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On IPv4 transfer markets: Analyzing reported transfers and inferring transfers in the wild

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ABSTRACT

IPv4 Transfer Markets have recently emerged as a mechanism for prolonging the usability of IPv4 address space. They facilitate the trading of IPv4 address space, which constitutes a radical shift transforming IPv4 addresses from a free resource to a commodity. In this paper, we conduct a comprehensive analysis of all IPv4 transfers that are published by three regional Internet registries. We analyze the overall evolution of transfer markets, whether they lead to a healthy redistribution of IP addresses, and the interplay between transfers and IPv6 adoption. We find that, to a large extent, IPv4 transfers serve their intended purpose by moving IP blocks from those with excess to those in need - transferred address blocks appear to be routed after the transfer, the utilization of transferred blocks is greater after the transfer date and a high percentage of the transferred space comes from legacy space. We have also proposed a methodology for detecting IPv4 transfers in the wild that tracks changes in origins of IP prefixes in the global routing table. This method yields promising results, yet it produces a large number of false positives due to the noisy nature of routing data. We have investigated the cause of these false positives and verified that they can be reduced to a volume analyzable by a human operator.

1. Introduction

In the course of the last few years we have witnessed a rapid decrease in the number of available IP version 4 (IPv4) addresses. Currently, four of the five Regional Internet Registries (RIRs) are allocating from their last /8 address block, which is the last 2^{24} addresses that a RIR has at its disposal [1–4]. Moreover, the American Registry for Internet Numbers (ARIN) reported in September 2015 that it has no more available IPv4 addresses [5]. The Internet community foresaw this problem and designed a new version of the IP protocol, IP version 6 (IPv6) [6], which considerably extends the IP addressing space (i.e., from 2^{32} to 2^{128} IP addresses). Even though this version was standardized more than 20 years ago, its uptake has been slow [7,8].

The continuing demand for IPv4 addresses and the slow transition to IPv6 have resulted in organizations looking for other means to fulfill their IP addressing needs. One such mechanism is the *IPv4 Transfer Market*, which facilitates the sale of IPv4 addresses between organizations with excess (*sellers*) and organizations with deficit (*buyers*) of IPv4 address space. IP address trading between these organizations is subject to rules and regulations imposed by the RIRs, which differ from one RIR to another. Buyers and sellers need to submit a transfer request to their local RIR, which decides whether to allow/disallow the transfer based on its internal policies. IPv4 transfer transactions can involve a third-party participant (known as *IPv4 broker*) that facilitates the process of exchanging the address blocks between a seller and a buyer. Four of the five RIRs have implemented policies that allow transfer of address resources; i.e., Asia Pacific Network Information Centre (APNIC), Réseaux IP Européens (RIPE), American Registry for Internet Numbers (ARIN) and Latin America and Caribbean Network Information Centre (LACNIC). The first intra-RIR transaction was reported by ARIN in 2009. Three years later, the first inter-RIR transaction was reported between organizations registered in North America (i.e., ARIN) and Asia Pacific (i.e., APNIC). The RIRs make the lists of completed transfers available to the public in an attempt to provide more transparency into the address transfer process.

IPv4 transfer markets are a source of controversial discussions [9–14]. On the one hand, the transfer markets can extend the usable life of IPv4, but they could also delay the adoption of IPv6 or halt it altogether, cause further fragmentation of the address space and larger IPv4 routing tables, or generate destabilizing speculation and/or hoarding behavior. It is not clear that address space owners, especially holders of legacy space, will adhere

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to RIR transfer policies; even now address blocks may be changing hands without the knowledge of the RIRs. We believe an empirically grounded characterization of address transfer activity will inform the on-going debate on the relative benefits and harms of IPv4 address space markets.

In this work we conduct an empirical analysis of IPv4 transfer markets. In the first part of the paper, we focus on the transferred address blocks published by the RIRs. We characterize these transactions along various dimensions: the type of address space being exchanged on the market, whether that space is subsequently used by the buyers, the organizations involved in the transfers, and the impact of the market on IPv6 adoption and the global routing table. Based on our results there does not appear to be any evidence of a hoarding behavior by the buyers of address space. Most of the address space is routed after the transfer date, and the utilization of transferred address blocks shows an increasing trend after the transfer. We find that 63% of the address space traded on the market represents legacy address space hinting at a healthy redistribution of such space. Our analysis also indicates the existence of a few dominating players that exchange most of the transferred blocks in each region.

In the second part of the paper, we propose a method for inferring transfers “in the wild”. Using routing data generated by the Border Gateway Protocol (BGP), we construct an initial list of candidate transfers based on the observed change in the origin Autonomous Systems (AS) of a prefix over time. A major challenge is that prefixes may change origin ASes for reasons other than transfers, e.g., movements internally within an organization, transient prefix hijacks, and traffic engineering. We devise a set of BGP filters to remove false positives from the list of candidate transfers. Our methodology infers more than 90% of the detectable reported transactions. However, our BGP-based approach also produces a large number of false positive BGP movements. We investigate possible causes of these false positives by analyzing three case studies. We find that many such movements are related to non-BGP speaker organizations, as well as operational changes in the IPv4 address space of the organizations. We also show that leveraging additional data sources, like Domain Name System (DNS) name data and RIR resource allocation records, can further reduce false positives to a level that can be vet by a human operator.

This paper is a longer and more comprehensive version of an earlier work [15]. More specifically, we have extended the measurement period by two years and revised our inferred methodology by investigating the usage of auxiliary data for detecting transfers. We also enhanced the IPv4 transfer market analysis by devising new metrics which offer a deeper understanding of the market. We improved the analysis of the transferred space utilization, involved players on the market and the impact of the market on IPv6 adoption. We also analyzed the impact of the on the global routing table growth, and investigated to what extent the market satisfies the organizations needs for extra IPv4 addresses. Also, we introduced a method for estimating the IPv4 prices and the IPv4 transfer market lifespan. The rest of the paper is organized as follows. Section 2 details the related work. In Section 3 we present a short summary of the IP address management evolution and describe the existing transfer policies implemented by the RIRs. In Section 4 we describe in detail the datasets used in this paper. In Section 5 we analyze the reported transferred address blocks, and in Section 6 we propose a method for inferring transfers using publicly available data. In Section 8 we discuss the implications of our work, and in Section 9 we list our conclusions and avenues for further research.

2. Related Work

The rapid decrease of available IPv4 addresses, as well as the significant increase in the number of transactions in the IPv4 market have drawn the attention of the Internet community. A number of research efforts have focused on IPv4 address space utilization and IPv4 transfer markets.

Richter et al. [16] presented a study on the IPv4 address space, focusing on the evolution of the allocation and management of the IP space, as well as the current scarcity problem. Dainotti et al. [17] proposed a method for measuring the IPv4 utilization by using data collected through both passive and active measurements. They reported that 3.4M /24 assigned blocks were not routed, and only 37% of the IPv4 address space appeared to be used as of 2013. Zander et al. [18] also studied the utilization of the IPv4 address space, reporting that 45% of the IPv4 address space was used as of 2014.

The work of Mueller et at. [19] is directly related to the IPv4 transfer market. Their analysis used the lists of published transfers from 2009 to June 2012. They found that more than 80% of the transferred address blocks were legacy allocations. In their follow-up work [20] the authors extended the list of published transfers until the first quarter of 2013, and analyzed transactions from the policy perspective, investigating the role of need-based policies. They found no clear evidence of the efficiency of these polices.

IPv4 transfers have been also reported and debated at operational venues and in press articles [21–25]. Huston [26,27] focused on the APNIC region, and reported general statistics related to the market. He also analyzed the allocations made from the last /8 block by APNIC after it started changing hands in the market. His analysis reports a small scale IPv4 transfer market within the APNIC region; only 1.4% of the APNIC's total address pool has been sold, and only 5% of the total space holders have engaged on the market. Despite these observations, Huston signaled the importance of monitoring the exchange of IP blocks in the market.

The work we presented in this paper extends previous investigation of the IPv4 markets [15], which was conducted when the size of the market was relatively small. It was a first step in analyzing the markets. In our current study we offer an in-depth analysis of the documented transfers, and also propose an approach for detecting transferred blocks using multiple publicly available datasets. We are not aware of any other study that has explored methods for detecting transfers, or has presented an analysis of the document transfer at the same level of depth as this paper. Part of our findings was published on two platforms that target network operators, developers and industry experts [28,29].

3. Background: IPv4 address management

The Internet Protocol (IP) is one of the core protocols used in the Internet, providing support for the *addressing* of packets. IPv4 was the first version of this protocol to be widely deployed in the Internet. Despite its well-known shortcoming (i.e., limited number of IPv4 addresses, security related issues) most of the communication in the current Internet still relies on IPv4. Analyzing the evolution of the IPv4 address management shows the existence of different factors that shaped the allocation policies and distribution of IPv4 address space.

Initially, the Internet Assigned Numbers Authority (IANA) was allocating IPv4 address space directly to organizations. These allocations are currently referred to as *legacy allocations* and were done using the *classful address scheme* [30]; i.e., IANA was distributing the address space using one of the following pre-defined network classes: class A (/8 network), class B (/16 network) or class C (/24 network). IPv4 address space consumption was not regarded as an issue, and allocations were decoupled from needs. The di-

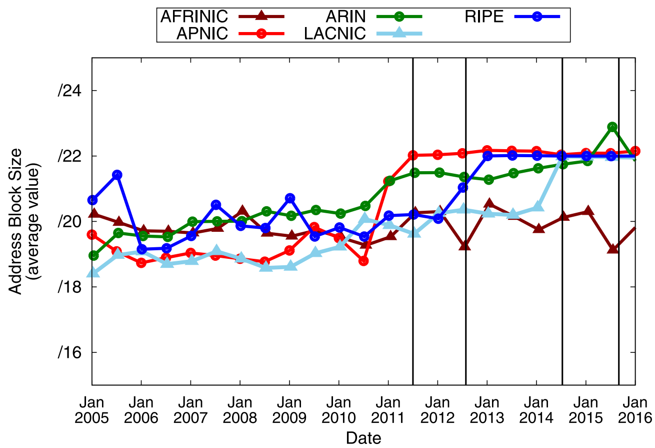


Fig. 1. Evolution of the average size of allocated IPv4 address blocks per RIR.

rect consequence was the underutilization and uneven distribution of the allocated address space; more specifically, 35% of the total IPv4 address space is legacy space [31].

