# Measuring NAT64 Usage in the Wild

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**Abstract** NAT64 is an IPv6 transition mechanism that enables IPv6only hosts to access the IPv4 Internet. Understanding the deployment of NAT64, and its performance impact, is crucial to the success of the IPv6 transition, by encouraging IPv6-only deployments. We develop a set of tests for detecting NAT64 and apply them to the RIPE Atlas testbed, finding 224 probes, in 43 networks, that can use NAT64 to access the IPv4 Internet. Using 34 dual stack probes, that have both NAT64 and native IPv4 access, to compare performance, we find that NAT64 paths are, on average, 23.13% longer, with 17.47% higher round-trip times.

Keywords: NAT64; IPv6; RIPE Atlas

### 1 Introduction

With the IPv4 address space being depleted [14], and IPv6 adoption continuing to grow [4], there is an increased need for transition mechanisms to allow IPv4 and IPv6 hosts to seamlessly communicate. Understanding the impact of these transition mechanisms is important, both to support short-term IPv6 adoption and to encourage longer-term IPv6-only deployments.

One transition mechanism is NAT64 [10]. Together with DNS64 [11], it defines a way to embed IPv4 addresses within IPv6 addresses, enabling network address translation between IPv6 and IPv4 so that IPv6-only devices can access the IPv4-only Internet. Successful NAT64 deployments must be located so they don't become performance bottlenecks or lead to paths that are longer, and have higher latency, than native IPv4 paths. If NAT64 significantly impacts performance, this will discourage IPv6-only deployments, slowing adoption.

In this paper, we conduct a preliminary study of NAT64 devices in the Internet. We develop a set of tests to detect NAT64 and apply them on RIPE Atlas to find probes that can use NAT64 to access the IPv4 Internet. We characterise the location of these probes and their NAT64 devices, and compare characteristics of NAT64-based and native IPv4 paths.

While several studies have explored NAT64 performance using small test networks (e.g., [9], [7], [16]), ours is one of the first large-scale studies of the



Figure 1. Address translation using DNS64 and NAT64.

behaviour of NAT64 deployment in the wild, alongside  $[6]^5$ . Specifically, we make the following contributions:

- We develop a set of tests for detecting NAT64 ( $\S3$ );
- We apply those tests on RIPE Atlas to detect RIPE Atlas probes situated behind NAT64 middleboxes, finding 224 such probes, in 43 networks (§4), and categorise the types of deployments (§5).
- We compare IPv4 and NAT64 translated paths, finding that, on average, NAT64 paths are 23.13% longer with 17.47% higher round-trip times (§6).

By studying NAT64 performance in the wild, we demonstrate some limitations of current deployments and provide a basis for further study.

### 2 Motivation

As the Internet transitions from IPv4 to IPv6, a number of mechanisms have been defined to allow IPv4 and IPv6 hosts to communicate [14]. These include NAT64 [10], a network address translation mechanism that allows IPv6-only hosts to access the IPv4 Internet, and the associated extensions to DNS, known as DNS64, that synthesise AAAA records for names representing IPv4-only hosts.

Figure 1 shows how address translation is performed using DNS64 and NAT64. An IPv6 host sends a DNS AAAA query to the DNS64 resolver, for a domain name that only has an IPv4 address. The DNS64 resolver synthesises a AAAA record containing an IPv6 address that encodes the IPv4 address of the target host. The IPv6 address is either made up of the standard NAT64 prefix, 64:ff9b::/96, or a different custom prefix, followed by the IPv4 address, usually in the least significant 32 bits of the IPv6 address [8].

Packets sent to that synthesised address by the IPv6 host are routed to the NAT64, which extracts the IPv4 address, translates the packet to IPv4, and sends it on to the IPv4 host. Replies from the IPv4 host are similarly translated back into IPv6. NAT64 devices can be set up by ISPs [2], public providers (e.g., as listed at https://nat64.xyz), or individual users [5].

Several small-scale studies have measured the performance impact of NAT64 [7,16,9]. These characterise the translation overhead, and the performance of different types of NAT, but in a testbed environment. Accordingly, they do not necessarily reflect real-world use in the Internet. Like [6], we study the behaviour of NAT64 in the wild, with comparative evaluation using the RIPE Atlas platform.

In the following, we first develop a set of tests that allow us to detect the presence of a NAT64 on the network path. We apply these tests to over 6,400

<sup>&</sup>lt;sup>5</sup> This work was not yet available to us at the time of writing.

