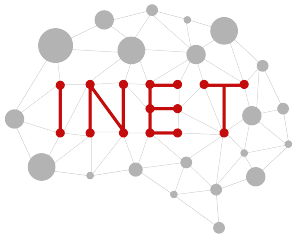

Bachelorthesis

Evaluating Dual-Stack against NAT64 deployment schemes with DNS64 and CLAT

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Zusammenfassung

Die Erschöpfung des IPv4-Adressraums beschleunigt den Übergang zu IPv6-first Netzen, die dennoch die Erreichbarkeit von ausschließlich IPv4 basierten Diensten sicherstellen müssen. Während Dual-Stack weiterhin das vorherrschende Bereitstellungsmodell ist, bieten übersetzungsbasierte Ansätze, NAT64 mit DNS64 sowie Clientseitige Übersetzung via CLAT im Rahmen von 464XLAT, eine Alternative, die die Abhängigkeit von IPv4 reduziert. Diese Arbeit quantifiziert die Leistungsabstriche zwischen Dual-Stack und CLAT anhand von TCP-Durchsatz und ICMP-Round-Trip-Time (RTT) unter realistischen Linux Implementierungen und Topologien. Drei Übersetzer, Jool (kernel space, SIIT/NAT64), Tayga (zustandslos im user space) und Tundra (multithreaded, user space, SIIT/CLAT), wurden in drei Umgebungen evaluiert: einer AWS-Umgebung, einem einzelnen physischen Ubuntu Server und zwei über Ethernet verbundenen physischen Ubuntu Server. Die Experimente nutzten Linux Namespaces zur Topologie Kontrolle und umfassten IPv6 Basislinien mit ein und zwei Hops, um Hop-Count-Effekte von Übersetzungskosten zu trennen. Die Ergebnisse zeigen, dass CLAT für die untersuchten Workloads nur einen geringen Leistungsmehraufwand gegenüber Dual-Stack verursacht. War der Host Datenpfad der Engpass, lieferte Jool konsistent höheren Durchsatz und niedrigere RTTs als die user space Übersetzer. Begrenzt hingegen ein physischer 1 Gbit/s Link die Leistung, komprimieren sich die Unterschiede zwischen den Übersetzern in Richtung der Link-Kapazität und die Diskrepanz zu Dual-Stack verschwindet weitgehend. Plattformseitige Timingeinflüsse erwiesen sich als erheblich: Virtualisierungsschwankungen und die Wahl der Clocksource (kvm-clock, hpet, tsc) beeinflussten die Glätte der Zeitreihen und die gemessenen Raten deutlich, was die Notwendigkeit unterstreicht, Ergebnisse stets relativ zur Basislinie mit identischer Clock zu interpretieren. Insgesamt stützen die Befunde CLAT als tragfähige Option für IPv6-first Netze, insbesondere dort, wo IPv4 Adressknappheit oder Kosten gegen Dual-Stack sprechen. Der Fokus lag auf Single-Flow-TCP und ICMP. Aspekte wie CPU-Kosten, Tail-Latenzen, DNS-Verhalten und container-orchestrierte Umgebungen bleiben Gegenstand zukünftiger Arbeiten.

Abstract

IPv4 address exhaustion has accelerated the shift toward IPv6-first networks that must still maintain reachability to IPv4-only services. While Dual-Stack remains the prevailing deployment model, translation-based designs, NAT64 with DNS64 and client-side translation via CLAT as in 464XLAT, offer an alternative that can reduce IPv4 dependency. This thesis quantifies the performance trade-offs between Dual-Stack and CLAT by measuring TCP throughput and ICMP round-trip time (RTT) under realistic Linux implementations and topologies. Three translators: Jool (kernel-space SIIT/NAT64), Tayga (stateless user space), and Tundra (multi-threaded user space SIIT/CLAT), were evaluated across three environments: an AWS setup, a bare-metal Ubuntu host, and a bare-metal network connected via Ethernet. The experiments used Linux network namespaces to control topology and isolate components and included native IPv6 baselines with one and two hops to separate hop-count effects from translation cost. The results show that CLAT introduces only a small performance overhead relative to Dual-Stack for the tested workloads. When the host datapath was the bottleneck, Jool consistently delivered higher throughput and lower RTT than the user-space translators, reflecting reduced context switches and copy overheads in the kernel datapath. When a 1 Gbit/s physical link bounded performance, differences among translators compressed toward the link limit and the gap to Dual-Stack largely disappeared. Platform timing effects were significant: virtualization jitter and clocksource selection (kvm-clock, hpet, tsc) measurably influenced time series smoothness and reported rates, highlighting the need to interpret results relative to same-clock baselines. Overall, the findings support CLAT as a viable choice for IPv6-first deployments where IPv4 addresses are scarce or costly. The study focuses on single-flow TCP and ICMP and leaves CPU cost, tail latency, DNS behavior, and container-orchestrated environments to future work.

Acknowledgments I would like to express my sincere gratitude to Dr. Philipp Tiesel for formulating the initial topic and for his mentorship throughout this thesis. His guidance, both technical and methodological, as well as his professional responses to my questions, were invaluable.

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Contents

Chapter 1

Introduction

The transition from IPv4 to IPv6 has progressed from a long-term goal to a practical necessity. Global IPv4 exhaustion and the growing cost of public IPv4 create pressure to reduce IPv4 dependency while maintaining reachability to IPv4-only services[1, 2]. Dual-Stack, where both IPv4 and IPv6 run in parallel on the same devices and networks, remains the most widely deployed model because it keeps native behavior for both protocols, but it does not reduce demand for IPv4 addresses and increases operational surface area[3]. Translation-based approaches convert traffic between IPv6 and IPv4. A common variant is NAT64 (translation at the network layer), often paired with DNS64 (synthesizing IPv6 addresses from IPv4 DNS records) or with client-side translation via CLAT, as in 464XLAT (extending NAT64 functionality to end devices). These methods offer an IPv6-first architecture while still enabling access to IPv4-only endpoints and have seen broad adoption in mobile networks[4–6]. In enterprise and cloud contexts, however, the performance trade-offs between Dual-Stack and 464XLAT remain less well quantified.

Problem Statement Motivated by this setting, the thesis investigates how much latency a CLAT-based path introduces and what performance impacts it has. The study focuses on measuring throughput and round-trip time as fundamental metrics under realistic software implementations and topologies. Specifically, it compares a Dual-Stack baseline with three Linux translators that reflect different implementation strategies: Jool (version 4.1.7), a kernel-space translator supporting NAT64 and SIIT[7], Tayga, a stateless user-space NAT64/NAT44[8, 9] and Tundra, a multi-threaded user-space SIIT/NAT64/CLAT implementation[10]. Measurements were conducted with iperf (version 3.16) and ping (version iputils 20240117) across three environments: an AWS cloud deployment (EC2 m5.large instance, Linux kernel: 6.8.0-1031-aws, 2 vCPUs, RAM: 7.6 Gi and Ubuntu Version: 24.04.2 LTS), a bare-metal host setup (Linux kernel: 5.15.0-87-generic, CPU: 4, RAM: 15 Gi and Ubuntu Version: 22.04.3 LTS) with translators in isolated Linux network names-

paces and a bare-metal network setup connected via Ethernet (specific machine configurations can be found in table 4.1). By limiting the scope to TCP throughput and ICMP RTT, the experiments provide a reproducible view on translation overhead relative to native Dual-Stack, while leaving topics such as tail latency, CPU cost, DNS performance, and application-level behaviors to future work.

The thesis tries to quantify if the measured overhead of CLAT relative to Dual-Stack is acceptable, IPv6-only access with translation becomes an attractive option where IPv4 addresses are scarce or expensive. If not, Dual-Stack remains the safer choice. The following background chapter summarizes the transition mechanisms and Linux implementations that support the experimental design[6, 11].

Industry collaboration This thesis was conducted in close cooperation with SAP SE and was supervised from the industry side by Dr.Philip Tiesel. This collaboration ensured that the research questions addressed are directly aligned with the real-world challenges faced by large-scale platform engineering teams. The primary motivation comes from the architectural decisions required by projects like SAP Gardener, an open-source initiative for managing Kubernetes clusters at scale[12]. Within SAP's Gardeners ecosystem, operators decide between Dual-Stack clusters and IPv6-only clusters. The choice has implications for cost, operational complexity, and performance.

Thesis Structure Following the introduction, which frames the problem and outlines the industry motivation, Chapter 2 provides the technical background required to interpret the results. It revisits IPv4 exhaustion and the transition to IPv6, describes IPv6 transition mechanisms and introduces the principles of client-side translation. The chapter closes with a description of the Linux components used in the experiments: Jool, Tayga and Tundra. Chapter 3 presents related work and identifies the specific gap this study addresses. Chapter 4 then explains the experiment design by introducing the three test environments: an AWS cloud setup, a single Ubuntu host with translators running in separate network namespaces, and a dual-host Ubuntu setup connected via Ethernet with the iperf server on the second machine. Documenting how Tayga, Tundra, and Jool are set up, how namespaces and routing are configured, how measurements are taken for TCP throughput and RTT and discussing practical challenges encountered during setup. Chapter 5 presents the evaluation, analyzing the translators against the Dual-Stack baseline and synthesizing findings across environments. Finally, Chapter 6 concludes the thesis by summarizing the main findings with respect to the central question and suggesting directions for future work, while the document ends with references and an appendix containing configuration files, scripts and further plots to support

reproducibility.

Chapter 2

Background

To understand the choices we're making for the internet today, we have to look back at a long-standing problem: we've run out of the original internet addresses (IPv4). This has forced us into a decades-long transition to a new system (IPv6), where parts of the internet will use only the new addresses. The core challenge is well-known: the old and new systems don't speak the same language, yet both have to work together on a global scale. At the same time, we're trying to balance running out of old addresses, increasing costs, and the constant risk of things breaking[1, 2].

2.1 IPv4 exhaustion and transition to IPv6

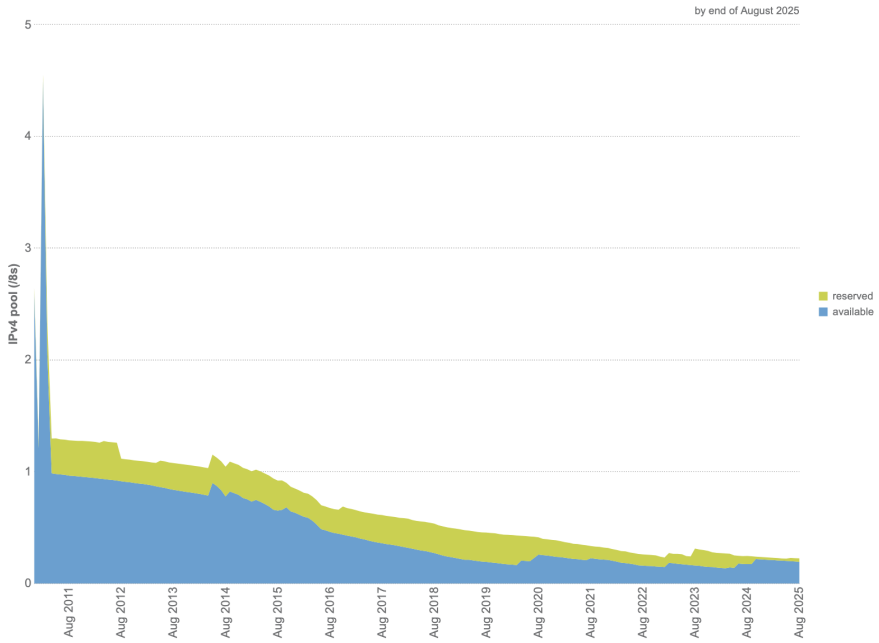
Internet use has expanded to critical infrastructure across consumer, enterprise, and public sectors. Services running at any time of the day and the increase of connected devices have driven steady growth in traffic and endpoints, making address management a central concern[1, 2]. IP addresses perform two fundamental roles: identifying endpoints and enabling packet delivery across networks, and uniqueness at global scale is essential[2].

IPv4, standardized in 1981-1983, provides a 32-bit address space of roughly 4.3 billion addresses[13].In practice, not all addresses are usable on the public Internet due to special-use and private allocations, and early design choices further reduced the effectively usable pool[1, 2, 14]. Management techniques such as CIDR and NAT slowed the pace of consumption but could not eliminate the finite limit[1].

Exhaustion means that the pool of unused IPv4 addresses has run out, not that IPv4 connections themselves have stopped working. The process started at the global level and then moved downward: IANA allocated its final IPv4 blocks on 3 February 2011, after that, each Regional Internet Registry (RIR) moved into its final phase: APNIC in April 2011 (Figure 2.1), RIPE NCC in September 2012,

LACNIC in June 2014 while AFRINIC held on the longest[2]. A global policy passed on 6 May 2012 established mechanisms for the recovery and redistribution of returned IPv4 address space, yet scarcity has continued to persist[1]. The impact has been uneven across regions because historical allocations left some operators with far fewer addresses per user than others[2].

Figure 2.1: APNIC IPv4 address exhaustion timeline[15].



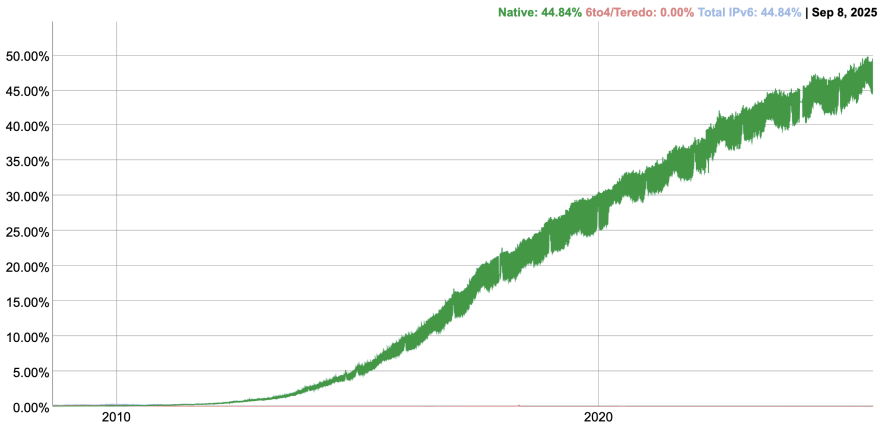
The shortage was unavoidable because demand kept rising: by 2014, about 2.9 billion people were online, with more than 200 million new users joining each year after 2010. Internet use jumped from less than 1% of the world's population in 1994 to over 40% by 2014, and surpassing 4 billion by 2020 and 5.5 billion in 2024[1, 16]. In short, exponential demand confronted a finite IPv4 pool.

IPv6 was standardized in 1995 as the long-term successor, expanding addressing to 128 bits—on the order of 3.4×10^{38} unique addresses—and introducing protocol-level improvements aimed at routing scalability, mobility support, and operational security[1, 2, 17]. The allocation data highlights how abundant IPv6 is compared to IPv4, even when large IPv6 distributions are considered[1]. However, IPv4 and IPv6 don't work together on their own, so bridging mechanisms are needed while both remain in use[2].

Even though the technical benefits of IPv6 were clear, its adoption lagged behind the urgency created by IPv4 shortages. IPv6 allocations reported by the RIRs lagged behind user growth, with especially low adoption in some regions, like Africa.

