# Sublet Your Subnet: Inferring IP Leasing in the Wild

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## Abstract

IPv4 addresses have become a commodity with monetary value since the exhaustion of unallocated IPv4 space. This led to the rise of a secondary market for buying, selling, and leasing IPv4 addresses. While prior work has studied the IPv4 transfer behavior, the IPv4 leasing ecosystem remains largely unexplored. In this paper, we analyze the IPv4 leasing ecosystem by designing a methodology to infer leased address space for all RIRs and study its impact on routing and hosting security. We infer that 4.1% of all advertised IPv4 prefixes (0.9% of routed v4 address space) were leased in April 2024. Our method achieves 98% precision when evaluated against our validated dataset. Finally, we show that leased address space is five times more likely to be abused compared to non-leased space.

## CCS Concepts

• **Networks** → **Network security**; **Network measurement**.

## Keywords

IP Leasing; IPv4 Address Market; IPXO; IPv4 Exhaustion; IP Abuse

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## 1 Introduction

The Internet numbers resource ecosystem has become more active since the exhaustion of unallocated IPv4 address space: the Regional Internet Registries (RIRs) have reported growing numbers of in-region and out-of-region IPv4 transfers over the past decade [48, 49, 65]. Major cloud companies have purchased IPv4 address space from various organizations [12, 61, 70] to support their growing customer base and market share in the hosting and content distribution industry [18, 77], creating more demand in the IPv4 address market. This led to the rise of IP address brokerage businesses [61, 63] which facilitate buying, selling, and leasing of IP address space, providing a convenient platform for organizations to monetize their unused address space and for those who need address space to easily obtain it. The resulting secondary market has improved the utilization of IPv4 address space.

Recent shifts in business dynamics have contributed to the increasing demand for IP leasing. Some cloud companies introduced an IPv4 surcharge to offset the cost of obtaining IPv4 addresses [13], but allow customers to avoid these surcharges by using the cloud companies' Bring Your Own IP (BYOIP) services [13, 15, 28, 29, 43]. This pricing asymmetry has created a budget-friendly operational pipeline: customers can first lease IP address space from a brokerage company and then bring it to cloud hosting providers [35]. In addition, commercial virtual private network (VPN) providers often lease different address spaces on a short-term basis to bypass the geo-filters of streaming services [39, 40, 50].

The increased circulation of IP addresses driven by the IP address market and BYOIP services presents challenges to Internet routing and hosting security. Previous studies have shown that IP address circulation contributes to inaccuracies in routing databases [19, 21, 23, 24, 38], noncompliance with routing security practices [25, 26, 45, 75], and susceptibility of cloud services to malicious scanners [37]. Bad actors exploit the IP transfer market to obtain address space for spamming or running botnet command and control (C2) servers [27]. More recently, attackers started to simultaneously employ IP address leasing platforms and BYOIP services to conduct malicious activities, which caused some of the leased IP address blocks to be blacklisted, creating operational challenges for the legitimate parties involved in the leasing process [2, 3].

In this paper, we study the IP leasing ecosystem in the wild and discuss the implication of the IP leasing businesses on routing and hosting security. Our main contributions are as follows:

(1) We provide a taxonomy of the IP leasing business model and operational pipeline.
(2) We design a methodology to infer leased IP address space and compare it with prior work.
(3) We curate a reference dataset using data from registered IP brokerage companies and ISPs to evaluate our inferences.
(4) We show that our inferred leased address space is more likely to be abused compared to non-leased address space.

## 2 Background

We define IP leasing as follows: an organization is *leasing IP addresses* when it provides its customer with IP addresses but does not provide the customer connectivity to the Internet [63, 73]. To infer leased IP address space, we need to understand relevant RIR

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policies on IP resource distribution, the routing system, and the IP leasing business model.

