE used recovered address space to fulfill all approved waiting list requests [64, 84]. Currently, its address pool still contains around 340k IPv4 addresses (equivalent to more than a /13) [82]. In contrast, APNIC abolished its waiting list on 2nd July 2019 [9] since it only included requests from members whose already allocated address space exceeded a /22. Since then, APNIC only hands out IPv4 addresses to new members.

Buying IPv4 addresses. Since neither the limited size of approvable IPv4 address space nor the required waiting time satisfies their needs, many LIRs started to buy additional IPv4 address space. Formally, LIRs do not buy IP addresses per se—there is no clear notion of legal IP ownership [90]—but rather acquire their usage rights. In October 2020 the RIPE NCC had a first time incident where the "Right to Registration of IPv4 Addresses During a transaction, a buying LIR pays the selling LIR such that the latter invokes a resource transfer of the address space to the buyer. This resource transfer may involve additional payments to the RIR. After the transfer, the buying LIR is responsible for the RIR's annual resource maintenance costs. Certificated IPv4 brokers help to facilitate this process [16, 17, 85]. They connect buying and selling LIRs, help them in price negotiation, and often handle the formalities of the address transfers. Based on discussions with 13 brokers, their commissions range from ~5 % to ~10 % and may be charged to either LIR or partially by both of them.

Leasing IPv4 addresses. While Internet Service Providers (ISPs) lease address space to their customers for a long time, there is a recent increase in the number of organizations that lease their address to any organization independently of routing or connectivity agreements. Leasing providers are LIRs that temporarily delegate the usage rights for some of their address space to a customer. While leasing does not involve any resource transfers at the RIR, it may encompass altering objects in the WHOIS database—a database that contains information about Internet resources, organizations, and contact persons. A leasing contract can restrict address usage and may include hosting or network connectivity agreements, or both. For hosters, the leased address space is usually still located in their own AS. In this paper we are considering two types of IP leasing models. In the first model an IP broker only leases IP address space to a customer, while in the second the IP leasing is bundled with antoher service contract, e.g., infrastructure hosting.

Not all IP addresses are equal. Over the years, IP based blacklists have become very popular to mitigate malicious activities, e.g., E-Mail spam or flooding attacks [93]. These blacklists contain IP address blocks that are associated with said activities, and network operators rely on them to filter ingress traffic. Once an IP address block appears on a blacklist, it can be hard to remove it again—the IP address is tainted. IP address blocks that never appeared on a blacklist and have no association with any malicious activity are

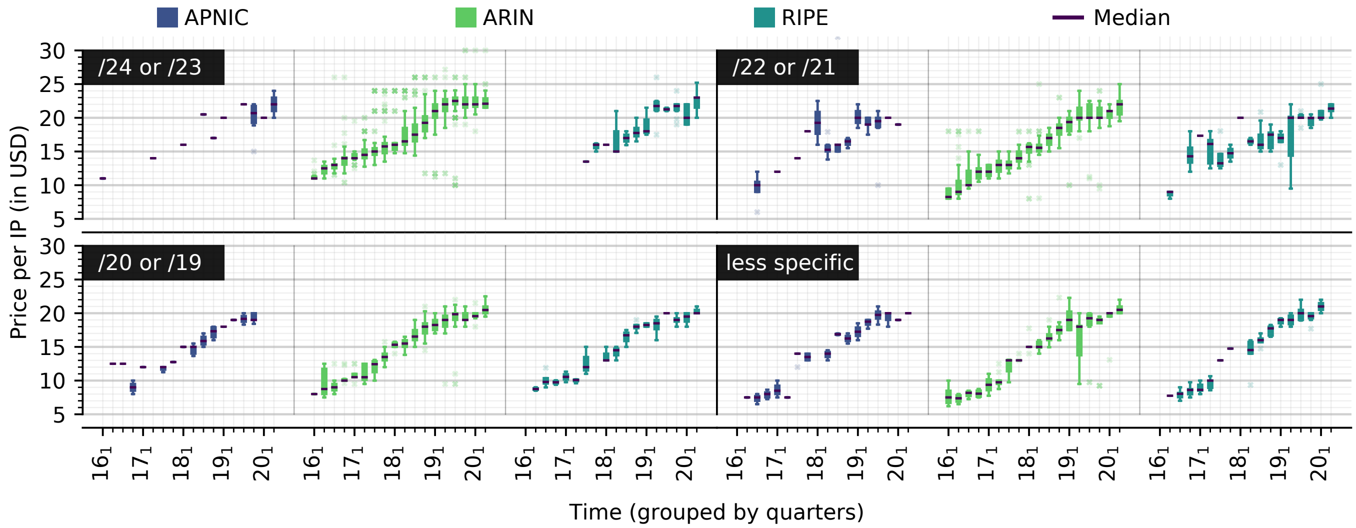

Figure 1: Evolution of Price per IP based on prefix size and region.