At the same time, user-side measurements, such as those from Google, showed less than 10% IPv6 usage (Figure 2.2), though the trend was gradually increasing[1]. Operators had to cover costs for enabling IPv6, including new equipment and configuration, which extended the period of running both protocols, often well beyond 2020 and in some networks possibly past 2030[1].

Figure 2.2: IPv6 connectivity among Google users over time[18].



Operators and policymakers have followed two main approaches: allocating the remaining IPv4 space more efficiently and transitioning to IPv6[2]. On the technical side, NAT, especially carrier-grade NAT (CGN), conserves public IPv4 addresses by multiplexing many private hosts behind a smaller set of public addresses[19]. By around 2014, a measurable fraction of users were estimated to traverse CGN[20]. While NAT is effective at saving IP addresses, it can make end-to-end connectivity more complicated and add to operational complexity[21]. Dual stack (running IPv4 and IPv6 in parallel) is broadly available and will remain common for years, but it does not address the IPv4 address exhaustion[2]. Policy measures like smaller allocations and efforts to reclaim unused addresses have helped ease IP address scarcity somewhat, but they don't eliminate the need for IPv6[2].

Strategically this means that IPv4 and IPv6 will continue to coexist for a long time, connected through integration methods[1, 2]. This situation drives the focus of this thesis: as network operators decide whether to keep dual-stack setups or move to IPv6-only access with translation technologies (like NAT64/DNS64, often paired with CLAT on the client side), it's important to understand the performance trade-offs involved. The next section takes a look at the main transition mechanisms that form the basis of this comparison[1, 2].

2.2 IPv6 transition mechanisms

According to the IETF's classification of transition strategies, there are three main approaches: dual stack, tunneling, and translation[22]. Because this thesis focuses on comparing dual stack and translation, tunneling will not be covered.

Dual-Stack Architecture Dual stack allows networks and hosts to gradually migrate, letting IPv4 and IPv6 run side by side[23]. In this model, a node runs two IP protocol stacks side by side: one for IPv4 and one for IPv6. This applies to both end systems, clients and servers, and to intermediate devices such as routers and gateways, which can natively handle and forward both IPv4 and IPv6 traffic when they support dual stack [23].

Applications written for IPv4 use the IPv4 stack, and IPv6-capable applications use the IPv6 stack. When sending a packet, the destination address decides which stack to use[3]. In practice, this works through DNS: A records point to IPv4 addresses, while AAAA records point to IPv6 addresses. The host's resolver and socket APIs then automatically choose the appropriate protocol stack[23].

From a deployment standpoint, dual stack is practical because most modern operating systems come with mature support for both IPv4 and IPv6[24]. The wide support for both protocols, combined with the fact that most applications run over their native IP without any modifications, helps explain why dual-stack has become the common approach for running IPv4 and IPv6 together in real-world networks[23]. Its main goal is to ensure compatibility and enable a gradual transition: dual-stack lets operators roll out IPv6 while staying connected to the still-dominant IPv4 Internet, but it isn't meant to solve the issue of address shortages on its own [2].

Dual stack also has clear limits. It only allows direct communication between the same protocol: IPv6 to IPv6 and IPv4 to IPv4, so it doesn't bridge the two by itself. When communication across the protocols is needed during the transition, extra mechanisms like tunneling or translation have to be used[23]. Moreover, dual-stack doesn't actually save IPv4 addresses. Seeing it as a way to conserve them is misleading, if anything, it maintains high demand for IPv4, since every dual-stacked device still requires IPv4 connectivity[11] . Global IPv4 exhaustion has continued even with widespread dual-stack deployments, highlighting that dual-stack alone cannot solve the shortage [2].

Within this thesis, dual stack serves as the performance and behavior baseline when no translation is involved. As a result, any differences we observe compared to NAT64 with CLAT can be seen as the extra cost of using translation-based approaches. At the same time, dual stack can't reduce reliance on IPv4 without additional tools, which is why the translation-based mechanisms in the next section are important [2, 23].

NAT64/DNS64 Principles NAT64 with DNS64 has emerged as a practical response to the limits of dual stack in the current Internet[25]. Although dual stack was initially seen as the main strategy for transitioning to IPv6, the ongoing shortage of IPv4 addresses and the uneven adoption of IPv6 make it increasingly difficult to keep every endpoint and network fully dual-stacked[25]. Translation technologies help bridge the gap, letting IPv6-only devices talk to IPv4-only systems without needing upgrades on every device or huge pools of public IPv4 addresses. In many networks NAT64 and DNS64 can either support or even take the place of dual stack, especially when IPv4 addresses are scarce or updating software everywhere isn't practical[26].

NAT64 was designed as the next step in the evolution of IP translation technologies. Earlier approaches like Stateless IP/ICMP Translation (SIIT) handled translation on a per-packet basis but needed a strict one-to-one mapping between IPv4 and IPv6 addresses, which limited scalability and flexibility[4]. NAT64 and DNS64 were created to overcome these limitations, offering clearer design, well-defined behavior, and explicit support for DNSSEC, while keeping the effective header translation techniques from SIIT[26].

Stateful NAT64 enables two-way translation between IPv6 and IPv4, allowing IPv6-only clients to connect to IPv4-only servers using TCP, UDP, or ICMP. It's designed for the long transition period where new networks and devices are primarily IPv6, while many services are still IPv4-only. When used with DNS64, neither the IPv6 client nor the IPv4 server needs any changes to communicate across the translator. Typically, a NAT64 device sits at the boundary between an IPv6-only network and the IPv4 Internet, with one interface facing each side. Packets from an IPv6 host going to an IPv4 server are routed to the NAT64, translated into IPv4, and sent onward. Replies from the server are translated back into IPv6, using the translation state established for that session[4].

In practice, NAT64 works through three main components. First, it translates IP and ICMP headers while making sure transport-layer checksums and communication rules are preserved across the IPv6-to-IPv4 boundary. Second, it uses algorithmic address embedding: an operator-assigned IPv6 prefix (Pref64::/n) is combined with the IPv4 address to create "IPv4-converted" IPv6 addresses that the translator can use. Third, its NAT behavior follows standard practices for TCP, UDP, and ICMP—like consistent endpoint mappings and typical filtering modes—so applications and network traversal techniques continue to work as expected. [4, 26].

Address representation is a key part of how NAT64 works. It uses two address pools: an IPv6 pool, made up of a dedicated IPv6 prefix (Pref64::/n) that embeds IPv4 addresses, and an IPv4 pool—usually a small shared prefix—that represents IPv6 clients on the IPv4 Internet. The IPv6 addresses are formed by combining the

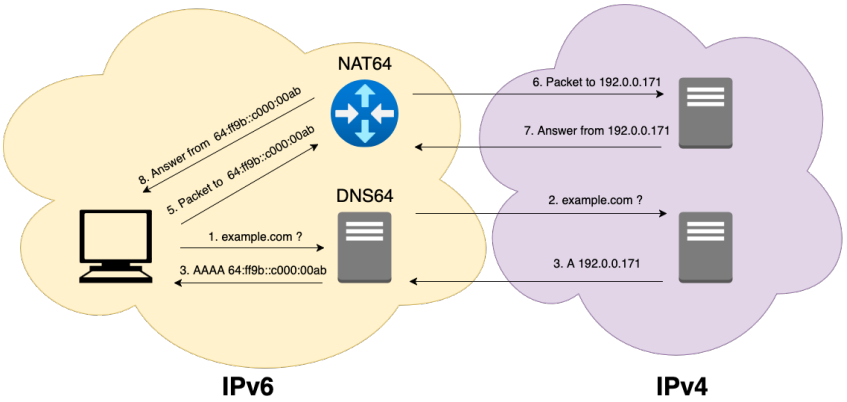
Pref64::/n with the 32-bit IPv4 address, adding zeros if the prefix is shorter than 96 bits. The Well-Known Prefix 64:ff9b::/96 provides a globally recognizable format, but operators can also use local prefixes. This Well-Known Prefix is especially useful when DNS64 and NAT64 are managed by different parties, as it separates the resolver from the translator while still ensuring packets reach the NAT64 device correctly. On the IPv4 side, the NAT64 translator usually maintains a small pool of public IPv4 addresses that are shared among many IPv6 clients. To make the most of this limited resource, NAT64 often uses address-and-port translation (A+P), allowing multiple IPv6 flows to share a single IPv4 address by assigning each flow a distinct range of ports[4, 26].

NAT64 is stateful. Every time an IPv6 client starts a new connection to an IPv4 server, the translator creates a binding that links the IPv6 address, port, and protocol to an IPv4 address and port from its pool. Inside the translator, the Binding Information Base keeps track of these mappings, connecting each internal IPv6 transport address to its assigned IPv4 address. These mappings can be reused across different destinations, enabling consistent endpoint-independent connections. A separate session table keeps track of each individual flow to allow more detailed filtering and maintain per-flow state when needed. Connection lifetimes follow BEHAVE guidelines (IETF behavioral requirements for NATs): UDP bindings typically last a few minutes (around two minutes), while TCP bindings can last hours for established connections. The translator also detects TCP connection closures so it can quickly free up resources. Without an existing state in the translator, only IPv6 clients can start new connections to IPv4 servers. For connections initiated from IPv4 to IPv6, the translator needs recent outbound traffic, explicit static mappings, or support from the application itself. Since NAT64 uses endpoint-independent mapping, standard NAT traversal techniques can still work across the translator[4, 26].

DNS64 complements NAT64 by synthesizing AAAA records from A records. When an IPv6-only client looks up a domain and the server only has an IPv4 (A) record, DNS64 steps in: it queries the A record, embeds the resulting IPv4 address into an IPv6 address using the operator's Pref64::/n, and returns that synthesized IPv6 address to the client[5]. DNS64 and NAT64 share no runtime state, they only need to agree on the Pref64::/n, using the Well-Known Prefix by default or a specific local prefix[26].

An end-to-end flow is therefore: an IPv6-only client receives a synthesized AAAA embedding the server's IPv4 address, sends IPv6 packets to that address (routed to the NAT64), the translator allocates or looks up the binding, translates headers, and forwards to the IPv4 server. Return traffic is reverse-translated using the session and Binding Information Base state until idle timers expire or TCP teardown is observed [5, 26]. The following figure (Figure 2.3) illustrates this.

Figure 2.3: NAT64/DNS64 architecture example showing the translation process.



Choosing between the Well-Known Prefix and a local prefix can affect how well networks work together when DNS64 and NAT64 are run by different organizations, but it doesn't significantly impact the cost of translating individual packets[26]. From a deployment standpoint, setting up NAT64 with DNS64 at the network edge is relatively simple. It lets operators run IPv6-only access networks while still reaching IPv4-only services. This is different from running a full dual-stack network, where both IPv4 and IPv6 are enabled throughout. The main trade-offs of NAT64 with DNS64 are that session initiation tends to favor IPv6 to IPv4 connections, it relies on DNS64 for translating names, and some protocols aren't fully supported. In return, it allows for much more efficient sharing of IPv4 addresses[4].

From both an operational and cost perspective, NAT64/DNS64 allows operators to run IPv6-only networks at the edge, with IPv4 needed only at the gateway. This makes managing IPv4 addresses easier and avoids the complexity of running dual-stack everywhere. According to a 2024 study, large-scale measurements show that public deployment in DNS resolvers is still quite limited. Among public IPv4 resolvers, only about 0.1

Finally, NAT64/DNS64 forms the foundation of 464XLAT. In this setup, a client-side stateless translator (CLAT) handles local IPv4-only applications, while the provider's NAT64 performs the stateful IPv6-to-IPv4 translation. Both use the same Pref64::/n and DNS64 principles. This approach makes legacy applications work more seamlessly on IPv6-only networks, as discussed in the next section[26].

Client-Side Translation: The role of CLAT and 464XLAT Building on the NAT64/DNS64 principles, 464XLAT is a practical method to provide limited IPv4 connectivity across IPv6-only access networks without tunnels, keeping the network IPv6-first while allowing legacy IPv4-only applications to function. It is

not a full IPv4 replacement: it supports outbound, client-to-server IPv4 use cases toward globally reachable IPv4 servers, does not provide inbound IPv4 reachability, and is not aimed at IPv4 peer-to-peer scenarios. The goal is to restore just enough IPv4 to keep legacy software usable while keeping native and modern traffic on IPv6 wherever possible [6].

The architecture defines two roles and introduces no new control protocols. On the customer side, the CLAT (Customer-side Translator) performs stateless IPv4/IPv6 translation (SIIT) as specified in the earlier section. On the provider side, the PLAT (Provider-side Translator) is a stateful NAT64 that allows many IPv6-only clients to share a pool of IPv4 addresses. Together, CLAT and PLAT build on existing SIIT and NAT64 technologies—no new protocols are needed[6].

464XLAT can operate with or without DNS64. It doesn't need synthesized AAAA records: an IPv4-only application can open IPv4 sockets or use IPv4 addresses directly, and the CLAT will translate those packets into IPv6 and send them to the PLAT, which then translates them back to IPv4. When DNS64 is used, name-based connections to IPv4-only destinations go through a single stateful translation at the PLAT. This avoids having both a stateless step at the CLAT and a stateful step at the PLAT, reducing per-connection processing and keeping the translation state centralized at the provider[6].

The resulting packet flows are straightforward. If the destination supports IPv6, traffic goes directly over IPv6 with no translation. If the destination is IPv4-only and DNS64 is used, the client receives a synthesized AAAA record, sends IPv6 packets, and the PLAT performs a single NAT64 translation. For applications that use IPv4 addresses directly or only support IPv4 sockets, the CLAT first translates the private IPv4 packets to IPv6 in a stateless manner, and the PLAT then applies stateful NAT64. This two-step translation ensures compatibility with applications that rely on hardcoded IPv4 addresses. [6].

This model works for both fixed and mobile networks. In wired networks, the CPE (customer premises equipment) acts as the CLAT: devices on the LAN keep using private IPv4, the CPE routes native IPv6 traffic, and it applies SIIT toward the PLAT for IPv4-only traffic. In 3GPP mobile networks, the user equipment usually runs the CLAT: it provides a private IPv4 stack for local apps, translates IPv4-only traffic into IPv6 for the PLAT, and sends IPv6-native traffic directly without involving the CLAT. When tethering, the user equipment can create a small private IPv4 LAN behind it (using NAT44) and still perform stateless translation before sending traffic over the IPv6 connection, staying compatible with mobile policies[6].

From an operational perspective, 464XLAT has several advantages. By keeping IPv4 state centralized in the PLAT, providers can efficiently share limited IPv4 resources among many subscribers. Deployments are also faster to roll out, since

the access network can stay IPv6-only and existing standards are reused. Running an IPv6-only access network can be simpler than maintaining dual-stack, it involves fewer protocols to manage and troubleshoot. Native IPv6 traffic stays end-to-end, and translation only happens for IPv4 flows. The PLAT can even be provided by a third party, letting an access provider run an IPv6-only network while sending CLAT-translated traffic to an external NAT64 service. This approach works especially well in mobile networks, where maintaining separate PDP contexts for IPv4 and IPv6 adds complexity[6].

Some practical considerations apply. CLAT uses standard IPv4-embedded IPv6 formats. It usually reserves separate /64 blocks for the uplink, each downlink segment, and stateless translation traffic. If a dedicated translation prefix isn't provided, the CLAT can combine LAN addresses to a single IPv4 address and map that to an IPv6 address it controls. The CLAT also needs to know the PLAT's translation prefix, which can be discovered automatically or set manually. By design, the prefixes for CLAT and PLAT translations are kept separate[6].