## 2.1 RIR Address Policy

The RIPE NCC, ARIN, APNIC, AFRINIC, and LACNIC are the five RIRs in the world. They are each allocated IP addresses from the Internet Assigned Numbers Authority (IANA) and further distribute IP addresses to organizations within their designated geographic region. According to the RIR address policies, there are three broad categories of IPv4 address space:

(1) **Portable:** Portable address space is typically directly distributed to organizations by the RIRs. Organizations holding portable address space can choose any Internet connectivity provider, as the RIRs themselves do not offer connectivity services. Therefore, portable address space is generally not considered *leased*. RIRs mark portable address space with different statuses such as `Allocated PA` (Provider Aggregatable) or `Assigned PI` (Provider Independent) (RIPE [55], AFRINIC [4]), `(Direct) Allocation/Assignment` (ARIN [11, 76], LACNIC [42]), or `Allocated/Assigned Portable` (APNIC [9, 66]).
(2) **Non-portable:** Non-portable address space is typically allocated or assigned by holders of portable address space (address providers) to other organizations. Organizations that hold non-portable address space are expected to use their address provider's Internet connectivity. If they do not, the non-portable address space is considered *leased*. This space is labeled as `Sub-allocated PA` or `Assigned PA` (RIPE, APNIC), `Reallocation` or `Reassignment` (ARIN, LACNIC), or `Allocated Non-portable` or `Assigned Non-portable` (APNIC).
(3) **Legacy:** Legacy address space was directly distributed to organizations by IANA before the RIRs were established [56]. Since this space is not managed by the RIRs, it has no defined portability, so we do not apply the definition IP leasing to it. However, legacy address holders can choose to register their address space with RIRs to access certain services and privileges [57]. Once registered, the address space will no longer be legacy and will have defined portability.

In our study, we follow the above definitions to design our methodology and identify non-portable *leased* address space (§5.2).

## 2.2 The Routing System

An organization needs to advertise their IP addresses in the routing system via the Border Gateway Protocol (BGP) before they can send or receive traffic. BGP is vulnerable to attackers who advertise IP addresses without authorization. The Resource Public Key Infrastructure (RPKI) was introduced to mitigate this vulnerability [44]. RPKI databases contain cryptographically attested routing authorization information. Address holders can create Route Origin Authorizations (ROAs) to authorize any AS(es) to originate their prefix in BGP.

## 2.3 IP Leasing Business Model

We define the following terms to describe different business parties involved in the leasing process.

- **IP holder:** This entity's IP address space is portable.

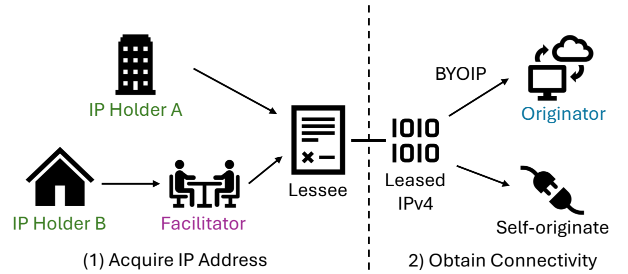


**Figure 1: An entity (lessee) can follow this two-step pipeline to establish Internet presence without having their own IP addresses or even network infrastructure.**

- **Lessee:** The entity that pays to temporarily acquire address space from an IP holder.
- **Facilitator:** An entity who facilitates the transaction between an IP holder and lessee. The IP leasing process does not always require a facilitator.
- **Originator:** The entity who advertises (leased) IP address space in BGP, *a.k.a.* the entity behind the origin AS of the advertised prefix. The originator may be the same entity as a lessee if the lessee has its own routing infrastructure.

Figure 1 illustrates the business model of IP leasing. An individual or organization plays the role of a lessee when it leases IP address space from an IP holder directly or through a facilitator (e.g., an IP broker). Some IP brokerage companies have multiple leasing business models: they can act as an IP holder to lease their own IP address directly to customers, or act as a facilitator between the customer and a different IP holder. After acquiring IP address space through leasing, the lessee can either provide their own Internet connectivity by originating the address space in BGP themselves or use BYOIP services to have cloud providers originate their newly leased address space.

## 3 Related Work

Prior work has studied the IPv4 transfer ecosystem and its abuse. In 2013 and 2017, Livadariu *et al.* [48, 49] studied routing activity of RIR-reported transfers and found 85% transferred IP prefixes were advertised in BGP, suggesting that most transfers were due to legitimate operational need for IP address space. In 2020, Giotsas *et al.* [27] found that ASes that advertised transferred address space in BGP were more likely to engage in malicious activities compared to ASes that had not.

In 2023, Beverly [14] compared the geographical information of IP addresses registered in the RIRs to the physical locations in which the address space was being used. They found that 3.4% of 50K randomly selected IP prefixes were operating outside of the region of their allocating RIRs. Prehn *et al.* [63] provided the first quantification of the prevalence of IP leasing in the RIPE region in 2020 and found a growing number of leasing providers' websites between 2019 and 2020. They also found that the leasing ecosystem was still maturing at that time as the market price for leasing IPv4 addresses varied significantly.

