Measuring the Satellite Links of a LEO Network

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***Abstract*—Low-earth-orbit (LEO) satellite networks have become very popular in recent years, exemplified by Starlink, OneWeb, Kuiper and others, due to the dramatically reduced launch cost and increased demand for connectivity anytime, anywhere. After an exploration of Starlink access, core and backbone networks, in this paper we focus on the satellite access network (SAN) of Starlink around the world. Particularly, we measure the access performance in terms of one-way delay and round-trip time from user terminal (UT) to ground station (GS) and point-of-presence (PoP), both inside-out and outside-in, and even on inactive dishes. It reveals the unique characteristics of Starlink SAN in terms of satellite-GS scheduling, media access control and user contention, and sheds light on the challenges and opportunities for network protocols and applications. The paper will be complemented by public dataset release and conference on-site demo for the research and industry community.**

***Index Terms*—LEO satellite networks, Starlink, measurement**

I. Introduction

Low-earth-orbit (LEO) satellite networks have become very popular in recent years, e.g., Starlink has more than two million residential, roaming, maritime and aviation users around the world as of September 2023, OneWeb has started its service offerings to business, enterprise and government sectors, and Telesat and Kuiper have launched their test and prototype satellites [1]–[4], driven by the dramatically reduced satellite launch cost and hugely increased demand for connectivity anytime and anywhere. Compared with their geostationary (GEO) counterparts, these LEO networks boast much higher capacity and lower latency, despite many more satellites and handovers needed to cover the entire earth. However, the inner working of these LEO networks is largely hidden and has attracted a lot of attention from the research community.

After an exploration of Starlink access, core and backbone networks initially with one Starlink user terminal (UT) associated with the ground stations (GS) near the Seattle point-of-presence (PoP) with the assistance of RIPE Atlas probes and Reddit Starlink community [5], we have extended our UT coverage through acquisition and collaboration to many PoPs around the world. In this paper, we particularly focus on the satellite access network (SAN) of Starlink, and measure its performance in terms of one-way delay, round-trip time and packet loss from UT to GS and PoP, both inside-out (i.e., from UT toward the Internet) and outside-in (from the Internet toward UT), on both active and inactive dishes (i.e., dishes without an active service subscription). We reveal the unique characteristics of Starlink SAN in terms of globally synchronized satellite-GS scheduling, media access control (MAC) and user contention, and shed light on the challenges and opportunities for network protocols and applications.

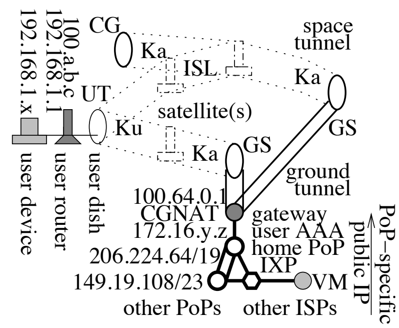

Fig. 1. An illustration of the Starlink satellite access network.

The rest of this paper is organized as follows. After a quick review on the Starlink background and related work in Section II, we present the measurement methodologies in details in Section III, including those on both active and inactive dishes. Measurement results are analyzed in Section IV with further discussion in Section V, followed by conclusions and future work in Section VI. The paper will be complemented by public dataset release and conference on-site demo.

II. Background and Related Work

A. Starlink in a Snapshot

Starlink is a fast moving target and its offerings expand quickly [1]. As of November 2023, it has more than 5,000 active satellites in several shells around the earth, mostly at 53° inclination and around 550km above the earth to cover highly populated areas and some at higher inclinations to cover polar regions. Among its more than two million users, mostly are residential ones, while roaming, mobility, maritime and aviation services are offered at higher price tags and generating more revenue, resulting in a break-even cash flow in about three years, thanks to its reusable rocket launch and commodity satellite manufacturing technologies.