2.3 Linux implementations of CLAT

Tayga Tayga is a free, stateless NAT64 implementation for Linux, positioned as a lightweight, production-quality translator for environments where deploying a dedicated hardware or full-blown software NAT64 device would be excessive[9]. At the time of the cited study, the latest release referenced was 0.9.2, which the authors evaluate as representative for open-source NAT64 on Linux[8].

Its design philosophy is to perform transparent IPv6–to–IPv4 address and header translation while explicitly leaving policy enforcement and state handling to the Linux packet filtering and NAT framework (iptables)[9]. The authors stress that Tayga does not aim to replicate the flexibility of Linux's packet filters; instead, it is built to integrate cleanly with them, keeping the translator itself simple and predictable [9].

Functionally, Tayga provides one-to-one IPv6↔IPv4 address mapping (stateless translation) and does not offer many-to-one address multiplexing. In a typical deployment, Tayga is paired with DNS64 and a stateful NAT44 configured in iptables [9]. For an IPv6 client reaching an IPv4 server, Tayga maps the client's IPv6 source to a private IPv4 from a configured dynamic pool (1:1), and then NAT44 performs SNAT from that private address to the NAT64 gateway's public IPv4 [9]. On the return path, NAT44 restores the private IPv4, after which Tayga reconstructs the corresponding IPv6 destination using its 1:1 mapping and forwards the IPv6 packet back to the client [9]. This design requires provisioning a sufficiently large private IPv4 pool to support concurrent mappings [9].

From a deployment perspective, Tayga's stateless core means there is no built-in

session tracking or policy engine; scalability and IPv4 address conservation depend on the NAT44 stage and the size of the private IPv4 pool, making Tayga a good fit when a simple, transparent translator is needed[9].

Tundra Tundra is an open-source IPv6-to-IPv4 and IPv4-to-IPv6 translator for Linux that runs entirely in user space. It is written in C, implements SIIT[27], and is designed to take advantage of multicore CPUs with a multi-threaded architecture. Packet input and output can be handled through the Linux TUN driver or via inherited file descriptors[10].

Functionally, Tundra supports several stateless translation modes. In Stateless NAT64 mode it enables a single host to reach IPv4-only destinations and, when combined with NAT66, it can be used to serve multiple IPv6-only hosts behind it [10]. In Stateless CLAT mode it allows IPv4-only applications on an IPv6-only network with NAT64 to access IPv4-only hosts. Deployed on a router with an IPv6-only uplink and NAT64, it can produce a dual-stack internal network when paired with NAT44 [10]. Beyond these, a pure SIIT mode translates addresses that embed IPv4 within an IPv6 translation prefix and vice versa [10].

The design focuses on providing a minimal feature set for SIIT/NAT64/CLAT. It avoids unnecessary features and doesn't allocate any extra memory after initialization. [10]. The addressing model doesn't use a dynamic pool, it relies on a single fixed IP from the configuration. This means that on its own, the translator can only serve one host. However, it can scale to multiple hosts or networks when used together with NAT66 or NAT44[10].

Compared to similar user-space, stateless translators like Tayga, Tundra offers multi-threading, multiple configurable modes and the option to operate on inherited file descriptors, while it deliberately lacks a dynamic address pool[10].

Jool Jool is another well-known open-source implementation for IPv4/IPv6 translation, specifically designed for Linux systems[7]. Unlike Tundra's focus on userspace implementation, Jool operates within the kernel space and provides support for both Stateful NAT64 and SIIT modes. The SIIT functionality, which was introduced starting with version 3.3.0, is particularly relevant for 464XLAT deployments as it enables CLAT-like functionality on Linux systems, while the NAT64 mode can handle the PLAT side of the translation process[7].

From an architectural perspective, Jool offers two distinct integration modes for packet interception: Netfilter mode and iptables mode. Both approaches hook into the PREROUTING chain but differ in their operational characteristics[7]. The Netfilter mode, which was the sole operation mode until Jool version 3.5, exhibits what can be described as "greedy" behavior. It intercepts all inbound packets within its network namespace without any matching conditions and attempts to

translate everything, only leaving packets untouched when translation fails [7]. This mode is limited to at most one Netfilter SIIT instance and one Netfilter NAT64 instance per network namespace and begins translating immediately upon creation.

In contrast, the iptables mode, available since Jool 4.0.0, implements a more selective approach by functioning as an iptables target that can be used within specific rules[7]. This mode leverages iptables matching system, meaning only packets that match a particular rule are handed to Jool for processing, while other traffic proceeds normally through the network stack. This design allows for any number of iptables-based Jool instances and rules per namespace, with instances remaining idle until a matching iptables rule directs packets to them [7].

An important characteristic shared by both modes is their handling of successfully translated packets. Rather than following the conventional path through the FORWARD chain, translated packets are sent directly to POSTROUTING, effectively bypassing the FORWARD chain entirely[7].

Jool's packet handling logic follows a systematic approach for determining which packets can be translated. For packets that cannot be translated, Jool returns them to the kernel under various conditions, such as when an iptables rule references a non-existent instance, when translation succeeds but the resulting packet is unroutable, or when the translator is disabled by configuration[7]. In SIIT mode, specific untranslatable conditions include scenarios where addresses cannot be translated due to local interface addresses or absence of applicable translation strategies[7].

The fact that Jool supports the essential protocols used in our measurements makes it well-suited for the throughput and RTT evaluations conducted with iperf and ping respectively [7].

Chapter 3

Related Work

Other researchers have already shown that using NAT64 is a good way to switch from IPv4 to IPv6. They found that NAT64 is just as fast as the old ones (NAT44), and proved it using cheap, standard software[28]. The methodology includes NAT64 using ping/ping6, complemented by a laboratory comparison of NAT44 and NAT64 that records RTT, CPU, and memory[28]. NAT64 is realized with Tayga. The results show that native IPv6 achieves the best RTT. NAT64 and NAT44 perform similarly, with only minor differences in throughput, though NAT64 has a slight edge[28]. A t-test finds no significant differences between NAT64 and NAT44 for RTT, total time, bytes transferred, successful keep-alives, requests per second, and time per request, but reports a positive difference for transfer rate favoring NAT64 [28].

Another study examined IPv4 and IPv6 performance across various operating systems and transport protocols, and evaluated tunneling methods. However, their insights into translation-based strategies were largely limited to specific implementations [29]. In the case of NAT64, evaluations mostly focused on individual implementations (e.g., Tayga), with little effort made toward cross-implementation comparisons[29].

However, research gaps remain. The first evaluation[28] centers on web workloads driven by ApacheBench without bulk TCP/UDP generators such as iperf and does not assess dual-stack versus NAT64 with CLAT, nor evaluate alternative NAT64 implementations such as Jool. Similarly the second study[29] does not evaluate client-side translation (CLAT/464XLAT) leaving the end-to-end impact of NAT64 versus dual-stack open[28, 29].

Chapter 4

Evaluation

The experiments were executed in three environments to keep the topology constant while varying the platform: an AWS cloud instance, a single physical Ubuntu host, and two physical Ubuntu hosts connected by an Ethernet link. Across all environments, the setup isolated components using Linux network namespaces and instantiated the three translators under test (Jool, Tayga, Tundra) with identical addressing and routing. Configuration choices such as forwarding and addressing were held consistent across environments to support comparability.

While conducting the experiments, it became apparent that the choice of clock source (e.g., tsc, hpet, kvm-clock) significantly influenced the measurement results. The primary comparison was conducted between the Time Stamp Counter (tsc) and High Precision Event Timer (hpet), while kvm-clock was employed for the AWS cloud environment due to its operational similarity to tsc in virtualized contexts.

Time Stamp Counter (tsc) The tsc is a counter-based clock source that increments at a fixed frequency, typically matching the processor's base clock frequency. It provides CPU-local timing with extremely low access overhead, making it ideal for high-frequency timing measurements, though it can suffer from synchronization issues across multiple CPU cores without proper calibration.

High Precision Event Timer (hpet) The hpet is a hardware-based timer that operates independently of the CPU clock and provides system-wide consistent timing across all processor cores. It offers higher precision than traditional timing sources but incurs greater access latency due to its external hardware nature, making it more suitable for applications requiring absolute time accuracy rather than high-frequency sampling.

KVM Clock (kvm-clock) The kvm-clock is a paravirtualized clock source designed specifically for kernel-based virtual machines that provides stable timing in virtualized environments. It combines the low overhead characteristics of tsc with virtualization-aware adjustments to account for hypervisor scheduling delays, making it the optimal choice for timing measurements within cloud instances where direct hardware access is unavailable.

Additional technical details on Linux kernel timekeeping mechanisms are available in the official kernel documentation[30].

4.1 Test environments

For the environments the detailed configurations can be found in the following table 4.1.

AWS In the AWS environment, a single EC2 instance within a dual-stack VPC hosted the entire virtual topology. Client, translator, and server roles were realized as separate namespaces interconnected by veth pairs[31]. DNS64 and CLAT ran locally on the instance to avoid external dependencies, and the dual-stack baseline followed a direct namespace path that bypassed translation.

Bare-metal host On the bare-metal host, the same namespace-based topology was reproduced on bare metal. Client and server namespaces were connected via veth, translators were deployed in dedicated namespaces with uniform routing, and CLAT was instantiated to mirror the cloud setup.

Bare-metal network In the bare-metal network setup, two Ubuntu machines were connected via a dedicated Ethernet link. The client machine hosted the namespace topology and the translator variants. The second machine provided a standard IPv4/IPv6 stack reachable over the Ethernet link. CLAT ran on the client machine, the dual-stack baseline traversed the link natively without translation. Hardware details and all configuration artifacts for these environments are provided in the Appendix.

Table 4.1: Machine Configuration Specifications

Specification	AWS (m5.large)	Bare-metal
System Information		
Instance Type	m5.large	N/A
Availability Zone	eu-central-1c	N/A
Operating System	Ubuntu 24.04.2 LTS	Ubuntu 22.04.3 LTS
Kernel Version	6.8.0-1031-aws	5.15.0-87-generic
CPU Specifications		
Architecture	x86_64	x86_64
CPU Op-modes	32-bit, 64-bit	32-bit, 64-bit
Address Sizes	46 bits physical, 48 bits virtual	39 bits physical, 48 bits virtual
Byte Order	Little Endian	Little Endian
CPU Count	2	4
Online CPU List	0,1	0-3
Vendor ID	GenuineIntel	GenuineIntel
Model Name	Intel Xeon Platinum 8259CL @ 2.50GHz	Intel N95
CPU Family	6	6
Model	85	160
Threads per Core	2	1
Cores per Socket	1	4
Sockets	1	1
Stepping	7	0
CPU Max MHz	N/A	3400.0000
CPU Min MHz	N/A	800.0000
BogoMIPS	4999.99	3379.20
Memory & Storage		
RAM	7.6 GiB	15 GiB
Storage	6.8 GB	476 GB

4.2 Networking Namespace Configuration

The experiments relied on Linux networking namespaces to isolate each translator and to keep the surrounding network conditions reproducible across local and

the cloud setup[1]. For Tayga and Tundra, a single namespace per translator was connected to the host through a veth pair[31]. Both ends of the veth received link-local IPv6 addresses and the namespace end additionally received a globally scoped IPv6 address. Inside the namespace, the default IPv6 route pointed to the host-side link-local address, while the host installed a route towards the namespace prefix via the namespace-side link-local address. IPv6 forwarding was enabled on the host and inside the namespaces to allow transit of translated traffic. Jool required a slightly different arrangement with two namespaces to create a single hop through the translator: an application namespace was linked to the translator namespace using a second veth pair. This common namespace wiring, addressing, and forwarding configuration was applied consistently on all machines so that the translator initialization in the next section could proceed without repeating network setup details.

4.3 Implementation of Translation Technologies

Tayga was implemented using a TUN device (nat64) inside a dedicated network namespace. Following Tayga's stateless design, the translator was configured with the well-known NAT64 prefix 64:ff9b::/96, one local IPv4 address for the CLAT side and one local IPv6 address for the NAT64 side, and a static one-to-one map to keep address selection deterministic. After creating and bringing up the nat64 device, the CLAT's IPv4 was assigned as a /32 and an explicit route for the mapped IPv6 was installed. The namespace's default IPv4 route was directed to the nat64 device so that IPv4-only applications would traverse the translator, and IPv6 forwarding was enabled to forward translated packets toward the host-side IPv6 path. This minimal setup produced a stable and reproducible CLAT path and integrated with the shared namespace wiring described previously. The configuration mirrors Tayga's intended use as a simple, stateless NAT64 that offloads policy and state handling to the host's packet filtering/NAT framework and is typically paired with DNS64 in practical deployments, which aligns with prior descriptions of Tayga's design [8, 9].

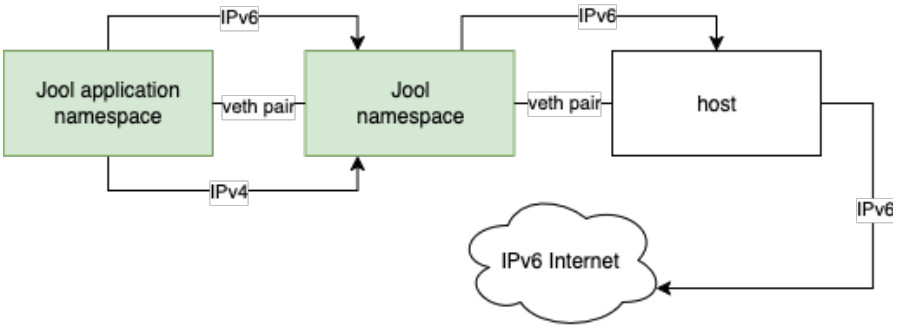
Tundra was deployed as a user-space, stateless CLAT translator built from source with CMake and gcc and operated via the Linux TUN driver, consistent with its SIIT design and multi-threaded architecture [10, 27]. Address synthesis used the well-known 64:ff9b::/96 prefix, and translation of private IPv4 addresses was enabled to prevent corner cases during testing. The TUN interface was named "clat", configured with static local endpoints. The interface was brought up, an

[1]Complete setup scripts and configuration details are available at: `https://github.com/thisIsDanielJin/bachelorthesis_scripts.git`

explicit route to the CLAT IPv6 address was added, and the namespace's default IPv4 route was set over the TUN interface. IPv6 forwarding was enabled to allow translated traffic to leave to the host's IPv6 domain. This configuration yielded a minimal user-space CLAT setup comparable in spirit to Tayga[10].

Jool was deployed as a kernel-space, stateless SIIT translator in its own network namespace and paired with a separate application namespace to enforce a single hop through the translator. The namespaces were connected by a veth pair configured as an IPv4 link with additional IPv6 addresses on the same link, while a second veth pair connected the Jool namespace to the host and carried an IPv6 address.

Figure 4.1: Jool network namespace architecture with dual veth pairs.