known as "clean IPs." To keep their address blocks clean, leasing providers often demand information on how a potential customer intends to use the leased resources. Besides, leasing providers often install registry data—e.g., Shared WHOIS Project records (also known as SWIP records [18])—to secure their remaining address space from getting blacklisted when spamming is detected in a delegated block [94]. Similarly, most LIRs check the "reputation" of address blocks before buying them to ensure the addresses are globally reachable.

3 IPV4 ADDRESS RESELLER MARKET

When the RIPE NCC entered the "Recovery Only"-phase, many organizations expected an increase in brokered IPv4 transfers as well as address prices. Therefore, we first analyze the number of transfers. Next, we augment our findings with public and private pricing information from four IPv4 address brokers. Finally, we discuss the ability to obtain address space from foreign RIRs.

Each RIR publishes daily transfer statistics. Those not only include transfers between LIRs but also include transfers that are results of mergers or acquisitions of companies (M&A) that consolidate their IPv4 address space. While AFRINIC [2], ARIN [14], and RIPE NCC [83] label such transfers APNIC [11] and LACNIC [51] do not. Thus, we can remove M&A transfers for the former RIRs. For the latter RIRs, we could potentially use the heuristics proposed by Giotsas et al. [30]. However, since the authors do neither present an evaluation nor an analysis of the output's sensibility to the input parameters, we decided against this option.

Figure 2 shows the number of transfers aggregated over three months for each region from October 2009 to June 2020. Observe that the regional transfer markets[1] start, i.e., for APNIC, ARIN, and the RIPE NCC, once the RIR was down to its last /8 (compare to Table 1). ACNIC has recently depleted, the number of transfers in those regions is negligible. This can be attributed to two factors: (i) cloud providers consume a huge amount of IP space [97], yet most of their data centers are located in the ARIN, APNIC, and RIPE NCC regions [61]; (ii) mobile rather than fixed-line broadband access is the norm in the AFRINIC and LACNIC regions—mobile operators often rely on IPv6 [91] and deploy carrier-grade NAT for IPv4 more aggressively [79]. We further observe that the number of monthly transfers fluctuates significantly. While for the RIPE NCC the pattern aligns with the end of each year, we cannot identify any specific patterns for ARIN. This indicates that the IPv4 transfer markets are in flux.

To understand the cost of buying IPv4 addresses, we use publicly available pricing information from IPv4.Global [46] as well as private pricing information obtained from Brander Group [32], IPTrading.com [44], and IPv4 Market Group [33]. All data is anonymized: Rather than containing the IPv4 prefix and the participating organizations, we track the number of IP addresses transferred per region. Since prefixes less-specific than a /16 are rarely transferred, they are identifiable; therefore, our data set only contains transactions for /16 or more-specific prefixes. In total, we obtained pricing information for 2.9k transactions between 1st January 2016 and 25th June 2020. Since our data set only contains 31 transfers for those regions, and they do not yet have vibrant transfer markets, we exclude AFRINIC and LACNIC from our analysis.

Figure 1 shows the pricing information as box plots grouped by prefix size, region, and three months interval. Across all prefix sizes, our data contains 8-23, 83-196, and 12-19 transactions APNIC, ARIN, and RIPE per interval, respectively. We first observe that there is no statistical difference in pricing across the regions, i.e., whether a prefix is allocated to the APNIC, ARIN, or RIPE NCC region has no significant impact on its price. In contrast, buying IP addresses in /24 or /23 blocks is more expensive than buying larger address blocks; when a broker decides to sell a large address block in separate small parts, the associated secondary costs increase. The broker not only needs to find more buying parties but also

[1] Here, "region" refers to the region associated with the RIR that allocated (and maintains) the IPv4 address block. ICANN established this relationship when initially handing our addresses to an RIR. If an RIR transfers address space to another RIR, the region is updated accordingly. Therefore, every region-based analysis refers to the RIR that an IP address block belongs to.

needs to initiate more separate transfers. As our analysis does not cover prefixes less specific than /16, we can only report on them based on information from IPv4 brokers: Since large continuous blocks are rare, the price per IP rises again. Overall, we observe that prices, regardless of the actual prefix size or region, have doubled since 2016, which correlates with the diminishing availability of unallocated address blocks from the RIRs.