RIPE Atlas probes, to identify probes that are using NAT64, potentially in combination with DNS64, and characterise these deployments. Finally, we run UDP **traceroute** from these probes to measure the path length and latency impact of the NAT64 deployments.

While traceroute measurements do not directly reflect the performance of real-world applications, they can reveal some impediments to traffic. Further, traceroute provides a fine-grained view of variation in path characteristics such as latency and number of hops. This allows us to measure the relative impact that the introduction of NAT64 has on these characteristics. Further application performance issues are out of scope for this paper.

**Relation to 464XLAT**. DNS64 and NAT64 assist the IPv6 transition in the common case where an application resolves a service name via a AAAA DNS lookup, but the service they are resolving has only published an A record. They do not address cases where the host sends directly to an IPv4 address without a DNS lookup (e.g., if it received the address via some out-of-band means).

464XLAT [12] is an IPv6 transition mechanism that is intended to provide compatibility for such cases. It specifies use of a customer-side NAT46 ("CLAT") for IPv4-to-IPv6 translation in addition to the provider-side NAT64. 464XLAT thus translates IPv4 packets twice: the CLAT translates them from IPv4 to IPv6 on the host, for transit over the provider network, then the provider-side NAT64 translates them back to IPv4 for onwards delivery to their destination. DNS64 is not strictly required in a 464XLAT deployment, but it is typical: IPv6 address synthesis will reduce the number of address family translations required to support application traffic. Thus, DNS64 and NAT64 may be standalone from a 464XLAT environment, or may be components of a 464XLAT deployment. 464XLAT is most typically deployed in cellular networks, but guidelines for deployment in other network types are available [13].

As we discuss in §3, it is possible to systematically discover DNS64 and NAT64 deployments. We have no equivalent mechanism to detect the existence of a CLAT since the translation provided by the CLAT hides IPv6 addresses on the path. We therefore limit our results to measuring NAT64 and DNS64 deployment, and do not further consider 464XLAT. RIPE Atlas probes do not implement an on-device CLAT, though it may be possible that a CLAT is implemented elsewhere in a network [13].

**Applicability**. We use RIPE Atlas as a measurement platform, giving wide coverage in residential and operator networks but limited visibility into mobile networks. The use of a wireless testbed platform, such as was previously provided by MONROE, would give broader visibility into such networks but, to the best of our knowledge, no such testbed is available at the time of writing.

### 3 Detecting NAT64 Devices

We develop and use four tests to detect and characterise NAT64 devices: two tests of DNS behaviour and two **ping** tests, described in Figure 2 and below. These categorise probes into two groups: (i) those with a working NAT64 and



Figure 2. NAT64 detection tests and result groups.

DNS64 resolver (NAT64+DNS64); and (ii) those with working NAT64 that lack access to a DNS64 resolver to synthesise AAAA records for IPv4-only names (NAT64-only). The four tests are as follows:

- DNS Test 1 uses the NAT64 prefix discovery procedure described in RFC 7050 [15]. Hosts send a DNS AAAA query for the ipv4only.arpa. name. This is a special-use domain name that only resolves to IPv4, so where DNS64 is in use hosts will receive a synthetic AAAA record in response. IPv6 only hosts without DNS64 will receive NXDOMAIN.
- DNS Test 2 is similar to DNS Test 1, but with a request for a different IPv4-only name (time-c-b.nist.gov.). This test is needed because we found that some hosts have access to a DNS64 resolver that can correctly synthesise a AAAA record for ipv4only.arpa., and hence pass DNS Test 1, but that fail to synthesise AAAA records for other IPv4-only names.
- The Standard Prefix ping Test involves sending ping requests to the address of a widely available IPv4-only host (91.201.7.243; RIPE Atlas anchor probe #6771), encoded into IPv6 as 64:ff9b::5bc9:7f3 using the standard NAT64 prefix. This test is used to confirm that hosts receiving the standard prefix from DNS64 can ping addresses in that prefix.
- The **Custom Prefix ping Test** is used when DNS Test 1 returns a AAAA record using a non-standard NAT64 prefix (i.e., not 64:ff9b::/96). The custom prefix is used to encode the same IPv4 address as in the Standard Prefix ping Test (i.e., 91.201.7.243), which is then used as the target of an IPv6 ping request to confirm that the NAT64 works.