The *classless inter-domain routing (CIDR)* [32] was the first significant change in the IP address management. Replacing the classful system, CIDR allowed networks of variable length to be allocated. Another change in the management of IP addresses was the *establishment of the regional registry system* [33], that resulted from the Internet growth and the need for a structured allocation mechanisms. The RIRs are non-profit organizations responsible for administering Internet resources (IPv4/IPv6 addresses and AS numbers) within their corresponding region. Five RIRs were established: RIPE (responsible for Europe, Middle East and part of Asia) in 1992, APNIC (responsible for the Asia Pacific region) was founded in 1993, ARIN (responsible for North America and part of the Caribbean) in 1997, LACNIC (responsible for Latin America and part of the Caribbean) in 2001 and AFRINIC (responsible for Africa) in 2005. Address space allocation was done in a hierarchical manner. IANA allocated /8 address blocks to RIRs, that was designed to sustain the registry needs for at least 18 months; additional allocations were also possible if the RIR's available space satisfied certain conditions; i.e., the available space was less than 50% of a /8 block or the available space for the following 9 months was less than the necessary space [34]. Each of the five RIRs is responsible for distributing the space within their own region. RIRs allocated the address space to either end users or national (NIRs) and local internet registries (LIRs). The latter, in turn assigned this space to their customers; these allocations were regulated through local policies, which required organizations to document the usage of the requested address space.

The *IPv4 address exhaustion phase* represented another milestone for the address space management. In the beginning of 2011, IANA reached the minimum of five /8 available blocks, which caused the uniform distribution of these address blocks to the five existing RIRs [35]. In the following years, four of the five RIRs started allocating space from their last /8 block triggering several restrictions in the allocation policies; i.e., smaller size of allocated address blocks, detailed utilization plan for the requested space, efficient usage of the allocated IPv4 address space. Fig. 1 shows the average allocated block size over time per RIR. On the same figure we mark with vertical lines the exhaustion dates for APNIC, RIPE, LACNIC and ARIN. For the former three RIRs, we note that after the exhaustion date the average allocated address space block is /22, which corresponds to the restrictions imposed by the RIRs address policies.

The *IPv4 transfer markets* emerged as a mechanism for prolonging the usability of the IPv4 address space. Apart from providing organizations with a method for acquiring IPv4 addresses, the existence of the markets fundamentally changed the nature of the IPv4 addresses as these shifted from a free resource to a commodity that can be bought or sold. The first IP transaction was reported in October 2009. Since then, the average number of reported transactions per month has increase from 6.63 in 2009 to 229.41 in 2015 (see Section 5 for a detailed analysis of the reported transfers). RIRs publish periodically information related to both inter-RIR and intra-RIR transfers: the approved transactions [36–39], IPv4 transfer listing services through which organizations can list address space that they want to sell or buy [40–42] and the registered IPv4 brokers [43–45].

RIPE was the first RIR to approve an intra-registry transfer policy in December 2008 [46]; ARIN, APNIC and LACNIC also approved such policies [47–49] in 2009, 2010 and 2016, respectively. The intra-RIR policies, however differ across regions. ARIN, APNIC and LACNIC mandate the *need assessment* requirement; i.e., buyers have to demonstrate a detailed plan of the address space usage for up to 24 months and have to acquire at least a /24 address block. Moreover, LACNIC's policy imposes restrictions for the organizations involved in the IPv4 transfer market–sellers are not eligible to receive IPv4 address for a year after the IP transfer occurred, and buyers are not able to resell the acquired space for a period of three years. RIPE, however implements *no need-based* intra-RIR transfer policy, imposing only that buyers are registered as LIRs. In the following years, the RIRs established inter-RIR transfer policies; APNIC and ARIN implemented an inter-RIR transfer policy in July 2012 [50], allowing organizations from the two RIRs to exchange address blocks. In September 2015, RIPE also implemented an inter-RIR transfer policy [51]. In contrast with their intra-RIR policy, RIPE's inter-RIR policy mandates buyers from RIPE to document the usage of at least 50% of the transferred IP space for five years. Thus, all the existing inter-RIR transfer policies are *need-based* policies.

4. Datasets

In this section we present a short description of the datasets used in our work.

List of reported transfers: Registries periodically publish the intra-RIR and inter-RIR IPv4 address space blocks exchanged on the IPv4 transfer market[1]. ARIN reports the first intra-RIR transferred IP block in October 2009 [36], APNIC in November 2010 [37], RIPE in October 2012 [38]. The first inter-RIR transfer is reported in October 2012. We use the reported transferred IP blocks in the analysis we conduct in Section 5.

BGP data: In Section 6 we propose a method for inferring transferred IP blocks. Our methodology is based on routing data collected from two public repositories: Routeviews [52] and RIPE [53]. The collected data spans from 2004 until 2015. Our inferring approach leverages changes in the origin AS of the routed prefixes over time.

AS classification: In the analysis of the published transfers (see Section 5) we employ the AS classification scheme [54]. The scheme divides ASes based on business types into: EC (Enterprise Customers), STP (Small Transit Providers), LTP (Large Transit Providers) and CAHP (Content/Access/Hosting Providers). EC and CAHP represent edge networks, and STP and LTP represent transit networks.

AS-to-organization dataset: Researchers at the Center for Applied Internet Data Analysis (CAIDA) developed an AS-to-organization inference method [55] that employs WHOIS data to

[1] LACNIC reported recently the first intra-RIR transfer [39].

map ASes to their organization. We use the AS-to-organization datasets in Section 6 to filter out movements of the IPv4 address space that occur within the same organization.

RIR extended resource files: RIR publishes daily files about their current allocated and assigned resources (i.e., IP address space and AS numbers) [56]. Each line of these files contains details about the RIR's resources: type, country, date of the allocation/assignments of the resource, the resource and an organization identifier, that represent the holder of the resource (see [57]). The holder's identifier *may* differ across files generated in different days, but is guarantee to be constant within the same file. We leverage these information in Section 6 where we investigate how additional data sources can aid our BGP-inferring methodology.

IP census data: Researchers at the Information Sciences Institute (ISI) collect the Internet census data by probing with Internet Control Message Protocol (ICMP) echo-request messages all the allocated IPv4 addresses every two-four months [58]. The ICMP reply message received from a probed IPv4 addresses indicates the state of the host behind the IPv4 address. Thus, an ICMP echo-reply message shows that the host is active and the probed IPv4 address is utilized. In Section 5, we use the IP census data to study the utilization of the transferred IPv4 blocks before and after the transfer occurs. To this end, we employ data that spans from November 2009 until December 2015, and compute the utilization of an IP block as the fraction of IPv4 addresses in the block that are active.

DNS data: We investigate in Section 6 whether the usage of DNS resource records [59] can improve our BGP-inferring methodology. To this end, we extract the DNS records from DNS data published by the CAIDA and the Internet Systems Consortium (ISC). The former comprises two full DNS scans of the routed IPv4 address space [60] and DNS name datasets obtained from DNS lookups performed on IPs addresses chosen from topology traces obtained from CAIDA's Archipelago (ARK) active measurement infrastructure (see [61]). The latter source is obtained from quarterly queries of domain names assigned to IP addresses delegated within the IN-ADDR.ARPA domain [62].

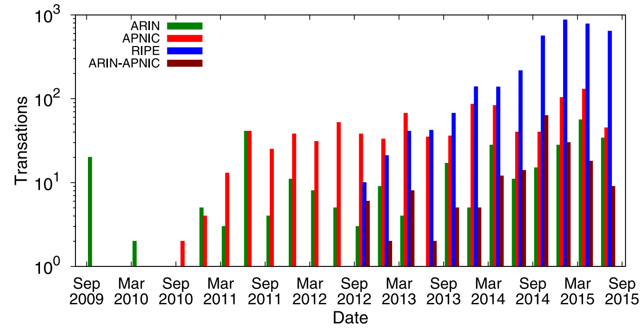
5. Analysis of the reported transfers

We present in this section an in-depth analysis of the documented IPv4 transactions within each of the three RIRs. To this end, we consider the lists of reported transferred IP address blocks.

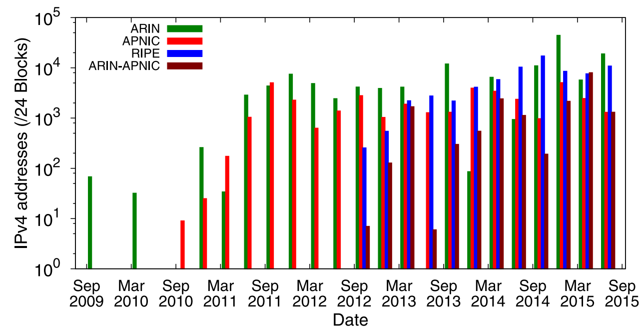
5.1. Overview of the market transfers

As of September 2015, the overall number of transferred IPv4 address blocks was 4947; ARIN reported 309 completed transactions, APNIC reported 941 and RIPE 3523. As in our previous study [15], we excluded from our analysis a set of ARIN and APNIC intra-RIR transactions. More specifically we removed 26 transactions reported by ARIN that involved blocks reserved by ARIN for Internet Exchange Points (IXPs), and 111 transactions from APNIC that involved transfers within same organization.

Fig. 2 shows the quarterly evolution of the reported transfers per RIR. We present in Fig. 2(a) the number of transactions and in Fig. 2(b) the number of /24 blocks transferred. Starting from 2013, the overall number of transactions has increased by more than 80% per year, with the most significant increase occurring in RIPE. The transactions completed within this region account for 71.20% of the total number of transactions. However, counting the IP addresses shows a different picture. Half of the total address space exchanged in the market came from organizations in the ARIN region; 87% and 65% of the blocks bought within RIPE and APNIC, respectively, are smaller or equal to /20. Our analysis shows a difference in terms of the exchanged address blocks across RIRs. We investigate whether this difference is caused mainly by the presence of legacy holders within the ARIN region.