Starting from Spring 2019, the IPv4 market seems to have entered a *consolidation phase*, i.e., a state in which the market price barely changes and where the number of transfers no longer corresponds to the actual demand [41]. We observe the first, see Figure 1, and learned about the latter via discussions with the brokers. During a consolidation phase, sellers hold back many of their assets as they wait for the largest sellers to dictate new pricing trends. When discussing our findings with thirteen additional brokers, they argued that the disclosure of market prices by IPv4.global provided a reference point for the average cost of an IP address that is also available to potential buyers. Thus, increasing prices beyond this reference point lead to a decrease in potential customers. As a result, most brokers told us that they strictly align their prices with those advertised by IPv4.Global.

An organization can also get IP address space from a foreign RIR and then request a transfer of the addresses to the RIR associated with its actual region. While such action must adhere to the policies of all involved RIRs, some policy regulations are easy to satisfy. For example, ARIN's current policy practice for out-of-region requestors is [23]: A requestor is eligible for receiving an allocation if it announces the least-specific prefix in ARIN's service region. Thus, organizations with a single PoP in ARIN's service region (even if it only consists of a single router) are eligible to receive addresses. However, inter-RIR-transfers can only take place between APNIC, ARIN, and the RIPE NCC since these RIRs agreed on common transfer policies [80]. Figure 3 shows the number of inter-RIR transfers by origin and destination for each RIR from 2012 to 2020. While the number of inter-RIR transfers continuously increases, the blocks transferred get smaller. Most transfers move address space away from ARIN and either to APNIC or RIPE. The latter may, in part, be explained by ARIN's assignment policy and different feature sets of the RIR management interfaces.

4 THE IPV4 ADDRESS LEASING MARKET

Buying IP addresses does not only require a significant upfront investment but also introduces delay (i.e., for the address transfer). Leased address space is often available in less than a day [43] and only requires monthly payments. Thus, IP leasing is an attractive option for businesses with immediate needs, small budget, or limited long-term perspective. To understand to which extend the leasing option is currently used, we analyze two sources of data: *(i)* we *infer* leasing agreements from routing information by revisiting the concept of BGP delegations; *(ii)* we use a snapshot of RIPE's WHOIS database and queries to its RDAP database to track address block delegations.

Inferring BGP delegations. Leasing IP address space is only economically useful if the organization also announces the prefix within the BGP eco-system. Therefore, most leased address space should be visible as delegated address space whereby the leasing provider may still announce a less-specific prefix. We say that a *delegator* AS S owns a prefix P and delegates a more-specific sub-prefix P' to a *delegatee* AS T. We infer a delegation P'_{ST} if we observe that S and T originate P and P', respectively. To infer such delegations, we build upon the work of Krenc and Feldmann [48] (our extensions are marked with +): *(i)* We obtain the set of all prefix-origin pairs. *(ii)*$^+$ We remove all pairs seen by less than half of all BGP monitors to ensure global visibility[2]—this limits the impact of, e.g., local misconfigurations or locally-spread BGP hijacks. *(iii)* We remove pairs for which the respective prefix is originated by an AS_SET or multiple ASes. *(iv)*$^+$ Relying on CAIDAs AS-to-Organization mapping [20], we remove delegations between ASes of the same organization within the next available snapshot[3]. *(v)*$^+$ We compensate for temporarily not announced delegations—many delegations show on-off-patterns—based on insights from analyzing delegation consistency in RPKI: If we observe the same delegation ten days apart while not observing a conflicting delegation (i.e., we observe P being delegated to another delegatee AS T') in the meantime, we presume that the delegation also exists for all days in between. We chose this rule as its fail-rate (i.e., the fraction of possibilities with an invalid conclusion based on all possibilities with a valid premise.) is below 5 % for delegations inferred from RPKI snapshots between 01/01/2018 and 06/01/2020, see Appendix A.

