Roam Without a Home: Unraveling the Airalo Ecosystem

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Abstract

Recently, various Mobile Network Aggregators (MNAs) have emerged, leveraging the coverage of a few base operators to offer global connectivity. These MNAs reap the benefits of network softwarization and virtualization, such as eSIM technology or control/data-plane separation. This paper explores a new type of MNA – a *thick* MNA – that uses multiple base operators from different regions to provide eSIM profiles and employs public internet gateways outside the base operators' home countries. Specifically, we analyze Airalo, a thick MNA operating in 219 countries. Unlike other MNAs that our community has scrutinized, we show that Airalo often decouples the geographical location of the public internet gateway from the native country of the base operator via IPX Hub Breakout (IHBO). To map Airalo's underlying infrastructure, we ran web-based measurements that 14 volunteers performed while traveling and using an Airalo eSIM on their personal devices. We further dive into Airalo's performance by running device-based measurements (speedtest, traceroute, etc.) in 10 countries. We find that IHBO, despite offering some latency benefits over traditional Home-Routed Roaming, still results in inflated latency and degraded bandwidth compared to non-roaming traffic, introducing new challenges for user experience, content access, and privacy.

CCS Concepts

• **Networks → Network measurement**; **Network performance analysis**; *Topology analysis and generation*; *Network economics*; Location based services.

Keywords

Mobile Networks, Roaming, IPX Network, eSIM

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1 Introduction

Mobile Network Aggregators (MNAs) like Google Fi and Twilio have disrupted the Telco sector by enhancing the the Mobile Virtual Network Operator (MVNO) model [42, 48, 51] to use infrastructure from multiple base operators, offering global connectivity. With the rise of embedded SIM (eSIM) technology in smartphones and wearables, some MNAs allow travelers to avoid the hassle of purchasing local SIM cards and the high costs of roaming.

The combination of MNA and eSIM technology with the recent advances in network virtualization [22, 25, 29] enables a new era in global mobile connectivity, characterized by varying degrees of operational complexity. Until now, we have seen (commercial) evidence of MNAs that rely on the core networks of base operators (light MNAs) or run their own (full MNAs) [9, 50] to provision their eSIM profiles. Both models gain access to (visited) radio access networks globally via interconnection through roaming hubs [31].

In this paper, we provide the first empirical evidence of a new breed of MNAs – *thick MNA* – that only run specific core network functions (e.g., the gateway function to the public internet access), while still relying on the cellular ecosystem, similar to earlier models. Airalo [8] is a popular thick MNA that has gained more than 5 million customers since its inception in 2019. Airalo decouples the internet gateway location from both the base and the visited operators' infrastructure. Despite its popularity, anecdotal reports on Airalo's quality of service have been largely mixed [41].

Motivated by the above, we investigate thick MNA operations by dissecting Airalo from *infrastructural*, and *performance* perspective. We acquired Airalo eSIMs for 14 countries, and had volunteers use them while traveling, performing high-level measurements via JavaScript on our website [1]. To compare with local physical SIMs, volunteers also carried rooted Android device running automated tests in 10 additional countries. Overall, we measure 11% of Airalo's global footprint across 24 of its 219 served countries.

Our analysis shows that 6 base operators provide Airalo eSIMs via roaming in 21 of the 24 countries measured; in the remaining 3 countries, Airalo uses native profiles from local operators. This extensive roaming network allows Airalo to achieve global coverage without lengthy direct agreements with local operators. For roaming eSIMs, we map their public IPs to Autonomous System numbers (ASNs) and identify prevalent use of Home Routing (HR) and IPX Hub Breakout (IHBO), with no evidence of Local Breakouts (LBO). We next summarize the main takeaways from our analysis.

Limited PGW Selection. To the best of our knowledge, this is the first study to show evidence of IHBO used by a commercial operator. In theory, IHBO can enable dynamic routing of roaming traffic, prioritizing Packet Data Network Gateways (PGW) closer to (but not belonging to) the *visited Mobile Network Operator* (v-MNO) [5, 9, 32]. In practice, we find that the PGW locations are restricted via pre-configured agreements among MNOs, IPX-Ps and PGW providers, limiting the possible performance benefits of using

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IHBO (Section 4). Most Airalo eSIMs rely on a single, fixed PGW provider, indicating a static pre-arrangement of PGW selection.

Latency Degradation. Popular providers like Google and Facebook place edge nodes close to PGWs operated by major IPX-Ps and MNOs. As such, we find that Airalo (roaming) eSIMs tend to have comparable *public* distance – *i.e.,* number of hops on the public internet after breaking out – with respect to their physical SIM counterparts (Section 4.3). However, this is insufficient to offset the preceding *private* distances between end user and PGWs, which are often due to the inefficient PGW selection discussed above. Approximately 14.5% of the latency measurements done via roaming eSIMs provide *less desirable* latencies (*i.e.,* exceeded 150 ms), while only 3% of measurements done in physical SIM cards reached such high latency levels. However, IHBO reduces the impact of home routing latency through the base operator's infrastructure. Compared to the native setup, IHBO inflates the latency by 64%, an order of magnitude less than the 621% increase of home routing, the standard setup for roaming [15, 34].

Negligible Impact on Data Speeds. We find that the underlying roaming configuration for the Airalo eSIMs did not correlate with the end-user's network bandwidth (Section 5.1). Specifically, IHBO did not lead to significant improvement over home routing in terms of download speed. Overall, however, we find considerable variation in the downlink among eSIMs from the same base MNNO (b-MNO), e.g., spanning from 31.7 Mbps in Georgia up to 11.2 Mbps in Spain, despite both being provisioned from *Play Poland*. These findings highlight that network throughput for roaming eSIMs is largely contingent upon the policies of the v-MNO, rather than the specific roaming topology chosen.

2 Background and Related Work

eSIM Technology. Unlike physical SIM cards, which store subscriber information tied to a specific MNO, embedded SIMs (eSIMs) are built into devices and can host multiple subscriber *profiles* without physical swapping, enabled by Remote SIM Provisioning (RSP) [19]. This paper will use the term "eSIM" to refer to an "eSIM profile" for brevity. RSP supports a marketplace of eSIM providers that act as intermediaries between users and MNOs, offering web and mobile interface for purchasing customized eSIM plans.

Roaming. MNOs support international mobility of their users via *roaming*. In the context of mobile communication, the terms *native* and *roaming* user distinguish between the network to which an end user connects. A native user is connected to the b-MNO's network, the infrastructure of the MNO that issued the SIM. Conversely, a roaming user is outside the coverage area of the b-MNO. To access mobile services in a foreign visited country, the device connects to a v-MNO that has a roaming agreement with the b-MNO.

MNOs typically rely on the IP Packet Exchange (IPX) network [17, 18, 20] to facilitate world-wide roaming services. This consists of a small set of IPX Providers (IPX-P) that peer with each other over a private IP backbone, forming a tightly meshed network isolated from the public internet [31, 32]. By contracting an IPX-P, an MNO establish communication with other operators that are also connected to the IPX network. With IPX network serving as the central hub, MNOs can expand their service footprint globally through a single point of contact. The connections between MNOs can be

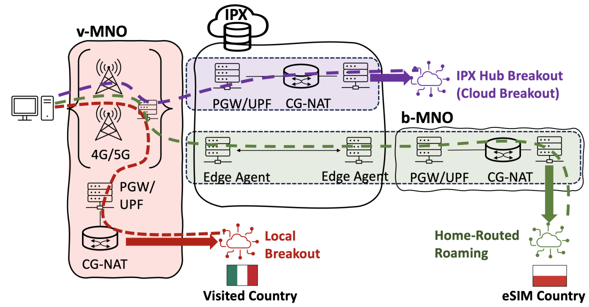

Figure 1: Roaming configuration for the data path of eSIM provisioned by b-MNO in Poland (green), and operating in Italy (red) via a local v-MNO: HR routes the traffic through the home country, LBO routes the traffic through the visited country, and IHBO routes the traffic via a third-party location offered by the IPX-Provider.

further configured in accordance to their roaming agreements, with the IPX-P enabling policies to control roaming services.

Figure 1 shows the architectural differences of the three main roaming architectures [5, 33, 34]. *Home-Routed Roaming* (HR) involves assigning the public IP address of a roaming user by the b-MNO. All inbound and outbound traffic flows through a GPRS Tunneling Protocol (GTP) tunnel between a Serving Gateway (SGW) within the v-MNO and a PGW of the b-MNO. While this allows access to IP-based services provided by the b-MNO, it comes with higher latency due to the GTP tunnel. *Local Breakout* (LBO) allows the v-MNO to assign the public IP address of a roaming user, enabling direct internet access without traversing the IPX network to reach the b-MNO. However, LBO may limit access to b-MNO-specific services and prevent service control and charging from the b-MNO. *IPX Hub Breakout* (IHBO) uses PGWs hosted by a third-party within the IPX network to assign public IP addresses to roaming users. A GTP tunnel links the v-MNO's SGW to a selected PGW based on factors like geography, latency, and business agreements. The IPX network, trusted by the b-MNO, assigns an IP address recognized by the latter to support operator-specific services for the roaming user.

Mobile Network Aggregators (MNAs). Figure 2 captures the differences between MNA flavors. The MNAs run a limited part of the network: the *light* – only sales, the *full* – sales and full core deployment, and the *thick* – sales and a limited part of the core. Their global service relies on aggregating the international footprint of several b-MNOs (*i.e.,* for the light/thick model), or accessing directly one or more IPX-P for roaming hub services (*i.e.,* for the full model).

Airalo decouples the b-MNO that provisions the eSIM from the traditional notion of the *home* MNO of the user: we show that the b-MNO may be from a different country than the home or the visited countries of the end-user, breaking apart from other models of MNAs. For example, a user from the US travels to Italy, where their Airalo eSIM uses a profile issued from a Polish operator (b-MNO) that connects locally to an Italian provider (v-MNO).

Comparison With Related Works. Several studies have shown that roaming users suffer from penalties in network performance and Quality of Experience (QoE). In [15, 33–35], physical SIM cards from popular MNOs in Europe were found to rely on HR for roaming, causing additional latency with respect to the geographical

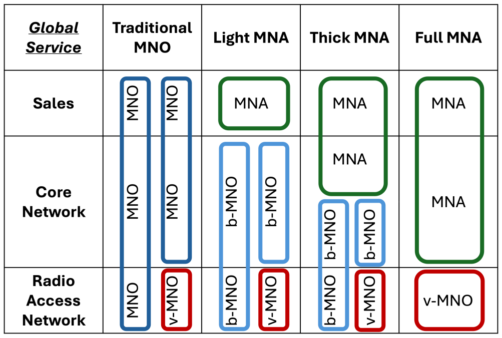

Figure 2: MNAs run a limited part of the network (the *light* – only sales << the *thick* – limited core function << the *full* – all the core), and provide global service by exploiting the roaming agreements of several b-MNOs.

distance between the roaming user and the b-MNO. Our work differs from these papers in two ways. First, we focus on a thick MNA operating at a global scale (Airalo). Second, we discover that significant portion of eSIM plans in Airalo depends on international roaming, with a mix of HR and IHBO configuration, which had not been previously observed. Accordingly, we offer the first comprehensive comparison of these two roaming architectures with respect to network performance.