## 4 Dataset

We use the following datasets to infer leased IP address space.

**RIR WHOIS Database.** We collected the April 1, 2024 WHOIS database snapshots from RIPE, ARIN, APNIC, AFRINIC, and LACNIC as our primary dataset for inferring leased IP address space.

**Registered IP Brokers.** ARIN and APNIC currently provide a list of registered brokers. In April 2024, ARIN listed 9 organizations as "qualified facilitators" [10] and APNIC listed 38 organizations as "registered brokers" [8]. The RIPE NCC used to provide a list of "recognized brokers" until December 2023 but decommissioned the list thereafter [54]. We used the Internet Archive to retrieve the December 2023 snapshot of RIPE NCC's recognized brokers page [53] and found 115 organizations. Overall, we construct a list of 162 organizations considered to be registered brokers.

**BGP dataset.** We downloaded the public routing tables collected by Routeviews [59] and RIPE RIS [58] between April 1 and April 15, 2024 to capture leased prefixes that were not immediately originated in BGP.

**RPKI dataset.** We downloaded RPKI archives [71] of 30-minute granularity between April 1 and April 15, 2024 to capture RPKI records for prefixes that were not immediately created at the time the lease occurred.

**Spamhaus.** We downloaded the Spamhaus ASN-DROP lists monthly from February through May 2024. The Spamhaus ASN-DROP list contains ASes used by attackers for malicious activities such as spam operations and botnet control [72].

**Other datasets.** We downloaded April 1, 2024 snapshots of the CAIDA AS2org [17] and AS Relationships [16] datasets.

## 5 Methodology

In this section, we introduce our workflow to infer leased IPv4 address space based on the definition of IP leasing (§2.1) and steps to curate an evaluation dataset.

### 5.1 Processing RIR WHOIS Databases

We first parse the RIR WHOIS database records to obtain the necessary parts for our inference. Figure 2 shows an example of processed WHOIS records relevant to a leased prefix; we explain our workflow (circled numbers in Figure 2) and refer to the shapes of each component below.

(1) **Parse relevant WHOIS objects.** For our study, we need WHOIS database objects containing address blocks, Autonomous System (AS) numbers, and organizations. For RIPE, APNIC, and AFRINIC, those objects are `inetnum`, `aut-num`, and `organisation` respectively. We also obtain the maintainers of `inetnum` objects from their `mnt-by` fields for our inference evaluation (§5.3). LACNIC does not store organizations independently but includes the `owner` field in other objects. For ARIN, those object are `NetHandle`, `ASHandle`, and `OrgID`.

(2) **Construct address allocation tree.** For each RIR WHOIS database, We parse all objects containing IANA allocated (non-legacy) IPv4 address blocks and convert the address-range notation into CIDR-prefix notation. We remove all hyper-specific prefixes longer than /24 as they are mostly for internal infrastructure use [68]. We input the prefixes into a prefix tree and find the root nodes and leaf nodes (Figure 2 rectangles). The root nodes represent portable prefixes directly allocated to the IP holders by the RIRs, and the leaf nodes contain non-portable prefixes sub-allocated or assigned by IP holders to other organizations (§2.1). We do not focus on the intermediate nodes in the tree, as they represent intermediate sub-allocations and are not critical to our inference process.