(a) Number of reported transactions



(b) Number of transferred /24 blocks

Fig. 2. Evolution of the number of reported IPv4 transfers per RIR. RIPE exhibits the highest activity: 71.20% of the transactions occur within this region. Half of the address space comes from the ARIN region.

5.2. Legacy allocation

The underutilization of the legacy space has been pointed out by previous studies e.g. [16]. Transfers of legacy blocks would indicate a redistribution of such address space. Our analysis of the reported transfers shows that legacy space accounts for 63.82% of the total transferred space. However, this space is not equally distributed across RIRs. More than 90% of the transferred space coming from sellers in ARIN is legacy space. In contrast, in the APNIC and RIPE regions this space accounts for 27.15% and 13.20%, respectively. When counting how much the transferred legacy space represents of the total legacy space, we find that it accounts for less than 3% within each region.

5.3. How much of the IPv4 address space need is covered by the market?

We further investigate to what extent the market satisfies the organizations needs for extra IPv4 addresses. To this end, we extract for the three RIRs that reported transfers, the total number of allocated IPv4 addresses per year. These numbers are publicly reported by the RIRs [56]. We then compare these values to the number of transferred blocks. Fig. 3 shows the number of transferred and allocated /24s per RIR since the emergence of the transfer market until the end of our measurement period (i.e., September 2015).

As expected, we observe an increase (decrease) in the number of transferred (allocated) /24 address blocks over time. Staring from 2014, the number of transferred and allocated address blocks are comparable. In 2015, however, the number of trans-

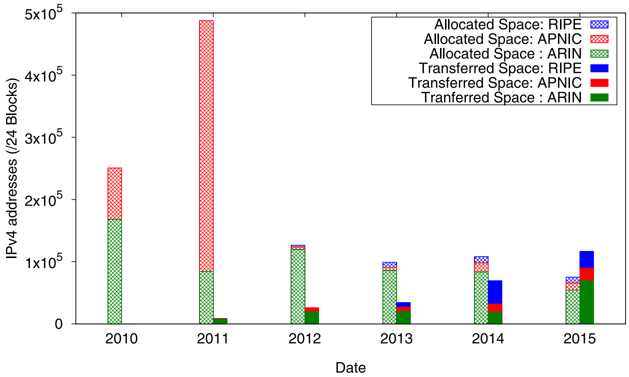


Fig. 3. Overall number of allocated addresses versus the overall number of reported transferred addresses over time.

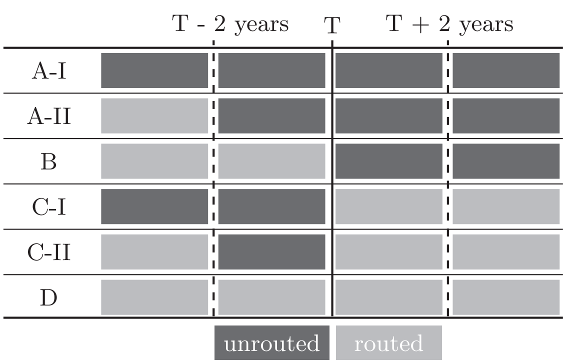


Fig. 4. IPv4 visibility classes of the transferred address space. Classes C-I, C-II and D mark address space that is routed after the transfer date (T). Space classified in either A-I, A-II or B is currently not routed.

ferred blocks, has for the first time surpassed the number of allocated blocks across RIRs. Hence, the IPv4 transfer market appears to play an important role in satisfying the demand for IPv4 addresses.

We further break down our analysis per RIR. Except for 2011, most of the new allocations are in ARIN. This is likely because of differences in the allocation policies followed by RIRs once they stared allocating from their last pool of IPs (last /8). Once they reached their last /8 block, both RIPE and APNIC, imposed an upper limit on the size of allocated blocks [1,3]. ARIN, however, did not impose any restrictions on the allocation size [4]. Our analysis shows that most of the transferred space is exchanged within ARIN. This is likely due to the presence of a large number of legacy holders in ARIN. Also, we believe that the increase in the transferred space observed in the last snapshot is mainly due to the 2015 complete runout of ARIN's available IPv4 addresses. According to the observed trends, IPv4 transfer markets are becoming the primary source for meeting demands for IPv4 addresses.

5.4. Do organizations use the transferred space?

We analyze the usage of the transferred address space from two perspectives. First, we investigate whether this space is advertised in the routing table before and/or after the transfer date. To this end, we define six visibility classes which reflect the life-cycle of the transferred space (see Fig. 4). *Class A-I* includes space that is not routed throughout our study period. *Class B* comprises address space that appears in the routing table only before the transfer date, and *class A-II* includes space that stops being advertised in the routing system at least two years before the reported transfer date. We separate the IP blocks that appear in the routing system after the transfer date into two classes: *C-I and C-II*. The former includes space that is only routed after it has been transferred, and the latter includes address blocks that are not routed at least two years before the transfer date. *Class D* includes address space that appears before and after the reported transfer date. Table 1 lists the percentage of reported transaction for each visibility class. We find that 94% of the transferred space is currently routed (i.e., classes C-I, C-II, and D). Moreover, 85% of the address space is either routed for the first time or rerouted after two years (i.e., C-I and C-II classes). Thus, we observe a high routing visibility of the space exchanged on the IPv4 market, indicating the organizations are using the acquired address space.

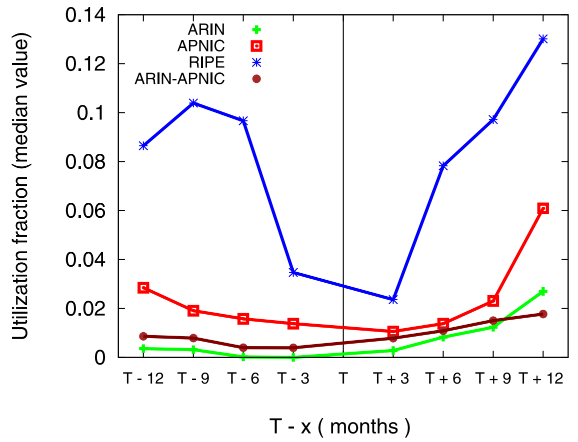


Fig. 5. Reported transferred space utilization per RIR. The utilization fraction of the space increases after the transfer date with at least 50% across RIRs.

We further analyze to what extent the transferred space is used by leveraging information extracted from the IP census data [58]. A snapshot from this data provides results from sending ICMP probes to allocated IPv4 addresses. We consider the *utilization of a prefix* to be the fraction of IP addresses that replied to the ICMP echo requests. To evaluate transferred space utilization, we take the following steps. We first compute the utilization fraction of each transferred prefix for each snapshot in the census data. Second, we extract for each prefix the maximum value of the utilization fraction in x months before and after the transfer date; we consider x to be 3, 6, 9 and 12 months. For each RIR, we extract the median of the obtained maximum values; Fig. 5 shows the computed median values. The vertical line shows the reported transfer date *T*. On the plot we also mark the periods before and after the transfer as *T-x* and *T+x*, respectively. Our analysis shows a clear decreasing trend before the transfer date, indicating the decrease in the utilization of the prefixes by the sellers. We also observe an increasing trend in the utilization of the prefixes after the transfer, which indicates the increase in the usage of the space by the buyers. When comparing the transferred space usage 12 months before and after the reported date, we note that the utilization fraction increases by at least 50% across all regions. Moreover, in the ARIN region we observe the most significant increase as the fraction increases by 6 times. The high discrepancy in the utilization of the prefixes by the sellers and buyers indicates that organizations acquire IPv4 address to satisfy their address space needs.

5.5. Sellers and buyers in the market

We employ the AS classification scheme described in Section 4 to analyze the business type of the ASes involved in the market. A total of 1368 networks were involved in the market since its inception. Apart from these, our analysis shows the presence in the market of organizations that do not have an AS

Table 1
Number of reported transaction for each IPv4 visibility class per RIR and overall.

RIR	A-I	A-II	B	C-I	C-II	D
APNIC	48 (5.71%)	30 (3.65%)	66 (7.77%)	99 (12.03%)	26 (3.16%)	555 (67.68%)
ARIN	18 (6.36%)	16 (5.65%)	36 (12.72%)	60 (21.21%)	35 (12.36%)	118 (41.70%)
RIPE	109 (3.10%)	41 (1.16%)	485 (13.76%)	248 (7.04%)	73 (2.07%)	2567 (72.86%)
ARIN-APNIC	16 (9.14%)	5 (2.86%)	9 (5.14%)	12 (6.86%)	4 (2.29%)	129 (73.71%)
Total	190 (3.96%)	92 (1.91%)	592 (12.32%)	419 (8.72%)	138 (2.88%)	3373 (70.21%)

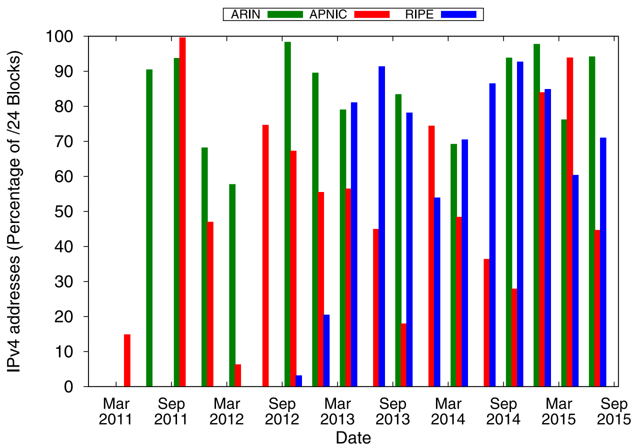


Fig. 6. Percentage of IPv4 address space exchanged between the top 10% participants in the IPv4 transfer markets.

number. These *non-BGP speaker* organizations are involved in 25% of the overall transfers. The market, however is dominated by *edge* networks (i.e., EC and CAHP); these networks are involved in more than 90% of the reported transactions.

We further focus on how much space participants[2] trade in the market. Our analysis shows that the IPv4 transfer markets are dominated by a small number of participants in every region; 80% of the IPv4 address space appears to be sold/bought by the top 10% participants in the market. We show in Fig. 6 the evolution of this percentage over time. In the ARIN region, half of the sold space comes from two organizations, and 62% of the space is acquired by only two organization; our analysis shows that most of this space is legacy allocations.