All probes perform the Standard Prefix **ping** Test, regardless of whether they pass any DNS tests. This allows us to find probes that can **ping** standard prefix addresses but didn't receive the prefix from DNS64. The Custom Prefix **ping** Test is applied to probes within the same IPv6 AS as a probe that received a non-standard prefix. These additional tests detect probes that use a DNS resolver that is unaware of any available NAT64 device (e.g., probes configured to use a public DNS resolver instead of the operator provided resolver). Together, these four tests allow for the detection of a range of NAT64 and DNS64 setups, including the use of custom prefixes and NAT64 without DNS64.

### 4 NAT64 Usage in RIPE Atlas

We ran the tests described in §3 on RIPE Atlas with the goal of understanding use of NAT64 in the wild. Tests were run over a period of several weeks in December 2022 and January 2023, with 6154 probes participating in the tests.

Table 1 summarises the results, showing the number of probes that consistently pass or fail the tests, and those that give inconsistent results from repeated runs of the same test. We observe that most RIPE Atlas probes fail all the tests and do not access the IPv4 Internet via NAT64, however 255 probes pass one or more of the three primary tests and so may have NAT64-based access.

**Table 1.** Number of probes that passed/failed the DNS tests and the Standard Prefix ping Test. Note that some probes pass multiple tests. Probes that presented different results to repeated tests are marked "Inconclusive".

Test	Failed	Passed	Inconclusive
DNS Test 1	5938~(96.5%)	201 (3.3%)	15 (0.2%)
DNS Test 2	6107~(99.2%)	$42 \ (0.7\%)$	5 (0.1%)
Standard Prefix ping test	6080~(98.8%)	66~(1.1%)	8 (0.1%)

Additionally, 765 probes either received a non-standard NAT64 prefix for DNS Test 1 or were located in the same AS as a probe that received a non-standard prefix, and so also performed the Custom Prefix **ping** Test.

**Probes with working NAT64 and DNS64**. Probes that pass the DNS tests and have reachability via the NAT64 have the most functional NAT64 environment of all the probes. As shown in Table 1, 201 probes pass DNS Test 1 and 42 probes pass DNS Test 2. Of these, 36 probes passed both DNS tests and can be considered to have fully working DNS64. 18 of these probes (50%) consistently passed the appropriate ping test. These probes have a fully functional NAT64 and DNS64 setup and comprise the NAT64+DNS64 group from Figure 2. This set contains six IPv6-only and 12 dual-stack probes.

**Probes with working NAT64 but not DNS64**. Some probes are not configured with a DNS64 but are able to reach a NAT64 device: 326 probes failed one or both DNS tests, but passed one of the ping tests. These probes can reach a NAT64 device, but have, at best, semi-functional DNS64. 120 of these probes were only able to ping targets via public NAT64 providers, they were excluded from this analysis. The remaining 206 probes, which were able to ping targets via a non-public NAT64, comprise the NAT64-only group in Figure 2. Of these, 52 were able to ping hosts using the standard NAT64 prefix, while 160 used a custom prefix. 6 probes could ping via both types of prefixes.

A probe may be categorised as NAT64-only if it is configured to use DNS resolvers without a DNS64 function. For example, a probe could be explicitly configured to use a public DNS service rather than its ISP's DNS. We checked for NAT64-only probes using public resolvers,<sup>6</sup> and found that 56 probes in this

 $<sup>^{6} \ \</sup>texttt{https://github.com/trickest/resolvers/blob/main/resolvers-trusted.txt},$ 

plus IPv4 and IPv6 resolvers provided by Google, Cloudflare, Quad9 and OpenDNS



Figure 3. ASes of the probes. "Other" denotes ASes with two or fewer probes.

set use a public DNS resolver (though they might also use the ISP resolver). Excluding these probes and the NAT64-only probes that passed *any* DNS tests, 139 probes are likely not intended to use the NAT64.

**Probes that pass DNS Test 1 without working NAT64**. We found 162 probes that passed DNS Test 1, indicating that they *should* be able to use NAT64 according to the discovery procedure in RFC 7050 [15], but that failed DNS Test 2 and both ping tests, indicating that they do not have functioning NAT64. These probes likely have a misconfigured DNS resolver (152 of the 162 such probes are in AS 12322, "Free SAS", suggesting a localised problem).

We note that probes may pass DNS Test 1 and fail DNS Test 2, but still have a functioning NAT64. Some DNS64 resolvers only respond to requests for ipv4only.arpa. to provide the NAT64 prefix and require hosts to synthesise their own IPv6 addresses [3].