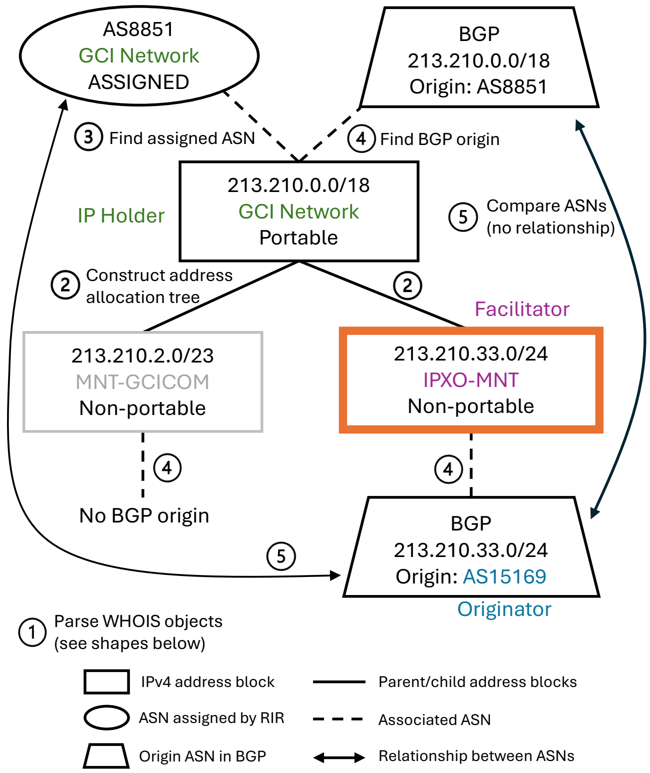


**Figure 2: Inference diagram of an example leased prefix. The bold orange rectangle marks the leased prefix. The leased prefix's BGP origin (AS15169) is related to neither the ASN assigned to its address provider (AS8851) nor the BGP origin of the portable parent prefix (also AS8851). The colored text is matched to that of Figure 1 to show the different business parties involved in the lease.**

(3) **Assign AS numbers.** For each root node, we first extract the `org` or `OrgID` fields and then find in the WHOIS databases all `aut-num` or `ASHandle` objects (ellipse) containing the same fields.

(4) **Find the BGP origins.** For each leaf node, we search in our BGP dataset for its exact-matching prefix and origin AS (trapezoids). We repeat the process for the root nodes, and if an exact-matching prefix does not exist, we then search for its least-specific covering prefix and origin AS (trapezoids). This accounts for cases where the organization holding consecutive portable address blocks choose to aggregate their corresponding prefixes in BGP.

### 5.2 Inferring Leased Address Space

After completing steps (1) through (4), we compare the components of the tree (5) to infer leased address space. We map the component colors in Figure 2 to the colors of their corresponding business parties in Figure 1. The inference process is as follows:

(1) If neither the leaf node nor its root node has a BGP origin, we consider it *unused*.

| | Inference Group | RIPE | ARIN | APNIC | AFRINIC | LACNIC | All Regions |
|---|---|---|---|---|---|---|---|
| 1 | Unused | 63,670 | 43,011 | 25,437 | 28,936 | 27,551 | 188,605 |
| 2 | Aggregated Customer | 204,337 | 98,316 | 21,515 | 1,741 | 11,950 | 337,859 |
| 3 | ISP Customer | 31,484 | 10,302 | 7,725 | 777 | 2,250 | 52,538 |
| | **Leased** | **26,774** | **6,697** | **3,275** | **2,172** | **627** | **39,545** |
| 4 | Delegated Customer | 27,610 | 22,927 | 8,291 | 1,236 | 1,294 | 61,358 |
| | **Leased** | **1,872** | **5,633** | **150** | **63** | **55** | **7,773** |
| | **# of Leased Prefixes**/Total | **28,646**/355,747 | **12,330**/186,886 | **3,425**/70,192 | **2,235**/45,330 | **682**/47,861 | **47,318**/705,016 |

**Table 1: Number of prefixes in each category. The 47k inferred leased prefixes were 4.1% of all routed prefixes in April 2024.**

(2) If only the root node has a BGP origin but not the leaf node, the leaf node prefix has likely been aggregated into its parent prefix in the root node in BGP. We call the leaf node an *aggregated customer*, e.g., the gray rectangle in Figure 2.
(3) If the leaf node has a BGP origin but not the root node we classify it into group 3. If an AS relationship exists between the leaf node's BGP origin (bottom trapezoid) and the RIR-assigned ASes associated with root nodes (top ellipse), we consider the leaf node to be an *ISP customer*, otherwise ***leased*** (bold orange rectangle). The different business parties are shown in Figure 2: the root node organization is the IP holder (green), the leaf node maintainer is the facilitator (purple), and the leaf node BGP origin is the originator (blue).
(4) If both the root node and leaf node have BGP origins, we classify the leaf node into group 4. If the leaf node's BGP origin AS is related to either the root node's assigned AS or the BGP origin AS, the leaf node prefix is likely a customer delegation of the root node prefix [41]. In this case, we consider the leaf node a *delegated customer*; otherwise we consider it ***leased***.