Our work is closely related to [9], which analyzes the roaming performance of three MNAs: Google Fi – a light MNA via eSIMs, Truphone – a full MNA via eSIMs, and Twilio – a full MNA via physical SIMs. The paper shows that, back in 2022, all providers relied on HR for roaming. However, the measurements were limited to roaming in two EU countries (Spain and Norway) using an international roaming plan from each MNA. In comparison, our work has larger geographical coverage – spanning 24 countries across 4 continents – and measures the performance of eSIMs tied to specific regions, which may or may not involve roaming. We also note that Airalo targets a different user demographic from Google Fi, which is limited to mobile customers in the US, or from Twilio, which is limited to IoT devices. Indeed, our paper is the first to study the reality of a thick MNA, which aggregates services from MNOs globally and exploits their roaming agreements, but also involves the IPX network.

3 Methodology

3.1 Web-Based Campaign

We ran the web-based measurement campaign from March 10th to 22nd, 2024, to investigate the infrastructure and high-level performance of Airalo. This campaign targeted 14 countries (9% of Airalo's current offering), selected based on the opportunity to have volunteers visiting such countries and use a complimentary eSIM. Accordingly, we acquire 14 Airalo eSIM plans for which we identify the v-MNO as the network operator displayed in the phone (while travelling), and its b-MNO as the MCC-MNC codes from the Access Point Name in the device settings.

While travelling, volunteers access a webpage [1] we developed; the webpage first prompts to upload a screenshot of network settings, which is analyzed with chatGPT vision [39] to verify that the device is using the provided eSIM (and not Wi-Fi). If successful,

Measurement	Description	Visibility
Speedtest	Speedtest to an Ookla server near user's IP-geolocation	Latency, Down/Up Bandwidth
Traceroute	Traceroute to Google/Facebook/Youtube via `mtr`	Latency, Network Path
CDN	Download `jquery.min.js` (v3.6.0) from different CDN providers	Download Speed, DNS lookup time (via curl's built-in timing features)
DNS	Retrieve the current DNS resolver via Nextdns	DNS resolver
YouTube	Collect video-streaming info from YouTube's `stats-for-nerds` while playing 4K video	Video Resolution, Buffer Occupancy

Table 1: Description of network measurements and data collected during the device-based campaign, via the `AmiGo` testbed.

the next step retrieves the DNS configuration via Nextdns [36]. We ensure that the volunteers have no custom on-device DNS settings.

Finally, we perform a speedtest by loading https://fast.com in an iframe. While fast.com measures bandwidth to Netflix's servers, which may not be the most representative benchmark in regions with low Netflix usage, it is (to our knowledge) the only popular speedtest provider that permits iframe embedding. We then ask the volunteers to upload a screenshot of test results upon completion; we again use chatGPT vision to analyze the screenshot, verify correctness, and extract data like download speed and latency. We use the public IP associated with an eSIM – derived both via fast.com and logged by our server – to characterize the roaming architecture by matching its Autonomous System Number (ASN) against the b-MNO's (HR), the v-MNO (LBO), or a third party such as an IPX-P (IHBO). Table 3 in the Appendix summarizes the measurements collected at each country throughout this campaign.

3.2 Device-Based Campaign

The device-based measurement campaign was conducted from December 2023 to April 2024, providing 10 volunteers with rooted Android phones with both an Airalo eSIM and a local SIM from the same v-MNO used by the eSIM. These phones, supposed to be carried and not used by our volunteers, are set up to run a plethora of measurements while switching between physical SIM and eSIM. The main goal of this campaign is to characterize the performance of Airalo, especially when compared with local SIM providers.

We extend the (open-source) `AmiGo` code [47], which provides a control server to remotely manage mobile measurement endpoints (MEs). The MEs are rooted Android devices instrumented via `termux` [45]. The control server offers restful APIs which the MEs call to perform two main functions: 1) report their current status, including device vitals like battery level and connectivity, as well as radio-level metrics (e.g., Received Signal Strength Indicator, Signal-to-Noise Ratio, Channel Quality Indicator), and 2) retrieve instrumentation code, which are shell scripts for execution within the termux environment. `AmiGo` only supports the Redmi-Go, which is unsuitable for our measurements as it lacks eSIM support. We identify the Samsung 21+ 5G as a suitable alternative, given its ease of rooting and eSIM compatibility. We subsequently extend `AmiGo` to support this device by implementing new automation hooks.

The devices are instrumented to periodically run various network experiments, which we summarize in Table 1. At low level,

Visited Countries	b-MNO (Country)	PGW Provider(s) (ASN)	PGW Country	Type
ARE, JPN, PAK, MYS, CHN	Singtel (SGP)	Singtel (AS45143)	SGP	HR
GBR, DEU, GEO, ESP	Play (POL)	Packet Host (AS54825)	NLD	IHBO
		OVH SAS (AS16276)	FRA	IHBO
QAT, SAU, TUR, EGY	Telna Mobile (USA)	Packet Host (AS54825)	NLD	IHBO
		OVH SAS (AS16276)	FRA	IHBO
MDA, KEN, FIN, AZE	Telecom Italia S.p.A (ITA)	Wireless Logic (AS51320)	GBR	IHBO
ITA, USA	Orange S.A (FRA)	Webbing USA (AS393559)	NLD, USA	IHBO
FRA, UZB	Polkomtel Sp. z o.o. (POL)	Packet Host (AS54825)	USA	IHBO

Table 2: ISO codes of visited countries (first column) with roaming eSIMs that have the same b-MNO (second column). The third column refers to their PGW Providers identified via our measurement endpoints' public IP addresses, with their country-level geolocation shown in the fourth column. The last column denotes the roaming architecture.

we measure download/upload speed and latency. When needed, we use as endpoint Ookla servers via speedtest [37], and content providers with global footprint like Google. Going up the stack, we measure 5 global CDN providers: `Cloudflare`, `Google CDN`, `jsDelivr`, `jQuery`, and `Microsoft Ajax CDN`. Our test consists of fetching a popular JS file (`jquery.min.js` v3.6.0) via curl [46], for which we measure download time and collect HTTP headers. We also identify the DNS resolver via Nextdns. We further derive insights on network paths by running traceroutes to global service providers (e.g., Google) using mtr [24].

Finally, to measure video-streaming performance, we develop a browser extension that injects JS code to enable YouTube's "stats-for-nerds", which provides detailed statistics such as playback resolution and buffer occupancy. This extension is installed on the Kiwi browser [11], which supports Chrome extensions on mobile platforms; Kiwi is further automated to open a YouTube link to a video with a resolution of (at most) 4K [49]. Similar to the web-based campaign, the public IP addresses obtained from these experiments are used to determine the roaming architecture of the activated eSIM. We provide an overview of measurements conducted per country during this campaign in Appendix Table 4. The interested reader can also refer to [47] for a more detailed description of metrics collected by the `AmiGo` testbed.

3.3 Crawler-Based Campaign

Another goal of this paper is understanding the economic aspect of Airalo, especially when compared to local SIM providers. We develop a web crawler targeting EsimDB [6] which aggregates eSIM offers, capturing key variables like cost, provider, and data limits from a comprehensive set of eSIM providers across 244 regions.

We conducted daily retrievals of eSIM offers over a four-month period from February to May 2024, identifying 54 unique eSIM providers. We further run the crawler at three different physical locations (Spain, New Jersey, and UAE) in April/May 2024 to investigate potential price discrimination tactics. Discovering local SIM offerings is instead more challenging since no global aggregator (like EsimDB) exists. Accordingly, we resort to online resources and insights from volunteers travelling to countries of our experiments.

4 Airalo Tomography

4.1 Network Architecture

We dissect Airalo's network architecture using measurements from 24 nation-level eSIMs. We first examine the role of the v-MNO; when the v-MNO and the b-MNO are identical, the user can access mobile data as a "native" v-MNO user (non-roaming), hence we refer to these eSIMs as *native* eSIMs. This applies to only three of the 24 eSIMs from our two campaigns: LG U+ (South Korea), Ooredoo Maldives (Maldives), and dtac (Thailand). In these countries, Airalo relies on the b-MNO to issue the eSIMs, essentially acting as a light mobile virtual network operator [28] "renting" the (RAN and core) infrastructure of the corresponding b-MNO.

For the remaining 21 eSIMs, the end user registers in the v-MNO as a roaming user from a b-MNO. Data roaming must be enabled for these eSIMs, hence we refer to them as *roaming* eSIMs. We find that six b-MNOs provision these 21 roaming eSIMs. Five eSIMs roam via Singtel, a Singapore-based MNO, using HR (*i.e.,* their public IPs belong to AS45143 from Singtel). The remaining 16 profiles employ IHBO, with data packets breaking out via PGWs provided by third-party infrastructure owners, such as the IPX-Ps.

Table 2 summarizes the b-MNO, PGW provider(s), and PGW location(s) of the 21 roaming eSIMs. Each row corresponds to a group of visited countries where the eSIMs shared the same b-MNO and PGW providers. Note that for eSIMs provisioned by *Play* and *Telna Mobile*, the PGW provider iterated between Packet Host (AS54825) and OVH SAS (AS16276). PGW locations were inferred from geolocation of the public IP assigned to device using each eSIM. We verify this approach with traceroute analysis in section 4.3.

Figure 3 visualizes the network infrastructure supporting Airalo's service, given our visibility in eSIMs from 24 visited countries. Each visited country is color-coded according to its b-MNO, e.g., Italy and USA are colored in purple as their eSIMs both rely on Orange S.A (France) as b-MNO. A black triangle indicates the city where the eSIM was used by our volunteers, approximating the SGW location within the v-MNO. We mark PGW locations with circles, colored according to their ASNs. For example, there are 2 PGW locations for AS54825 (Packet Host, which supports IPX peering) – one in Amsterdam (Netherlands) and one in Ashburn (Virginia, USA) – which are both colored in blue. Each line connecting a black triangle to a PGW location illustrates the straight-line distance between SGW and PGW for a given eSIM. This depicts the GTP tunnel traversed by packets before internet breakout, not to be confused with the data path from PGW provider's network to public servers as captured in traceroutes. We match a line color with the PGW location, and we use a solid line to indicate HR and a dashed line for IHBO.

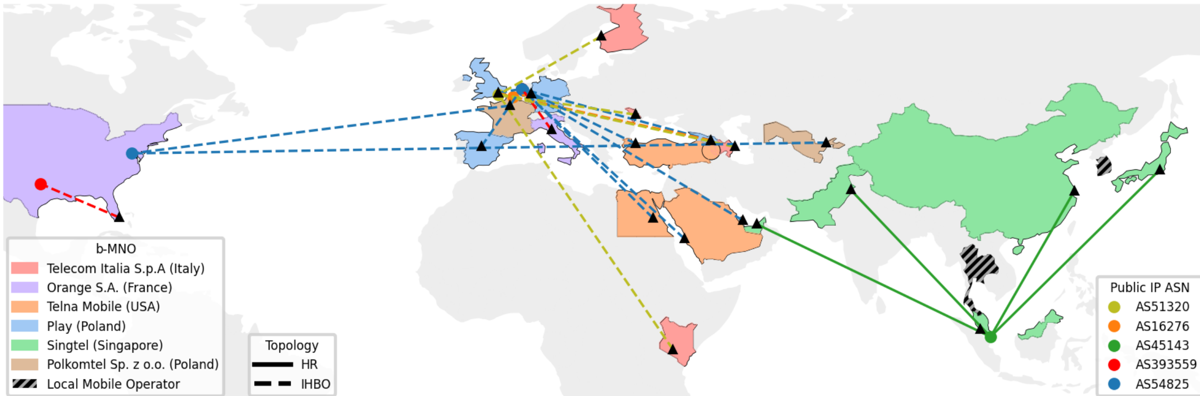

Figure 3: Mapping of end user location (triangle) and PGW location (circle) for 21 roaming eSIMs from Airalo. Each line visualizes the approximate distance between SGW and PGW for each eSIM, and the roaming architecture in use: solid line for HR, dashed line for IHBO. The color of PGW location and connected lines correspond to the PGW Provider (see legend in the lower right). Each country is colored based on the b-MNO (see legend in the lower left) associated with an eSIM.