Starlink users install their UT with an unobstructed view of the sky. After power on, the user dish will determine its own location by GPS and wait for the beacon signal from Starlink satellites. After user authentication and authorization, the dish will receive the satellite schedule and tilt toward a favorable view of the sky and use its electronically steered phased array antenna to track the communicating satellite according to the schedule. Communicating satellite will tunnel the user traffic, potentially through other satellites via inter-satellite laser links (ISLs), to a landing GS, which will be further tunneled back to user's home PoP, where a public IPv4 address will be assigned. For users opt in public IP address, the binding is at their router.

Figure 1 shows a schematic diagram of Starlink SAN with the default IP addressing scheme. User router at 192.168.1.1 for user devices also serves as the user gateway to SAN. From the SAN side, the user router further has a unique 100.a.b.c address in 100.64/10 derived from its dish ID. User dish, functioning as a satellite modem, is reachable from user devices at 192.168.100.1 (or dishy.starlink.com by DNS name) and 34.120.255.244 (my.starlink.com), where the latter is actually an address belongs to Google (244.255.120.34.bc.googleusercontent.com) for its public Compute Engine instances. Satellite and GS are transparent to user traffic which tunnels through them, until it arrives at the GS gateway (172.16.y.z) into the PoP, where a PoP-specific public address (e.g., 98.97.164.118 with name customer.sttlwax1.pop.starlinkisp.net, and sttlwax1 is the CLLI code for Seattle, WA, USA) is assigned at the carrier-grade network address translator (CGNAT). User's public IP address may change due to DHCP at CGNAT. Starlink releases the geographic location of its customer addresses at http://geoip.starlinkisp.net with a granularity finer than the PoP itself (e.g., 98.97.164.0/24, CA, CA-BC, Vancouver, while the dish is actually located in Victoria, BC, Canada).

Once arriving at the GS gateway, user traffic is subject to various authentication, authorization and accounting (AAA) functions including prioritization based on user subscription and usage history. Starlink PoP structure is quite similar to terrestrial Internet service providers (ISPs), and interconnects with other ISPs and Internet content providers (ICPs) at Internet exchange points (IXPs). Currently, Starlink has eight PoPs in North America (Seattle, Los Angeles, Denver, Dallas, Chicago, New York City, Atlanta and Mexico City), with a community gateway (CG) in Dutch Harbor, Alaska. In addition, it has four PoPs in South America (Bogota, Lima, Santiago de Chile and Sao Paulo), three in Europe (London, Frankfurt and Madrid) and one in Africa (Lagos). Asia-Pacific sees considerable PoP growth in Sydney, Auckland, Tokyo, Perth, Manila, Singapore and Jakarta recently. 206.224.64/19 and 149.19.108/23 are used within and between these PoPs.

B. Starlink-related Measurement Work

Since the announcement of Starlink, research community has been attracted to explore its performance, from geometry, physics, simulation and emulation viewpoint (please see [5] and the references therein). Network measurement started right after the beta test program launched and was shared by Reddit users [6], some of whom also host RIPE Atlas probes behind their dish for ping, traceroute and nslookup-like measurement [7]. Network researchers also explore Reddit posts and Atlas results, and conduct more sophisticated measurement with certain vantage points, for web browsing, video conferencing, and online gaming applications, between user device and Internet server and virtual machine (VM) in the cloud [8]–[14]. There are also efforts to reveal Starlink scheduling internals [15] and probe Starlink from outside [16].

Our work in this paper focuses on the unique SAN segment of Starlink, with comparison with OneWeb [2], i.e., just between user router and GS gateway (GW), with or without ISLs, as well as closely collocated cloud VMs, so the observation is not affected by the traffic dynamics within and between PoPs or remote servers. By carefully measuring the one-way delay (OWD) and round-trip time (RTT) between user and GWs and leveraging user dish's obstruction map construction process, we can identify and infer the communicating satellite and landing GS which are transparent to user traffic. Moreover, we can conduct similar measurements even on inactive dishes, which greatly increases the measurement capability of Starlink user and research community at large.