### 5.3 Curating Evaluation Dataset

We manually curate a reference dataset to evaluate our inference methodology. To the best of our knowledge, no existing ground-truth dataset for leased IP address space exists. The closest available data are the IP brokers provided by the RIRs. To identify the brokers' leased prefixes, we first map the company names of registered brokers to the `organisation`/`OrgID` objects in the corresponding RIR database and obtain their maintainer fields (e.g., `mnt-by`, `mnt-ref`). We then extract address blocks with matching maintainers from the WHOIS databases. Since not all address blocks managed by a broker are leased, we manually identify and exclude non-leased address blocks. We use the remaining prefixes as our positive labels. Additionally, we manually construct a list of non-leased prefixes from five residential ISPs across three RIRs as our negative labels.

## 6 Results

In this section, we quantify the leased prefixes in April 2024 for each RIR region, compare with prior work, evaluate our inference, and analyze the leasing ecosystem for each RIR.

### 6.1 Leased Address Space per Region

Table 1 shows the inferred number of leased prefixes for each RIR. We infer 47,318 leased prefixes across all RIRs, which is 4.1% of all 1,146,921 observed IPv4 prefixes in BGP and 0.9% of the entire observed routed IPv4 address space. We find that RIPE has the most leased prefixes compared to the other RIRs. This finding is consistent with the description of RIPE's IP address market as the most active: RIPE has the most reported IPv4 transfers of all time [63], the most available IPv4 blocks for sale [32], and the most available IPv4 blocks for lease [36] according to IP brokers' websites. Table 1 summarizes these statistics for all regions. We explain in detail our inference results for the RIPE region below.

**RIPE.** Overall we infer 28,646 RIPE prefixes are leased. We obtain 355,747 leaf nodes containing non-portable prefixes for RIPE (§2.1). Table 1 shows the number of prefixes in each category: we find 63,670 prefixes in group 1 *unused* that are not originated in BGP. Those prefixes may be available for lease (*e.g.,* available on brokers' marketplaces), but we do not consider them *leased* since they are not active. We classify 204,337 prefixes into group 2 *aggregated customer*. Those prefixes are likely assigned by ISPs to customers who could not provide connectivity for themselves and then aggregated to the less-specific root node prefix in BGP. We find 31,484 prefixes in group 3 *ISP customer* that are likely ISP customer prefixes that are not aggregated to a covering prefix in the routing system. We find 26,774 prefixes in group 3 ***leased***. Some of those prefixes we could falsely inferred to be leased due to unobserved AS relationship or uncaptured company structure (§7). We find 27,610 prefixes in group 4 *delegated customers* that are likely prefixes delegated to customers by ISPs or parent organizations [41]. We find 1,872 prefixes in group 4 ***leased***. Those prefixes could be redundantly connected to the Internet via their provider and a second upstream AS for resilience (multi-homing), and thus we could have falsely inferred them as leased prefixes (§7).

**Comparison with Prior Work.** We conduct a preliminary comparison between our methodology and that of [63]. Prehn *et al.* classified address blocks as leased if their maintainers differed from their parent blocks (*e.g.,* Figure 2). However, comparing maintainers can lead to false positives, such as classifying some customer prefixes as leased if the customer uses their own maintainer instead of the provider's (*e.g.,* prefixes in our *Aggregated Customer*, *ISP Customer*, or *Delegated Customer* groups). Conversely, there may be address blocks with the same maintainer that are actually leased, such as when an IP holder directly leases prefixes to lessees. On the contrary, their methodology can detect inactive leases that ours would falsely classify as *Unused*. We plan to conduct a more comprehensive replication analysis in future work (§8).

### 6.2 Evaluation

Of the 115 registered brokers in RIPE, we directly map 46 to their RIPE WHOIS database entries and manually match 39 due to inconsistencies such as variations in legal entity suffixes (e.g., LTD vs.

| | Inferred Lease | Inferred Non-lease | |
|---|---|---|---|
| Actual Lease | 7,735 (TP) | 1,743 (FN) | **Recall 0.82** |
| Actual Non-lease | 121 (FP) | 5,257 (TN) | Specificity 0.98 |
| | **Precision 0.98** | NPV 0.75 | **Accuracy 0.88** |

**Table 2: Confusion matrix: we evaluated our results against 14,856 validated prefixes (formulas detailed in §A).**

L.T.D.), abbreviations, and fictitious business names. The remaining 30 brokers could not be matched as they are not present in the RIPE database. We successfully map the 85 matching organizations to 107 maintainer handles, covering 11,076 prefixes. After manually filtering out 1,621 prefixes that are likely not leased (e.g., brokers that also served as ISPs providing connectivity for their customers), we identify 9,455 actively leased prefixes.