4.2 IHBO Configurations

When we detect a roaming eSIM, the network setup for the b-MNO is a mix between HR and IHBO. We did not detect any eSIM using LBO, likely due to a lack of trust among MNOs regarding roamer records and charges [30]. We now present the main insights from dissecting Airalo's roaming eSIMs from a topology perspective.

Suboptimal Choice of Roaming Configuration. IHBO aims to optimize roaming traffic by directing packets to an IPX-P PGW located near the v-MNO. However, for 8 out of the 16 eSIMs we identified as IHBO, packets break out in IPX-P PGWs that are farther away from the end user location than the b-MNO country. We further observe that the PGW selection within an IPX-P is often not geographically optimal.

Figure 4 shows end user and PGW location for 10 eSIMs, whose PGW provider was Packet Host (AS54825). Each end user location is marked with a triangle, colored according to the b-MNO country. We visualize the distance between SGW and PGW with one line per eSIM, colored based on PGW location. Notably, packets from France and Uzbekistan broke out in Virginia (US), despite the availability of closer PGWs operated by the same IPX-P in Amsterdam (Netherlands), which are used by eSIMs issued by Play and Telna Mobile. Given that the eSIMs for France and Uzbekistan were issued by Polkomtel Sp. z o.o., this suggests that the PGW location is decided based on the b-MNO. The figure further shows that IHBO directs traffic from the Turkey eSIM to Amsterdam, further away from its b-MNO network in Poland.

Compromised v-MNO Visibility. A v-MNO is unaware of the intricacy of Airalo's service, so it identifies Airalo users as inbound roamers from the b-MNO provisioning their eSIM. This obfuscates v-MNO's network intelligence as it is unable to delineate Airalo users' network usage and demand patterns. We collaborate with a UK MNO and investigate the behavior of Airalo users. To identify Airalo users from the group of b-MNO inbound roamers, we deploy mobile devices installed with (in total) 10 Airalo eSIMs, all of which rely on Play Poland as b-MNO while using our cooperating MNO as a v-MNO in the UK. We then verify from the v-MNO core the IMSIs associated with IMEI of our deployed devices. Given that only a limited, pre-determined range of Play IMSIs are "rented" to Airalo, we conduct a pattern matching analysis on the collected IMSIs, examining the MCC/MNC and their subsequent sub-patterns, to extract potential IMSI ranges that Play allocates to Airalo.

Figure 5 compares the traffic consumption of potential Airalo users in the UK – identified via IMSI pattern matching – connecting to our partner v-MNO, with the inbound roamers from Play Poland. As a reference, the figure also shows the traffic consumption of regular non-roaming users of the UK v-MNO. This analysis captured the user activity during April 2024. The figure shows that in terms of traffic consumption (both for data in Fig. 5-a and signalling in Fig. 5-b), Airalo is similar to the v-MNO's native users. Instead, Play Poland roamers show a different behavior, probably since they rely on multiple v-MNOs in the UK (not only the one we analyze). Interestingly, the signaling traffic volume for inferred Airalo users is slightly higher than what v-MNO's native users generate (Fig. 5.b), which is problematic for the v-MNO (signaling traffic in roaming is not charged) and might increase the device's energy consumption. This observation demonstrates how Airalo can add noise to v-MNO network intelligence.

Takeaway: *The IHBO configuration for Airalo's roaming eSIMs often result in geographically suboptimal traffic routing and increased latency. Additionally, v-MNOs cannot distinguish (IHBO) Airalo users from inbound roamers of the same b-MNO, which impact the v-MNO network intelligence.*

4.3 Path Analysis

To further dissect the network infrastructure supporting Airalo's service, we use traceroute from the 10 mobile devices in the device-based campaign. Each device was equipped with both physical SIMs and eSIMs, and measured two popular service providers (SPs) – Facebook and Google – which we chose for their global footprint. We use `nslookup` to resolve the IP address associated with each hop identified by traceroute; for public IPs, we obtain their geolocation and ASN using WHOIS information and ipinfo [21].

All observed paths begin with a variable number of hops associated with private IPs. Given the lack of visibility into GTP tunnels in end-to-end measurements [31], these hops represent internal

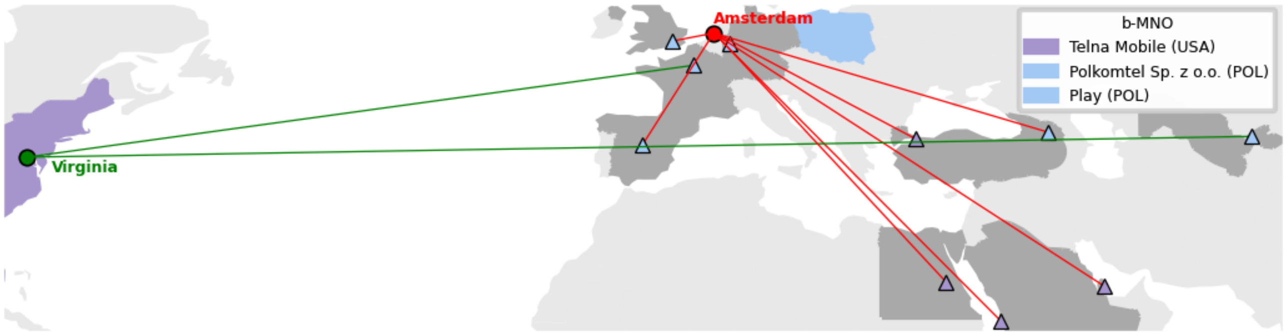

Figure 4: Mapping of end-user locations (triangles) and PGW locations (circles) for 10 eSIMs with AS54825 as PGW provider. End-user locations are colored by b-MNO country (see legend). PGW locations are color-coded: red-Amsterdam, green-Virginia.

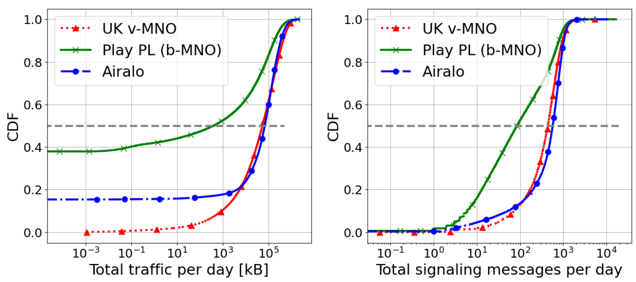

Figure 5: Data/signalling traffic comparison between inbound roamers from Airalo with those from Play (b-MNO).

routing within the PGW provider's core network. In line with prior work [34], the first hop is the PGW itself, followed by eventual forwarding to a Carrier-Grade Network Address Translation (CG-NAT), where packets are assigned globally routable IP addresses before internet breakout. To ensure the robustness of our inferences for Airalo, we validate this approach by applying it to another (IoT-focused) thick MNA(see Section 4.3.1). While we also reached out to Airalo directly for validation, we did not receive any response by the time of writing.

To identify the PGW provider, we refer to the ASN of the first public IP address in each traceroute. We verify this methodology by confirming the ASN matches that of the device's public IP address, obtained from Ookla Speedtest performed shortly before each traceroute [47]. This step renders impossible scenarios where the PGW and CG-NAT are hosted in different networks, which could lead to misclassification of network configurations (e.g., b-MNO's PGW forwards packets to a CG-NAT in another AS, resulting in misclassifying HR traffic as IHBO). In fact, Figure 6 shows that most traceroutes reveal just two unique ASNs: one associated with the PGW provider, and the other associated with the SP (Google or Facebook). Note that certain traceroutes identified more than two distinct ASNs due to b-MNO's inter-AS routing patterns, involving different intermediary networks or global points of presence before reaching the destination service provider. We provide a more detailed analysis of observed ASNs in traceroutes in Section 4.3.3.

Having ensured that traceroute captures the CG-NAT within the PGW provider's core, we use the first public IP address as the demarcation point in our analysis; we label preceding hops as the *private path* and subsequent hops as the *public path*, differentiating between the initial routing within the PGW provider's core and the routing after internet breakout. We further support the path analysis with SGW locations inferred from volunteers' geolocations. This provided insight on GTP tunnels traversed by roaming packets, lacking in traceroute.

Our approach compiles a dataset for each traceroute, detailing path length, PGW provider, private and public hop counts, as well as IP address, geolocation, ASN, and Round-Trip Time (RTT) for each hop (when ICMP was supported).

4.3.1 Methodology Validation. We validate our methodology – and the sanity of our conclusions – for breakout geolocation by testing with emnify [14], a thick operator whose internal setup we could confirm. We conducted our device-based measurements using their provisioned eSIM in London between October 24–26, 2024, with O2 UK serving as its v-MNO. Analyzing 219 traceroutes to three SPs (Google, YouTube, Facebook), our methodology identified the PGW provider as AS16509 (Amazon.com, Inc.) geolocated in Dublin. These results match the ground truth as provided by the operator, thus verifying our approach [3].

4.3.2 Private Path. Across the traceroutes, the latency difference between the first and last hop (the first hop with a public IP address) of the private path was generally negligible, with an average of 8.06 ms. This minimal difference in latency suggests a close physical proximity between the PGW and the CG-NAT. Thus we approximate the geolocation of the PGW by geolocating the first public IP address in the traceroute. We further refer to this address as the "PGW IP address" since it is assigned by the PGW provider.

Figure 7 shows the private path length, *i.e.,* the number of private hops, obtained from traceroutes to Google, distinguishing between country and network setup. Due to opaqueness of IPX-P network for end-to-end measurements, results for Facebook were equivalent and thus omitted. When the boxplots collapse to a single line, stable path lengths were measured, e.g., in Pakistan, with 4 hops for SIM and 8 hops for eSIM. For visual clarity, each country on x-axis is color-coded according to the architecture of its associated eSIM.

We first compare private path lengths between native eSIMs (Korea and Thailand) and physical SIMs. In Thailand, no significant difference was observed: the 1,073 traceroutes from both SIM and eSIMs encountered 15 distinct PGW IP addresses (owned by AS9587, dtac) at a distance comprised between 4 and 10 hops. Conversely, the 252 traceroutes performed using physical SIM and eSIM in Korea encountered 35 and 16 unique PGW IP addresses, respectively,

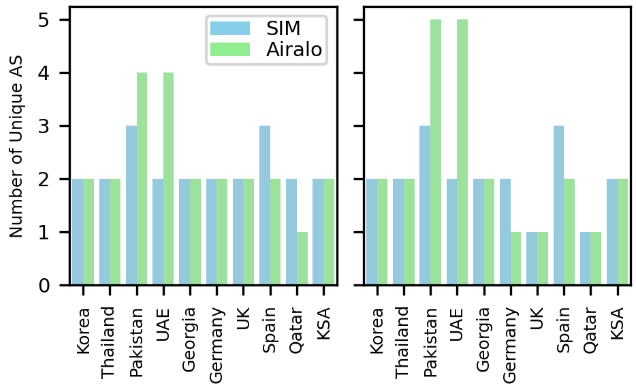

Figure 6: Median number of unique ASNs observed in traceroutes to Google (left) and Facebook (right); SIM versus Airalo.