*Summary*. Although RIPE Atlas probes that make use of NAT64 are rare, we find evidence of some usage, with various DNS64 and NAT64 configurations. We identify 224 probes that are potentially behind a NAT64. 18 of these have a fully functional NAT64 and DNS64 setup, and 206 probes can reach a NAT64 but don't use DNS64, of which 139 probes appear to be able to reach the NAT64 by accident. It is not enough to rely on the standard NAT64 prefix discovery, as defined by RFC 7050 [15], and we have shown that our tests (§3) provide a more comprehensive approach.

### 5 Classifying NAT64 Networks

Probes with reachability to NAT64 middleboxes are located in multiple networks. Figure 3 shows the ASNs of probes using NAT64; we find probes in 43 IPv6 networks and 143 IPv4 networks. Most IPv4 ASes host only one or two NAT64 probes. The most common IPv6 AS is AS 6939 (Hurricane Electric), hosting 145 probes. However, as discussed in § 6, only one of these probes is able to traceroute to IPv4 hosts via the NAT64, suggesting that this is a private NAT64 deployment which blocks outside traceroutes. Only 15 probes are not in any IPv4 AS, so most of these probes can use NAT64 and connect to native IPv4.

Category	$\mathbf{ASNs}$	Probes
Other ISP (business ISP, tier 2 AS, cloud provider, etc) (OI)	7	153
Residential ISP (RI)	18	41
Hobbyist network (run by individuals) (H)	12	14
Academic and research backbone (A)	2	5
Other (O)	2	4
Unknown (U)	2	3

Table 2. Categorisation of probe IPv6 ASes.

We use public information (e.g., websites of Internet service providers) to categorise the IPv6 ASes that the probes are in. The results are shown in Table 2. Out of 43 IPv6 ASes, 18 (41.9%) are residential ISPs; this suggests that NAT64 deployments are uncommon in fixed-line home networks, and are more common in alternative types of networks.

We use two tests to determine whether NAT64s are provided by the ISP, or are deployed in the local network. In **Test 1** we use the DNS test data (§3) to determine if the default resolver of an AS is a DNS64. If two probes in an AS query the same DNS64, it is likely provided by the ISP. Such an ISP likely provides a NAT64 as well. The DNS tests use the probes' default resolvers, so they expose the configuration of the probes' networks. A probe can't use a DNS64 "by accident", while this can happen in the ping tests.

For every NAT64+DNS64 probe, we analysed the results of the DNS tests for all probes in the same AS. If any other probe used the resolver with which the NAT64+DNS64 probe passed the DNS tests, we assume that this AS contains an ISP setup. Two such networks were found: AS 2027 (*MilkyWan*, a residential ISP) and AS 64475 (*Freifunk Frankfurt*, a public Internet infrastructure project). This test can over and underestimate the number of ISP setups. An overestimate can occur if several probes are deployed in a local network with a custom NAT64. To mitigate this, we compared the network prefixes of the probes using the DNS64s, which were different. An underestimate can occur if the AS only contains one probe, if only one probe uses the default ISP resolver, or if there are several ISP resolvers. 3 of the 14 ASes with NAT64+DNS64 probes contain only one probe that participated in the DNS tests, so they could contain undetected ISP deployments. However, eight of the ASes contain 10 or more probes.

Another possible ISP NAT64 setup is in AS 21928 (T-Mobile). Several probes in this network passed the DNS test some of the time, querying link-local addresses which return similar NAT64 prefixes. T-Mobile could be running several DNS64s and NAT64s for redundancy, preventing this setup from being detected.

In **Test 2**, we use the round-trip time to the NAT64 to detect custom setups. A custom (local) setup will likely have a lower RTT to the NAT64 than an ISP setup. This test is based on the traceroute data (§6). The RTT to the NAT64 is taken to be the RTT to the first hop that begins with the NAT64 prefix. Looking for probes with an RTT < 2ms to the NAT, we found five probes (2ms was chosen as an estimate of the RTT to a home gateway). Three of these probes



Figure 4. Probe categorisation. The size of the circles is not proportional.

are very likely custom setups (based on public information or contact with the owner). The fourth probe is in AS 2027, which, based on Test 1, likely has an ISP setup. We suspect the probe is owned by the network operator and located close to the ISP NAT64, as it is tagged "Datacentre" and "Core" on RIPE Atlas. We could not verify whether the fifth probe (ID 11149) is a custom setup. While this test detects some likely home setups, the RTT alone is not a complete indicator of the type of setup.