Limitations. Despite taking precautions against hijacks, our algorithm may still infer a delegation between a victim AS and a hijacking AS if the hijack is performed using a more-specific prefix. Our algorithm may wrongly infer delegations in combination with BGP-based scrubbing services (i.e., services that announce their customer's prefixes, analyze and drop incoming malicious traffic, and tunnel the remaining "clean" traffic back to their customer).

BGP-delegations. We apply our inference algorithm to the routing information collected by RIPE RIS [88], Route Views [70], and Isolario [40] between 1st January 2018 and 1st June 2020. We aggregated the data daily; i.e., we use the RIP snapshot at 0:00 UTC+0 and all update files for that day. If an update file is missing, we additionally download the first available rib snapshot afterward. To sanitize our data, we remove all routes for private and reserved address space [95], routes that contain ASes currently reserved by IANA [39], and routes that contain a loop in their AS-PATH. We find that our extensions significantly reduce the number of inferred delegations but eliminate the large variance produces by the previous approach, see Figure 6. Overall, we see an increase in delegations by ~7 % with a negligible change in delegated IPs caused by decreasing delegation sizes.

RDAP-delegations. Some RIR's maintain publicly accessible Registration Data Access Protocol (RDAP) [67] interfaces designed to eventually replace the WHOIS protocol. Like WHOIS, this database contains registration information but is more extensive. If an LIR assigns address space to an "end-host"[4], the `parentHandle` field contains an RIR-unique identifier for the parent network—this can be used to infer delegations. Since RDAP interfaces do not allow

[2] As long as the monitor threshold is chosen between 10% and 90% the difference in inferred delegations is negligible.

[3] Internet resources such as address space or AS numbers are assigned to organizations; thus, ASes that belong to the same organization can utilize each other's address space without an actual leasing agreement.

[4] Here, end-hosts are networks that cannot further assign the addresses to other LIRs or end-hosts.

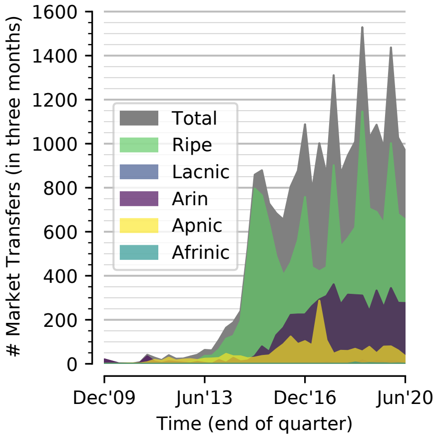

Figure 2: # of market transfers.

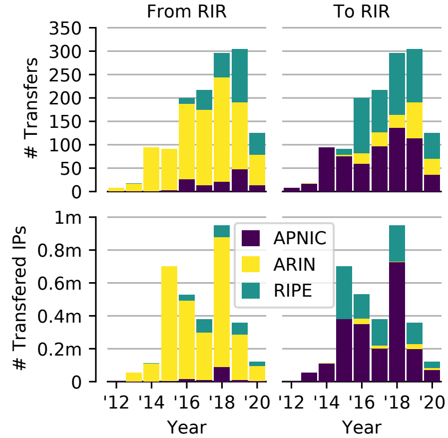

Figure 3: Inter-RIR transactions.

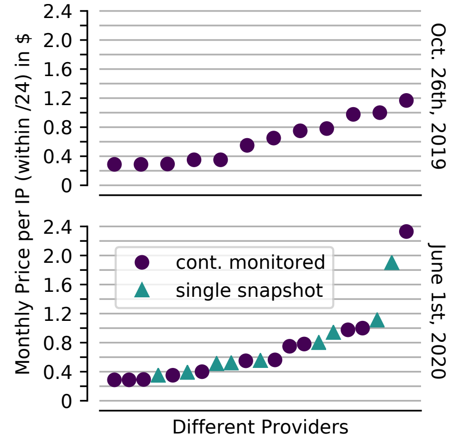

Figure 4: Advertised leasing prices.

wild-card or range requests, we rely on `inetnum` objects from a current WHOIS snapshot [87] as input space to our RDAP queries. While the RIPE NCC and ARIN provide the `parentHandle` field in their RDAP responses, only RIPE NCC also offers publicly available WHOIS snapshots. Thus, we restrict this analysis to the RIPE region[5]. First, we select all `inetnum` objects from RIPE's WHOIS database with delegation-related types: The `SUB-ALLOCATED PA` type refers to address space sub-allocated to another organization, and the `ASSIGNED PA` type refers to address space assigned from an LIR to an end-host. We find ~4.5k entries and ~3.96M entries for June 2020, respectively. Notably, most, 91.4%, of the `ASSIGNED PA` entries are for address blocks smaller than /24. To minimize the load on RIPE's RDAP interface, we ignore all blocks smaller than /24. We further remove intra-organization delegations, i.e., where the child block has the same registrant or administrator as the parent block. Aftward, we have 181k remaining RDAP-based delegations.