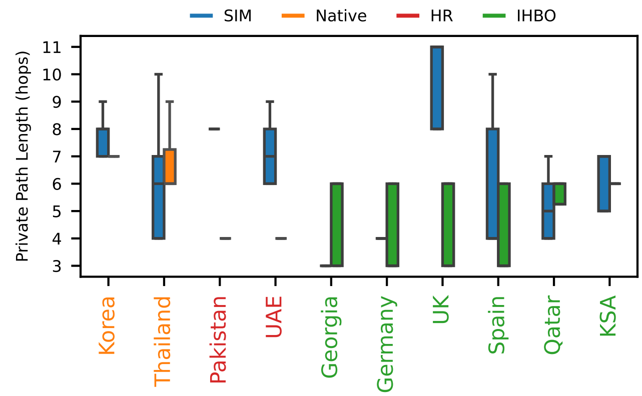

Figure 7: Private path length per country, analyzed from traceroutes to Google.

with no overlap. The traceroutes done via eSIM consistently had the private path length of 7 hops, with 16 PGW IP addresses all geolocalized in Seoul. Seoul also hosts 33 of the 35 PGW IP addresses accessed with the physical SIM, at a distance comprised between 7 and 9 hops. The two remaining PGWs are hosted in Goyang and Cheonan, at a distance of 7-8 hops.

The above observation suggests that the physical SIM – provisioned by U+ UMobile [4], an MVNO on top of LG UPlus – may be subjected to a different routing policy compared to the eSIM. This observation loosely aligns with findings from [43], which indicate that MVNOs might route packets less efficiently than their parent MNO networks.

For roaming eSIMs using HR (Pakistan and UAE), packets initially traverse from the v-MNO's network to the b-MNO (Singtel) via GTP tunneling. From their 1,803 traceroutes, we identify four PGW IP addresses within the IP range operated by Singtel (202.166.126.0/24), all geolocalized in Singapore. This suggests that IPX routing policy is consistent for HR traffic when the same base operator is involved.

To investigate the performance implications of the above observation, Figure 8 compares the Round Trip Time (RTT) towards Singtel PGWs from the two HR eSIMs deployed in Pakistan and UAE. The figure shows the Cumulative Distribution Function (CDF) of the "best" RTT values – as indicated by traceroute – at the hop where PGW IP was returned. We note that the RTT is shorter for the UAE eSIM, despite the same path length (4 hops) and being geographically farther from the PGW's location compared to the Pakistan eSIM. We conjecture that this difference could be the result of the v-MNO in the UAE (Etisalat) having better peering agreements with the IPX providers and/or the b-MNO (Singtel).

For roaming eSIMs using IHBO (green boxplots in Figure 7), packets must traverse from the v-MNO's network to an IPX-P via GTP tunneling. The eSIMs for Georgia, Germany, UK, and Spain were provisioned by *Play*, an MNO based in Poland. In Qatar and Saudi Arabia, they were provisioned by *Telna Mobile*, an MNO based in the US. Despite the variations in their b-MNOs, traceroutes from IHBO eSIMs consistently resolve to one of the 2 PGW providers: OVH SAS (AS16276) and Packet Host (AS54825). Most IHBO eSIMs alternate between these two PGW providers, except for the eSIM in Saudi Arabia, which relies on Packet Host only.

The two PGW providers differed in their internal routing behavior and public IP address assignment. For OVH SAS, six PGW IP addresses were identified, all reached within three hops. Most PGWs shared the same geolocation (Lille, France) except for one in Wattrelos (France). In addition, OVH SAS appears to assign PGWs for roaming traffic based on the b-MNO; Qatar eSIM (provisioned by *Telna Mobile*) exclusively used one PGW IP address, while *Play*-provisioned eSIMs alternated among the remaining 5. For Packet Host, we identified four PGW IP addresses, which are reached at either the 6th or 7th hop. This suggests potential load balancing within Packet Host's network core. Unlike OVH SAS, PGW IP addresses involving Packet Host were evenly distributed across different eSIMs, regardless of the b-MNO.

We now compare OVH SAS and Packet Host in terms of latency. Figure 9 depicts the CDFs of RTT at PGW IP hops from eSIMs in Georgia, Germany, and Spain (all provisioned by *Play*), with respect to the PGW providers. We exclude Qatar from this analysis due to the lack of statistically significant differences between the two PGW providers, likely due to the limited sample size. We also omitted Saudi Arabia because the eSIM exclusively utilized Packet Host.

The figure shows that in Germany and Spain, packets generally breakout to the internet faster when operated by Packet Host than by OVH SAS, despite the latter requiring half the number of hops. This trend was also observed in the UK, which we omit from the figure for brevity. This outcome contrasts with observations in Georgia, where Packet Host suffered from much higher RTTs especially in the fourth quartile. Statistical analysis did not support physical distance from the end-user as a factor influencing these latency differences ($p > 0.05$). Given the lack of visibility inside the IPX network, this result could be explained by several reasons: more efficient routing policies and/or load balancing strategies, or even the differences in the quality of interconnection agreements between the v-MNO and PGW providers.

Takeaway: *For roaming traffic carried via GTP tunneling, the latency to public breakout is largely driven by peering agreements among MNOs and/or IPX-Ps, rather than factors like physical distance or internal routing within the PGW provider core.*

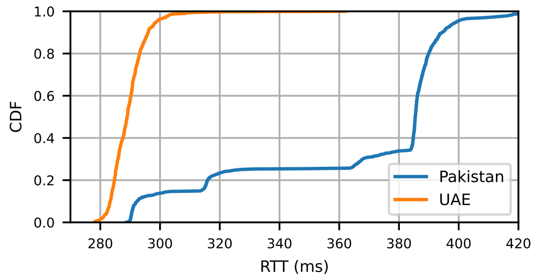

Figure 8: CDF of RTT towards Singtel PGWs from the HR eSIMs in Pakistan and UAE.

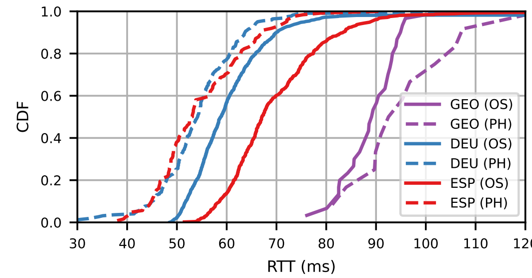

Figure 9: CDF of PGW RTT from IHBO eSIMs in Georgia, Germany and Spain. OS: OVH SAS; PH: Packet Host.

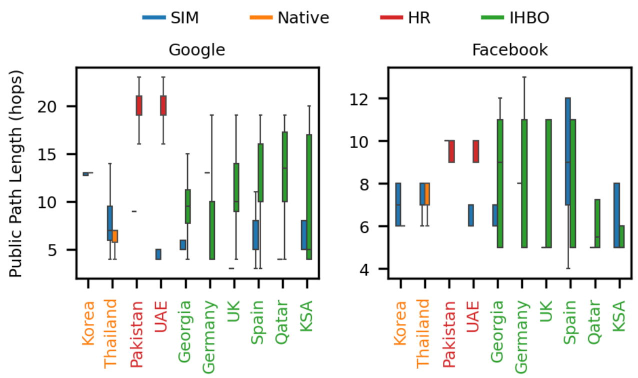

Figure 10: Public path length as a function of SIM/eSIM and country; traceroutes to Google (left) and Facebook (right).

4.3.3 Public Path. We now investigate the *public* paths, *i.e.,* the hops recorded after packet's breakout to the internet. Figure 10 shows the public path length from traceroutes to Google and Facebook as a function of country and network configuration. The data paths measured from native eSIMs (Korea and Thailand) and corresponding SIMs are comparable. Focusing on countries with roaming eSIMs, traceroutes to Google consistently required longer paths than physical SIMs. In contrast, the scenario for Facebook varied by country; traceroutes using physical SIMs in Pakistan, Spain, and Saudi Arabia, showed comparable or even longer paths compared to eSIMs. We conjecture that this stems from different peering arrangements between the SPs and PGW Providers [43]. Across both SPs, traceroutes from roaming eSIMs exhibit higher variance in public path length compared to their SIM counterparts, as evidenced by the wide spread of box plots.

Analysis of the AS path reveals similar inter-domain routing behavior across network configurations. Figure 6 plots the median number of unique ASNs observed in traceroutes to Google and Facebook, categorized by country and SIM configuration. Inter-domain routing was rare across most traceroutes, suggesting that the variability in the public hop counts (Figure 10) can be attributed to SPs' internal routing policies. Typically, traceroutes identified two unique ASNs that were indicative of direct peering between the PGW provider and the destination SP. However, a significant portion of traceroutes, particularly those reaching Facebook via eSIM in Germany and both SIM configurations in Qatar, revealed only the SP's ASN. This likely occurred due to the PGW provider's CG-NAT failing to respond within the traceroute timeout, possibly caused by router congestion or low-priority ICMP packet configuration.

Some countries exhibited complex inter-AS routing. In Spain, traceroutes via physical SIM consistently showed three ASNs, including AS3352 (TELEFONICA DE ESPANA) and AS12956 (TELEFONICA GLOBAL SOLUTION), with the latter likely serving as the global presence for the former. In Pakistan, Jazz's physical SIM routes passed through AS23966 (LINKdotNET Telecom Limited) and its upstream AS38193 (Transworld Associates Pvt. Ltd.). Moreover, eSIMs in Pakistan and UAE using Singtel as the base operator passed through three to five ASNs, all located in Singapore, before reaching their SPs.

Takeaway: *PGW providers (MNOs or IPX-Ps) generally have direct peering arrangements with global SPs. The variability in the number of public hops is likely due to internal routing policies of SPs.*

5 Airalo Performance

5.1 Network Performance

Network Latency. We measure it as the Round Trip Time (RTT) between mobile devices – equipped with physical SIMs and eSIMs – and: i) two popular content providers (Facebook and Google), ii) Ookla, a widely used speedtest tool. We chose these service providers (SPs) for their global footprint, with edge servers strategically located close to most users.

Figure 11 shows boxplots of latency to different SPs between physical SIMs and eSIMs across countries. We present latency data in boxplots grouped by country. Boxplots are further differentiated based on the Radio Access Technology (RAT) used during the measurements: empty boxplots refers to tests conducted over 4G/LTE, filled boxplots indicate tests conducted over 5G, and boxplots with a pattern comprise tests conducted via both 4G and 5G. The color coding in each boxplot reflects the network configuration; e.g., blue denotes a physical SIM from v-MNO.