**Probe categorisation**. To summarise, the probes that were found can be categorised as depicted in Figure 4. Of the **224** probes:

- 3 likely use an ISP-provided DNS64 (ISP DNS64), while 24 probes are in an AS providing such a DNS64 (AS with DNS64; including T-Mobile);
- 3 probes are likely home setups (based on contact with the owner or public information);
- 28 probes in NAT64-only only use a public (non-DNS64) resolver and might be NAT64+DNS64 probes if they used their network's configured resolver;
- **2** probes in NAT64+DNS64 use a public NAT64/DNS64 service;
- 7 probes can traceroute through a NAT64 in another AS (remote NAT64);
- 131 probes can't to traceroute to a NAT64 prefix that they can ping (no TR through NAT);
- 54 probes are uncategorised (unknown).

**Summary**. NAT64s are present in a variety of IPv4 and IPv6 ASes. Analysing the types of IPv6 ASes, we find that only 41.9% are domestic ISPs, indicating that NAT64s are more commonly deployed on other types of networks. We find three ASes with a likely ISP-provided NAT64s, and three probes that are likely home setups. Categorising NAT64 deployments is challenging due to a lack of publicly available information.

### 6 IPv4 and NAT64 Path Characterisation

Having identified RIPE Atlas probes that use NAT64+DNS64 or NAT64-only, we next perform NAT64 and IPv4 traceroute from the dual stack probes to known IPv4 targets. We characterise differences in reachability and latency.

Methodology. Out of 205 dual-stack RIPE Atlas probes with NAT64, 183 remained online and available for preliminary measurements (9 NAT64+DNS64

probes, 14 NAT64-only). We performed traceroute from these probes to 18 IPv4only targets: seven IPv4-only NTP servers<sup>7</sup> and 11 RIPE Atlas anchors which were IPv4-only at the time of the experiment.<sup>8</sup> The targets were chosen due to their geographic spread. The IPv6 address of each target was synthesised locally using the prefixes obtained from the NAT64 detection tests (§3).

**Preliminary traceroutes**. Initially we performed single Paris traceroute [1] measurements. We sent three UDP probe packets for each hop, but to reduce complexity, only the first detected address for each hop was analysed. For every assigned and functional NAT64 prefix on the identified dual stack probes, we ran a traceroute to the targets listed above with the aim of generating one native IPv4 and one NAT64 path for each probe/prefix/target combination (most probes can only use a single NAT64 prefix; all probes with multiple NAT64 prefixes are in AS 21928 *T-Mobile*).

Our initial result set contains 3565 pairs of IPv4 and NAT64 paths from the probes to the targets, but a number of paths were not suitable for analysis. Of note, 2320 of the traceroutes to synthesised IPv6 addresses don't contain any hops starting with the NAT64 prefix. Most of these paths target a NAT64 prefix in AS 6939 (Hurricane Electric). As these probes were able to ping addresses with this prefix, it is likely that these NAT64 devices don't respond with ICMPv6 Time Exceeded messages when the hop limit is reached at the NAT64, and don't translate ICMPv4 Time Exceeded responses from hosts beyond the NAT64, making the data for the paths unusable. A further 15 pairs of paths were excluded for other anomalies. Excluding these paths, the preliminary measurement set contains 1230 pairs of paths, starting from 54 probes to 18 destinations.

**Recurring traceroutes.** Of the 54 probes with usable results in the preliminary measurements, 37 probes were still available when the second round of measurements was conducted. Traceroutes were performed once per hour over a span of 41 hours, to 14 of the 18 targets - four of the Anchor probes used in the preliminary measurements were disconnected at this time<sup>9</sup>. Each hour, each probe performed one IPv4 traceroute per IPv4 target, and one IPv6 traceroute for each combination of translated IPv4 target address and prefix.