IPv4 and IPv6 forwarding were enabled in both host and Jool namespaces, the application namespace used a default IPv4 gateway so that all IPv4 flows traversed the translator, and IPv6 followed the link-local default routing pattern established earlier. Inside jool-ns (networking namespaces where jool was configured, not the namespace for the application), the jool_siit module was loaded and a SIIT instance was created in Netfilter mode with pool6 set to `64:ff9b::/96`. An explicit Address Mapping Table entry bound the application's IPv4 address to the Jool-side IPv6 address to keep the translation deterministic for the measurements. This choice of Netfilter mode, where inbound packets are greedily intercepted within the namespace, kept the configuration minimal while ensuring a low-overhead kernel datapath comparable to the user-space translators[7]. Given Jool's SIIT/CLAT capabilities the setup aligns with the stateless translation model defined by SIIT [7, 27].

4.4 Measurement Methodology

Throughput was measured with iperf3 (version 3.16) using a dedicated namespace (iperf-ns). The namespace was connected to the host via a veth pair, both

ends received IPv6 link-local addresses, and the namespace end was assigned an IPv6 address. The namespace installed a default IPv6 route toward the host's link-local address, while the host added routes to the translator prefixes over the same link. To enable NAT64-based reachability for an IPv4-only target within a stateless translation model, the well-known NAT64 prefix 64:ff9b::/96 was used to embed 192.0.0.171 as 64:ff9b::192.0.0.171, which was configured on iperf-ns so the server could accept both native IPv6 and synthesized IPv6 connections[27]. An iperf3 server ran inside iperf-ns, and clients were executed from tayga-ns, tundra-ns, and jool-app-ns as defined in Sections 4.2–4.3.

The measurement plan separated a native IPv6 baseline from the CLAT translation paths. The IPv6 target provided a no-translation baseline whose purpose was to show pure topology effects, in particular the extra namespace hop in the Jool setup compared to the single-hop topologies of Tayga and Tundra. In contrast, the IPv4 target is the focus of this evaluation: client traffic started as IPv4 inside each namespace and was translated by the respective CLAT implementation, enabling a direct comparison of Tayga, Tundra, and Jool and, secondarily, a comparison to the IPv6 baseline to measure how much of any difference came from translation versus hop count. All tests used iperf3 over TCP with two durations (30 s and 120 s) to capture short and sustained behavior. The same scripts and parameters were applied on all three environments.

RTT was measured with ICMP echo using a simple harness that iterates over namespaces and targets, executes ping inside each namespace, and stores raw outputs for later plotting. Two targets were probed: the IPv4 address (the CLAT case of interest) and the IPv6 address (baseline). The IPv6 baseline is included for completeness consistent with the TCP tests. For each run, the script selects ping (version iputils 20240117) or ping -6, uses a 1 s send interval and a deadline of 30s. The IPv4 measurements originate as IPv4 inside the namespace and are translated by the local CLAT toward the host-side IPv6 path. Replies are translated back by the same CLAT. The IPv6 target is reached natively without translation.

Chapter 5

Results

This chapter reports the empirical performance of the three Linux translation implementations relative to a native Dual-Stack baseline in the three environments described in Chapter 4. The evaluation isolates the translation overhead of a CLAT-based path along two metrics: TCP throughput and ICMP round-trip time (RTT). Within each environment, comparisons are made relative to the IPv6 baseline to control for differences in virtualization and CPU topology across environments. Sections 5.1 and 5.2 present the throughput and RTT results, respectively. The last section of this chapter, section 5.3 discusses the findings.

5.1 Throughput

All throughput plots show time in seconds on the x-axis and throughput in Gbit/s on the y-axis and depict iperf3 time series over the configured measurement window[1]. The AWS environment is considered first to set the stage for later changes in timing configuration and platform. The initial AWS measurement, which can be seen in Figure 5.1, run with the default kvm-clock shows a divergence in behavior between the user-space translators and Jool. Tayga and Tundra remain stable across repetitions, whereas both the native IPv6 baseline and Jool show large variability without a consistent trend. Since configuration, topology, and traffic generation were held constant, this pattern indicates platform caused timing artifacts rather than datapath specific instability. The clocksource was therefore assumed to be the primary source of variance, and following runs replaced kvm-clock with hpet to test this hypothesis.

[1]The scripts used for generating all plots and analyzing the measurement data are available at: `https://github.com/thisIsDanielJin/bachelorthesis_scripts.git`

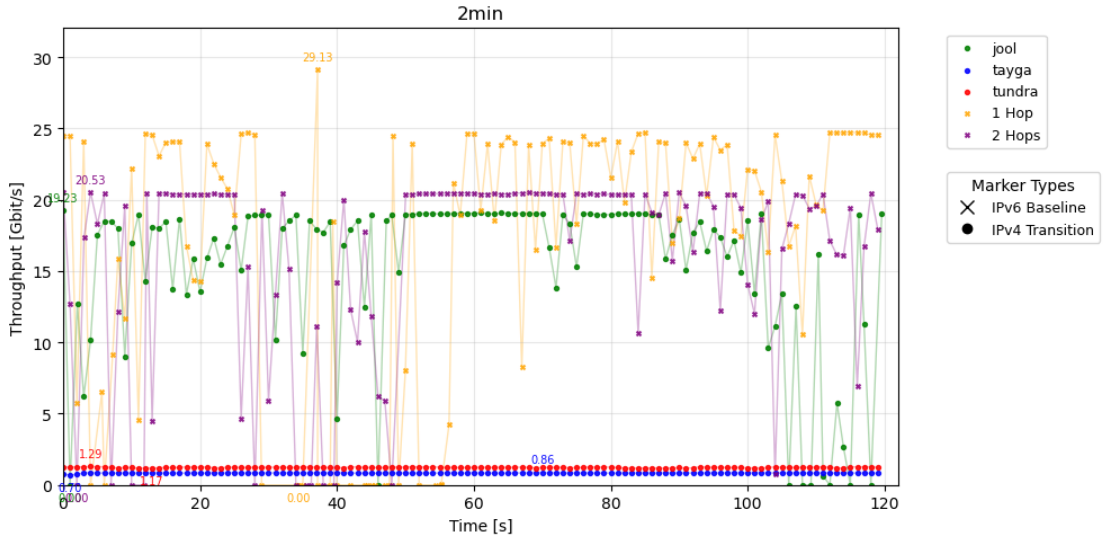


Figure 5.1: AWS cloud environment, KVM-clock, linear scale

Switching to hpet (Figure 5.2) reduces anomalies but does not fully eliminate irregular throughput steps for the IPv6 baseline. Because the native baseline clusters near the top of the axis while the CLAT implementations cluster near the bottom, a dual-y-axis variant (Figure 5.3) improves readability by separating the dynamic ranges without altering the underlying samples. The left y-axis scales the IPv6 baseline and the right y-axis scales the CLAT datapaths. Even here, the baseline still shows a step-like pattern, which is consistent with the remaining jitter. These results support the decision to move the same experimental topology to a local machine in order to reduce noise.

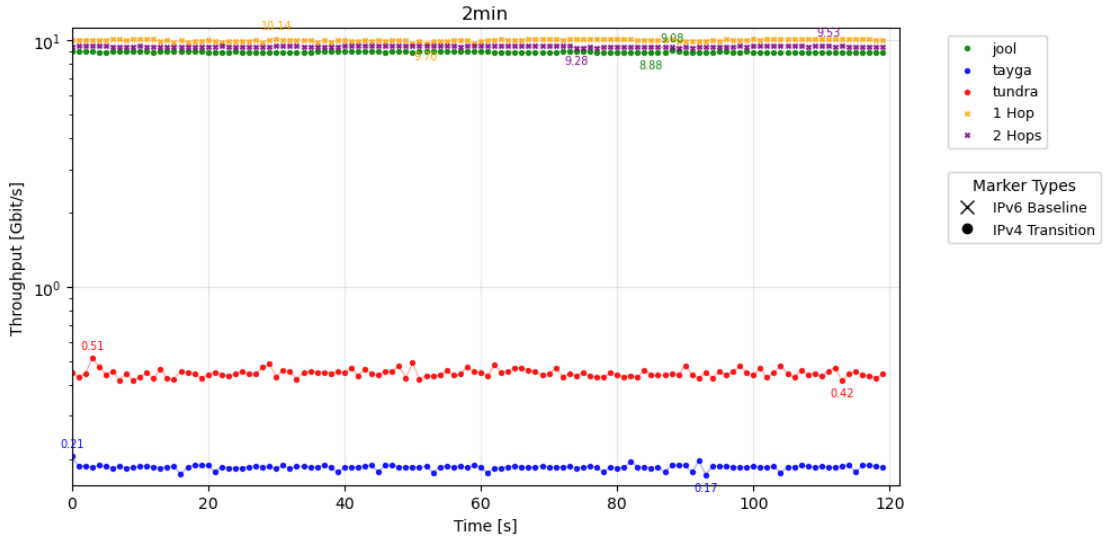


Figure 5.2: AWS cloud environment, hpet, log scale

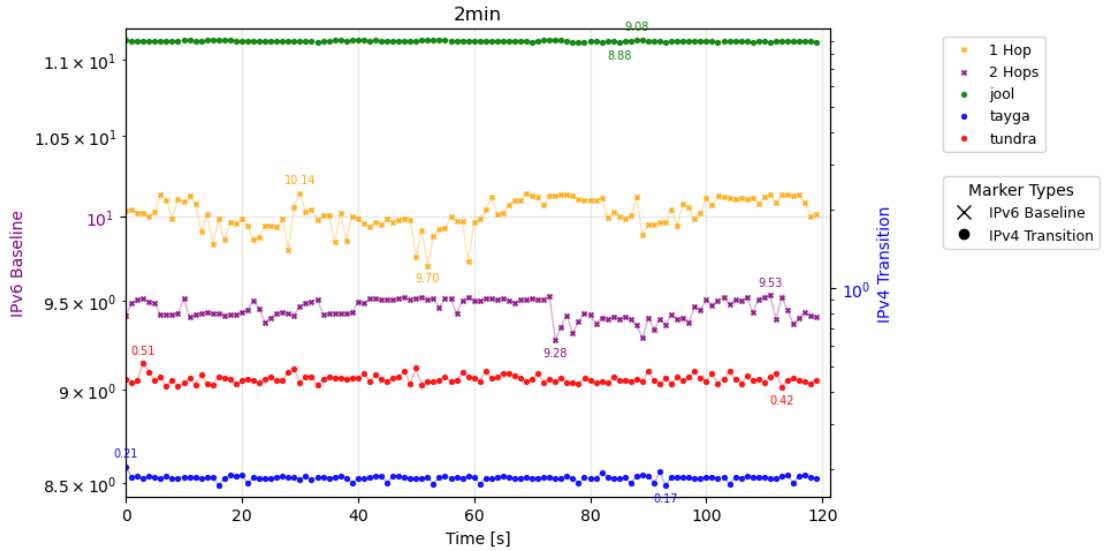


Figure 5.3: AWS Throughput Results, hpet, dual-y-axis, log scale

Bare-metal results On the bare-metal host (Figure 5.4), throughput stabilizes for both baseline and CLAT paths. The results show tight clustering across repetitions and a clear separation between one-hop and two-hop IPv6 baselines, consistent with the additional namespace traversal. Specifically, the one-hop baseline averages 42.039 Gbit/s and median of 42.215 Gbit/s, while the two-hop baseline averages

35.131 Gbit/s with median of 35.852 Gbit/s, which matches expectations for an extra hop. Within this environment, Jool consistently outperforms Tundra. Under TSC, Jool reaches a mean of about 33.81 Gbit/s versus 4.42 Gbit/s for Tundra. Under HPET, Jool's mean is about 6.64 Gbit/s versus 0.51 Gbit/s for Tundra. Tayga is not shown here due to the reasons summarized in Section 5.3. Because Tayga and Tundra are both stateless user-space translators with similar behavior, Tundra serves as a representative for this class in the single-host local setup, which is also in line with the AWS observations where Tayga and Tundra track closely.

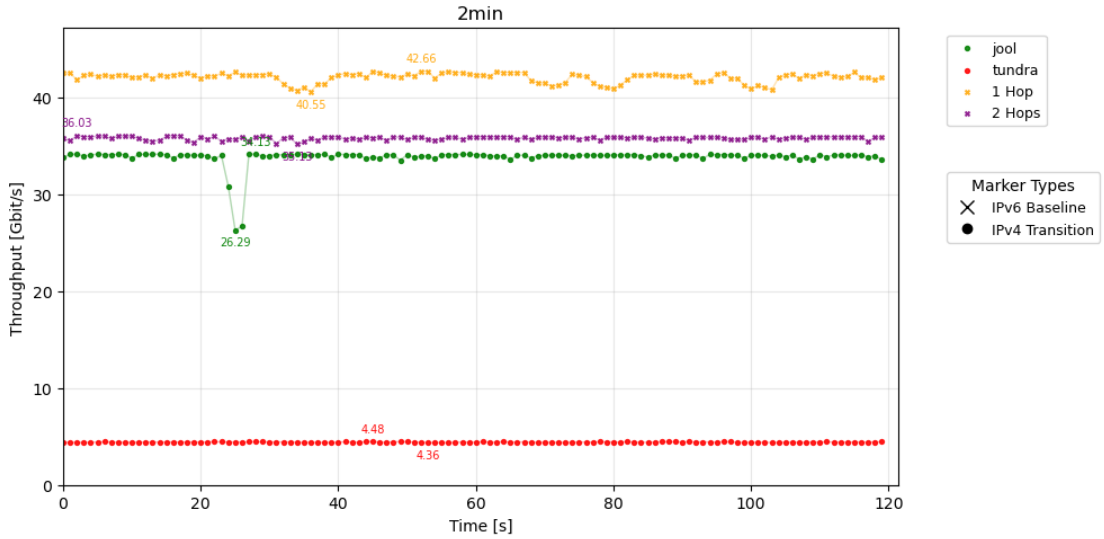


Figure 5.4: Bare-metal host, tsc, linear scale

For consistency we also switched the clocksource to hpet in the bare-metal host environment (Figure 5.5).

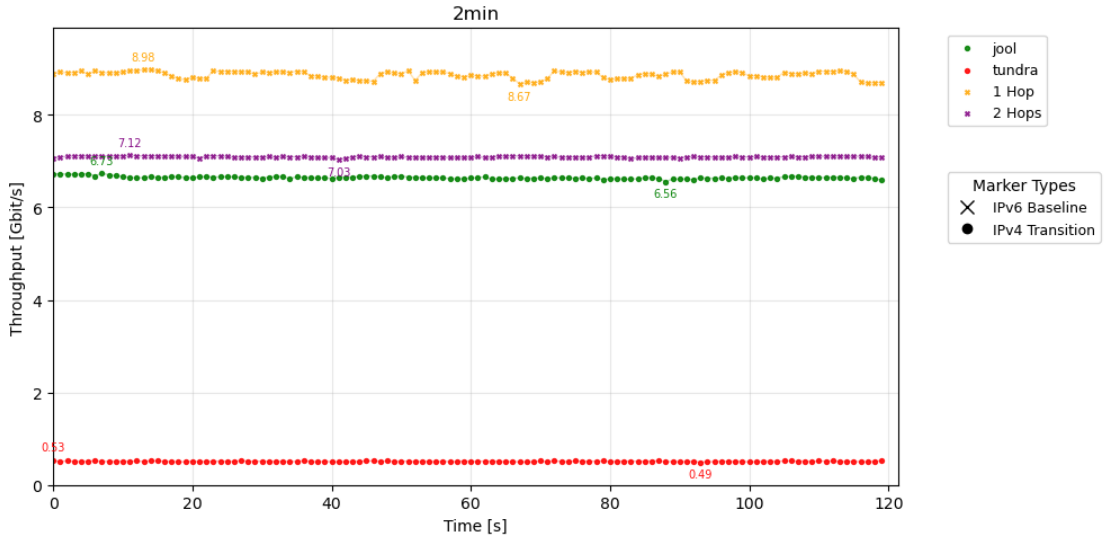


Figure 5.5: Bare-metal host, hpet, linear scale

Figure 5.6 illustrates, in contrast to the earlier AWS dual-y-axis plot, a significantly more stable IPv6 baseline and a clear distinction between the two CLAT implementations.