Our analysis reveals similar latency patterns across SPs: in each country, roaming eSIMs tend to exhibit higher latencies compared to their SIM counterparts, with average increases of roughly 621% and 64% for HR and IHBO, respectively. Interestingly, despite the similar distances of approximately 6000 kms from their PGWs, IHBO eSIMs in Qatar and Saudi Arabia reported significantly lower latency compared to those by the HR eSIM in UAE. In fact, all RTT measurements involving HR eSIMs from Pakistan and UAE provided *less desirable* latencies (*i.e.,* exceeded 150 ms) according to [44]. We observe the most profound disparity in Pakistan while

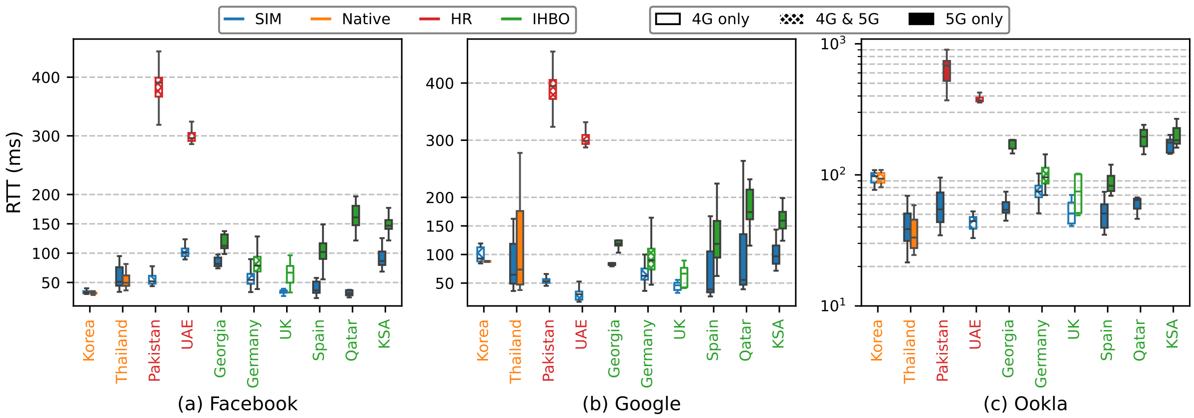

Figure 11: RTT to (a) Facebook and (b) Google from the last traceroute hop, and (c) latency to the nearest Ookla Speedtest server from the PGW. Boxplot colors and patterns represent the network configuration and RAT(s) used during measurement.

using 4G, where the eSIM was afflicted by a median RTT of 389 ms, versus 50 ms with the physical SIM.

The figure also shows that for native eSIMs (orange boxplots for Korea and Thailand), such consistent performance degradation was not observed. We substantiated these observations through t-tests to assess the statistical relationship between RTTs and SIM configurations. In countries with roaming eSIMs, the p-value was 7.65368e-5, indicating that physical SIMs perform significantly better than eSIMs. In contrast, the p-value for countries with native eSIMs (Korea and Thailand) was 0.152, indicating no significant difference in latency between physical SIMs and eSIMs.

Figure 11 further shows higher variances in RTTs measured for roaming eSIMs, suggesting less consistent performance. We confirmed this through Levene's test [26], designed to evaluate the homogeneity of variances across groups. The resulting p-value of 0.025 confirms greater variability in RTTs for eSIMs compared to physical SIMs.

Takeaway: *When roaming, Airalo eSIMs using IHBO demonstrate lower latency compared to those using HR. However, IHBO still results in higher latency than native SIM profiles. Airalo's native eSIMs perform comparably with physical SIMs, suggesting that the eSIM technology itself does not inherently degrade latency.*

Private Path Latency. We augment the latency analysis by investigating the impact of *private* paths, quantified as the percentage of RTT at the PGW hop – where first public IP address was observed – to the RTT at the final hop in traceroutes. Given that the private path differs vastly depending on the network configuration (see Section 4.3), we aggregate latency figures by the network setup associated with each eSIM, as shown in Figure 12. Note that physical SIMs consistently exhibit low private path latency, with mean of 31.06 ms and 95% confidence interval of ± 0.78 ms. We use this stability to identify eventual disruption in the public internet; accordingly, the "SIM" curves in Figure 12 captures the variability of the public internet latency in their respective regions.

Figure 12-a shows negligible differences in the impact of private latency on the total latency, when comparing SIM and native eSIMs (Korea and Thailand). The similar patterns in the CDFs for each country indicate that, overall, eSIM traffic is treated equally to SIM traffic when both are provisioned by the same MNO. The slight variations in their private latencies reflect their differences in private path lengths (see Figure 7).

In contrast, Figure 12-b shows a significant discrepancy between the CDFs of physical SIMs and HR eSIMs. For 80% of traceroutes with HR eSIMs in Pakistan and UAE, the private latency accounted for more than 98% of the overall latency – which instead only happens for less than 10% of the measurements when using a physical SIM. Such inflation is the result of packets passing through the GTP tunnels between SGWs of the v-MNO and the PGWs of the b-MNO, which in this case was located in Singapore. This further underscores the implications posed by extensive GTP tunneling.

Figure 12-c shows that IHBO could mitigate the latency associated with GTP tunnel traversals. Notably, the private latency was less than the public internet latency for 15% of the measurements, compared to only 1% of measurements for HR. Furthermore, the CDFs for SIMs and eSIMs exhibit similar patterns, suggesting comparably low latency in the public internet. Such low public latency is achieved by strategic placement of SP edge nodes near the PGWs, particularly in Western EU (e.g., France, Netherlands), where IHBO packets typically broke out. Our analysis implies that to further reduce the latency of roaming traffic to popular SPs, IPX network routing policies should aim to minimize GTP tunnel lengths by prioritizing the nearest available PGW, leveraging the global footprint of SP edge nodes, which are often close to most PGWs.

Takeaway: *The private path of the network, particularly the segments involving GTP tunnels before reaching the PGW, is the primary source of inflated latency for roaming eSIMs. While improving upon HR, Airalo's IHBO eSIMs are still constrained by pre-configured agreements and routing policies that don't always prioritize geographical proximity to the end-user.*

Download and Upload Speeds. We analyze Airalo's downlink using 117 `fast.com` measurements collected from 14 countries during the web-based campaign. Note that we do not control the devices from the web-based measurements, and as such, we lack visibility into additional information like channel quality. We summarize the results in Figure 13-a, where vertical dashed lines group countries based on their eSIM network configuration and b-MNO, specifically

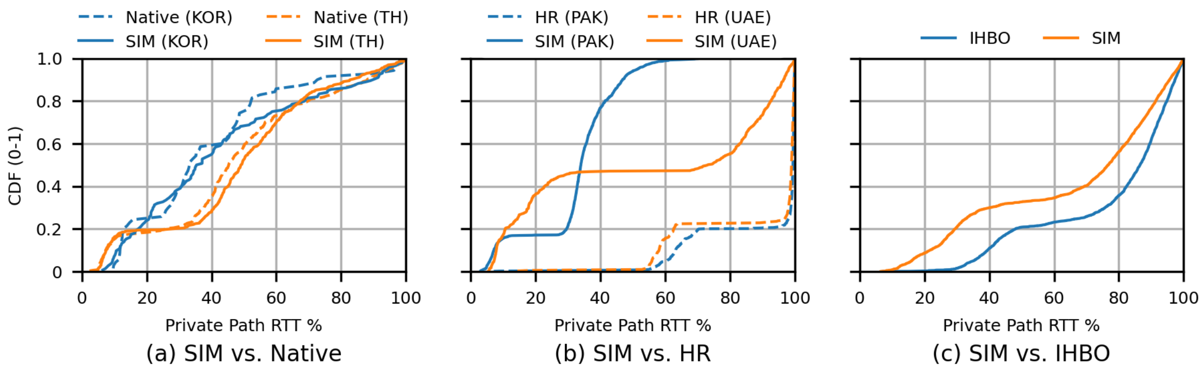

Figure 12: CDFs of the % of latency which is *private*, *i.e.,* due to RTT between mobile device and PGW. (a) SIM vs native eSIMs in Korea and Thailand; (b) SIM vs HR eSIMs in Pakistan and UAE; (c) data from 6 countries utilizing IHBO eSIMs.

eSIMs that utilize the same PGW providers. Our analysis reveals that eSIMs in countries geographically closer to their respective PGWs typically experience higher download speeds. For example, the median download speed in France (29 Mbps) was approximately twice as high as that in Uzbekistan (15 Mbps), despite both using PGWs located in Virginia (USA). However, there are exceptions to this trend. Notably, the eSIM in Azerbaijan experiences higher download speeds than the eSIM in Moldova, even though Moldova is closer to their shared PGWs in London.

We now investigate how downlink (Figure 13-b) and uplink (Figure 13-c) of Airalo eSIMs compared to physical SIMs, using Ookla speedtest performed during the device-based campaign. We first filtered the initial 749 measurements to exclude those conducted under poor channel conditions using the Channel Quality Indicator (CQI). In accordance to 3GPP specifications [7] followed by Android [16], we excluded any measurements with a CQI below 7, as this threshold corresponds to Quadrature Phase Shift Keying (QPSK) modulation scheme used in weak network conditions. This process left us with 604 measurements (80%). We use the results from native eSIMs (Korea and Thailand) to comment on whether eSIMs, by their nature, are subject to different network bandwidth than physical SIMs. In Thailand, both the SIM and eSIM exhibit similar download and upload speeds. In Korea, the eSIM generally achieved higher download speeds than the physical SIM, possibly because the latter was provisioned by a MVNO; past studies have shown that MVNOs could face traffic differentiation by their parent MNOs, potentially impacting bandwidth availability and user experience [40, 43].

In the remaining eight countries, physical SIMs showed higher download speeds compared to the roaming eSIM (either HR or IHBO). Visualized as red and green boxplots in Figure 13-b: 78.8% of roaming eSIM measurements fell into the slow download speed category – as per the SpeedTest Global Index [38] – (<= 15 Mpbs), whereas only 4.5% reached fast download speeds (>= 30 Mbps). In contrast, for physical SIMs in the same countries, only 31.9% of measurements were categorized as slow, while 48% achieved fast download speeds. Additionally, there were large discrepancies in average download speeds among these physical SIMs, ranging from 13.6 Mbps in Germany to 137.2 Mbps in Saudi Arabia.

A notable finding was that IHBO did not lead to significant improvement over HR in terms of download speed – we observe comparable download speeds from the eSIM between UAE and Georiga, and between Pakistan and Spain. Furthermore, we observe a considerable variation among roaming eSIMs provisioned by the same b-MNO. For instance, the mean and 95% CI of downlink (in Mbps) under 5G connection were 11.2 ± 2.16, 31.7 ± 2.26, 22.7 ± 1.98 in Spain, Georgia, and Germany, respectively.

The eSIMs' upload speed was notably slower only in Pakistan and Georgia ($p < 0.05$), possibly due to stricter bandwidth policies by the local v-MNOs, as also observed for the download speed. For remaining six roaming eSIMs, the upload speed wasn't as affected, indicating varying bandwidth policies for upload and download traffic among v-MNOs. This underscores how performance for roaming eSIMs depends heavily on v-MNO policies rather than roaming setup.

Takeaway: *Airalo's roaming eSIMs (both HR and IHBO) generally experience reduced and highly variable download and upload speeds, which appear to be predominantly governed by the v-MNO's bandwidth policies rather than the specific roaming configuration. Consistent with latency results, Airalo's native eSIMs demonstrate throughput performance comparable to their physical SIM counterparts.*

CDN Download Time. We measure the download time for `jquery.min.js` from five CDN providers via the device-based measurement. Given that all providers demonstrated similar trends across network configurations, we present the results from Cloudflare in Figure 14-a, and include results from the other providers in Appendix A.5. Overall, the performance of native eSIMs and physical SIMs was comparable, paralleling observations on latency and bandwidth. Interestingly, the median download time from Cloudflare in Thailand was 18% higher using the physical SIM, which can be partially attributed to a higher cache MISS rate of 7.7%, compared to no cache misses with the eSIM.