BGP-delegations vs. RDAP-delegations. When comparing the delegations identified via BGP on June 2020 with those from RDAP delegations we observe that: BGP-delegations cover only ~1.85 % of the RDAP-delegated IPs while the RDAP-delegations cover ~65.7 % of the BGP-delegated IPs in the RIPE region (using [83]). This limited coverage of BGP-delegations implies that the leasing market is significantly larger than previous work has predicted [48].

The limited coverage of BGP-delegations may be due to: *(i)* the assumption that the delegated prefix *and* the covering prefix are announced within the BGP eco-system; *(ii)* even if the delegatee announces it, the more-specific prefix may be aggregated and is no longer globally visible; and *(iii)* large LIRs often delegate medium-sized address blocks to ISPs. These ISPs use some of the address space but reserve significant chunks for future customers. The latter is invisible in BGP. While organizations have incentives to enter their leasing agreements into the WHOIS and RDAP databases (e.g., to reduce the blacklisting risk due to malicious activity in a leased prefix [94]), not all leasing provider require entries. Hence, RDAP-delegations will also miss some leasing agreements.

[5] Snapshots from other RIRs may depend upon signing access agreements.

RDAP-delegations are complementary to BGP-delegations—the former captures the administrative processes, the latter the actual usage. Neither can catch all leasing agreements. Thus, combining both data types is essential to estimate the size of the IPv4 leasing market.

Leasing prices. To understand the leasing price evolution, we fetched the advertised leasing prices from 12 websites [27, 29, 34, 37, 42, 43, 45, 47, 58, 59, 66, 74] between 26th October 2019 and 1st June 2020. On the 1st June 2020, we added 9 additional websites [5, 21, 26, 35, 55, 73, 75, 76, 92].

Even though some websites offer up to 10% discounts when either leasing larger prefix sizes or committing to multi-month contracts, we consider the prices for leasing a /24 for a single month. The advertised leasing prices are shown in Figure 4. In general, we observe that prices vary substantially: from \$0.30 to \$2.33 per IP per month. We also find no structural price difference between pure leasing providers compared to IP leasing bundled with infrastructure hosting. This indicates that the market has not converged yet. Still, only three providers changed their advertised leasing prices: Heficed reduced its monthly per IP price from \$0.65 to \$0.40; IPv4Mall [47] increased it from \$0.35 to \$0.56; and IP-AS [42] from \$1.17 to \$2.33. IP-AS also seems to have tested the market in January by increasing the price to \$3.90—a factor of >10 more than the lowest available price.

5 RELATED WORK

The IP address trading market is not yet widely discussed in the research world, as practical relevance became only apparent with the global IPv4 depletion. Livadariu et al. [56], in 2017, characterized the evolution of RIR allocations and transfers. Using the few publicly disclosed transactions, they proposed a model to predict the value of the IPv4 address market. Their estimated price of \$30 per IP for the end of 2015 exceeds the actual price at that time by about 200 %. In contrast to their claims, we also find no statistically significant difference in the prices of different regions. In 2015, Richter et al. [78] provided a detailed, historical perspective on changes and policies that preceded the current IPv4 exhaustion and pointed out possible solutions, e.g., Internet-wide adoption of IPv6, carrier-grade NAT, and efficient use of address space (reassign unrouted address space). In 2015, Edelman and Schwarz [28] proposed a market regulation rule to avoid excessive trading and provided an estimation model for IP leasing and buying prices. However, their model lacks validation based on real-world data and shows opposing trends to the market price evolution we observe. While Van Audenhove et al. [98] showed that permitting active transfers of IPv4 resources between entities of the same RIR leads to a "thriving" transfer market in 2013. Livadariu et al. [57] reported that most transfers until 2013 occur between a small set of countries. In 2011, Osterweil et al. [72] discussed the implications of possible regulations for IPv4 transfers. They argued for using additional reverse DNS records to validate IP ownership. Giotsas et al. [30] reported inconsistencies between RIR transfer data and information inferred from BGP data sets. They also point out that frequently transferred blocks are more likely to be involved in malicious activity.