Five of these probes failed to perform traceroutes to all 14 targets during one measurement run, this data was removed. The 41st measurement run was removed for the other probes. Six targets did not respond to any traceroutes, traceroutes to these targets were excluded. Pairs of IPv4 and NAT64 paths from the same probe to the same target, where the NAT64 path did not contain a hop starting with the NAT64 prefix (1076 pairs) were removed as well. Thus these measurements resulted in a set of 15564 pairs of IPv4 and NAT64 traceroutes, performed by 34 probes. Of these probes, 28 are in the set NAT64-only, 6 are NAT64+DNS64 probes. There are 27 probes that use one NAT64 prefix, two

<sup>&</sup>lt;sup>7</sup> We used the IPv4 NTP servers: dodo.mcc.ac.uk, d.st1.ntp.br, time-c-b.nist.gov, ntp1.nog.net.za, ntp1.st.keio.ac.jp, time-b-g.nist.gov, and ntp2.urz.uni-heidelberg.de

<sup>&</sup>lt;sup>8</sup> IDs 6771, 6994, 6678, 6827, 6688, 6356, 6366, 6138, 6712, 6299, and 6711. <sup>9</sup> One target was no larger IB $_{14}$  only at the time of these measurements, but

<sup>&</sup>lt;sup>9</sup> One target was no longer IPv4-only at the time of these measurements, but traceroutes were performed to its IPv4 address



Figure 5. NAT64 and probe locations (shaded: local NAT64, unshaded: remote).

probes use two prefixes, two probes use three prefixes, and three probes use four prefixes. This measurement set is used as the basis for the following analysis. **NAT64 locations**. We group paths by the AS that the NAT64 is in, relative to the AS(es) of the probe. The AS of the NAT64 is taken as the AS of the prefix used (if non-standard and announced), or otherwise it is taken as the AS of the final hop in the path that *doesn't* use the NAT64 prefix. If this process yields a different AS for different paths to the same NAT64, the AS corresponding to the hop that is furthest away from a probe is chosen. If the AS can't be determined, then the NAT64 is assumed to be within the same IPv6 AS as the probe.

Figure 5 shows the possible NAT64 and probe locations. In most cases (24/34), the probe's IPv4 and IPv6 ASes and the AS of the NAT64 are the same. We consider the NAT64s in the *all equal* and *NAT in v6 AS* categories to be *local NAT64s*: they are likely provided by the probe's ISP, or set up in its local network. All other categories are considered *remote NAT64s*, as the path leaves the local AS to reach the NAT64. These include public NAT64 services and other NAT64s that are accessible from outside the AS, e.g. due to a misconfiguration.

There are 27 probes with a local NAT64 (shaded area in Figure 5), and seven probes with a remote NAT64 (white area in Figure 5). Of the probes with a local NAT64, 23/27 are NAT64-only, compared to 5/7 probes with a remote NAT6. One of the five NAT64-only probes with a remote NAT64 can use a NAT64 with the standard prefix, but is likely not intended to it: the probe the uses ISP-provided resolver and did not pass either of the DNS tests. Since the NAT64 is not in its local AS, the packets are routed to another AS with a NAT64. This AS is likely the default destination for all packets, and it contains a NAT64 that doesn't check the source address of packets before translating them. This is a minor security concern, as it can be used to hide the source AS of the packets. *Impact of NAT64 on traceroute*. We first investigate the effect that NAT64 has on traceroute itself, in terms of reachability, and the number of missing hops.

The overall success rate (i.e., proportion of traceroutes that reach the target address, even if it isn't the final hop in the traceroute) across all IPv4 paths is 87.94%, compared to 87.07% for the paths via NAT64. There are 13519 pairs of IPv4 and NAT64 paths from the same probe to the same target that both reached the destination (86.86% of pairs). 12.03% of unsuccessful IPv4 paths and 0.00% of unsuccessful NAT64 paths reached the target AS. While paths via NAT64 are somewhat less successful than native IPv4 – with a difference of 0.87 percentage points – success rates don't differ much between groups.



Figure 6. Distribution of missing hops in successful pairs of IPv4 and NAT64 paths

If a hop does not respond to probe packets, then that hop is missing from the traceroute. Figure 6 shows the distribution of percentages of missing hops in paths where the IPv4 path and the equivalent path via NAT64 reached the destination. Paths via the NAT64s have more missing hops: the mean percentage of missing hops for the IPv4 paths is 16.52% (SD 11.92, median 16.67%), via the NAT64 it is 38.06% (SD 14.50, median 36.84%). A possible explanation for the greater number of missing hops via NAT64 is that the NAT64s filter out ICMP response packets. However, this is unlikely: all of the paths considered here contain at least one hop with a NAT64 prefix. It is more likely that the missing hops are due to specific routers filtering ICMP responses on these paths.