In contrast, significant performance degradation is evident for HR eSIMs in Pakistan and UAE (red boxplots in Figure 14-a). On average, download times from all five CDNs were 481% (Pakistan) and 360% (UAE) slower over eSIMs than physical SIMs. In Pakistan, the average download time using the eSIM exceeded 3 seconds across all CDNs, indicating a substantial impact on web user experience.

IHBO eSIMs (green boxplots in Figure 14-a) generally exhibit slower download speeds than physical SIMs, yet improve upon HR eSIMs. For Cloudflare, the average download time with IHBO eSIMs

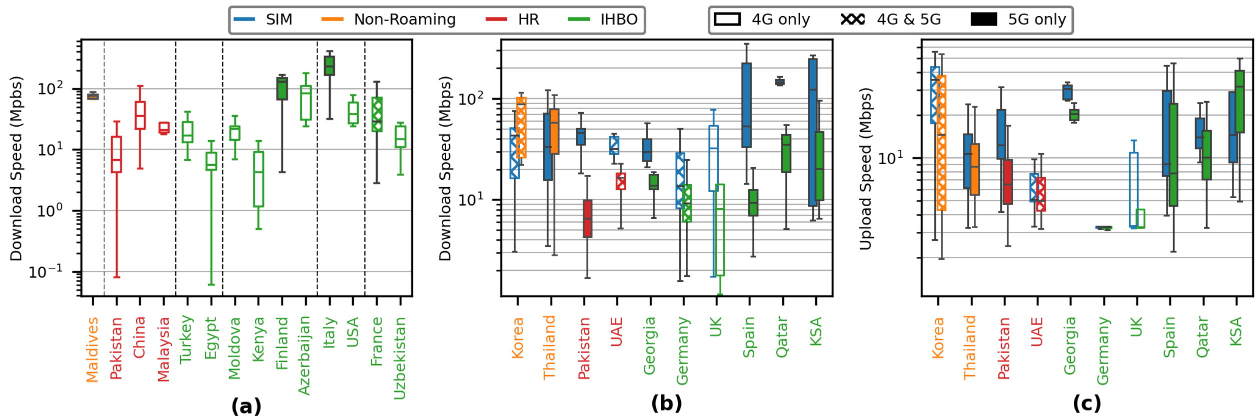

Figure 13: (a) Download speed of eSIMs from web-based campaign. Dashed vertical lines group countries by network configuration and b-MNO. (b) Download and (c) upload speeds from device-based measurement as a function of network configuration.

was 1,316 ms—higher than the two native eSIMs (306 ms in Korea and 514 ms in Thailand), yet lower than the HR eSIMs (3,203 ms in Pakistan and 1,781 ms in the UAE). Across all CDNs, the increase in average download time for IHBO eSIMs over physical SIMs varied, ranging from 45.4% in Germany to 181% in Qatar.

Takeaway: *CDN performance is substantially degraded for Airalo's roaming eSIMs. Although IHBO offers an improvement over HR, its CDN download times remain notably slower than those achieved with native SIM profiles (both eSIM and physical).*

DNS Lookup Time. For configurations where the PGW is within the b-MNO's network (*i.e.,* physical SIMs, native eSIMs, and HR eSIMs), DNS resolution occurs locally within the b-MNO. For instance, in Pakistan, DNS queries from the physical SIM and HR eSIM are resolved by their respective b-MNOs: PMCL (AS45669) and Singtel (AS45143). In contrast, IHBO eSIMs, which use external PGWs, rely on Google DNS (anycast via 8.8.8.8 or 8.8.4.4), leveraging Google's footprint and anycast routing to select resolvers near PGWs.

We geolocate Google's DNS resolvers using Nextdns [36], an authoritative DNS with a zero Time-To-Live. Resolver misses are forced by embedding a unique identifier in queries, identifying the resolver's (unicast) IP address despite anycast. ASN and geolocation are then obtained via ipinfo.

For IHBO eSIMs, we find that 74% of the DNS queries are directed to Google DNS resolvers located in the same country as the PGW. The greatest distance to a DNS resolver was observed for the US eSIM, involving a PGW in Dallas, Texas (operated by Webbing USA, see Table 2) and a DNS resolver in Tulsa, Oklahoma – approximately 381 km apart. Occasionally, this eSIM was directed to a Google DNS resolver in Fort Worth, Texas, merely 20 km from the PGW.

Our device-based measurement further explored the implications of network configurations for DNS performance. Figure 14-b plots the DNS lookup times across countries and network configurations. As expected, native eSIMs (Korea and Thailand) require short DNS lookup times, comparable to those of physical SIMs. On the contrary, substantial degradation in DNS lookup times is observed while using HR eSIMs (Pakistan and UAE). Compared to the physical SIM, the median DNS duration increases by 610% and 517% respectively, despite both PGWs and DNS resolvers being located within the same b-MNO (Singtel). This result again points to the limitation inherent to roaming technology, that extensive GTP tunnel traversals in the (private) IPX-network can undermine any performance optimizations implemented on the public Internet.

The six IHBO eSIMs, which used Google DNS instead of b-MNO resolvers, also exhibited significant percentage increases in DNS lookup times over physical SIMs: ranging from 103% in Germany to 616% in Qatar. However, our analysis revealed that DNS over HTTPS (DoH) was employed for these eSIMs, and DoH is typically slower than unencrypted DNS due to the overhead of setting up TLS [10]. DoH was used since this is a default setting in recent Android versions and we, unfortunately, *forgot* to disable it. Note that other network configurations reverted to unencrypted DNS since MNO-operated DNS mostly do not support DoH [12, 13].

Takeaway: *Airalo's IHBO eSIMs rely on Google DNS, leveraging its global footprint and anycast routing to select resolvers near PGWs. DNS lookup times generally correlate with overall network latency, as extensive GTP tunneling significantly contributing to delays for roaming eSIMs (HR and IHBO).*

5.2 User Experience

We conclude the section studying the user experience of Airalo customers, specifically focusing on video streaming through YouTube. Figure 15 shows the distribution of video quality across countries from the device-based measurements, with the exception of Spain and the UK due to limited sample sizes. The figure shows that 720p is the most common resolution across countries and available network configurations. The highest resolution observed was 1440p, recorded in 10% of video playbacks on the physical SIM in Korea and 1.3% on the eSIM in Thailand. However, the latter also reported the worst resolution, 480p, in 2.2% of video playbacks.

Results from IHBO eSIMs (green countries on the x-axis) show lower likelihood of 1080p streaming when using eSIMs compared to physical SIMs, with decreases of 20%, 43%, and 44% in Germany, Qatar, and Saudi Arabia. This trend reflects the effect of lower download bandwidth allocated to roaming traffic (see Figure 13).

Georgia was an exception to the trend, with comparable streaming quality between physical SIM and the eSIM – both configurations were equally likely to stream videos at 720p and 1080p.

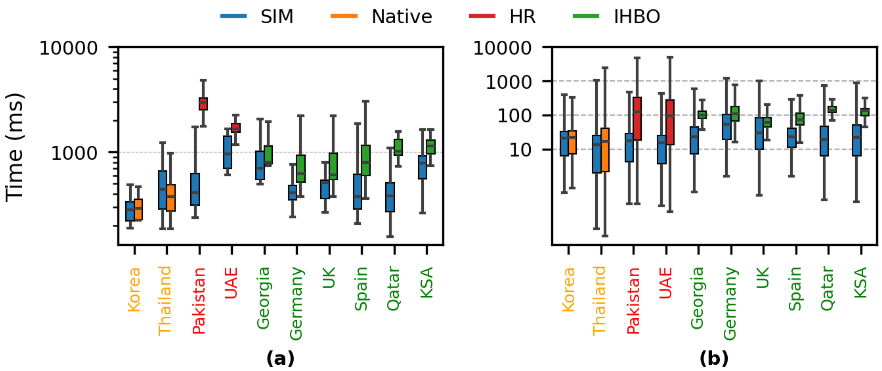

Figure 14: (a) Download time of the jQuery library via Cloudflare CDN. (b) DNS lookup time across countries as a function of network configurations

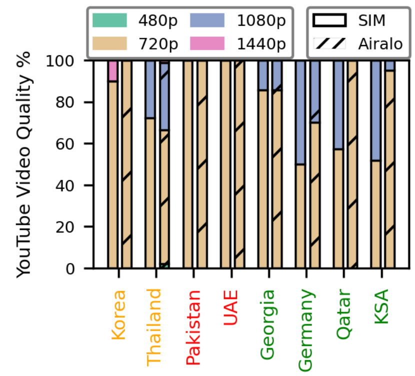

Figure 15: YouTube video res. across countries and network configurations.

Similar patterns were observed in Pakistan and the UAE, where HR eSIMs maintained constant streaming quality at 720p, matching that of physical SIMs. This was a rather surprising finding given that the physical SIMs in these countries averaged download speeds of 7.9 Mbps and 8.3 Mbps, respectively, which are theoretically sufficient for higher-quality video streams (1080p, > 5 Mbps). We conjecture that their b-MNOs may implement traffic differentiation, constraining bandwidth for YouTube, as suggested in [23, 27].

Takeaway: *Bandwidth constraints typically limit Airalo's roaming eSIMs from higher video streaming resolutions (e.g., 1080p). However, certain HR scenarios can surprisingly maintain a consistent moderate streaming quality, suggesting potential traffic differentiation policies by b-MNOs for YouTube.*

6 Airalo Economics

We conclude by investigating Airalo from an economic perspective. Given that Airalo offers thousands of plans, e.g., 2,243 as of May 1st 2024 (9 plans per country, on average), Figure 16 shows the time evolution (February to May 2024) of the median cost per GB ($/GB) across countries grouped by continent. The interested reader can refer to Figure 18 in the Appendix for a visualization of the median cost per country. We further run our crawler at three locations (Madrid, Abu Dhabi, New Jersey) in April/May 2024 but only report one data-point from NJ, since no location impact was observed.

Overall, Figure 16 shows a significant price difference when comparing plans across continents; for example, the median cost per GB in Europe is about $4.5, *i.e.,* half the price of that in North America. Note that the main culprit of such high cost in North America stems from the plethora of expensive plans in Central America (see Figure 18 in Appendix A.4). The figure also does not show dramatic cost changes over the last four months. There are, however, two changes to be reported. First, the median cost in Asia has increased from $5.5 per GB (02-14-2024) up to $6.5 per GB (04-01-2024). A similar increase is observed in Africa, with the 25th percentile growing from $4.5 per GB up to $6.5 per GB. Some minor fluctuations can be seen in other continents, but there is no major trend. Finally, no price discrimination was observed, *i.e.,* equivalent offers are presented to users from different regions, as suggested by the last boxplot which reports data crawled from New Jersey.

Additionally, we compare Airalo's pricing with some of its competitors. Figure 17 shows the CDF of the median cost per GB across countries when considering a few interesting providers, which cover about 12% of all the eSIM offers as per eSIMDB on 05/01/2024. The figure shows a median cost per GB ranging from $2.3 at Airhub – which has a presence in 181 countries – and up to $16.2 at Keepgo, which has a comparable footprint. MobiMatter has the majority of the offerings, e.g., 5% of the total versus 3% from Airalo, but lacks coverage in a few countries; however, it is 60% cheaper than Airalo, independent of the country. An interesting avenue for future work consists of leveraging our methodology to extend the analysis to other eSIM providers.