III. MEASUREMENT METHODOLOGIES

In this section, we present the measurement methodologies for both inside-out (i.e., from UT to GS and PoP) and outside-in (from PoP to GS and UT) for both active and inactive (i.e., without an active service subscription) dishes. More details will be released with the public dataset and on-site demo.

A. Inside-out Measurement

For inside-out measurement, we have access to a mini PC or VM behind the dish. We acquired three dishes installed in Victoria, BC, Canada, Louisville, CO, USA and Ottawa, ON, Canada, where the latter two are hosted by our alumni and their students, associated with PoPs in Seattle, Denver, and New York City, NY, USA, respectively. Through collaboration, we have access to more mini PCs or VMs associated with Seattle, Chicago, Dallas, Frankfurt and Lagos PoPs. For remote mini PCs or VMs, we separate access traffic and measurement traffic purposely wherever possible. We also get help from Starlink users associated with other PoPs (e.g., Sao Paulo, Auckland, etc) to run measurement scripts at given time.

1) Active dishes: For active dishes, i.e., dishes with an active subscription, we can reach any destination on the Internet. Starlink network is IPv4 and IPv6 dual stacked in terms of its PoP and backbone routers, and its dishes and provided user routers also become IPv6 capable through firmware upgrades gradually over the years, although the configurable features are still very limited, so we also bypass Starlink provided user router wherever possible and use OpenWRT-powered router with the latest firmware and configurable features.

From the user device or customer router at 192.168.1.1, we can reach its GS gateway at 100.64.0.1 (or equivalently fe80::200:5eff:fe00:101 for IPv6) in one IP hop, passing through the dish, satellites and GS. RTT measurement tools, such as ping and its variants, can be used to determine the round-trip time between the user router and GS gateway, reflecting the satellite-GS (Sat-GS) selection, MAC and user contention. GS may process and generate ICMP messages slower than regular data traffic, but the RTT measurement still provides an envelop metric for performance analysis.

Well-provisioned Internet destinations, such as Cloudflare (1.1.1.1) and Google DNS (8.8.8.8), can be reached with tools such as traceroute and its variant such as mtr to reveal the PoP structure and the PoP interconnection to the Internet, and Starlink backbone addresses (i.e., 149.19.108/23) can be used to reveal the topology of Starlink backbone around the world. Starlink user addresses can be reached over the destination satellite hop for users with public IPv4 option, or to their corresponding gateway. Starlink uses MPLS to route traffic to its users in its backbone, so traceroute or mtr-reported RTT at intermediate hops is inflated due to ICMP MPLS tunneling as these routers cannot return ICMP messages directly.

For users with public IP address option, their gateway is publicly addressable, e.g., 98.97.64.1 for a public IP user in Seattle. Due to a mis-configuration, Starlink used to filter out return ICMP messages for public IP users, even though their traffic traversed the same gateway and routers as private IP users, as verified by the outside-in measurement.[1]

We also employ time-synchronized cloud VMs collocated with Starlink PoPs, so we can measure one-way delay (OWD) for up (i.e., from UT to VM) and down (from VM to UT) links directly and correlate them to the measured RTT between UT and VM. From the OWD and RTT correlation, we can also infer the symmetric satellite-GS selection for up and downlink, i.e., Starlink currently uses the same satellites and GS for a bidirectional flow, following its tunneling design.

2) Inactive dishes: For inactive dishes, they still can reach certain Starlink addresses for firmware updates, and they can even reach some Internet addresses for users to access their Starlink account and resume their service through a captive portal. Thus, it provides an opportunity to conduct some meaningful measurement similar to active dishes, at link, network, transport and application layers. However, inactive dishes have a lower priority than active ones with the same GS and can be forced to change to different 172.16.y.* during the measurement session. Nevertheless, the availability of inactive dishes further increases the measurement capability.

B. Outside-in Measurement

For outside-in measurement, we initiate the session from the VM close to the Starlink PoP of the destination user dish.