Due to the large number of involved organizations in the APNIC and RIPE regions, we present our results at the country level. The organizations involved in the market come from 29 and 64 countries in APNIC and RIPE, respectively. In the former region, we identify three dominant countries: China, Japan and Hong Kong; more than 70% of the space transferred within APNIC is traded among these countries. For the latter, we also find that 50.13% of the address space sold in RIPE came from two countries (Romania and Germany), and 30% of the space is bought by organizations in two countries (Saudi Arabia and Iran).

5.6. Do the markets slow down IPv6 adoption?

We seek to understand the impact of IPv4 markets on IPv6 adoption. Our approach is to analyze whether AS buyers originate IPv6 prefixes after they purchase IPv4 address space. In order to quantify the number of such ASes, we compute the fraction of *future IPv6 adopters* (f_a) at a given time T as the fraction of buyers that originate IPv6 prefixes after T. Fig. 7 shows the evolution of this fraction. We first observe an increase in the value across all

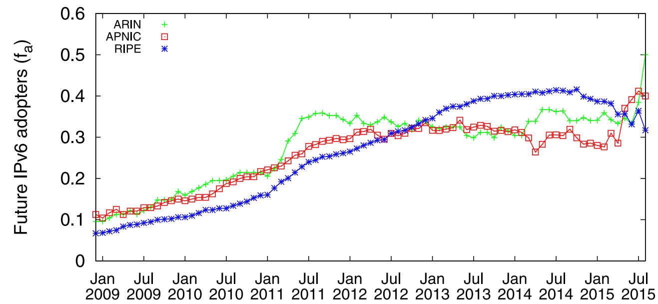


Fig. 7. Fraction of future IPv6 adopters per RIR.

RIRs, hinting that the markets do not slow down the IPv6 adoption process. However, staring with 2012 the fraction either decreases slightly or remains at approximately the same value. When computing our metric we consider only future buyers. However, their number depends on the time window during which we consider these buyers. Since the time window decreases towards the end of our measurement period, we acknowledge that the observed flattening effect can be an artifact of this decrease.

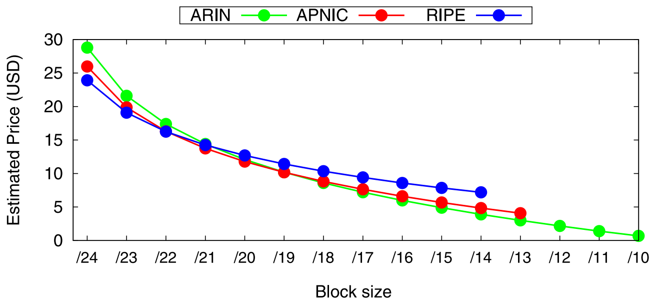
5.7. Value of the market

The monetary details of IP transactions are often not made public. Except for a few well-known transaction [63,64], the closest IPv4 price estimation is provided by the IPv4 brokers [65–67]. Several of these organizations periodically publish average prices for the IPv4 transferred blocks. We note, however, that involvement of the brokers in the IP transactions is not mandated in the RIR policies. Thus, prices published by IPv4 brokers offer only a partial view of the IPv4 transfer market value. The price varies based on several factors, e.g., the RIR where the transfer takes place, the size of the transferred address block, and the IPv4 broker that facilitates the transfer. Considering this observation, we estimate the IPv4 address prices using the *hedonic pricing* method [68]. This method determines the value of a good by considering both the *internal characteristics (i)* of the good and *external factors (e)*. We further present our approach to model each of the two types of factors. We note that when estimating one component, we consider the other one to be fixed.

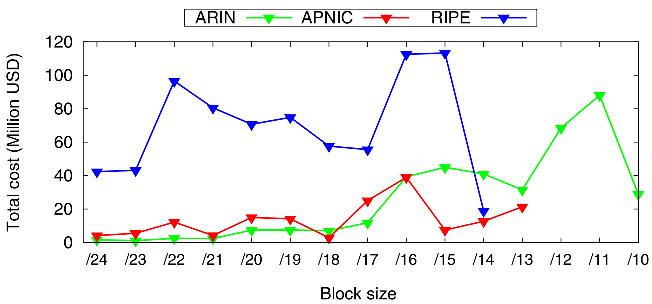
We consider as external factors the broker involved in the transaction (b) and the RIR where the transfer takes place (r). Due to the limited number of published prices, we use in our model only prices reported by one broker in 2015 which is the IPv4 Market Group broker. Since the IPv4 markets are regulated within each RIR, we assume that a constant function captures the selected external factors: $f_e(b, r) = C_r$.

We identify as an internal characteristic the size of the transferred address block (x, $x \in \{10, \ldots, 24\}$). When estimating the price for IPv4 blocks of different size, we take into account the basic *market supply curve*; i.e., the price of good increases sub-linearly with the increase in the quantity. Hence, we model the IPv4 block price using a *logarithmic* function: $f_i(2^{32-x}) = a * ln(x) + b * x$.

[2] We conduct our analysis of the participants in the IPv4 transfer markets at the level of the organizations in ARIN, and at the country level in APNIC and RIPE.

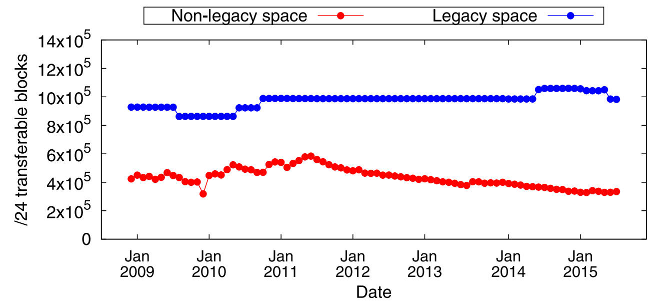


(a) Estimated IPv4 address price per address block

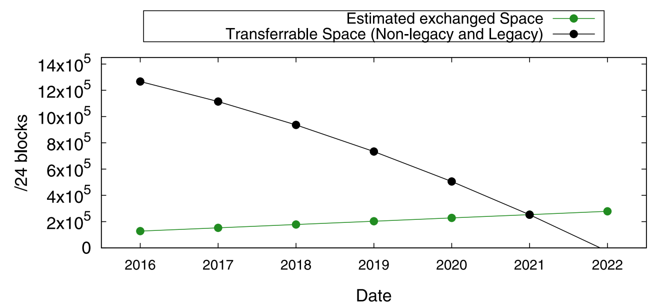


(b) Estimated value of the IPv4 market per address block

Fig. 8. IPv4 market value for transactions reported in 2015.



(a) Number of legacy and non-legacy transferable /24 address blocks over time.



(b) Estimated consumption of the transferable space on the transfer market.

Fig. 9. IPv4 transfer market lifespan.

Taking into account both of these functions, we express the IPv4 address price (P) as:

$$P = f_e(b, r) + f_i\left(2^{32-x}\right) = C_r - (a_r * ln(x) + b_r * x)$$

After we fit the parameters, we obtain the IPv4 price for different block sizes across the RIRs involved in the IPv4 transfer markets. Fig. 8(a) shows our estimated prices per address block. Our estimation indicates that in 2015 roughly $144 millions were exchanged in the market (see Fig. 8(b)). Using the same prices, we estimate the total value of the measured reported transactions at $368 millions.

5.8. Routing table impact

In order to assess the impact of the transferred prefixes on the routing table, we investigate the effect of these prefixes on the routing table size. We thus analyze the contribution of these prefixes to the *deaggregated prefixes* and the *routing table size increase*.

We focus on the first metric, and test whether the transferred address blocks appear deaggregated after the transfer date; i.e., do we observe more specific prefixes from the transferred prefix? Our analysis indicates that 13.45% of the transferred prefixes are deaggregated after the transfer date. The per-RIR analysis shows these percentages to be 28.77%, 14.55% and 7.93% in ARIN, APNIC and RIPE, respectively. We believe that the discrepancies between the three registries are due to the different blocks sizes; a high percentage of the blocks exchanged within ARIN are large blocks, whereas organizations in RIPE trade smaller blocks. We next check whether transferred prefixes are deaggregated more than other prefixes by comparing the average contribution of a transferred block to the overall set of deaggregated prefixes to that of a non-transferred prefix. These values, however, turned out to be comparable, 0.0041% and 0.0045%.

To evaluate the contribution to the increase of the routing table size, we take the following steps. For any two consecutive months, we extract the list of prefixes that are advertised only in the second month. Then, we determine how many of these newly advertised prefixes are transferred address blocks or more specifics of them. Our results indicate that on average 0.3% of the contribution to the routing table is due to transferred space in APNIC and ARIN. For RIPE, however, we find this percentage to be 1.46%. From the conducted analysis, we conclude that the transfers do not impact the routing table.

5.9. IPv4 transfer market lifespan

Estimating the IPv4 transfer market lifespan is highly dependent on both the number of sold and bought IPv4 addresses on the market. However, knowing what incentivizes organizations to sell IPv4 blocks is not trivial. Also, organizations' decisions to buy IPv4 addresses on the market can be influenced by different factors like IPv6 adoption and RIRs transfer policies. Thus, we base our estimation on the analysis of reported transfers and on some assumptions which we state next.

For estimating the IPv4 address space *supply* on the market we leverage two main findings extracted from our analysis: the majority of the transferred blocks are not routed prior to the transfer date, and a large percentage of the transferred space comes from legacy allocations. Hence, we assume that an IPv4 block might be traded if it has not been advertised for a certain period of time. More specifically, we consider an allocated block as *transferable* if it has not been advertised for five years or more. Assuming that organizations choose to sell all their transferable addresses, the market supply consists of the overall transferable IPv4 address space. Fig. 9(a) shows how the numbers of transferable non-legacy as well as legacy /24 blocks have changed between 2009 and 2015. For the latter category, we exclude IPv4 address space that appears to be a key to the legacy holders' core business. For example, we select MIT's legacy block (i.e., 18.0.0.0/8), but exclude Level 3's legacy block (i.e., 4.0.0.0/8). Thus, we employ for our analysis only 29 /8 legacy blocks. Starting with 2011, the number of transferable non-legacy blocks has been steadily decreasing. We use the least squares method to linearly fit ($R^2 = 0.90$) the decreasing trend and find that the number of transferable non-legacy /24s decreases at a rate of 1451 per month. Based on our estimation, the transferable non-legacy address space will be depleted by 2021. In contrast, the number of transferable legacy blocks has been consistently higher than the non-legacy blocks. Moreover, the number of transferable legacy blocks has remained at approximately the same value, indicating the underutilization of the legacy space. We further seek to determine the consumption date of the IPv4 address space supply.

