



Figure 6: Current address space transfer policies of the RIRs and the administered address space.

they complied with proper ARIN transfer policy. Mueller et al. [59] state that while ARIN was formally involved in the transfer, likely no needs-based evaluation was performed on the receiving side, and that ARIN’s intervention boiled down to a “*face-saving exercise*”. As the relationship of legacy holders towards the RIRs is not entirely clear, one IP address trader has suggested that legacy address holders in the ARIN region could de-register their address space there and re-register it with a different RIR, such as RIPE [50]. Doing so would effectively allow inter-region transfers from ARIN to RIPE without undergoing any transfer process. But currently there is no process to de-register from an RIR.

Aside from transfers that were formally noticed by the RIRs (such as the above example), address transfers can also happen without the involvement of any registry at all. While address space can be of various types (*legacy*, allocated to a holder by an RIR, assigned by a holder to an end-user, PI-assigned directly from the RIR to an end-user), bound to various contractual limitations, not much prevents any party from unofficially transferring an address block to another entity. This is known as a “*black market*” transfer. This possibility stems from the decoupled nature of address block management and actual address block use. If RIRs do not acknowledge such transfers, registry information becomes in turn inaccurate and incomplete, making the attribution of address blocks to their respective holders difficult.

In the simplest terms, we can view a transfer as simply an address block—or parts of it—formerly in use by some entity A now being used by some entity B, possibly outside the purview of any RIR regulation. If the routing of the concerned address block is possible after the transfer (it is not filtered by networks), and (to a lesser degree) the corresponding reverse-DNS zones become under the control of the receiver (e.g., by subdelegation of reverse-DNS zones by the previous owner), the transfer would be successful.

It is unclear whether it is even feasible to detect the occurrence of such transfers. Livadariu et al. attempted to detect such transfers by looking for changes in routing origins over time [58]. One difficulty here is that transferred address blocks are not necessarily routed before they are transferred. Indeed, prior routing might be unlikely, as un-routed address space is likely also unused and thus more likely to be transferred. Also, whether such a transfer would be reflected in the reverse-DNS is unclear, as NS records might simply not be changed and PTR records might be

unchanged or switched off. Shifts in traffic, latency changes or geographical changes might be due to transfers but also due to restructurings within a company.

Thus, defining the boundaries of what exactly an address transfer is and what it is not is not straightforward. It is likely that the official RIR transfer policies only cover a fraction of the total address transfers occurring in various instantiations of the above scenarios. While transfers undergoing the RIRs policies are publicly listed [7, 16, 76] and quantifiable, the number of address transfers outside this framework is unknown and requires further research.

5. OVERCOMING SCARCITY

IP address scarcity has become reality. That is, today only ARIN and AFRINIC still hand out address space under regular conditions, while RIPE’s, APNIC’s and LACNIC’s pools have become exhausted, and they only hand out one small allocation from their last /8 to a requesting LIR. Comparing allocation rates in 2014 to allocation rates in previous years, it is clear that the supply of address blocks from the RIRs cannot satisfy the demand. Thus, address shortage problems require other approaches. Generally, we can consider three possible solution spaces for this problem: (i) develop more address space by adopting IPv6, (ii) multiplex current IPv4 address space using address sharing techniques such as Carrier-grade NAT (CGN), and/or (iii) more efficiently use the current IPv4 address space.

Develop more address space. The successor to IPv4, IPv6 [35], extends the routable address space by orders of magnitude. (Its design also aimed to address some other shortcomings of IPv4, such as support for mobility and extensibility.) It reflects the ultimate natural solution to the scarcity problem. The RIRs advocate its use (e.g., RIPE hands out remaining IPv4 address blocks only to LIRs that have already received an IPv6 allocation [83]), and the community has undertaken many other efforts to promote IPv6 adoption (e.g., [47]). Nevertheless, the fraction of both IPv6-enabled networks as well as native IPv6 traffic on the Internet remains comparably small—adoption of IPv6 remains problematic and only slowly increases.¹⁶ IPv6 is by itself not compatible with IPv4, and requires complex transition mechanisms to ensure compatibility between the IPv4 and IPv6 Internet (e.g., [63]).