1) Controlled dishes: We first calibrate the outside-in measurement with the dishes under our control. This is feasible for public IP users (i.e., the public IP address is bounded at their user router) and our measurement endpoint is running on the customized, not Starlink provided, user router. For IPv6, Starlink allocates a /56 public IPv6 block to be delegated through the user router. However, Starlink provided user router does not allow incoming connection establishment requests to be traversed through the router (i.e., not configurable) unless bypassing the router. Therefore, we use the customized router for this purpose. The outside-in and inside-out measurement, when both endpoints are under our control, gives us the ability to correlate the measurement results and insights.

2) Uncontrolled dishes: A more challenging task is to reach the uncontrolled dishes. Starlink does not allocate IP address blocks separately for public or private IP users, where the former get their public IP at their router, while the latter have their temporary, public IP at CGNAT, both by DHCP. We can probe the public IP in these blocks. However, services such as Censys are available to list the IP addresses that are externally reachable [16], so we can leverage such information. By correlating the measurement to controlled and uncontrolled dishes with the same PoP and even GS, we can infer more user-perceived performance, even without direct access behind the dish, which greatly increases the measurement capability.

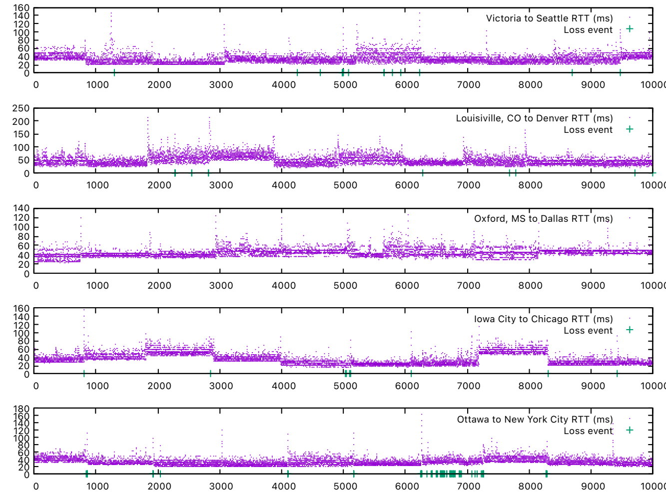

Fig. 2. Starlink access RTT sequence in 15ms intervals with US PoPs.

IV. Measurement Results and Analysis

In this section, we present the measurement results following the methodologies described in the previous section, and offer insights leveraging from both the inside-out and outside-in measurement approaches, as well as on inactive dishes.

A. UT-Sat-GS Performance

The UT-Sat-GS performance is of most concern for most Starlink users, as reflected on Reddit, Facebook and X (formerly Twitter). By comparing such performance at PoPs with different satellite density at different latitudes, user population and weather condition, one can also figure out the dominating factors, e.g., larger dish may achieve a higher throughput but latency is determined by service tiers, as we previously revealed [5]. Now we can examine further around the world.

1) User access: As shown in Fig. 2, 3 and 4, user-perceived performance such as RTT by ping in about 15ms intervals to its GW is actually heavily influenced by their local setup. Gen-2 user router removed the built-in Ethernet port, so unless users acquired Starlink's proprietary Ethernet adapter and use more powerful WiFi routers, they are often limited by Starlink's limited WiFi signal strength and coverage (e.g., the one with Denver), although Starlink mesh router can extend the coverage, so our measurement tries to use Ethernet connections to dishes.[2] More critically, many users do not have a clear view of the sky, and even slight obstructions at the place where Starlink often picks satellites to communicate

[1]Starlink has since fixed this bug in late 2023 based on our feedback.

[2]Ethernet ports have returned to the Gen-3 Starlink router in late 2023.