We assume external factors affecting the market (i.e., IPv6 adoption, RIRs transfer policies) and the growth rate of the market size do not change in the following years. In other words, the IPv4 address space *demand* increases at the same rate. Based on the analysis in Section 5 less than 2% of the reported transfers appears to be resold on the market. Thus, we build our prediction just for first-time sales of the IPv4 address space. A linear fitting ($R^2 = 0.90$) of the yearly number of transferred /24 blocks reveals the market has grown each year by 25140 /24 blocks. We project the demand curve and obtain the estimated number of transferred /24 blocks for the following years. Given these estimated values and assuming that all the address space we previously defined as transferable is available on the market, we further predict the consumption date of the market supply. For each year, we extrapolate the observed demand for addresses, and determine the number of non-legacy and legacy transferable blocks that are present on the market, accounting for the rate at which the non-legacy blocks decreases. Then, we find how much of the demand would be accounted for by the non-legacy versus legacy blocks, which would determine the number of available transferable space in the following years. The *fist-time* transfer market is exhausted when the demand exceeds the available transferable blocks. Fig. 9(b) shows both the estimated number of transferred /24s and the consumption of the available transferable space (non-legacy and legacy). Based on our estimation, the transferable space will be depleted by 2022.

Our predictions regarding the market lifespan are valid given that the initial assumptions regarding the market factors continue to hold. Resale of the IPv4 address space, changes in the IPv6 adoption rate, transfer policies or IPv4 address pricing may cause the estimated trajectory of the market lifespan to change. Also, organizations might choose to readvertise or return to the RIRs their own transferable space changing the available IPv4 address space supply and modifying the IPv4 transfer market lifespan.

5.10. Summary

Our analysis of the reported transfers indicates a clear increase in the overall number of transferred blocks in the last two years. We note that a large percentage of this space is legacy space. We also find that buyers across RIRs appear to utilize more the IP space acquired on markets, as more than 90% of the IPv4 blocks exchanged on the markets are currently routed.

The IPv4 transfer markets, however differ across regions in terms of size and type of transferred blocks. Transfers in ARIN are dominated by a few organizations that exchange large blocks of legacy space. Thus, while the market seems to facilitate the redistribution of legacy space, this space is actually exchanged between a few organizations. For APNIC, most of the space is transferred within the same country. The address space in RIPE is transferred mostly in small blocks between organizations that are registered in different countries. Furthermore, IPv4 transfers seem not to slow the IPv6 adoption process or impact negatively the global routing table.

Our estimation of the market evolution indicated that the legacy space is going to continue to represent the main resource for at least six years, given the current state of different external factors and the current growth rate of the market size.

6. Inferring transfers

Approved address space transactions are made in accordance with the RIRs transfer policies. However, there is no clear mechanism to ensure that organizations report these transactions to their regional registry. Due to the restrictions imposed by the RIRs through both their transfer and allocation policies, organizations could be exchanging address blocks without RIRs approval, leading to inaccuracies in prefix ownership in RIRs records. It is thus important to develop a method that infers transfers *in the wild*.

In this section, we present an approach to inferring IPv4 transfers. We first build a list of candidate transfers by analyzing prefix origins as they appear in the global routing system. Secondly, we investigate how other sources of data (i.e., DNS resource records and RIR resource records) can help our basic approach. Finally, we conduct an analysis of the inferred movements by investigating the address space and the networks involved in these movements.

6.1. BGP detection

Our proposed approach is built on the assumption that a routed prefix is *owned* by its originating AS. Using this assumption, we employ BGP routing data to build monthly prefix-AS mappings as follows. First, we collect routing tables form RIPE RIS *rrc04* [69] and Routeviews *routeview2* [52] collectors[3], on the first seven days of each month from 2004 to 2015. For each day, we construct prefix-AS mappings, and retain only the prefixes that were present for at least four days and were seen from monitors that observe more than 90% of all routed prefixes. We obtained 1282475 unique mappings during the study period. Using these mappings, we identify *candidate transfers* as prefixes for which the origin AS changes over time. We classify the transfers as either *full* or *partial*, depending on whether we observe an origin change for the entire address block or just for a part of it. However, we note that using the routing data we are able to detect only transfers of the *routed* IPv4 blocks of the *BGP-speaking* organizations. Also, such movements can occur due to well known reasons and practices; e.g., prefix hijacking or internal changes to an organization. During a prefix hijack, an AS falsely advertises a prefix that it does not own; example of such cases are the YouTube prefix hijack and the Level3 Outage [70,71]. Internal changes to organization can occur due to merger and acquisition (M&A). To remove false positives caused by such reasons, we devise a set of *BGP-filters*. Fig. 10 shows an overview of our BGP-based inference methodology.

Map-to-organization filter: RIRs allocate address space and AS numbers to local organizations. From the ownership perspective, these resources are mapped to the organizations. Thus, IPv4 address space that appears to move between ASes of the same organizations does not change ownership, and consequently does not constitute a transfer. We use the AS-to-organization dataset described in Section 4 to identify the ASes that belong to the same organization, and filter out movements that occur between these ASes.

Transient filter: Short-lived prefix advertisements in the routing systems can be due to different reasons; e.g., prefix hijacks or misconfigurations. Such transient advertisements cause origin AS changes, that in turn generate candidate transfers. We seek to filter out these movements by imposing a minimum advertisement period for a prefix. We note that documented cases of prefix hijacks report the duration of such events to be less than one month. Since we build the prefix-AS mappings every month, we choose one month as the minimum advertisement period. Thus we keep

[3] The chosen collectors offer the largest view of the routed prefixes. For each day, we combine the largest routing table from both collectors.

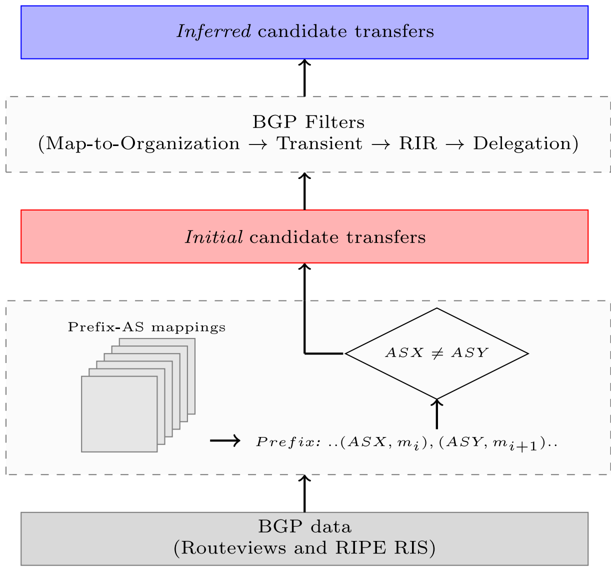


Fig. 10. BGP detection overview

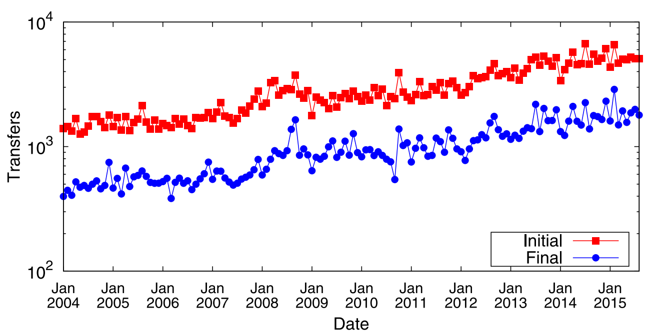


Fig. 11. Number of inferred candidate transfers.

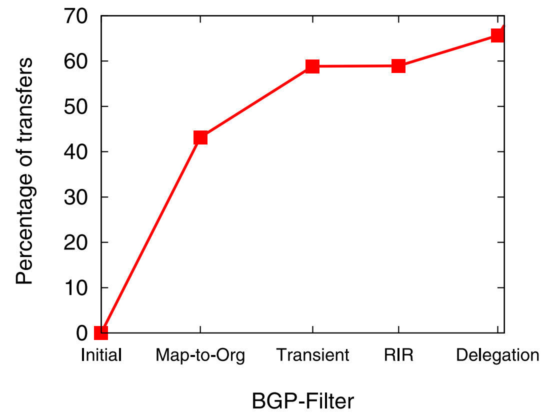


Fig. 12. BGP-filtering methodology analysis.

Table 2
BGP-Inferred transfers validation with the reported transfers by the RIRs.

RIR	Undetected	False negative	Detected
APNIC	136	25	395
ARIN	24	4	90
RIPE	556	195	1817
ARIN-APNIC	73	4	52
Total	789	228	2354

as candidate transfers, prefixes that are advertised by the same AS for at least two months.

RIR filter: Our detection methodology seeks to identify address space that moves between organizations. To this end, we filter out candidate transfers in which the address space is moved from or to an AS assigned to a RIR.

Delegation filter: We design this filter to remove provider aggregatable (PA) space assigned by service providers to their customers. To this end, we employ a classification method [72] that separates routed prefixes into four classes: lonely, top, deaggregated and delegated. The first two classes comprise prefixes that are not covered by any other routed prefix. Lonely prefixes do not cover any other routed prefixes, whereas top prefixes cover more specific prefixes. Address space classified as deaggregated and delegated is covered by a less specific prefix in the routing table; deaggreagated space is advertised by the same AS that advertises the less specific prefix, while delegated space is advertised by a different AS. From the ownership perspective, the covering prefix and deaggreagated/delegated prefixes are mapped to the same organization. Our filter is designed to remove BGP movements that involve delegated space.