For ARIN, we find 24 prefixes managed by 2 out of 9 brokers and remove 1 prefix that is not leased. In the case of APNIC, we are unable to match any registered brokers to address blocks because its database does not provide maintainer fields for organization objects. Overall, our evaluation dataset includes 9,478 actual leased prefixes (positive labels). We also collect 5,378 actual non-leased prefixes (negative labels) managed by 5 ISPs (AT&T, Comcast, Orange, Vodafone, IIJ), which are originated in BGP by their respective ASNs. We reached out to IIJ and confirmed that the IIJ prefixes we collected are indeed used for providing connectivity to their customers. In total, our evaluation dataset contains 14,856 prefixes.

Table 2 is a confusion matrix that shows that our inference methodology achieves 98% precision, 82% recall, and 88% accuracy when evaluated against the reference dataset. Upon further analysis, we find that the 1,605 false negatives are classified as group 1 *unused.* Since our methodology relies on the BGP origin of the leased prefix, it cannot detect leased prefixes that are not yet originated in BGP (inactive leases). The remaining 138 false negatives are legacy address blocks, which is outside of the RIR's portability definitions and thus not captured by our methodology. Additionally, we examine the 121 false positives and find that 110 were associated with Vodafone, which registered 17 `organisation` objects for different subsidiaries. These subsidiaries use different AS numbers, and their relationships are not captured by our AS Relationships dataset. We further discuss the limitations of our methodology in §7.

## 6.3 IP Leasing Ecosystem

To analyze the leasing ecosystem in each region, we look at the most popular IP holders, facilitators, and originators.

**Top IP holders in each RIR.** Table 3 lists the three IP holders that lease out the most prefixes. In RIPE, Resilans, a Swedish IP management company, leases 806 prefixes within Sweden. Cyber Assets FZCO, a U.A.E. company, leases prefixes to 44 countries, including 332 prefixes to the U.S. and 110 to Brazil. In ARIN, the top IP holder, EGI Hosting, is a U.S. company that leases 1,418 prefixes to 18 countries, where 651 prefixes are leased in Cyprus and 195 in Panama. The second largest IP holder, PSINet, was an ISP that ceased operation in 2002 and was acquired by Cogent.

| RIR | Organization | Count |
|---|---|---|
| RIPE | Resilans AB | 1,106 |
| | Cyber Assets FZCO | 941 |
| | Russian Scientific-Research Institute | 675 |
| ARIN | EGIHosting | 1,418 |
| | PSINet, Inc. | 1,233 |
| | Ace Data Centers, Inc. | 533 |
| APNIC | Orient Express LDI Limited | 145 |
| | Capitalonline Data Service (HK) | 135 |
| | Aceville PTE.LTD. | 96 |
| AFRINIC | Cloud Innovation Ltd | 2,014 |
| | ATI - Agence Tunisienne Internet | 38 |
| | Nile Online | 32 |
| LACNIC | Radiografica Costarricense | 114 |
| | Impsat Fiber Networks Inc | 88 |
| | Newcom Limited | 25 |

**Table 3: Top 3 IP holders by # of inferred leases, April 2024.**

Some of their prefixes were reallocated to IP leasing companies, but the majority are misclassified as leased due to our AS2org dataset not capturing the acquisition (§7). For AFRINIC, the top IP holder, Cloud Innovations, leases 2,014 prefixes, far exceeding the second top IP holder with 38 leased prefixes. This finding is consistent with previous reports and studies of Cloud Innovations' pervasive leasing practices in AFRINIC [14, 52].

**Top originators.** We find three hosting providers—M247, Stark Industries, and Datacamp—among the top-five originators of leased prefixes in both RIPE and ARIN. We compare the 9,217 originators for all leased prefixes with a list of 957 inferred serial BGP hijackers [74] and find that 2.9% (269/9,217) of all originators are also serial hijackers. Those serial hijacker ASes originate 13.3% (6,312) of all 47,318 inferred leased prefixes. We retrieve 1,100,025 non-leased prefixes from our BGP dataset and find 3.1% (33,503/1,100,025) are originated by a serial hijacker AS. This shows that leased prefixes are more likely to be originated by serial hijackers compared to non-leased prefixes.