To determine how often the same hops are missing in similar traceroutes, we compared the NAT64 traceroutes for the two most successful targets in two measurement periods. We considered all the runs of missing hops that are preceded and followed by the same hops in both traceroutes. For example, if traceroute one contains [address 1, missing hop, missing hop, address 2], and traceroute two also contains address 1 and address 2, then we check if traceroute 2 also contains the exact sequence of hops (i.e., address 1 followed by two missing hops, followed by address 2). In the runs of missing hops identified using this method, on average 89.50% also occurred in the second traceroute (median 100.00%, SD 16.46%). This provides some evidence that the missing hops are not due to random failure, but rather caused by specific hops not responding to these traceroutes.

*Impact of NAT64 on path length and latency*. To analyse NAT64's impact on path length and latency, we consider the 13519 pairs of paths where both the IPv4 path and the corresponding NAT64 path reached the destination.

First, we compare the path length (in IP hops) between IPv4 and NAT64 paths. We consider the path length in hops and not the number of ASes traversed, because the high number of missing hops in the NAT64 paths makes it impossible to accurately determine the number of ASes, and because using the number of IP hops provides a finer grained view of possible detours added by using NAT64.

The average path length across all IPv4 paths is 17.72 hops (SD 5.25, median 17.00), the average NAT64 path length is 20.99 hops (SD 6.10, median 21.00). As expected, given the potential detours introduced by NAT64, the NAT64 paths are about three hops longer. The average length difference for paths with a remote NAT64 is 2.21 hops, for paths with a local NAT64 it is 3.45. This is

caused by the probe in AS 15751, which appears to have a router on the path that is manipulating the probing packet's TTL, resulting in traceroutes that reach the destination in very few hops. Excluding this probe, the paths with a remote NAT64 have an average length difference of 5.08 hops. Some of the NAT64 prefixes with the largest length difference are of the form 2607:7700:0:x:0:y, used by T-Mobile US. These paths have an average length difference of 4.38 hops; the average difference of other paths is 2.49 hops.

Taking the RTT as measured by traceroute to the first hop matching the target, and averaging across all successful UDP probe packets, we find that the mean RTT across all IPv4 paths is 160.82 ms (SD 91.61, median 169.80 ms), the mean NAT64 RTT is 184.55 ms (SD 105.59, median 193.51 ms). While the difference is small, the NAT64 paths have a larger mean RTT. Local NAT64 paths have a higher average RTT difference (27.56 ms) than the remote NAT64 paths (1.22 ms), due to the high RTTs of paths using the T-Mobile prefixes (2607:7700:0:x:0:y). Excluding these the local NAT64 paths have a average RTT difference of 1.34 ms. We also find a moderate correlation between RTT difference and path length difference (Pearson correlation coefficient 0.29).

Summary. NAT64 has a moderate impact on path length and RTT, increasing the average number of hops by 23.13% (3.27 hops), and increasing the average RTT by 17.47% (23.74ms). There is a moderate correlation between differences in path length and RTT (Pearson correlation coefficient 0.29).

### 7 Related Work

Parallel work by Hsu et al. [6] also uses RIPE Atlas to study NAT64 deployments. It differs from our work by not using traceroute, and not focusing on path characteristics such as RTT, number of IP hops, or number of missing hops. Instead, they perform additional ping, DNS and HTTP(S) measurements, and also study the behaviour of public resolvers. They find a similarly low number of NAT64 probes on RIPE Atlas, deployed in a variety of networks<sup>10</sup>.

Small-scale studies have evaluated the performance of NAT64 implementations. Lencse and Répás [7] compared the performance of NAT64 implementations in TAYGA and PF under load on a small test network, showing that both degrade gracefully, but that PF has better performance. Llanto and Yu [9] compare the performance of NAT44, NAT64 (TAYGA) and native IPv6 on a small test network and compare NAT44 and NAT64 on a larger university network, showing that while NAT64 and NAT64 and NAT64 on a larger university netformance of IPv6 was better than NAT64. Tsetse et al. [16] used a small test deployment to quantify the translation overhead of the IVI translator, a translator similar to NAT64 used by CERTNET [18]. These studies are very different from the measurements done in this paper, as they are small-scale, fine grained measurements of particular NAT64 implementations, performed in a controlled environment. Our work studies the behaviour of NAT64s on the public Internet,

 $<sup>^{10}</sup>$  This work was not yet available to us at the time of writing.

and thus does not distinguish between NAT64 implementations. While the number of NAT64s found is relatively small, this work still provides an insight into the prevalence of NAT64, and the behaviour of a number of real-world deployments.