The dashed orange line in Figure 17 further shows the cost incurred by our volunteers to acquire a physical SIM card along with *some* data. The figure shows that, overall, the cost per GB is the lowest when locally acquiring a physical SIM card. However, the *total* cost incurred was overall higher than with Airalo, since most offers come with a larger data plan, e.g., 40 GB in Spain for $22.59, or require paying for a SIM, e.g., $15.72 in the UAE.

Finally, Appendix Figure 19 compares the prices of various Airalo plans that share the b-MNO, further differentiating between plan sizes. For visibility reasons, we limit the plot to 5 GB, covering about 70% of the plans. Despite sharing the same b-MNO, the prices vary significantly across countries; for example, a Play Poland eSIM used in Georgia costs more than in Spain, up to twice as much as the data size increases. As Airalo does not explicitly state that its pricing policy is based on network performance or availability per region, this discrepancy likely stems from the distinct roaming agreements between b-MNO and v-MNO. However, the non-linear cost increase as a function of data size seems unjustified.

Takeaway: *Airalo's eSIM plans typically present a higher cost per gigabyte compared to local physical SIM cards, though the total expenditure can differ depending on local offers. Furthermore, the cost of Airalo plans can fluctuate significantly across countries even when they are provisioned by the same b-MNO, indicating the influence of specific roaming agreements and complex pricing mechanisms.*

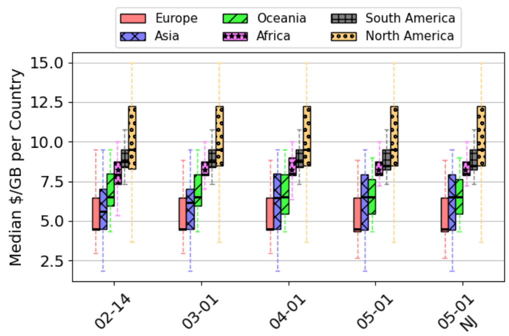

Figure 16: Evolution over time (Feb-May, 2024) and space (UAE, NJ) of the $/GB charged by Airalo. Boxplots show the distribution of median $/GB across countries in each continent.

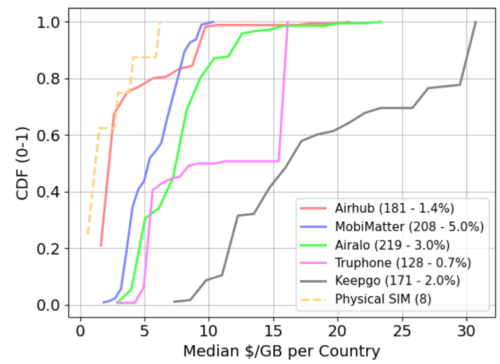

Figure 17: CDF of median $/GB per country (05/01/2024). The parenthesis holds the number of countries with at least 1 offer, and the % of the 75,875 offers from EsimDB.

7 Discussion

User Implications Beyond network performance, Airalo's implementation of IHBO carries two critical implications for the end-user's Quality of Experience (QoE). First, since user traffic egresses from the PGW located in a country distinct from both v-MNO and b-MNO, the user is subject to that location's digital jurisdiction. This leads to potentially receiving unexpected geo-localized content (e.g., Netflix served in a different language) while being subjected to that country's content access policies and censorship. In addition, Airalo's IHBO eSIMs create a lack of transparency, as users are typically unaware that their data is being handled by a third-party network (IPX-P) in an intermediary country, which obscures data ownership and complicates regulatory oversight.

Measurement Limitations. Our investigation of Airalo's service across multiple countries was designed to provide foundational insights into IHBO as a novel roaming architecture. However, our methodology has inherent limitations. The measurement campaigns relied on a relatively small number of volunteers per country, and their opportunistic selection meant we had limited control over the distribution of eSIM types (HR, IHBO, or native) encountered in each location. Additionally, our study did not account for various confounding factors that could influence network performance, such as the measurement environment (e.g., rural vs. urban settings), network conditions (e.g., time of day, network load), or the volunteers' mobility patterns. Consequently, the findings should be interpreted as an initial, high-level analysis of IHBO (as implemented by Airalo), rather than a definitive performance benchmark for specific countries.

Future Directions. Building on the foundational insights presented in this paper, several avenues for future work could significantly enhance our understanding of thick MNAs and the IPX ecosystem. To provide a more comprehensive assessment of network performance for modern applications, future measurement campaigns could incorporate a broader suite of network performance metrics, specifically including jitter and packet loss, which are crucial for evaluating real-time services like Voice over IP (VoIP) and video streaming. Another direction for future research involves extending our methodology to study additional eSIM providers that may also operate as thick MNAs, while also addressing current data collection limitations through larger-scale and more controlled measurements, which would help absorb the potential impact of confounding factors not captured by our current dataset.

8 Conclusion

This paper presents the first measurement study of Airalo, a concrete example of a novel category of Mobile Network Aggregator (MNA) that we label as *thick* MNA. The main innovation Airalo brings is a diverse eSIM marketplace, which combines native (sponsored) eSIM connectivity and roaming eSIMs, with their own deployment of internet breakout points in third-party infrastructure, decoupled from both the base and the visited Mobile Network Operators (b-MNO and v-MNO, in short). For example, we find Airalo uses Telecom Italia as b-MNO for eSIMs in Azerbaijan, Finland, Moldova, and Kenya, with roaming traffic routed through London-based IPX Hub Breakouts (IHBO) operated by Wireless Logic.

With the rise of aggregators such as Airalo, the cellular ecosystem evolves in complexity, with data paths that were once confined to a single operator realm now traversing multiple domains, and relying on resources from different entities (including v-MNO, b-MNO, PGW provider, or IPX provider). Our measurement campaign, covering 11% of Airalo's footprint (24 of 219 countries), reveals that 21 eSIMs rely on roaming, provisioned by six base MNOs—five with Home-Routed Roaming (HR) via Singtel and 16 via IHBO. In theory, IHBO aims at optimizing roaming traffic by directing packets to a PGW located near the v-MNO. However, we find that, for 50% of the IHBO eSIMs we measured, packets break out in PGWs that are farther away from the end user location than the b-MNO country. This stifles the potential of IHBO, despite overall improving upon the considerable latency impact of HR.

Roaming configurations also showed lower download bandwidth than native setups, impacting user experiences such as YouTube video quality. The fragmented paths and varied v-MNO capabilities complicate correlations between service configurations and user data rates, underscoring the complexity introduced by thick MNAs like Airalo. Achieving performant global connectivity will likely require thick MNAs to evolve beyond today's static IHBO setups, for example by leveraging PGW deployment that adapts dynamically to user geography/preference, or by realizing Local Breakouts (LBO) where traffic is directly handled by v-MNOs.

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A Appendix

A.1 Ethics

The underlying intention of our research was to assess the mobile network quality and performance of Airalo in multiple locations across the globe, measuring different metrics from low-level networking ones such as speed tests, DNS resolution, etc., to upper-layer application performance such as YouTube. Given that we recruited participants to carry custom-prepared mobile devices around, we obtained institutional review board (IRB) approval (IRB number is anonymized in order not to break double-blind) to conduct these studies. In addition, two of the authors have completed the required research ethics and compliance training, and are CITI [2] certified. Participants were also provided with a consent

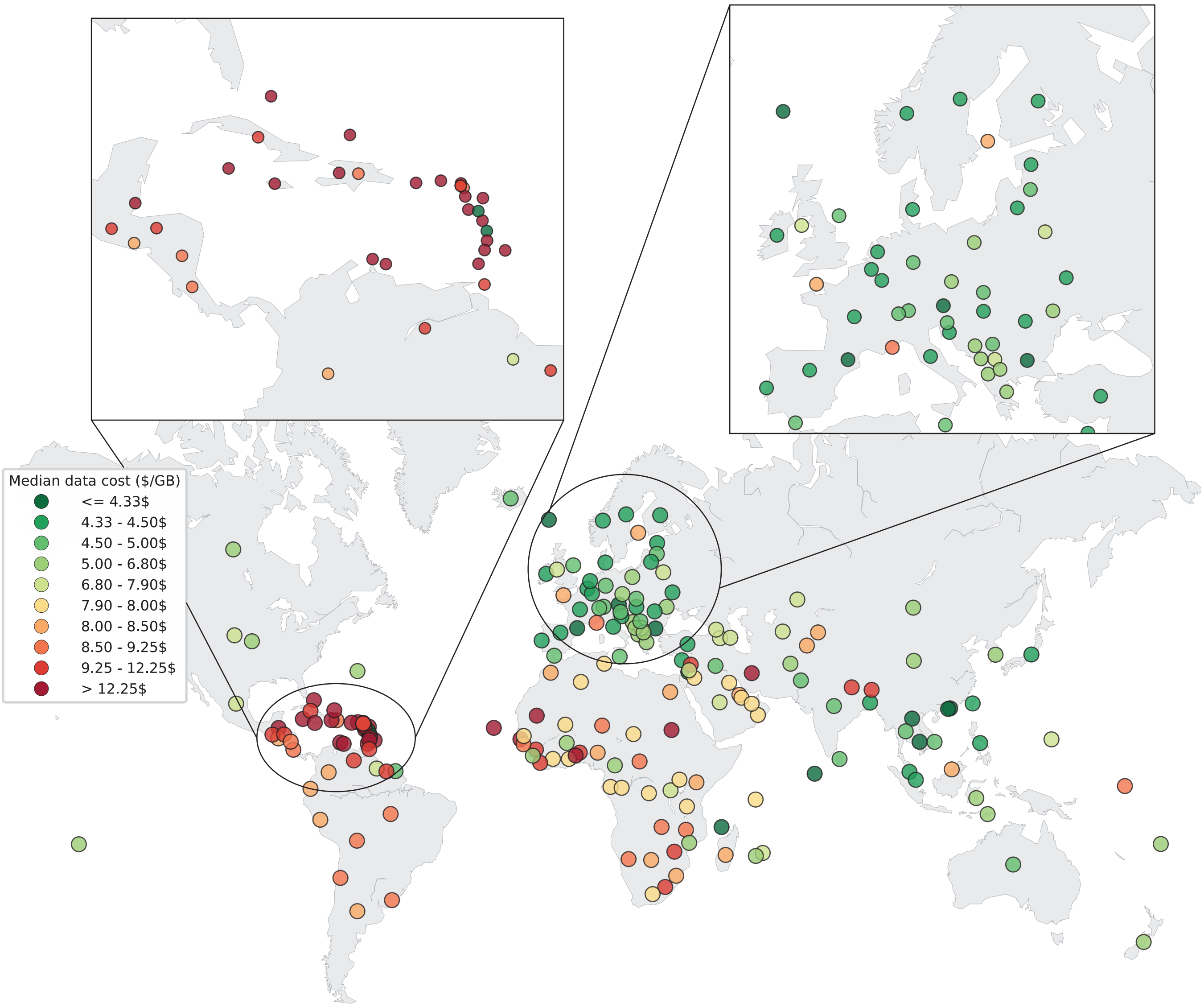

Figure 18: Median eSIM cost per country ($/GB) from low (green, less than $4.33) to high (red, more than $12.25)

form to read and sign, acknowledging their willingness to participate. They were given the opportunity to ask questions about the study and what was being collected.