**Top facilitators.** We discover that IPXO, an IP broker, is in the top-three facilitators for each of the RIPE, ARIN, and APNIC regions. In AFRINIC, the largest facilitator is Cloud Innovations, which also ranks as the top IP holder in that region. This is an example of the IP holder that facilitates its own leasing business (§2.3).

## 6.4 Potential Abuse of Leased Prefixes

To assess the potential abuse of leased prefixes, we check whether leased prefixes are more likely to be originated by AS numbers on the Spamhaus ASN-DROP list compared to non-leased prefixes. In our analysis for April 2024 leased prefixes, we obtain 47,318 unique leased prefixes, of which 1.1% (541) are originated by AS numbers on the Spamhaus ASN-DROP list. In contrast, we find that only 0.2% (2,224) of the 1,100,025 non-leased prefixes in our BGP dataset are originated by blocklisted AS numbers. In other words, leased prefixes are approximately five times more likely to be advertised by an AS considered abusive by Spamhaus than non-leased prefixes, and numerous blog and forum posts discuss such abuse [1, 3].

We also look for ROAs associated with leased prefixes and blocklisted AS numbers in our RPKI dataset. We find 31,156 ROAs for the

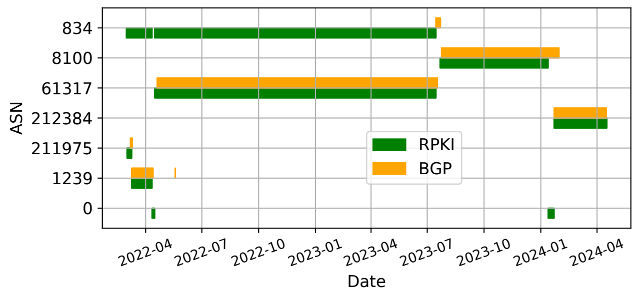


**Figure 3: The RPKI and BGP behaviors of an IPXO-leased prefix suggests its periods of lease.**

47,318 leased prefixes, 1.6% (498/31,156) of which contain ASes on the block list. In contrast, the percentage of non-leased prefixes with ROAs containing blocklisted ASes is similar to the fraction of BGP advertisements from those same ASes, namely 0.2% (1,260/506,629). This suggests that leased prefixes are even more likely to have a ROA authorizing an abusive AS to use them. We then look into how ROAs were signed for leased prefixes and discover that some facilitators either require the IP holder to create proper ROAs for the leased prefixes, or offer RPKI management services where the IP holder can delegate RPKI signing capability to the facilitator [34].

The above findings show that the IP leasing market could enable attackers to circumvent routing security mechanisms such as RPKI. For example, previously spammers that hijacked another organization's address space for spam campaigns [64] might have had their unauthorized BGP announcements filtered by the RPKI. However, by leasing IP addresses, they can now bypass this obstacle.

## 6.5 Defense against Abuse

We manually browsed through several IP leasing companies' websites and found that one company, IPXO, provided extensive description on abuse policy [33]. Operators have also discussed their experiences with IPXO's strict abuse handling process on forums [2]. This suggests that IP leasing facilitators can step in to help mitigate and prevent abuse of leased prefixes.

We also find that although RPKI might provide routing authorizations for abusers, it can also be leveraged to prevent abuse. Oliver *et al.* [60] showed that operators can create ROAs with AS0 for the abused prefixes, allowing them to be filtered in BGP and leading attackers to cease activity. We observe AS0 usage when analyzing the historical routing activity of an IPXO prefix. Figure 3 shows that IPXO already uses AS0 in between different leases of that prefix, likely for marking the end of a lease or abuse-related purposes such as removing the prefix from blocklists [60].

## 7 Limitations

We identify the following limitations of our methodology that may affect its accuracy:

**Legacy IP Addresses.** We do not consider the leasing of legacy address space since it is not managed by the RIRs and has undefined portability (§2.1). Future work could expand our methodology to support leasing inference for legacy address space.

**Incomplete BGP Data.** This can lead to false positives in our inferences. Previous studies [5–7, 69] have shown that BGP data collection is prone to bias. Additionally, since AS relationship data is derived from BGP data, it inherits these limitations [51, 62]. Complex business relationships, such as mergers, acquisitions, and international subsidiaries, that are not captured can also result in incorrect lease inferences.

**Multi-homing.** Some prefixes we classify as *group 4 leased* (§6.1) may be using both their IP holder's and originator's connectivity, which we cannot confirm with our datasets. Reactive measurements from suitable vantage points are required for further analysis.