6 DISCUSSION

In the first half of 2020, the IPv4 address market showed a stable price range. When, in contrast, considering current leasing, buying, and maintenance prices, we observe that possible amortization times for buying IPv4 addresses are somewhere between 10 months and multiple tens of years. Through our discussions with brokers, we learned that the average amortization time for their customers is between two to three years. Given the current state of the buying market, IPv4 address holders need to be careful *when* to sell their assets: An early sell may not reach the maximum economical gain (if prices increase) while waiting for too long may result in an economical loss (if prices fall). On the other end, the demand for IPv4 addresses currently outweighs its supply. As a result, potential customers are currently willing to pay higher prices.

How an organization engages with the leasing and transfer markets is often strongly correlated to its business model: Internet Service Providers (ISPs) often buy blocks larger than /20 with the intent of leasing parts of them to (potential) customers; on the other end, long-term customers buy address space smaller than /20 to fulfill their addressing needs and terminate their address leasing contracts with, e.g., an ISP. Young businesses often start by leasing small address blocks and then increase their leased address space until they have secured enough funding to buy address space. In contrast, many VPN providers continuously lease address space but frequently "rotate" the actual IPs such that it is harder to block their service. Finally, spammers often use short-lived leasing agreements of varying sizes while ensuring that their own address space remains clean when they engage in malicious activities. Another strategy we have encountered in discussions with brokers is *buy and lease back*: In this model organizations owning more IPv4 address space than they currently utilize (e.g., ISP) sell this address space to a broker and, in return, only lease the amount they need with previously agreed terms should they ever need additional space. Such a contract can provide the selling organization with immediate cash flow while ensuring a continuous supply of addresses.

There are still allocated but unused IPv4 addresses even though the RIRs have moved to shortage management. The active policies require the return of unused addresses [63, 68], but the current market situation provides little incentive to release acquired resources. As such, the number of available IPv4 addresses will soon hit rock-bottom, a point at which the world-wide deployment of IPv6 becomes inevitable for future services. With advancements in IPv6 deployments, the focus may shift away from IPv4 addresses. Thus, one might argue that the question is no longer if IPv4 address prices will drop, but *when*. On the other hand, brokers also told us that they expect a huge price increase because many players prefer to engage in the "known" costs of acquiring IPv4 address space rather than moving their networks forward to IPv6.

7 CONCLUSION

In this work, we present the current state of the IPv4 address market and provide a base for further scientific analysis as well as a starting point for organizations to assess their options for offering and obtaining IPv4 addresses. The current state of IPv4 address exhaustion is: APNIC and AFRINIC still have a small amount of address space available, RIPE NCC was recently able to fulfill the approved requests in its waiting list using recovered addresses, ARIN's waiting list has waiting times up to 130+ days, and LACNIC's waiting list currently holds 275 approved but not fulfilled requests. As a result, networks that are still relying on IPv4 lead to vibrant leasing and buying markets.

Although prices for IPv4 addresses doubled since 2016, previous work [57] significantly over-estimated the price development—especially for small address blocks. While the prices per IP decrease with address block sizes (except for large blocks), we find no statistically significant difference between regions. We observe that the buying market has been volatile since 2016 but went into a consolidation phase at the beginning of 2019. Even though individual price changes by the "big players" may dictate future pricing trends, directly buying IPv4 address space—at an average cost of $22.50 per IPv4 address for a /24—is currently an economically viable option. When focusing on the IPv4 leasing market, we find that, through the lens of BGP, the amount of leased IPv4 addresses increased by 7% over the last two years. Current leasing prices range from $0.30 to $2.33 per IP per month (for a /24). This huge range (even though the service levels may differ) indicates that the market has not converged on a price tag.

We showed that state-of-the-art delegation inferences are noisy and only reveal a small fraction of the actual delegations. We highlight that delegations in the RPKI system provide a rather different perspective on the consistency of delegations. We argue that future research efforts should combine routing information, RPKI data, as well as the RDAP databases to obtain a better picture of the leasing ecosystem and its characteristics.