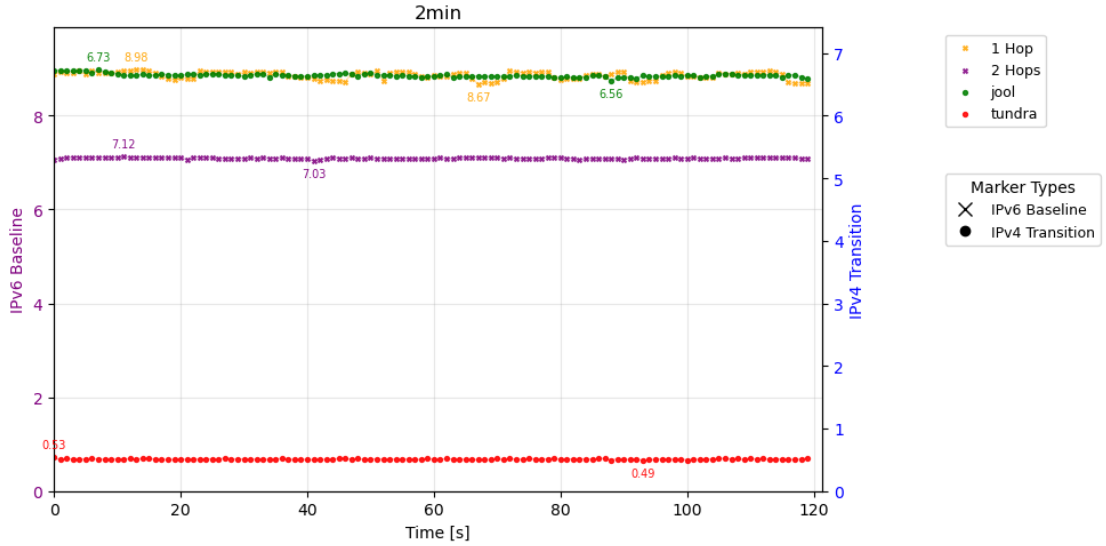


Figure 5.6: Bare-metal host, hpet, dual-y-axis, linear scale

Moving on the bare-metal network setup (Figure 5.7), it introduces a physical 1 Gbit/s Ethernet link that caps the achievable throughput for all datapaths. In this environment, the absolute advantage of the kernel-space datapath on loopback

is compressed by the link bottleneck, and both Jool and Tundra approach the capacity limit. Jool peaks at 0.66 Gbit/s while Tundra approaches 0.57 Gbit/s and the IPv6 baselines are bounded by 1 Gbit/s as expected under both TSC and HPET. The slight upward trends over time are caused by TCP congestion control behavior[32] but does not affect the ordering of the results. The key observation is that when the bottleneck is the external link rather than the host datapath, the differences between CLAT implementations become small relative to the link capacity, and the gap to the dual-stack baseline largely disappears.

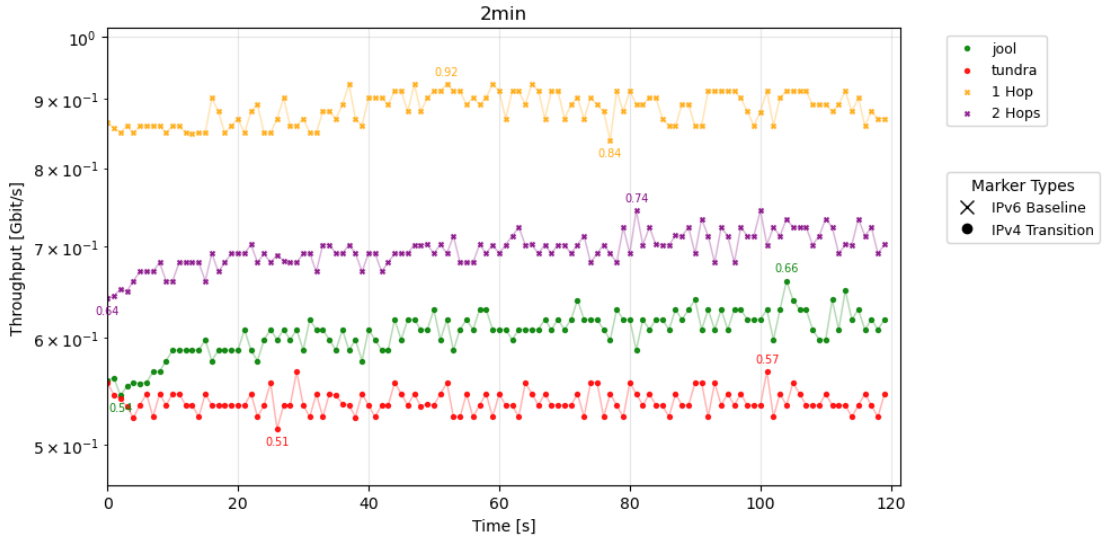


Figure 5.7: Bare-metal network, hpet, log scale

The tsc results in Figure 5.8 exhibit an artifact in which all plots oscillate between 0.92 and 0.93 Gbit/s. As discussed in Chapter 4, this behavior arises from the way TSC operates. Although all values are constrained by the 1 Gbit/s link, the low-resolution clock source of TSC causes the measurements to cluster tightly around the link limit. The observed oscillation is therefore a measurement artifact rather than an inherent property of the datapaths. This effect does not appear when using HPET, whose lower resolution and higher jitter smooth out the measurements.

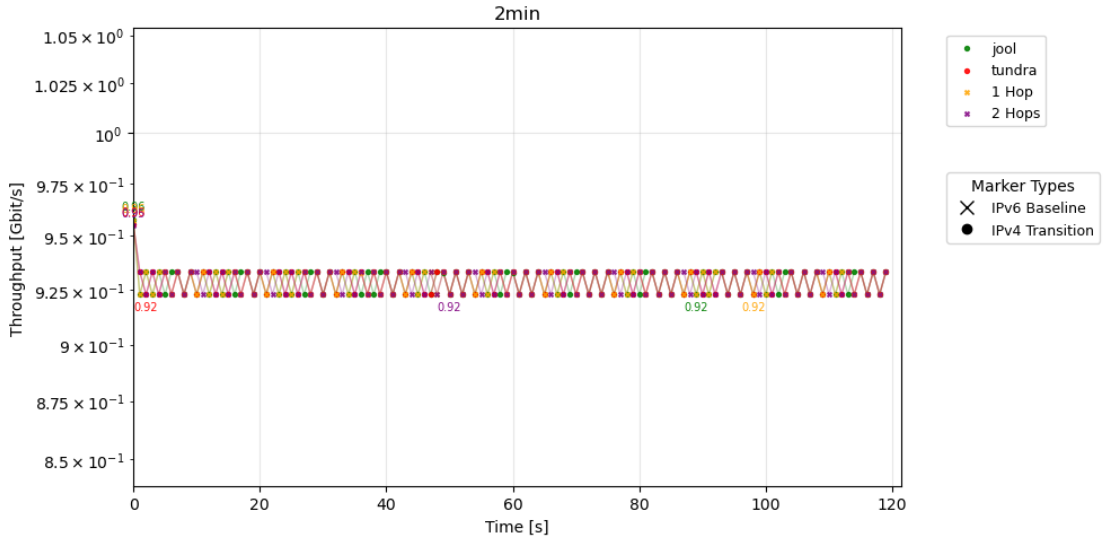


Figure 5.8: Bare-metal network, tsc, log scale

Looking at the dual-y-axis plot in Figure 5.9 for this scenario, the IPv6 baseline shows a stable throughput compared to the AWS environment.

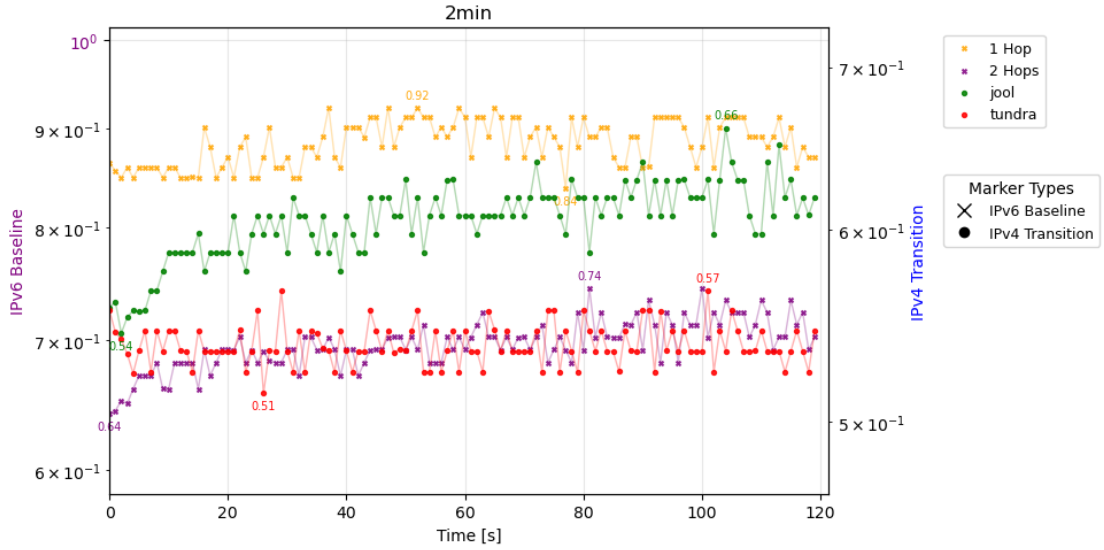


Figure 5.9: Bare-metal network, hpet, dual-y-axis, log scale

Across environments, two effects stand out. First, the translation overhead of CLAT relative to a native IPv6 baseline is strongly environment-dependent. On loopback, Jool's kernel datapath yields a substantial advantage over user-space due

to fewer context switches and reduced packet copy overhead, while on a 1 Gbit/s physical link the advantage compresses toward the link limit. Second, clocksource selection has a measurable impact on time series smoothness and on the dispersion of repeated measurements, especially under virtualization. The local machine results show that platform-induced jitter can dominate differences in the cloud.

5.2 RTT

The RTT results mirror the throughput analysis in showing that the translation cost is small and that kernel-space translation retains a consistent advantage over user-space, while environment and topology shape absolute values. In the AWS environment under HPET (Figure 5.10), a clear gap separates the IPv6 baselines from the CLAT datapaths, consistent with the expectation that translation introduces additional per-packet processing. The one hop IPv6 baseline has a median at 0.042 ms and the two hop baseline around 0.053 ms. Among translators, Jool achieves a mean of 0.064 ms, while Tayga and Tundra lie around 0.091 ms and 0.099 ms, respectively. The relative ordering is therefore consistent with the throughput results.

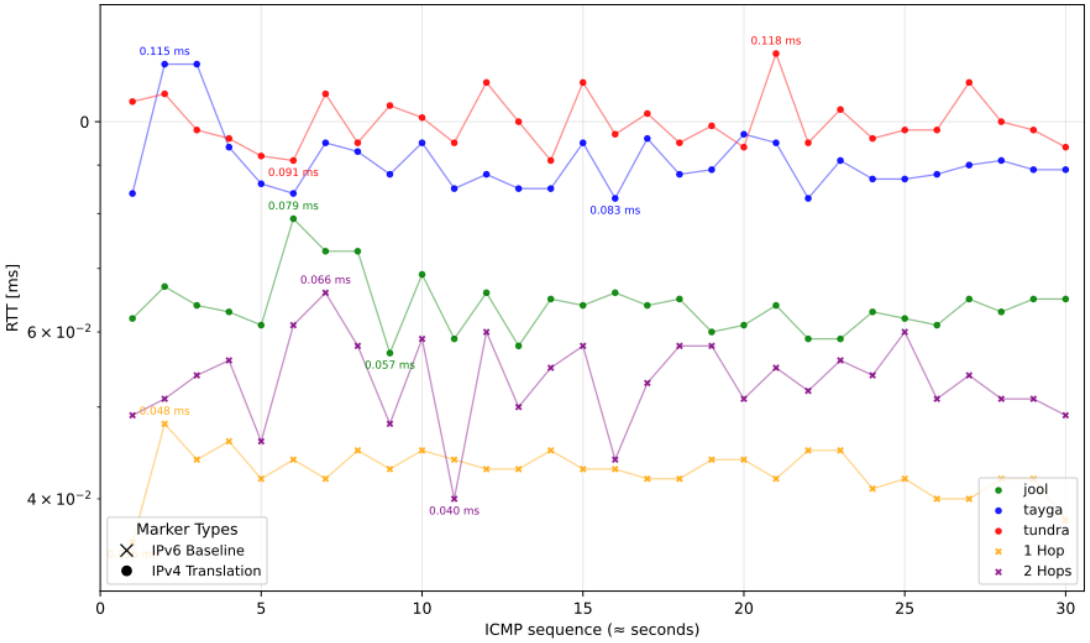


Figure 5.10: AWS cloud environment, hpet, log scale

On the bare-metal host (Figure 5.11), RTTs increase across all datapaths relative

to AWS, which is explained by the host's lower CPU performance. The ordering remains unchanged: Jool again exhibits the lowest CLAT latency with a mean of 0.189 ms, while Tundra's mean is around 0.24 ms. The spread within each series is narrower than in AWS, consistent with the reduced timing jitter observed for throughput.

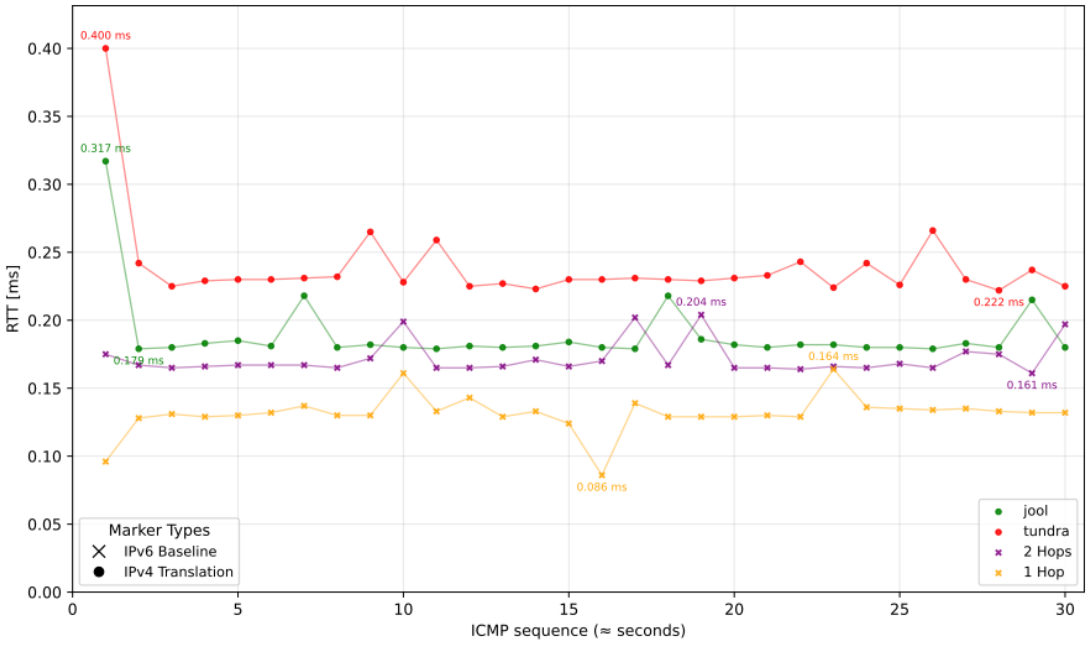


Figure 5.11: Bare-metal host, hpet, linear scale

The bare-metal network environment (Figure 5.12) produces the highest RTTs due to the additional physical hop traversing the Ethernet link. Variability increases across all datapaths, reflecting the added queueing opportunities along the path. Despite the shift in absolute values, the relative ordering persists, with Jool maintaining a modest latency advantage over user-space translation. The gap to the IPv6 baselines remains small in absolute terms, which supports the thesis that CLAT overhead is limited in practice.