**Routing Attacks.** We may mis-classify routing attacks (*e.g.*, prefix squatting [67]) as IP leasing. However, our methodology is designed to overlook most squatting cases, as squatters generally cannot register WHOIS records for the victim's address space.

## 8 Discussion and Future Work

When IANA exhausted the available IPv4 address pool in 2011, operators and RIRs began to discuss the legal ambiguities of IP leasing and the development of relevant governing policies. Since then, legacy address space holders—who are not subject to RIR policies—have found a way to profit through leasing [46]. While most RIRs have remained neutral on the issue, some have deemed IP leasing to violate their policies [52]. Nevertheless, the number of IP brokerage businesses has continued to grow [63]. In 2023, ARIN clarified that organizations may lease IP address space they already hold if they comply with ARIN policies but cannot use IP leasing as a justification to acquire additional address space [73].

The impact of IP leasing on other aspects of the Internet merits further study. For example, some IP leasing behavior may be falsely identified as routing attacks [30, 74]. IP leasing may also contribute to inconsistencies across geolocation databases [20, 22, 47]; anecdotally we find prefixes on the IPXO marketplace geolocate to four different continents according to five geolocation databases [36]. Future work will refine our methodology with insights from [63], infer legacy address space leases, and longitudinally assess IP leasing market dynamics and its impact on IPv6 adoption [31].

## 9 Summary

The IPv4 leasing market has been growing due to the increasing demand for IPv4 addresses. The prevalence of IP leasing behavior and its potential for abuse was previously unexplored. We infer that, across all RIR regions, 4.1% (47,318/1,146,921) prefixes advertised in BGP were leased in April 2024 and our inference achieves 98% precision in the evaluation. By comparing the BGP origins of leased prefixes with the Spamhaus ASN-DROP list, we find that our inferred leased prefixes are five times more likely to be advertised by blocklisted ASes. We make our inferred leases, inference code, and curated evaluation dataset publicly available in Appendix C.

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# A Evaluation Metrics

We use the following information retrieval metrics to evaluate our inference results (§6.2, Table 2) and explain their definitions within the context of IP leasing:

**True Positive (TP):** Prefixes correctly predicted as leased.

**False Positive (FP):** Prefixes incorrectly predicted as leased (Type I error).

**True Negative (TN):** Prefixes correctly predicted as non-leased.

**False Negative (FN):** Prefixes incorrectly predicted as non-leased (Type II error).

**Precision:** The ratio of correctly predicted leases to the total predicted leases. Too many false positives (low precision) can obscure the true extent of abuse in leased prefixes, potentially undermining efforts to detect and mitigate such abuse.

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}}$$

**Recall (Sensitivity):** The ratio of correctly predicted leases to total actual leases. Too many false negatives (low recall) may lead to an underestimation of the prevalence of IP leasing and the size of the IP leasing market.

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}}$$

**Specificity:** The ratio of correctly predicted non-leases to total actual non-leases.

$$\text{Specificity} = \frac{\text{TN}}{\text{TN} + \text{FP}}$$

**Negative Predictive Value (NPV):** The ratio of correctly predicted non-leases to the total non-leases.

$$\text{NPV} = \frac{\text{TN}}{\text{TN} + \text{FN}}$$

**Accuracy:** The ratio of correctly predicted observations (both leases and non-leases) to the total number of observations.

$$\text{Accuracy} = \frac{\text{TP} + \text{TN}}{\text{TP} + \text{TN} + \text{FP} + \text{FN}}$$

## B Ethical Considerations

This work does not raise ethical concerns. All the routing datasets we used are public. The records we extracted from the RIR WHOIS Database archives were either redacted by the RIRs or contained no personally identifiable information (PII).

## C Replicability

Our inferred leased prefixes and analysis code are publicly available on: https://github.com/CAIDA/IP-Leasing-Inference.

The RIPE NCC and AFRINIC provide their current WHOIS databases for public download. ARIN, APNIC, and LACNIC's bulk WHOIS databases are available under their Acceptable Use Policies.

- RIPE: https://ftp.ripe.net/ripe/dbase/
- AFRINIC: https://ftp.afrinic.net/dbase/
- ARIN: https://www.arin.net/reference/research/bulkwhois/
- APNIC: https://www.apnic.net/manage-ip/using-whois/bulk-access/
- LACNIC: https://www.lacnic.net/2472/2/lacnic/accessing-bulk-whois