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A APPENDIX

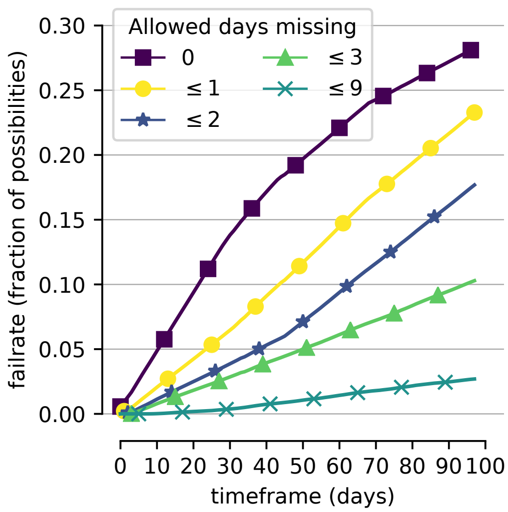

Figure 5: Validation of different consistency rule values on RPKI delegations.

Delegations and RPKI. In order to observe delegations in BGP data the delegated address space needs to be announced. Since the deployment of route origin validation has increased significantly [22, 77, 96], the Resource Public Key Infrastructure (RPKI) database has become a valuable source to infer delegations. Rather than taking the announcements of P and P', we now check whether those prefixes have Route Origin Authorizations (ROAs) assigned to different ASes. When inferring delegations based on the preprocessed RPKI snapshots by [22], we observe an order of magnitude less delegations compared to BGP. Yet RPKI-based delegations provide a different view on delegation consistency: If S has a ROA assigned for P and delegates P' to T, than T *continuously* needs to have a ROA for P throughout the entire delegation period, otherwise many ASes would filter and not propagate the delegated prefix P'.

We utilize this characteristic of RPKI-based delegations to evaluate the correctness of different consistency rules; based on our evaluation, we then pick one rule to compensate for the on-off-patterns observed for BGP delegations. In general, we analyze rules of the form: "If we observe a delegation on day X and on day $X + M$, the delegation also exists for all but N days in between." In Figure 5, we present the fail rate (i.e. the fraction of possibilities for which a rules' premise is valid but its conclusion is violated) for rules with different values for N on the y-axis against an increasing values of M (i.e., increasing time frame) on the x-axis. First, we observe that ~90 % of delegations that are seen at least 90 days apart are visible for the entire time frame except for at most 3 days. We also observe that the fail rate never reaches 30 % even when picking extremely large time frames of 100 days. Finally, we observe that even when N is 0 (i.e., the delegation must be visible for *all* days within the time frame) the rule is only violated for ~5 % of all possibilities when choosing a time frame of ten days; therefore, we decided to apply the following consistency rule to all BGP delegations: When we observe the same delegation ten days apart and we do not observe a conflicting delegation (i.e. we observe P being delegated to another delegatee AS T') in the meantime, the delegation also exists for all days in between.

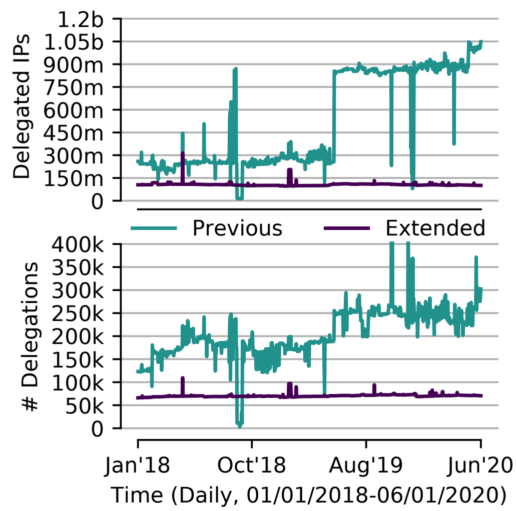

Figure 6: Number of BGP delegations and delegated addresses w/wo our extensions.

Delegations. Figure 6 shows the number of delegations as well as the amount of delegated address space inferred by the previously proposed algorithm [48] as well as our extended algorithm over time. While we observe that our extensions significantly reduced the number of delegations inferred for each day, we also see that it almost completely eliminated the high variance that can be observed when using the previously proposed inference algorithm. While the previous approach suggests a significant increase in both, the number of delegations as well as the number of delegated addresses, our extended algorithm only yields an increase of delegations by ~7 % with a negligible change in delegated IPs. When looking further into this result we found that delegation sizes decreased: While the fraction of /20 delegations decreased from ~7% to ~3%, the fraction of /24 delegations increased from ~66 % to ~72 %.