We asked the participants to carry these mobile phones, charge them, and install both a physical SIM and an eSIM we provided. We also instructed the participants not to use these phones or add any of their personal information or logins. As such, we do not collect any unidentifiable, sensitive, or personal information about the participants. The only foreseeable concern that might put our users' privacy at risk is the collection of the phones' GPS data, which in principle can reveal the participants movements. We did inform the participants before hand about this concern and we obtained their written consent that they approve this collection. As such, we believe that this are deemed to be of low-risk.

In our collaboration with the UK operator, the datasets we leverage in our research are protected under Non-Disclosure Agreements (NDAs) that explicitly forbid the dissemination of information to unauthorized parties and public repositories. The procedures for data collection and storage within the network's infrastructure strictly follow the guidelines set forth by the MNO, and are in full compliance with local regulations. No personal and/or contract information was available for this study, and none of the authors of this paper participated in the extraction and/or encryption of the raw data. Ultimately, our datasets and research do not involve risks for mobile subscribers, while they provide new knowledge about the dynamics of virtual mobile operators.

Country	# Volunteers	Duration (days)	# Measurements
Italy	1	11	9
China	1	5	6
Moldova	1	10	11
France	2	9	15
Azerbaijan	1	4	5
Maldives	1	3	5
Malaysia	1	3	5
Kenya	1	4	9
USA	1	4	9
Finland	1	1	3
Pakistan	1	11	16
Egypt	1	6	8
Turkey	1	7	9
Uzbekistan	1	3	6

Table 3: Overview of web-based campaign conducted by volunteers across 14 countries. We report the number of measurements completed fully (successful uploads of DNS and Speedtest results using Airalo eSIM) for each country.

A.2 Acknowledgments

We are grateful to our anonymous reviewers and shepherd for their insightful feedback and guidance. We also thank Steffen Gebert (Emnify) for his assistance in verifying aspects of our research methodology. Finally, this work would not have been possible without the 24 volunteers who participated in our data collection campaigns across various countries. This work was partially supported by the European Commission through Grant No. 101139270 (ORIGAMI).

A.3 Measurement Campaign Overview

From March 10th to 22nd, 2024, the *web-based campaign* was conducted where volunteers were each provided with an Airalo eSIM specific to their travel destination. Table 3 summarizes the number of volunteers, the duration of data collection, and the total number of measurements collected per country. Each volunteer was assigned to a single country, with the exception of France, which had two volunteers who participated on non-overlapping dates. A "measurement" consists of the volunteer uploading their current DNS configuration followed by the result of a fast.com speed test while using the provided Airalo eSIM. Only fully completed measurements are reported in the table.

During the *device-based campaign* from December 2023 to April 2024, volunteers were equipped with an Airalo eSIM and a physical SIM for their travel destination, along with a rooted Android device. This device was configured to automatically run various network diagnostics while alternating between the two SIMs. There was a single volunteer per country in this campaign. Table 4 reports the data collection period and the total number of network tests (see Table 1 for more details) performed in each country. We present the test counts as `<physical SIM> // <Airalo eSIM>`, showing the number of tests conducted with the physical SIM and the Airalo eSIM, respectively. The large differences in the number of tests between the two SIMs can be attributed to several factors. For instance, some physical SIMs had a longer measurement duration due to issues like a volunteer initially struggling to activate the eSIM in Korea. Additionally, Ookla Speedtests using the physical SIM often failed due to (Ookla's) server-side rate-limiting, likely triggered by IP address aggregation by the local operator. Note that we have excluded the video streaming test results from Spain and the UK from our analysis because of the limited data collected in those locations.

A.4 Airalo Cost Analysis

Figure 18 visualizes the median eSIM cost per country, expressed as \$/GB. The location of each dot represents the country, while the color of each dot reflects the median eSIM cost in \$/GB. We divided eSIM costs into deciles, where each decile represents one tenth of the cost distribution (see Figure 17), ranging from the lowest decile (dark green, ≤ \$4.33) to the highest decile (dark red, > \$12.25). The figure provides more fine-grained details on the price difference observed per continent in Figure 16. Further, it highlights that Central America (left circle in the figure) exhibits a consistent high cost per GB, *i.e.,* higher than the overall median cost worldwide (\$7.9) regardless of the country.

We further compare pricing differences among Airalo eSIM plans (≤5 GB) that rely on the same b-MNO in Figure 19. Even though these plans share the same network infrastructure, their prices fluctuate widely across regions.

A.5 CDN Analysis

We compare the performance of five CDN providers across physical SIMs and eSIMs in our device-based campaign, measured as the download time for the last version of "jquery.min.js". Figure 20 plots the results for Google CDN, Microsoft Ajax, jQuery and jsDelivr. Refer to Figure 14-a for results from Cloudflare.

Across all CDN providers, the download speeds exhibit a consistent pattern depending on the network configuration: native eSIMs typically achieve download speeds comparable to physical SIMs, while HR eSIMs experience notable performance degradation. This degradation is attributed to the technological limitations associated with data roaming. Although the six IHBO eSIMs also underperform relative to their physical SIM counterparts, the disparity in download speeds is less pronounced than that observed with HR eSIMs.

A notable exception was observed for Google CDN in Georgia, which occasionally experienced exceptionally slow download speeds, due to unusually long DNS lookup times that exceeded 5 seconds.

Country	Duration (days)	Ookla Speedtest	MTR (Facebook)	MTR (Google)	MTR (YouTube)	CDN (Cloudflare)	CDN (Google)	CDN (jQuery)	CDN (jsDelivr)	CDN (Microsoft Ajax)	Video Streaming
Georgia	2	11 // 8	12 // 12	12 // 12	12 // 12	12 // 10	12 // 10	12 // 10	12 // 10	12 // 10	7 // 7
Germany	25	154 // 136	331 // 319	332 // 319	329 // 318	322 // 305	324 // 313	323 // 284	324 // 283	324 // 278	5 // 10
South Korea	2	18 // 10	32 // 18	32 // 18	26 // 13	32 // 16	32 // 17	32 // 17	32 // 17	31 // 15	10 // 9
Pakistan	9	49 // 121	213 // 205	214 // 205	213 // 202	210 // 200	211 // 200	210 // 197	211 // 198	206 // 195	98 // 101
Qatar	1	3 // 7	14 // 10	14 // 10	13 // 10	14 // 12	15 // 11	15 // 12	15 // 12	15 // 11	7 // 4
KSA	3	10 // 17	49 // 44	49 // 45	49 // 42	170 // 165	170 // 165	170 // 164	170 // 165	164 // 164	79 // 74
Spain	4	15 // 31	171 // 164	171 // 165	166 // 163	166 // 158	168 // 159	168 // 158	166 // 157	165 // 157	
Thailand	8	34 // 42	100 // 80	99 // 80	99 // 79	96 // 96	95 // 96	97 // 96	95 // 96	96 // 96	36 // 29
UAE	4	19 // 47	100 // 97	100 // 97	99 // 96	99 // 165	99 // 164	99 // 165	99 // 165	99 // 165	45 // 46
UK	4	10 // 6	11 // 9	11 // 9	11 // 9	15 // 12	15 // 12	15 // 13	15 // 13	15 // 13	

Table 4: Overview of device -based campaign. For each country, we report the number of successful Ookla Speedtests, traceroutes (mtr to Facebook, Google, YouTube), CDN tests (file download from five CDN providers), and video streaming tests. All values are presented as a comparison between the physical SIM and the Airalo eSIM, formatted as `<Physical SIM> // <Airalo eSIM>`.

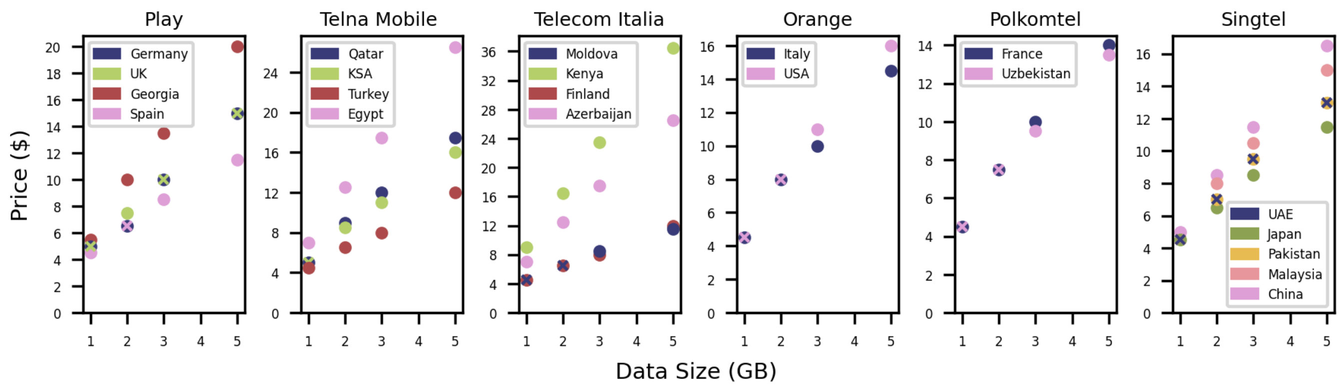

Figure 19: Size (GB) versus price ($) per eSIM and b-MNO.

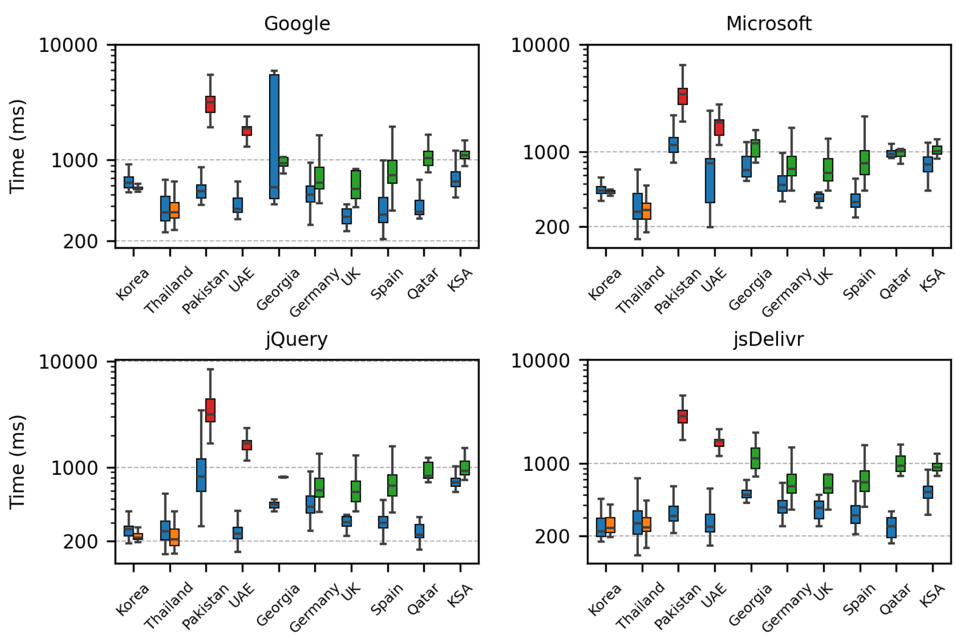

Figure 20: Time taken to download a jQuery library from four CDN providers across countries and network configurations.