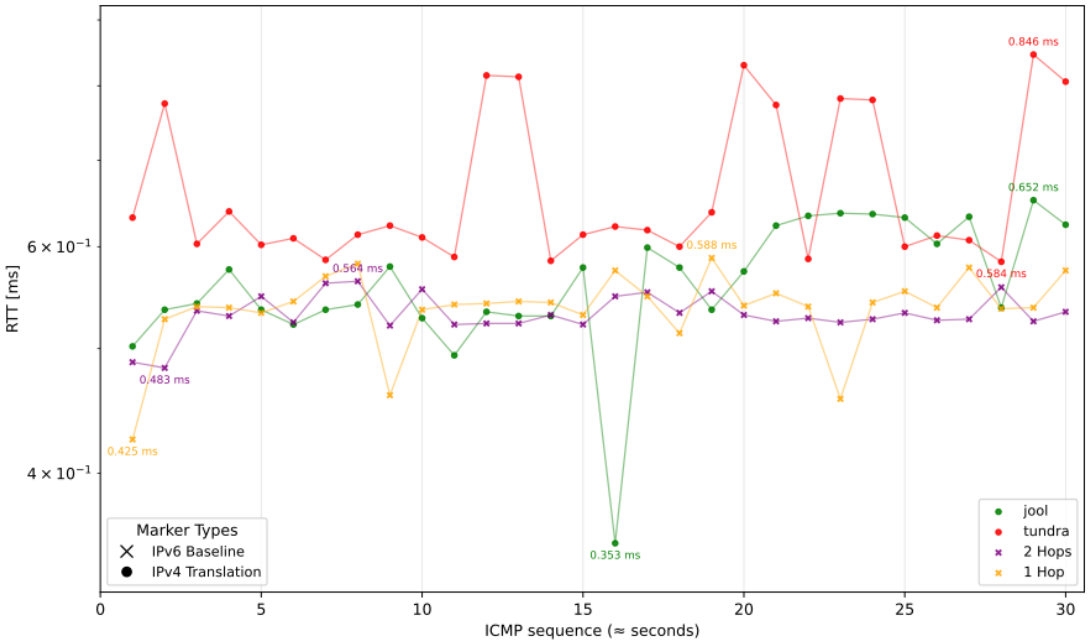


Figure 5.12: Bare-metal network, hpet, log scale

The following tables 5.1, 5.2, 5.3, and 5.4 summarize the key statistics across all measurement scenarios.

Table 5.1: RTT Performance Comparison Across Translation Tools and Scenarios

Scenario	**Type**	**Tool**	**Min (ms)**	**Avg (ms)**	**Median (ms)**	**Max (ms)**	**Std Dev (ms)**	**P95 (ms)**
AWS	IPv4	jool	0.057	0.064	0.064	0.079	0.005	0.073
AWS	IPv4	tayga	0.083	0.091	0.089	0.115	0.008	0.107
AWS	IPv4	tundra	0.091	0.099	0.098	0.118	0.006	0.110
AWS	IPv6	tundra	0.036	0.042	0.043	0.048	0.002	0.046
AWS	IPv6	jool	0.040	0.053	0.054	0.066	0.005	0.061
AWS	IPv6	tayga	0.033	0.042	0.043	0.049	0.004	0.048
Bare-metal host	IPv4	jool	0.179	0.189	0.181	0.317	0.026	0.218
Bare-metal host	IPv4	tundra	0.222	0.239	0.230	0.400	0.032	0.266
Bare-metal host	IPv6	jool	0.161	0.171	0.167	0.204	0.012	0.201
Bare-metal host	IPv6	tundra	0.086	0.131	0.132	0.164	0.014	0.153
Bare-metal host	IPv6	tayga	0.122	0.134	0.127	0.251	0.024	0.167
Bare-metal network	IPv4	jool	0.353	0.563	0.558	0.652	0.060	0.637
Bare-metal network	IPv4	tundra	0.584	0.666	0.615	0.846	0.091	0.823
Bare-metal network	IPv6	jool	0.483	0.532	0.529	0.564	0.018	0.560
Bare-metal network	IPv6	tundra	0.425	0.537	0.540	0.588	0.035	0.580
Bare-metal network	IPv6	tayga	0.403	0.539	0.540	0.577	0.037	0.575

Table 5.2: AWS Cloud Environment Throughput Performance Comparison

Clock-source	**Time**	**Type**	**Tool**	**Min (Gbps)**	**Avg (Gbps)**	**Median (Gbps)**	**Max (Gbps)**	**Std Dev (Gbps)**	**P95 (Gbps)**
hpet	30s	IPv4	tayga	0.176	0.187	0.186	0.209	0.005	0.193
hpet	30s	IPv4	tundra	0.398	0.432	0.433	0.454	0.012	0.450
hpet	30s	IPv4	jool	8.929	9.021	9.014	9.094	0.039	9.090
hpet	30s	IPv6	tayga	9.921	10.062	10.083	10.160	0.069	10.140
hpet	30s	IPv6	jool	9.362	9.418	9.398	9.516	0.050	9.511
hpet	30s	IPv6	tundra	9.908	9.996	9.982	10.119	0.054	10.111
hpet	2min	IPv4	jool	8.884	8.964	8.958	9.082	0.043	9.037
hpet	2min	IPv4	tayga	0.173	0.186	0.187	0.205	0.004	0.190
hpet	2min	IPv4	tundra	0.416	0.447	0.445	0.515	0.016	0.477
hpet	2min	IPv6	tundra	9.705	10.016	10.014	10.142	0.093	10.130
hpet	2min	IPv6	tayga	9.714	10.079	10.111	10.188	0.094	10.180
hpet	2min	IPv6	jool	9.276	9.451	9.445	9.530	0.056	9.519
kvm	30s	IPv4	tayga	0.732	0.834	0.842	0.854	0.027	0.851
kvm	30s	IPv4	tundra	1.205	1.236	1.235	1.286	0.021	1.270
kvm	30s	IPv4	jool	0.001	15.995	17.840	18.967	4.426	18.929
kvm	30s	IPv6	tayga	0.000	14.808	19.622	24.638	9.113	24.214
kvm	30s	IPv6	jool	11.579	19.922	20.824	20.955	2.134	20.903
kvm	30s	IPv6	tundra	14.209	23.299	24.482	24.732	2.653	24.688
kvm	2min	IPv4	jool	0.000	15.488	18.075	19.234	5.507	19.047
kvm	2min	IPv4	tayga	0.703	0.838	0.841	0.861	0.019	0.854
kvm	2min	IPv4	tundra	1.168	1.227	1.228	1.288	0.028	1.271
kvm	2min	IPv6	tundra	0.000	17.034	21.558	29.127	9.261	24.690
kvm	2min	IPv6	tayga	0.000	17.865	23.146	24.881	8.718	24.835
kvm	2min	IPv6	jool	0.000	16.228	20.346	20.525	6.637	20.474

Table 5.3: Bare-metal host Throughput Performance Comparison

Clock-source	Time	Type	Tool	Min (Gbps)	Avg (Gbps)	Median (Gbps)	Max (Gbps)	Std Dev (Gbps)	P95 (Gbps)
hpet	30s	IPv4	tundra	0.495	0.518	0.520	0.537	0.008	0.527
hpet	30s	IPv4	jool	6.677	6.746	6.757	6.786	0.028	6.771
hpet	30s	IPv6	tayga	8.678	8.868	8.937	8.968	0.109	8.961
hpet	30s	IPv6	jool	6.984	7.090	7.105	7.114	0.033	7.113
hpet	30s	IPv6	tundra	8.706	8.900	8.905	9.038	0.100	9.019
hpet	2min	IPv4	jool	6.557	6.644	6.642	6.735	0.028	6.714
hpet	2min	IPv4	tundra	0.493	0.510	0.510	0.535	0.007	0.521
hpet	2min	IPv6	tayga	8.674	8.852	8.876	8.942	0.070	8.927
hpet	2min	IPv6	tundra	8.670	8.860	8.891	8.977	0.080	8.948
hpet	2min	IPv6	jool	7.033	7.092	7.092	7.121	0.015	7.112
tsc	30s	IPv4	tundra	4.394	4.435	4.435	4.477	0.020	4.464
tsc	30s	IPv4	jool	33.255	33.873	33.929	34.084	0.181	34.060
tsc	30s	IPv6	tayga	41.221	42.328	42.521	42.888	0.550	42.885
tsc	30s	IPv6	jool	35.586	35.879	35.932	36.082	0.139	36.034
tsc	30s	IPv6	tundra	41.615	42.307	42.340	42.977	0.294	42.685
tsc	2min	IPv4	jool	26.289	33.813	34.015	34.131	1.008	34.105
tsc	2min	IPv4	tundra	4.362	4.417	4.415	4.478	0.025	4.455
tsc	2min	IPv6	tayga	40.713	42.063	42.229	42.839	0.585	42.763
tsc	2min	IPv6	tundra	40.553	42.039	42.215	42.658	0.496	42.572
tsc	2min	IPv6	jool	35.131	35.778	35.842	36.032	0.167	35.967

Table 5.4: Bare-metal network Throughput Performance Comparison

Clock-source	Time	Type	Tool	Min (Gbps)	Avg (Gbps)	Median (Gbps)	Max (Gbps)	Std Dev (Gbps)	P95 (Gbps)
hpet	30s	IPv4	tundra	0.524	0.541	0.538	0.566	0.010	0.559
hpet	30s	IPv4	jool	0.540	0.584	0.587	0.608	0.019	0.608
hpet	30s	IPv6	tayga	0.848	0.859	0.860	0.891	0.009	0.876
hpet	30s	IPv6	jool	0.631	0.672	0.676	0.703	0.019	0.692
hpet	30s	IPv6	tundra	0.837	0.856	0.849	0.891	0.012	0.876
hpet	2min	IPv4	jool	0.544	0.606	0.608	0.661	0.021	0.630
hpet	2min	IPv4	tundra	0.514	0.538	0.535	0.566	0.010	0.556
hpet	2min	IPv6	tayga	0.849	0.883	0.881	0.923	0.024	0.923
hpet	2min	IPv6	tundra	0.839	0.885	0.891	0.923	0.023	0.912
hpet	2min	IPv6	jool	0.641	0.696	0.692	0.745	0.020	0.724
tsc	30s	IPv4	tundra	0.923	0.929	0.933	0.950	0.006	0.933
tsc	30s	IPv4	jool	0.923	0.929	0.933	0.954	0.007	0.933
tsc	30s	IPv6	tayga	0.923	0.929	0.933	0.959	0.008	0.933
tsc	30s	IPv6	jool	0.923	0.929	0.933	0.949	0.006	0.933
tsc	30s	IPv6	tundra	0.923	0.929	0.933	0.959	0.008	0.933
tsc	2min	IPv4	jool	0.923	0.929	0.933	0.958	0.006	0.933
tsc	2min	IPv4	tundra	0.923	0.929	0.933	0.956	0.006	0.933
tsc	2min	IPv6	tayga	0.923	0.929	0.933	0.955	0.006	0.933
tsc	2min	IPv6	tundra	0.923	0.929	0.933	0.957	0.006	0.933
tsc	2min	IPv6	jool	0.923	0.929	0.933	0.955	0.006	0.933

5.3 Discussion

Across the three environments, two technical factors consistently shaped the measurements more than the mere presence of translation: the location of the bottleneck (CPU/memory path versus network link) and the behavior of the system clocksource under the given platform. When the host datapath was the limiting resource, Jool achieved higher throughput and slightly lower RTT than the user space translators. This is consistent with expected mechanisms: fewer user/kernel context switches, fewer packet copies, and tighter cache locality in the kernel datapath. Contrarily, when a physical 1 Gbit/s link capped the rate, the differences among CLAT implementations compressed toward the link limit and the gap to the IPv6 baselines largely reflected the shared network bottleneck rather than translation.

Virtualization timing artifacts were clearly visible in the AWS environment. With kvm-clock, both the native IPv6 baseline and Jool exhibited large swings despite a constant topology and traffic profile, while Tayga and Tundra reported stable but lower throughputs. Switching to hpet reduced but did not eliminate irregular patterns in the IPv6 baseline time series. The divergence under kvm-clock and the residual artifacts under hpet indicate that timer behavior can overshadow datapath differences at high rates in virtualized settings. This observation motivated repeating the same topology on local machines, where platform-induced jitter was indeed reduced.

On bare metal, the role of the clocksource remained a first order effect. The tsc based runs produced tightly clustered, higher reported throughputs on loopback, while hpet yielded smoother traces with consistently lower throughputs. On the 1 Gbit/s ethernet link, tsc introduced a characteristic quantization around 0.92–0.93 Gbit/s for all datapaths, an artifact of timing resolution rather than a property of the translators, whereas hpet smoothed out the measurements at the cost of higher timing overhead. These patterns suggest that clock selection affects both the stability and the absolute levels of reported results, which in turn implies that comparisons should always be interpreted relative to a same-clock baseline.

Topology and hop count had a measurable, separate effect from translation. In the bare-metal host setup, the two-hop IPv6 baseline showed lower throughput than the one-hop IPv6 baseline. This baseline separation quantifies the cost of an extra namespace traversal and helps attribute what fraction of observed differences stems from topology rather than translation. It also supports reading the Jool versus user space gap on loopback as a combination of translation placement (kernel versus user space) and the additional hop required by the Jool setup.

Regarding the representation of user space translators, the plots for the single host bare-metal throughput focus on Jool and Tundra. Two considerations motivated this choice. First, Tundra consistently outperformed Tayga in the AWS IPv4 translation tests, so including Tayga would not change the ordering and would

add redundancy in the figures. Second, Tundra's multi-threaded design makes it a reasonable user-space upper bound under the single-flow conditions used here. Using it as the representative user-space datapath simplifies comparisons while preserving the visibility of trends. Tayga remains included where it illuminates behavior (e.g., AWS throughput, baseline IPv6 throughput, and RTT tables) and its qualitative positioning relative to Tundra is consistent across environments.