6.2. Evaluating the results

Evaluating the methodology: Our BGP-filtering removed 65.63% of the initial 407046 candidate transfers, reducing this value to 139871. Fig. 11 shows the evolution of the initial and final number of candidate transfers. We note that both time series exhibit a similar strong upward trend increasing at the same rate. To assess our approach, we compute the percentage of candidate transfers removed by each filter. Fig. 12 shows the contribution of each filter to the overall percentage of removed candidate transfers. About 43% of the initial transfers are removed by the “map-to-organization” filter. The high impact of this filter is a direct consequence of organizations having many ASes allocated, which can be due to either M&A or usage of different routing policies. As expected, the “RIR” filter has the lowest impact, removing only 0.10% of the initial movements.

Validating the methodology: To test our detection methodology, we validate the inferred candidate transfers with the published transfers. Since our methodology relies on information retrieved from the routing tables, we validate only the reported transferred blocks advertised before and after the transfer date (i.e., transferred address blocks in *class D*). Moreover, since our approach relies on origin AS changes, we are able to analyze routed prefixes for which such a change occurs. We refer to these prefixes as *detectable*, and note that for such prefixes the date of the origin change may differ from the reported transferred date. We classify as *undetectable*, prefixes advertised by the same AS before and after the reported transfer date. These undetectable blocks represent 23.37% of the reported transfers. A closer analysis shows that for 40% of the undetectable transferred prefixes, one of the parties involved is a *non-BGP* speaker organization. We list the validation results in Table 2. Our methodology infers more than 90% of the detectable transfers. However, our approach also filters 6.8% of the reported transactions. About 90% of these false negatives are removed by the Transient filter. Two thirds of the prefixes removed by this filter are filtered out because their measured transfer date is the last month in our study period. Extending the study period will increase these prefixes advertisement period and thus they will not be filtered out. The bulk of the remaining false positives are removed by themap-to-organization filter. Most of these transfers occurred in the APNIC region and are due to M&A. For example, we exclude IP blocks acquired by Vocus from Digital River and Go Talk, as both companies were bought by Vocus [73–75].

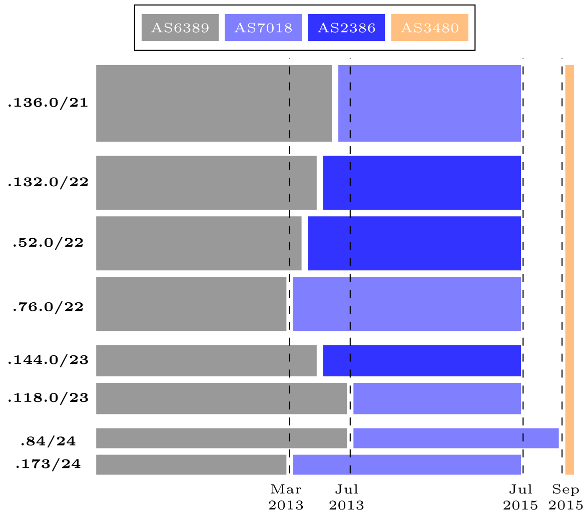


Fig. 13. Case study - BGP movements of 168.8/14 address space.

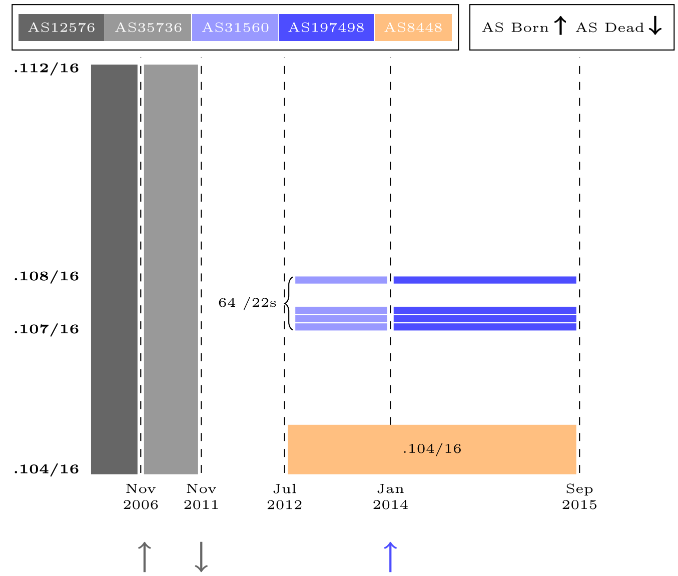


Fig. 14. Case study - BGP movements of 91.104/13 address space.

6.3. Possible causes of false positive BGP movements

Although our method infers a large percentage of the published transfers, it also produces a large number of false positives. We note that our BGP-approach captures events related to *BGP-speaking* organizations. Thus, the methodology does not reflect changes related to organizations that do not have an AS assigned (*non-BGP speaking* organizations); e.g., non-BGP speakers switching provider or becoming BGP-speaker organizations. Also, the employed BGP-based approach can produce false positives related to operational changes in IPv4 address space management and redistribution like reallocated IPv4 blocks, IPv4 address space movements within the same organization and AS numbers acquisitions by organizations.

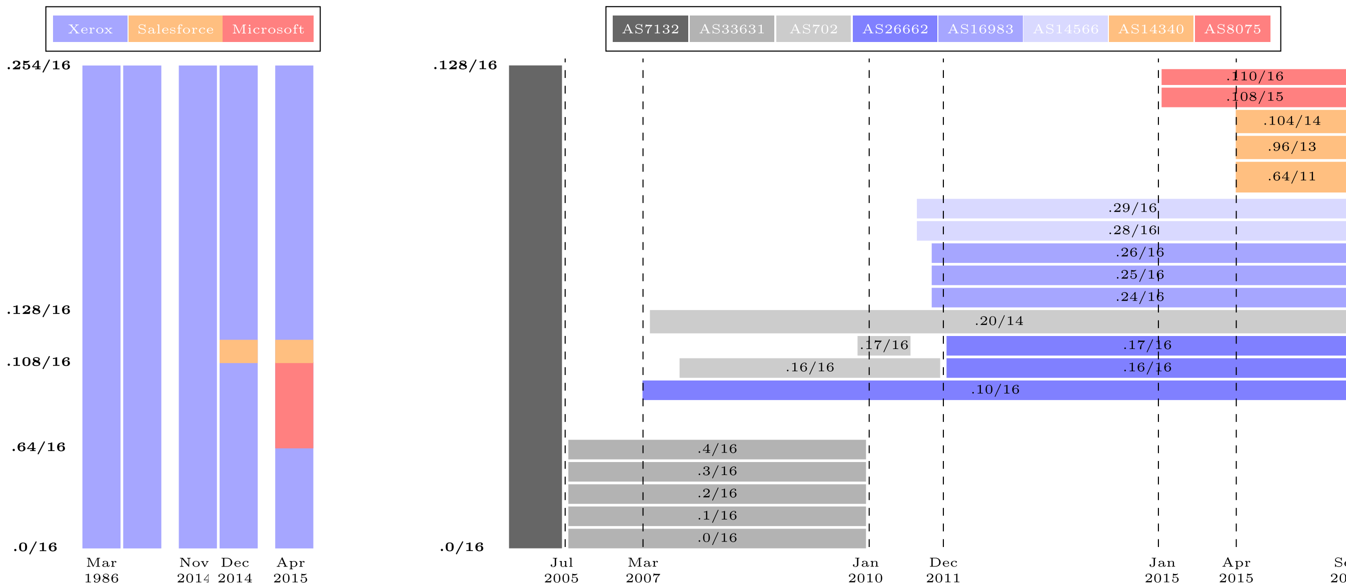
To dig deeper into the causes of the false positive movements, we analyze three case studies. For the IPv4 address space involved in each of the presented cases, we determine whether any changes related to the address blocks are documented by inspecting the WHOIS data, the RIR allocation and assignment files, and WHOWAS [76] data service provided by ARIN.

Non-BGP speaker switching providers: Fig. 13 shows the BGP movements of the 168.8/14 address space. AS6389 (BellSouth Network Solution) advertised eight prefixes of different length from this address space until the beginning of 2013, then all of these prefixes started being advertised by AT&T (AS7018 and AS2386) until the second half of 2015. Staring from September 2015, the /14 block is advertised by AS3480, which is assigned to Kennesaw State University, that is part of the University System of Georgia. The WHOIS dumps show that the /14 address block was assigned from 2006 to the University System of Georgia. According to the delegation files the organization does not have an AS assigned. AS3480 also appears in the routing system for the first time when it starts advertising the /14 block. According to these records, we conjecture that AT&T and Bellsouth were just providing transit for the non-BGP speaker organization. Once Kennesaw State University acquired an AS number, it started advertising the address block. Thus, the inferred movements reflect the dynamics of a non-BGP speaker organization.

BGP movements of the 91.104/13 address space: Fig. 14 illustrates movements of IP blocks from the selected network range. In November 2006, the /13 block moved from AS12576 to AS35736. The latter AS appears (disappears) in the routing table at the same time it starts (stops) advertising the /13 block. WHOIS dumps show that the two ASes were assigned to the same organization (Orange), and that in September 2006 Wanadoo UK [77] received the /13 block. The company was a division of Orange S.A (former France Telecom) and operated worldwide until June 2006, when Wanadoo merged with the mobile subsidiary of the parent company. Thus, the inferred movement is a false positive caused by business restructuring. This movement, however, is not removed by our methodology as the employed AS-to-organization data does not map two ASes to the same organization.

In November 2011, AS12576 stopped advertising the /13 block. The following year, 152 more specific prefixes from the address block started being advertised by different ASes. We focus on two /16 address blocks: 91.104/16 and 91.107/16. The former was advertised from July 2012 until the end of our measurement period by AS8448 (Telenor Hungary). The latter prefix appears in the routing table as 64 /22 blocks advertised first by AS31560 (Insource LLC), and then by AS197498 (Verbeta Ltd.). Analyzing the 2012 WHOIS data for the two /16 blocks shows that Telenor Hungary and AVK Computers own the former and latter address block, respectively. Accordingly, we believe that these movements were caused by reassignment of the address space. In order to remove such cases, we require information about reassigned and reacquired address space.