Multiplex address space. Alternatively, we can get by with many fewer addresses by multiplexing. Enterprise networks have long employed NAT to avoid having to allocate individual public IP addresses to every Internet-attached device. Today, numerous approaches to perform address sharing at scale are available—see [85] for a comprehensive study—and are already in use by several large ISPs. While widespread use of NAT raises concerns about eroding end-to-end connectivity and semantics, as well as concerns by law enforcement agencies due to the erosion of attribution of IP addresses to end-users [37], it poses fewer compatibility issues than IPv6 when employed for legacy network infrastructure. According to [26], already more than 3% of

¹⁶As of February 2015, Google reports some 4.5% of clients accessing Google to be IPv6 enabled, with adoption rates as high as 28% in Belgium, around 10 to 15% in the US and Germany, and increasing support in other European countries. Nonetheless, the per-host adoption rate still ranges at or below 1% for most countries, including China, India and Russia [42].

Internet users are behind CGNs, and Web hosting companies already employ heavy address sharing.

Use address space more efficiently. As visible in Figure 4, about a third of all Internet address blocks remain unrouted, and thus not in (at least public) use. Moreover, even routed address space is not necessarily in active use. As mentioned above, recent studies find utilization levels for the routed address space at around 50% to 60% [33, 34, 89]. Hence, significant usable address space remains. Making more efficient use of address space will require adapting address management policies, guidelines and technologies, including the difficult (both technically and politically) problem of re-assigning already allocated address blocks.

Network operators are currently adopting all of these options to varying degrees: IPv6 adoption, CGN, and address transfers. We would expect that cost will determine the manner and timeline when different options predominate. We should in turn find these costs reflected in the price of IPv4 addresses as exchanged via secondary markets.

6. OUTLOOK

IPv4 address scarcity is an issue requiring attention from the networking and research community. Depending on the success of transitioning towards widespread use of IPv6, we face a mid-to-long term scenario in which IPv4 addresses will have significantly more demand than supply. The key question is for how long the cost of IPv4 addresses will be viewed as lower than the cost of transitioning to IPv6 or using CGN.

That said, we note that while the limited IPv4 address space clearly will not suffice in the longer term to provide every Internet device with its own address, the current scarcity arises due to address management practices, and not (yet) due to protocol limitations. Large fractions of the address space remain unrouted, and of those address blocks that are routed, again only a fraction is actually in use.

Just how to adapt the governance of the available address space to the current situation remains a pressing question. While it is unclear whether IP address block holders have ownership rights for their IP addresses, secondary markets already exist to facilitate their exchange. However, the uncertainties associated with address space transfers—both the legal status of legacy address blocks and the varying policies among RIRs when it comes to such transfers—will also complicate how pricing develops. This, in turn, makes it increasingly difficult for network operators to make decisions on which technology to adapt when.

As IPv4 addresses become an ever more scarce resource, increasing numbers of transfers, both inside the RIR framework as well as outside, are likely. As transfers outside the RIR framework can result in less accurate registration data provided by the RIRs—which in turn limits the possibility to use formal defenses such as RPKI-based origin validation—address block hijacking events presumably will also increase. Viewing IP addresses as resources, other issues arise, such as resource certification and the exercise of control over “who uses what address space”. As an inherently global resource, it is questionable whether the distributed registry framework can cope with the looming issues and provide sufficient resource liquidity. Future scenarios for the management could include a more competitive environment among RIRs, or even a re-centralization of the registries.

From a research perspective, several issues arise: How to

overcome scarcity issues? What technologies will have what impact on the Internet? Will the community succeed in fully deploying IPv6 within the next decade, or will we find ourselves stuck in a long-term situation in which IPv4, IPv6 and technologies like CGN operate in parallel? What will be the corresponding impact on the Internet topology, its performance, and its reliability?

How to effectively deploy resource certification of address blocks and how to ensure routing only by the respective holder? How commonly do address transfers occur outside the RIR framework and with what sort of historical development and likely future trends? What measurements could inform recommendations on how to govern the address space, in light of both IPv4 and IPv6 allocations? Did the creation of the distributed registry framework influence topological properties? How should the RIRs agree on implementing consistent policies?

We argue that the Internet community as a whole would greatly benefit from empirical studies tackling the above questions, which will both aid network operators with resolving business-critical decisions, as well as policy makers as they adapt to this new landscape and work towards ensuring further unhindered growth of the Internet.

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