The RTT results parallel the throughput findings. The kernel datapath retained a modest latency advantage over user space in all environments. Absolute RTTs were lowest on AWS, higher on the bare-metal host, and highest on the bare-metal network, consistent with CPU differences and the additional physical hop and queueing opportunities in the networked case. Variability was highest under virtualization and lowest on single-host bare metal, matching the throughput jitter patterns and reinforcing the role of timing sources and platform effects.

Chapter 6

Conclusion

This concluding chapter revisits the thesis question, whether client-side translation via CLAT imposes a performance penalty compared to Dual-Stack and synthesizes the empirical evidence gathered across three environments and three Linux CLAT implementations. It draws together the main findings on throughput and latency, interprets their significance in light of platform and topology effects and outlines directions for future work that would extend the scope from benchmarks toward system level validation in containerized environments.

Summary of Key Findings The measurements show that CLAT can deliver performance close to native Dual-Stack for the tested workloads and that the magnitude of any overhead depends less on the abstract notion of "translation" and more on where the performance bottleneck lies. When the host datapath was the limiting resource, the kernel-space implementation achieved substantially higher TCP throughput and modestly lower RTT than user-space translators, consistent with the expected advantages of avoiding additional copies and context switches and of maintaining cache locality in the kernel datapath. Conversely, when the bottleneck moved to a 1 Gbit/s Ethernet link, the differences among CLAT implementations compressed toward the link limit and the gap to the Dual-Stack baselines reflected the shared network bottleneck rather than translation overhead. This pattern was consistent across environments. In the bare-metal host setup the one-hop and two-hop IPv6 baselines established the cost of an extra namespace traversal and the kernel versus user space gap aligned with that baseline separation. In the bare-metal network setup, overall rates converged and the relative ordering persisted only as a small difference within the link cap.

Timing sources emerged as a primary factor in virtualized and local runs alike. In the AWS environment, kvm-clock produced pronounced swings in both the native IPv6 baseline and Jool despite constant topology and workload, while Tayga and Tundra appeared stable at lower rates. Switching to hpet reduced but did

not fully eliminate irregularities in the baseline time series. On bare metal, tsc yielded higher reported loopback throughputs and on the 1 Gbit/s link whereas hpet smoothed traces at the cost of higher timing overhead. These effects underscore that reliable comparisons require interpreting translation results relative to baselines taken under the same clocksource. Furthermore, they also explain why cloud based measurements, if not carefully controlled, can obscure datapath differences behind platform jitter.

RTT results mirror the throughput trends. Across environments, Jool consistently showed a small latency advantage over user-space translation, while absolute RTTs scaled with CPU capabilities and the presence of a physical hop. The ordering among translators remained stable even as absolute values shifted between cloud, bare-metal host and bare-metal network conditions. Together, the throughput and RTT evidence supports the central claim: for the tested single flow TCP and ICMP workloads, CLAT introduces only a limited overhead relative to Dual-Stack and that overhead becomes practically negligible when the network link, not the host, is the binding constraint. This finding strengthens the case for IPv6-first designs that rely on 464XLAT to maintain IPv4 reachability, especially in settings where IPv4 scarcity or cost pressures make Dual-Stack unattractive.

Future Work Several extensions would broaden both the technical depth and operational relevance of the conclusions. First, additional metrics should be incorporated to illuminate the costs and limits of translation under load. CPU utilization would quantify efficiency and reveal headroom. Memory bandwidth and cache behavior would connect datapath choices to hardware limits. Tail latency distributions under sustained traffic are particularly important for user experience and could be coupled with congestion control dynamics to capture impacts not visible in averages.

Second, future experiments should remove or raise the external bottleneck to expose intrinsic translator limits. Running on hosts with 10/25/40/100 Gbit/s NICs and exploring fast paths would help distinguish translator overhead from network interface card constraints. These setups would also allow a more direct comparison between Jool's kernel datapath and user-space translators when neither the link nor the timing source is the dominant limiter.

Third, concurrency should be used to exercise Tundra's multi-threaded design and to establish scaling curves for user space translation. Using many parallel iperf flows, mixed short and long connections would test whether Tundra approaches kernel-space performance.

Finally, the motivation for this work, supporting IPv6-only clusters and services, calls for validation in containerized environments. Integrating CLAT into Kubernetes, for example by packaging the CLAT as a DaemonSet with per node

configuration, would enable measurements across common CNIs. An automated test environment that provisions clusters, applies network policies, configures translators, and runs reproducible benchmarks would turn the methodology into a continuous integration workflow and provide operational guidance for adopting 464XLAT at scale.