BGP movements of the 13/8 legacy block: We illustrate in Fig. 15(b) how the 13/8 block was routed during our study period. The entire address space was advertised by AS7132 (AT&T) until July 2005. After this date, more specific prefixes from the /8 were advertised by other ASes; five /16 blocks are originated by AS33631 (Palo Alto Research Center Incorporated - subsidiary of Xerox) for five years, and AS702 (MCI) advertised one /14 prefix and two /16 prefixes. Staring from 2007, AS26662 (Xerox) advertised one /16, and from December 2011 seven other /16 start being originated by ASes that are assigned to Xerox (i.e., AS16983 and AS14566). From 2015, AS14340 (Salesforce) and AS8075 (Microsoft) advertised address blocks form the /8 address space. We infer partial BGP movements for the selected network range which map to the /8 block advertised by AS7132. Based on the inferred movements, we may assume that AT&T has either sold or delegated parts of the address space to the other organizations. In order to determine whether our previous assumption is correct, we analyze the ownership of the /8 address block. To this end, we employ WHOIS and WHOWAS, and present in Fig. 15(a) the evolution of the 13/8



(a) Evolution of 13/8 assignments

(b) BGP movements of 13/8 address space

Fig. 15. Case study - 13/8 legacy space.

assignments. This /8 block is a legacy allocation made in 1986 to Xerox. In the end of 2013, four /16 blocks were assigned to Salesforce; the following year, 44 /16 blocks were assigned to Microsoft. Investigating further, we find that these assignments correspond to transactions on the IPv4 transfer market within the ARIN region.

The considered address space exemplifies cases when organizations use large networks (e.g. AT&T) to advertise their space due to reasons like address space management, backup solutions or historic arrangements. Inferring movements that occur due to such relation is hard without additional information from the address space owner.

6.4. Summary

We present a methodology to infer transfers *in the wild*. The basic idea of our proposed approach leverages changes in the origin AS of the routed prefixes. While using the BGP-based methodology we are able to infer most of the reported transfers, we also obtain a high number of false positive BGP movements. These false positives can be attributed to dynamics of non-BGP speakers, address space relocation and reassignment, and complex address space management practices.

7. Reducing false positive movements

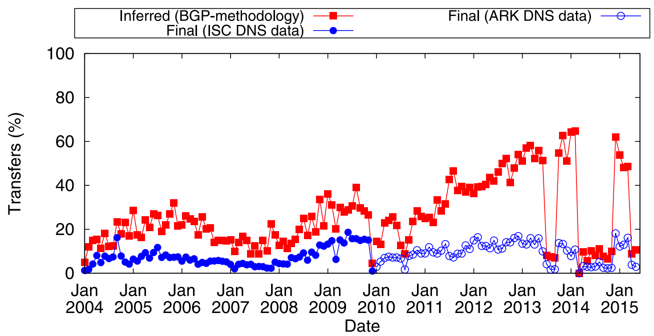
This section explores additional approaches to reduce the inferred false positives.

7.1. Filtering false positives caused by non-BGP speakers

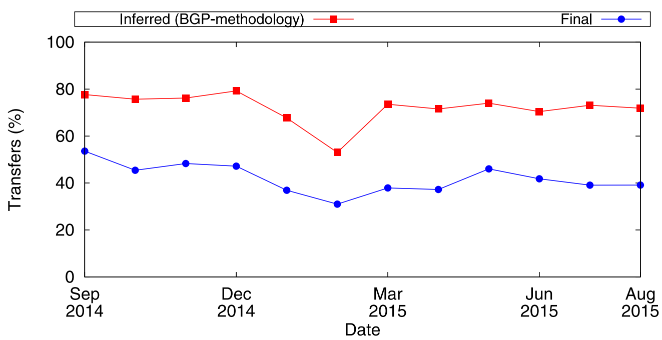
Having seen that non-BGP speaker organization can contribute to the high number of inferred BGP movements, we investigate in this section whether we can filter such movements. More specifically, we explore how additional data sources could provide different insight on the inferred candidate transfers than the one obtained from BGP data. We use two distinct data sources: *DNS name* data and *RIRs extended resource allocation* files (see Section 4 for a detail description). Both datasets provide information related to IPv4 address space registered to different organizations. The RIRs extended resource files report the owners of the address space, while the DNS data gives domain names mapped to different address blocks. Ownership changes of the IPv4 address space should reflect in changes in these datasets. We note, however, that there is a significant difference between this data and the routing data used in our detection methodology. In the case of the routing data, both RIPE RIS and Routeviews projects publish high-frequency historical BGP data, whereas the RIR and DNS datasets suffer from different limitations. We detail each of these limitation in the following subsections, and also acknowledge that due to these restrictions we are able to analyze only a limited number of inferred BGP movements. These are, however, enough to demonstrate the potential of the two datasets for reducing the number of false positives.

Changes in DNS information: The DNS name maps domain names to IP addresses [59,78]. Thus, changes of IPv4 address space ownership can also lead to changes in respective DNS records. We use in our analysis information provided by two DNS data records: *Pointer (PTR)* and *Start of Authority (SOA)*. The former record maps an IP address to the hostname, and the latter provides information about a particular domain (i.e., primary name server for the domain, contact name for the domain, version number). For each prefix in the BGP inferred movements we test whether we detect any change in the DNS information extracted from SOA and/or PTR records. To this end, we first extract the DNS information for prefixes that completely matches the prefix in the inferred movement or for the covering ones. Next, we compare both DNS information before and after the observed transfer date. Finally, we remove only those inferred movements for which we detect a change in both DNS records. If we do not find such a change or the prefix does not have corresponding DNS records we keep it in the inferred movements.

Our analysis employs DNS data collected from the ARK project [61] and ISC data [79]. The former is collected from 2008 for a subset of the routed IPv4 address space through measurements that run on ARK monitors. At each round of measurements, one monitor probes a randomly selected IP address from each /24 routed prefix; the monitor-IP address destination pairing differs from one round to another. Thus, at each round the collected data is obtained from different set of monitors to most likely different set of IP addresses. The PTR records are collected each month, while the SOA records are collected quarterly. The ISC



(a) DNS Data Source: ARK and ISC DNS data



(b) DNS Data Source: DNS scanning of the IPv4 address space

Fig. 16. Applying DNS filtering to inferred movements.

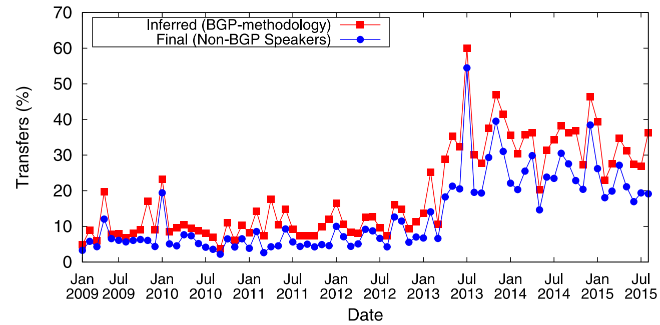


Fig. 17. Percentage of BGP movements caused by non-BGP speaker organizations switching providers.

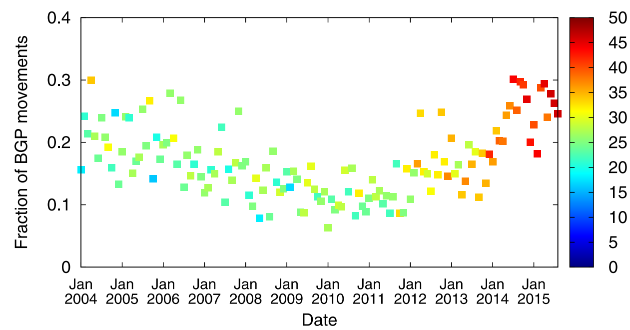


Fig. 18. Inferred BGP movements that come from legacy space.

project collected only PTR records, and collected data spans from 2003 to 2010. The available DNS datasets complement each other in terms of time. However, due to the way the data is collected, both datasets are limited in frequency and scope. As a result, we are able to analyze an overall of 27.5 % BGP-inferred movements. Fig. 16(a) shows the evolution of this percentage, as well as the effect of our DNS filtering approach; two thirds of the analyzable movements are removed by the filtering. As expected, the filtering removes a higher percentage of the movements after 2010, when we employ both PTR and SOA records. Our analysis indicates the potential of our proposed approach. However, in order to employ this method we believe that finer-grain DNS scans are needed.

Taking into account the mentioned limitations of the available DNS data, we have actually attempted to confirm the potential of using a better dataset. To this end, in August 2014 and September 2015, using the ARK infrastructure we conducted two full DNS scans of the entire routed IPv4 address space [60]. From this data, we extract the DNS records of the IP blocks involved in the BGP movements that occur within this 12 months period. We present in Fig. 16(b) the DNS filtering results for the selected period of time. The DNS data covers 71% of the 22618 movements that occur between the two dates; the DNS filtering removes 58.50% of these movements. These results reinforce our belief in the need of dedicated measurements for the DNS filtering approach. We also note that the collected data did not comprise DNS records for all the routed IPv4 address.

Changes in the RIR records: Each of the five RIRs publishes daily information abut the allocation and assignment of Internet resources (i.e., IPv4/IPv6 address space and ASes) within their region, providing for each resource the *unique identifier* of the resource holder. We use this identifier to map each organization to its resources, and determine organizations that have been allocated IP space but have no ASes allocated to them. Such organizations are *non-BGP speakers* as they most likely advertise their address space in the routing system via their provider. To identify movements of such address space, we classify for each inferred movement both the seller and the buyer as BGP speaker/non-speaker organizations. The RIRs, however, have started only recently to publish the organization identifier; APNIC started publishing this data in January 2009; AFRINIC and LACNIC in 2012, ARIN in April 2013; and RIPE in September 2015. As a consequence of the limited availability of this data we are able to analyze 22.61% of the 102019 of the transfers inferred by our BGP-based methodology from January 2009 to September 2015. For a third of these transfers (i.e., 7% of the inferred movements), the address space remains at the same non-BGP speaker organization. Thus, these movements are false positives caused by non-BGP speakers changing providers. The difference between the two lines in Fig. 17 shows the percentage of such false positives over time. We note, however that such movements have a small contribution to the overall number of inferred BGP movements.