De Vries et al. [17] use RIPE Atlas to explore the difference between the forward and reverse traceroute paths. This is similar to our study, because it is also a large-scale traceroute measurement study investigating path similarities.

### 8 Conclusions

We developed tests for identifying NAT64, and applied them to RIPE Atlas to study NAT64 usage in the wild. We found that, while RIPE Atlas has around 12,000 probes, NAT64 usage is rare with only 255 probes able to use NAT64 to access the IPv4 Internet, and only 18 having a fully functional NAT64 and DNS64 setup. Importantly, it is not sufficient to rely on the standard NAT64 prefix discovery procedure [15]; our tests (§3) are more effective. Having identified NAT64 use (§4), we performed traceroute from dual-stack NAT64 probes to compare IPv4 and NAT64 paths (§6). On average, the NAT64 paths were 23.13% longer, had 17.47% higher RTT, and lower traceroute visibility. NAT64 is a workable substitute to native IPv4, but impacts latency and reachability.

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Figure 7. Difference in NAT64 and IPv4 path lengths by NAT64 prefix and probe AS.

## A Ethics

This work does not raise any ethical issues. We identify and characterise the use of NAT64 by probes on a public measurement platform (RIPE Atlas). We generate a relatively small volume of traceroute measurement traffic towards NTP servers, which are publicly listed, and RIPE Atlas anchors, which are architected as measurement targets.

# **B** Additional data tables & figures

Set	IPv4 success IP	v6 success
NAT64-only	87.94	86.92
NAT64+DNS64	87.92	88.07
Local NAT64	88.01	86.99
Remote NAT $64$	87.50	87.50

Table 3. Percent success rate for groups of probes/NAT64s.

**Table 4.** ASes of the NAT64-only and NAT64+DNS64 probes. Count of users is based on https://stats.labs.apnic.net/aspop. Some holder names are shortened; category labels are as in Table 2.

ASN	Holder name	Category	Users (est.) $\neq$	≠ probes
6939	Hurricane Electric	OI	793668	145
21928	T-Mobile US	RI	19377903	14
2027	MilkyWan Association	RI	479	9
2107	ARNES-NET - ARNES	А	11923	4
205100	F3 Netze e.V.	Ο	4148	3
15954	Tecnocratica Centro de Datos, S.L.	OI	—	3
133481	AIS Fibre	RI	5598723	2
15751	Meteor Mobile Communications Limited	RI	286273	2
203528	Fabrizzio Jose Petrucci	Η	—	2
201723	R. van der Meijden	Η	_	2
43950	SPILSBY-AS - Terence Froy trading as "Spilsby I	U	—	2
7713	PT Telekomunikasi Indonesia	RI	31773744	1
3320	Deutsche Telekom AG	RI	24767366	1
3209	Vodafone GmbH	RI	17566119	1
12322	Free SAS	RI	7223746	1
1136	KPN B.V.	RI	5763278	1
45629	JasTel Network International Gateway	RI	5404250	1
2527	Sony Network Communications	RI	3925106	1
6568	EntelNet	RI	2594067	1
34779	T-2, d.o.o.	RI	266187	1
1916	Rede Nacional de Ensino e Pesquisa	А	68162	1
4800	LINTASARTA-AS-AP PT Aplikanusa Lintasarta	OI	42633	1
25596	Cambrium IT Services B.V.	OI	27970	1
12611	RKOM	RI	24572	1
57809	SERVEURCOM - UNYC SAS	OI	19850	1
13030	Init7 (Switzerland) Ltd.	RI	15863	1
31349	a-net Liberec s.r.o.	RI	15719	1
206238	Freedom Internet BV	RI	13410	1
25660	CTC	U	1698	1
29670	Individual Network Berlin e.V.	RI		1
211579	Laura Hausmann	Η	—	1
212037	Marc Provost	Η	—	1
203062	Alexandre Roux	Η	—	1
213204	Marvin Gaube	Η		1
208069	Cecile Morange	Η		1
213318	None	Η		1
208261	Pomme Telecom SASU	Η	—	1
212972	Nicolas VUILLERMET	Η		1
62538	IPFAIL	Η		1
204345	Timothy Stallard	Н		1
64475	Freifunk Frankfurt am Main e.V.	0	—	1
56381	level66.network UG	OI		1
211722	Nullroute ry	OI	—	1



Figure 8. % of paths that reached the destination or destination AS, by target.