Appendix

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Additional Plots

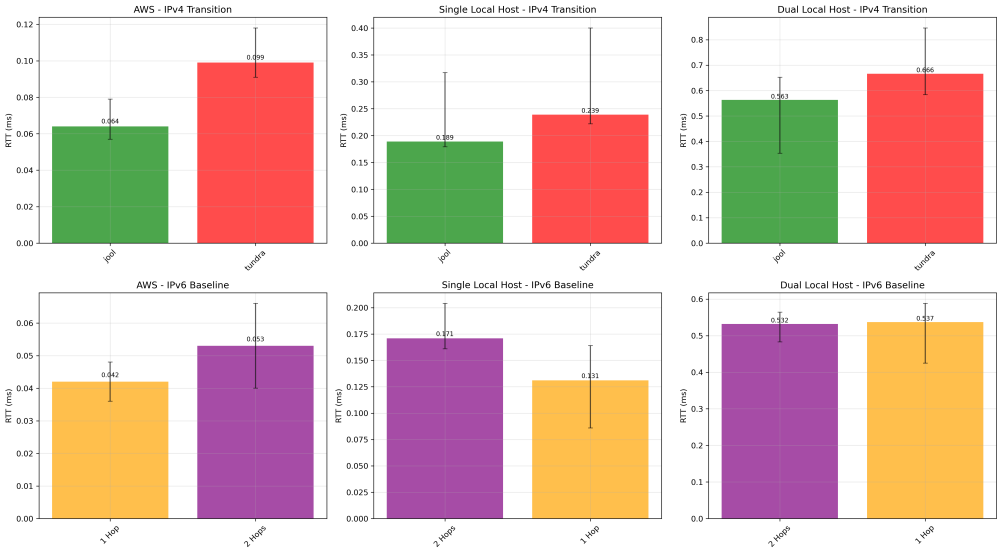

Figure 1: RTT Comparison Summary

TCP Plots for 30s Duration

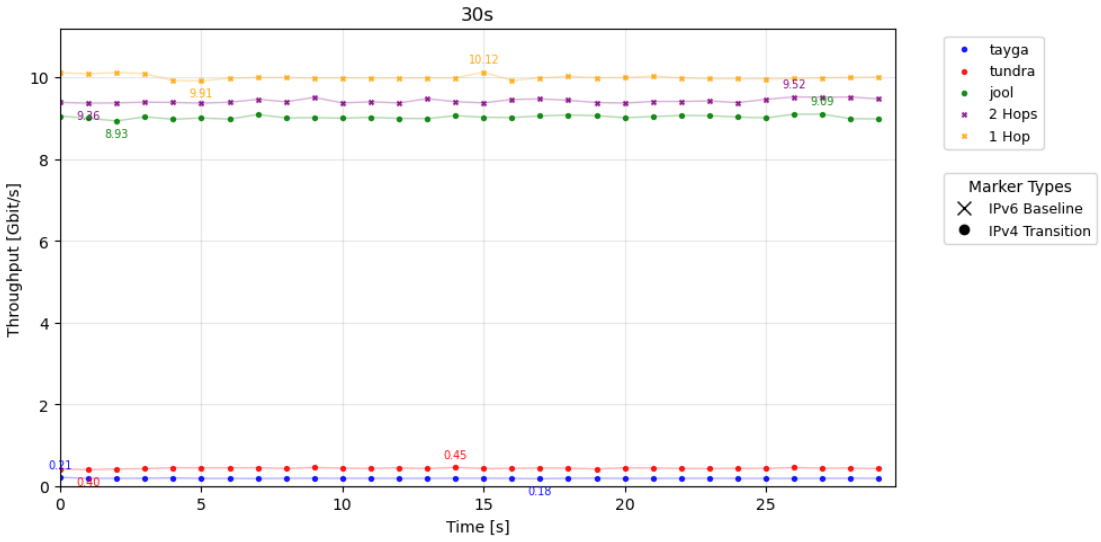

Figure 2: AWS HPET 30s Linear

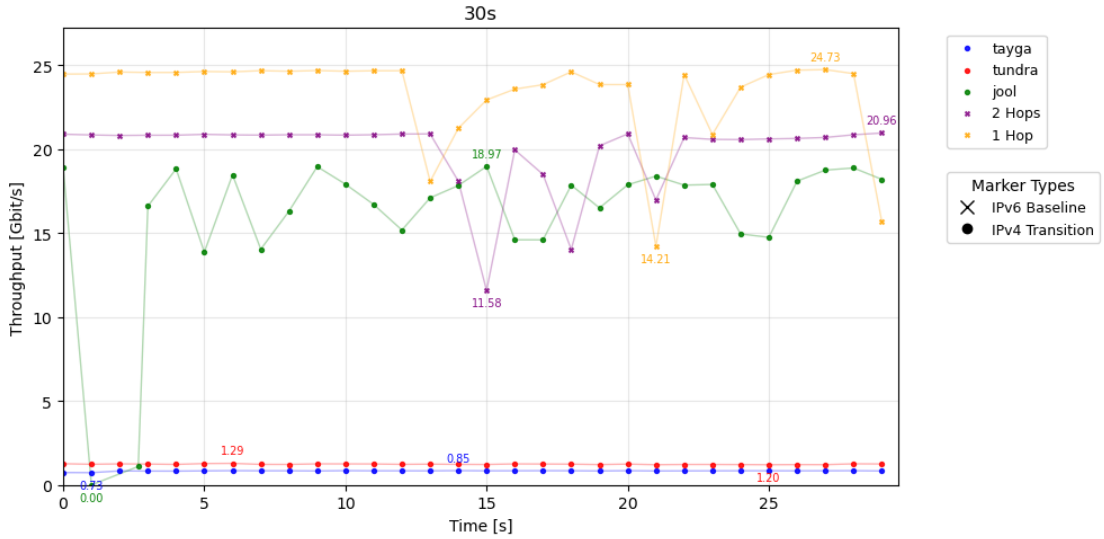

Figure 3: AWS KVM-Clock 30s Linear

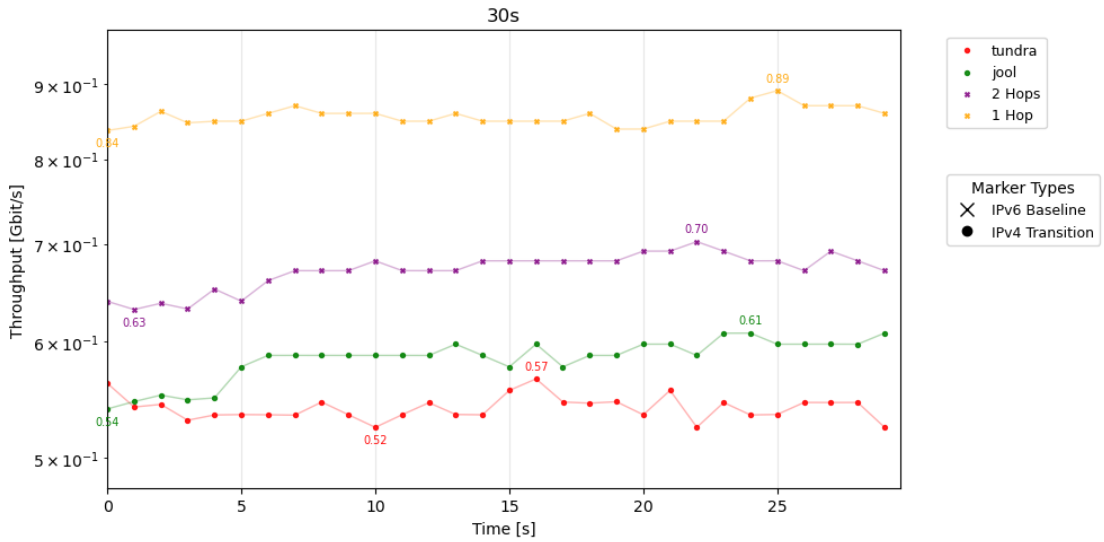

Figure 4: Bare-metal network HPET 30s Log

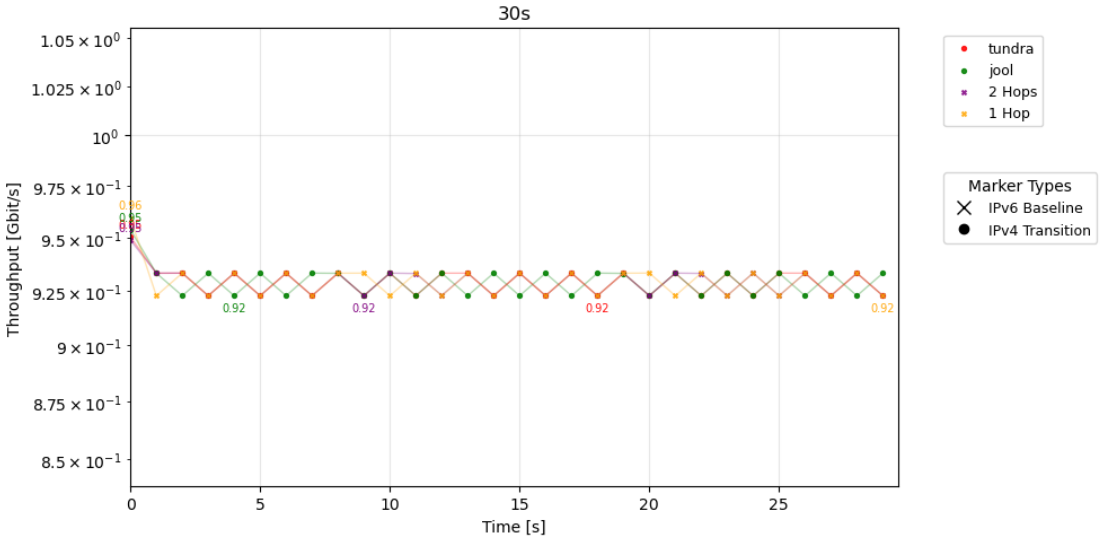

Figure 5: Bare-metal network TSC 30s Log

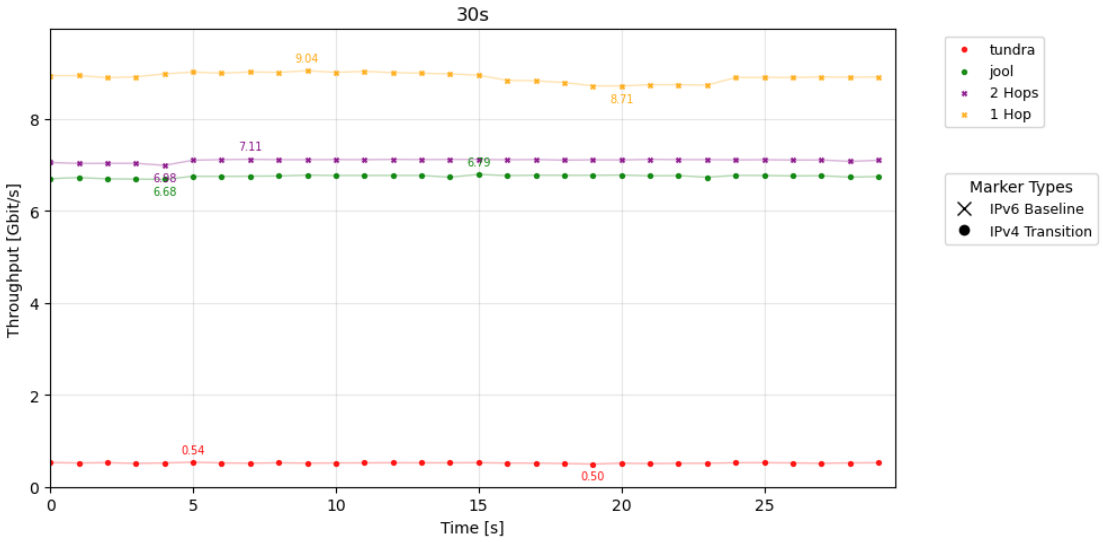

Figure 6: Bare-metal host TCP HPET 30s Linear

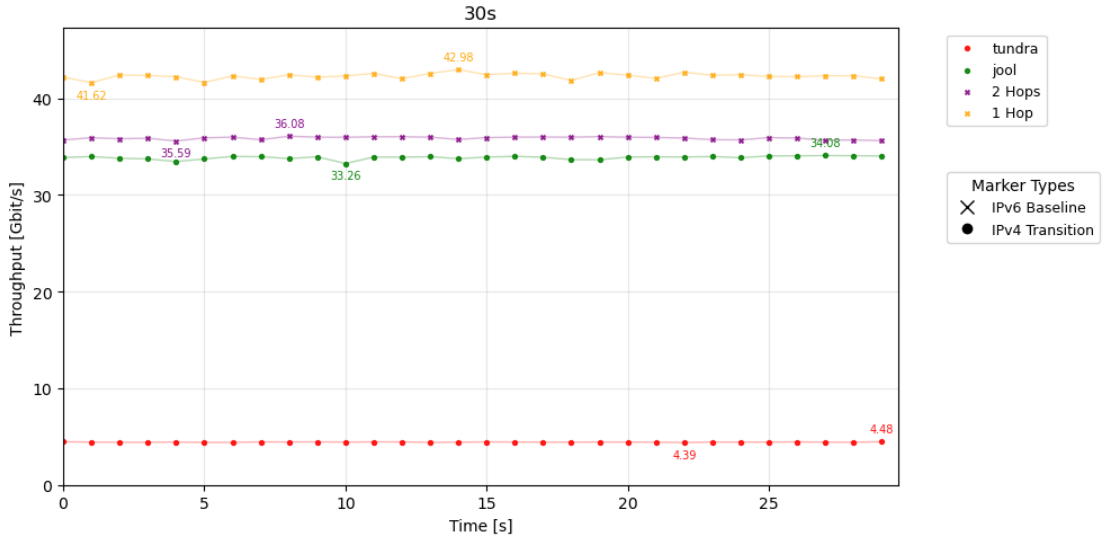

Figure 7: Bare-metal host TSC 30s Linear

Dual-y-axis TCP Plots for 30s Duration

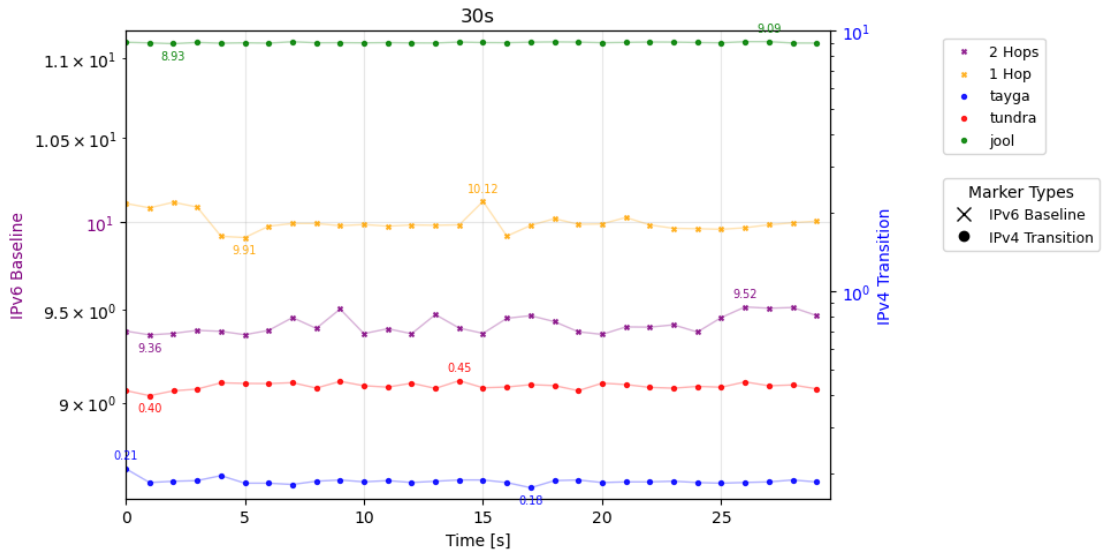

Figure 8: AWS TCP HPET 30s Log

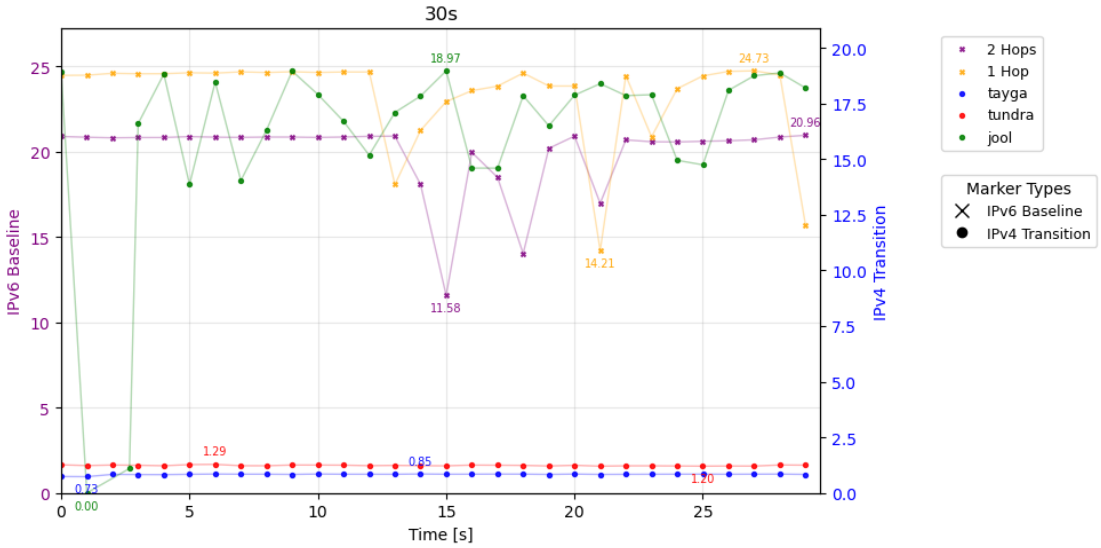

Figure 9: AWS TCP KVM-Clock 30s Linear

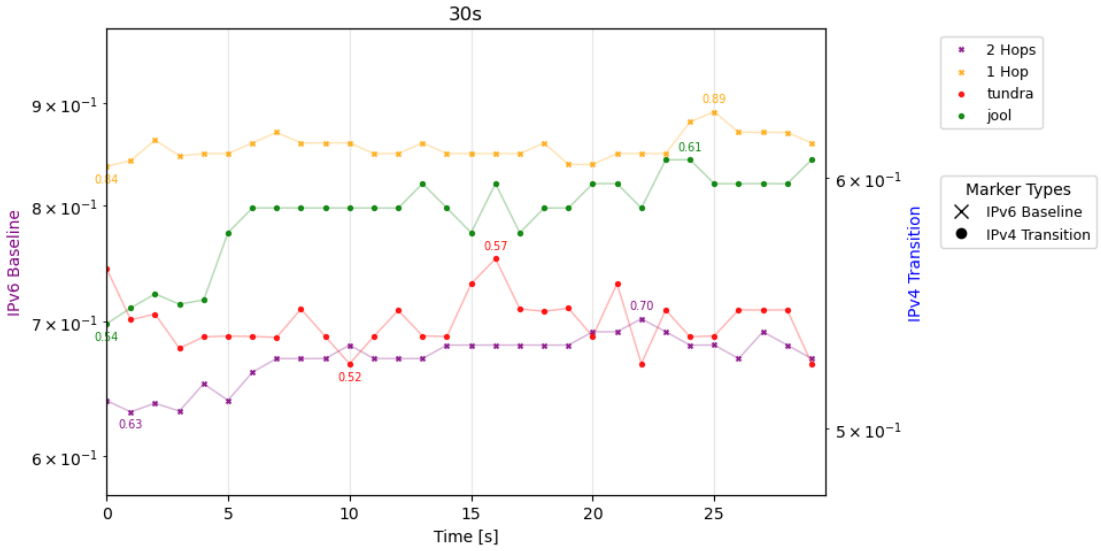

Figure 10: Bare-metal network HPET 30s Log

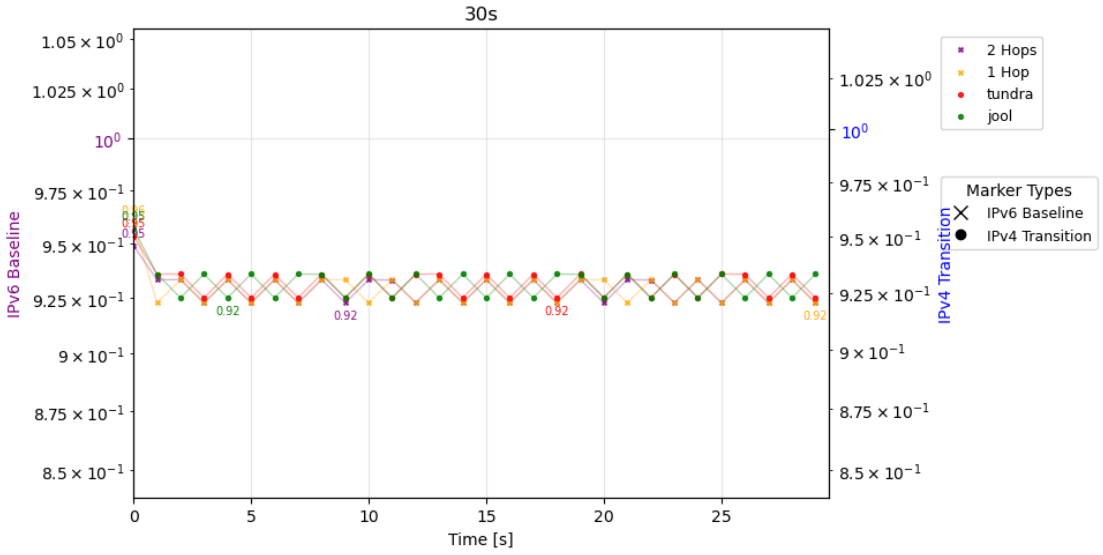

Figure 11: Bare-metal network TSC 30s Log

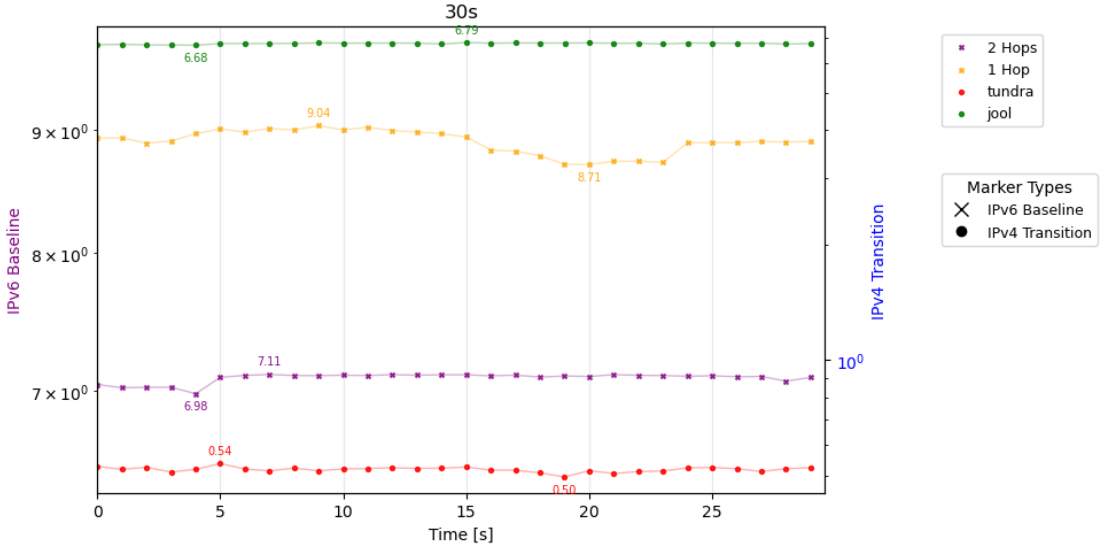

Figure 12: Bare-metal host HPET 30s Log

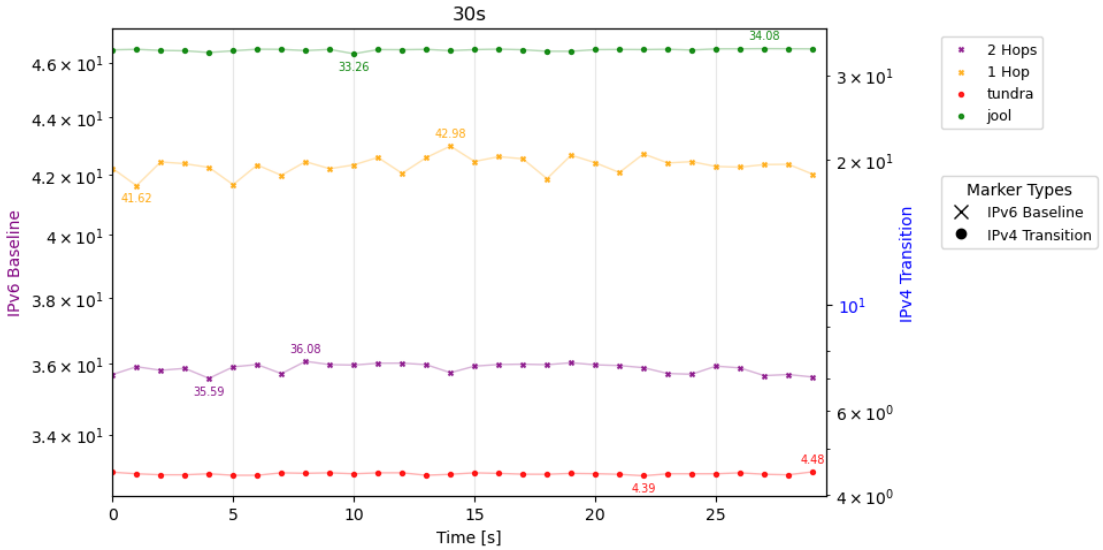

Figure 13: Bare-metal host TSC 30s Log

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