7.2. Filtering false positive due to organization dynamics

Legacy space movements: As we saw in Section 6, dynamics of legacy space can result in false positives. Legacy space is expected to exhibit complex dynamics, since legacy holders are not bound by any contractual agreements to the RIRs as this type of address space was distributed prior the RIRs existence. In the last few years, the RIRs have made several efforts to redistribute legacy space, i.e., the early registration transfer (ERX) project [80] - migration of the early registration records from ARIN to the corresponding RIR, and policies for returning unused space [81] and for retrieving IPv4 address space from legacy holders [82]. We hypothesize that our detection captures movements of the IPv4 blocks caused by the redistribution and dynamics of the legacy space, and verify this by mapping the IPv4 blocks involved in the inferred BGP movements with /8 legacy blocks [31]. We present in Fig. 18 the fraction of such movements over time; such movements account for 17.38% of the overall inferred movements. The exchanged legacy

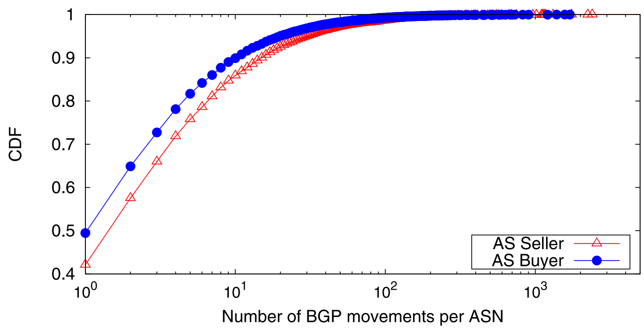


Fig. 19. CDF of the number of BGP movements per AS (seller/buyer).

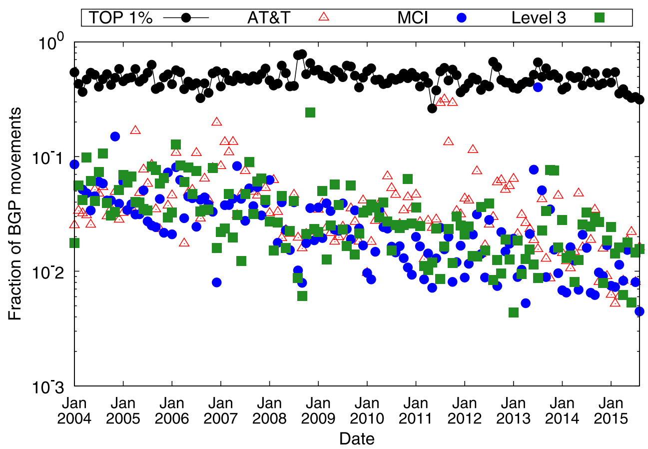


Fig. 20. Top 1% contributors to the BGP inferred movements. The top 3 organizations are involved (either as seller or buyer) in 9.60% of the total BGP movements.

space accounts for 14.28% of the overall legacy space and comes from 65 /8 legacy prefixes. The color-code on the plot reflects this number. The evolution of such movements reflects the difference before and after the emergence of IPv4 transfer markets, which occured in the end of 2009. In the pre-market period (i.e., before 2010), the movements came from a few legacy blocks. A closer look at these blocks shows that they were distributed to different RIRs as part of the ERX project; e.g., 128/8, 129/8, 130/8 and 140/8. We observe in the latter period (i.e., after January 2010) a clear increase in the number of legacy blocks that cover the BGP-inferred movements. The movements in this period account for 11.90% of the overall number of inferred movements which is 68% of the inferred movements that involve legacy space. The high percentage of legacy blocks-related movement confirms our hypothesis above.

Top contributors: As demonstrated by the third use case in Section 6, complex address management and historical arrangements can result in apparent transfers. These arrangements often involve ASes that involve backup connectivity or global interconnections. If such cases are prevalent, we expect that a large fraction of movements to involve a few ASes. To test this, we measure the number of apparent transfer per AS. Fig. 19 shows the CDF of the number of times an AS appears as a buyer or a seller in all inferred movements. About half of ASes appear only once, however, the top 1% ASes are featured in about half of all movements. Fig. 20 shows the fraction of movements that involve the top 1% contributors over time. It also shows the fraction contributed by the top 3 contributors which are AT&T (AS7132), MCI (AS702) and Level3 (AS3356). These ASes collectively appear in $\approx$ 10% of all movements. We also note that the fraction due to the top 1% contributors remains stable over time. This suggest that the underlying address management processes are stationary. In other words, addresses activity related to top contributor seems to be unrelated to all significant changes that have affected the IPv4 address space. Hence, these movements can be flagged as false positives.

AS birth and death: Our case studies showed that valid address space movements can be caused by business restructuring and organizations becoming BGP-speakers. These actions would manifest themselves in the routing table as ASes appearing (*AS birth*) or disappearing (*AS death*) and consequently would cause BGP movements. We identify inferred movements for which at least one party involved either disappears or appears within δ months from the apparent transfer date. We set the value of δ to 3 months; we obtain similar results when we set δ to 9, 6, or 12. For δ equal to 3 months, 35% of the total movements are caused by AS death and AS Birth. Flagging movements that involve AS birth and death can reduce the number of false positives greatly.

7.3. Summary

In this section, we explore a set of additional criteria, based on the insight gained in Section 6, to reduce the number of inferred false positives. These includes identifying movements related to non-BGP speakers, legacy space, organizational changes, and complex IP space management. The combined percentage of movements that are caused by any of these criteria is 80.43% of all inferred movements. When removing these movements, the average number of inferred movements per month drops to $\approx$ 200. Hence, the average per RIR is even lower, which means that it can easily be vetted by a human operator. RIRs can reduce this number even further by factoring any additional internal information about their allocations.

8. Discussion

We discuss in this section the implication of our work.

Reported transfers: In the course of the last years, the IPv4 transfer markets have significantly increased in size. From our analysis, we observed that address blocks acquired on the market appear to be utilized by the buyers; there is thus no evidence of any hoarding behavior on the part of the buyers. Moreover, markets do not appear to have a negative impact on the IPv6 adoption or the global routing table. The markets, however appear to differ across RIRs in terms of size and type of transferred blocks, as well as participants; i.e., the IPv4 market within ARIN is dominated by a few organizations that exchange large blocks of legacy space, whereas in the RIPE region, most organizations exchange small size block and come from different countries. We believe these to be a cumulative result of allocation strategies used in the pre-RIR period, RIRs organization and existing transfer policies.

Inferring transfers: Due to the rapid decrease of the available IPv4 address pool, and the strict conditions that RIRs impose on both the transfers and new allocations, organizations might already be exchanging IP blocks without RIRs approval. Such actions would cause inaccuracy in the RIR records (i.e., WHOIS database, RIRs delegation files) regarding the IPv4 address space allocation, that would in turn cause inaccuracy in other data sources (e.g., IP geolocation databases, IRR data). We thus believe that it is important to develop methods for inferring such transfers. Our approach gives promising results as it detects most of the published transfers. The method also infers a large number of false positive movements. To further reduce this number, we explored several possible reasons for such movements. First, we explored whether DNS data and RIR allocation data can hep in reducing the number of false positives. Using information extracted from DNS and RIR allocation data we are able to remove 18% and 7.5% of the inferred movements, respectively. We note however that both sources of data suffer from limitations regarding coverage and frequency. Thus, we are able to analyze less than 30% of the inferred movements for both datasets. The low coverage of the employed data highlights the need for dedicated measurements for the detection of the transfers in the wild.

Second, we analyze three case studies and determine that false positive movements can be due to dynamics of non-BGP speakers and complex IP space management. We further employ these criteria on the BGP-inferred movements and find that such events contribute to up to 76% of the inferred movements. Our investigation showed that reducing the volume of inferred movements to a number that can be vetted by a human operator is conditioned by the usage of multiple datasets.

Evolution of the transfer markets: The IPv4 transfer market is becoming a viable source of IPv4 address space. However, the number of IPv4 addresses that could be exchanged on the market is limited. Based on our estimation, organizations will continue to exchange *transferable* space on the market for at least six years. We also predict that most of the IPv4 address space that would appear on the market would come from legacy allocations. Thus, legacy holders will play an important role in the evolution of the market. We note that our predictions assume that organizations do not resell the IPv4 blocks and that the current market factors remain the same; i.e., IPv6 adoption rate, growth rate of the market and transfer policies. Thus, we consider the obtained values as an upper bound for the market evolution. It is thus interesting to continue analyzing the IPv4 transfer market in the future and periodically report our findings.

9. Conclusion and future work

Our work has focused on the IPv4 transfer market. In the first part of this paper we presented an analysis of the reported transfers published by the RIRs. The overall number of these blocks appears to have rapidly increased in the last years, indicating that organizations are considering markets to be a viable mechanism for fulfilling their IP addressing needs. Currently, three of the five RIRs (APNIC, RIPE and ARIN) are reporting both intra-RIR and inter-RIR transfers. LACNIC has recently adopted an intra-RIR transfer policy [49], and has under discussions a policy for allowing organizations to transfer IPv4 address from other regions [83]. Also, AFRINIC has a resources transfer policy under discussion [84]. We believe that in the coming years the IPv4 transfer market will become global, comprising all the five RIRs. It is thus important to continue evaluating both the evolution of the market and its impact on the global routing table and on IPv6 adoption.

In the second part of the paper, we have developed a methodology for inferring transfers in the wild. Our detection approach is promising as it detects most of the published transfers. However, our experience with detecting transfers revealed that this problem is not addressable by using a single data source, but rather it requires multiple data sources each offering different perspectives on the IPv4 address space. In our current and future work, we are investigating the use of IP path and latency measurements to improve the inference accuracy. Our hypothesis is that a transfer of an IP prefix from one organization to another should lead to a measurable change in the IP path or latency towards that prefix as measured from a set of distributed probing vantage points such as CAIDA's Archipelago monitors [85].

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