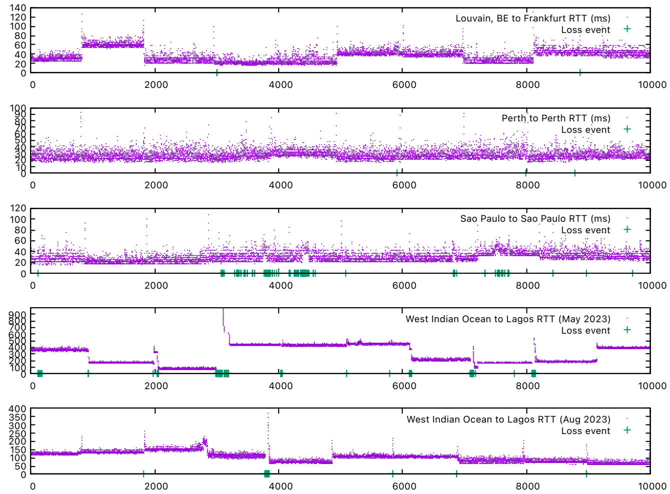

Fig. 3. Starlink access RTT sequence in 15ms intervals with oversea PoPs.

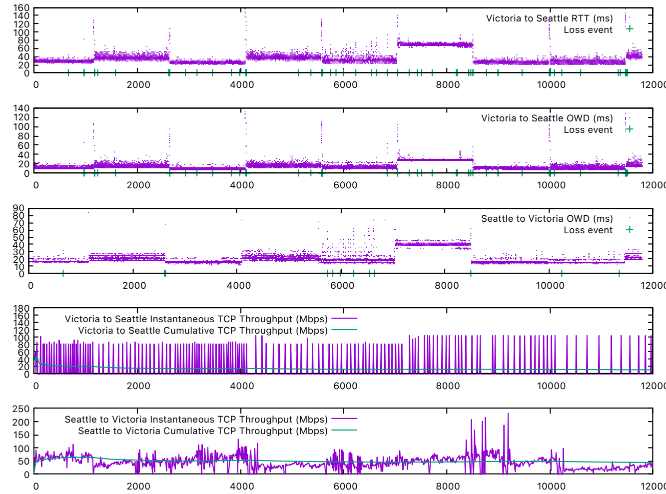

Fig. 5. Starlink access RTT, OWD and throughput with the Seattle PoP.

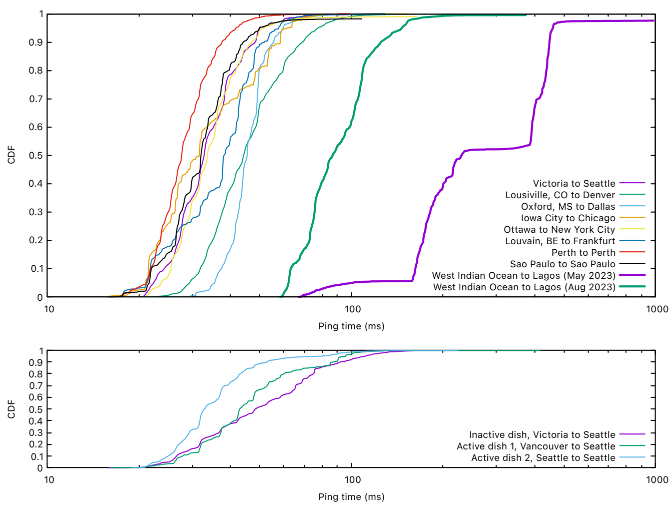

Fig. 4. Starlink access RTT with global PoPs and (in)active dishes in CDF.

with can considerably affect the performance (e.g., the one with New York City), so our measurement tries to utilize the dishes mounted on roof and without obstruction. Next, user performance is also dominated by the competing users in the same service cell (e.g., PoPs such as Perth with few active users have the lowest UT-to-GW RTT). Even though Starlink re-configures satellite-GS selection every 15 seconds, congestion is unavoidable during peak hours. Starlink also limits new customers in certain cells until most recently with more satellites launched and so capacity, or puts them at lower priority (best effort or roaming, e.g., the one with Denver) to maintain a reasonable performance for high-priority users, so our measurement continues for a long duration to capture capacity changes over time (not shown here but we have released some data at https://zenodo.org/records/10020034).

2) Satellite-GS selection: When comparing UT-Sat-GS performance around the world, a distinct feature emerges despite the location, satellite and user density, and weather condition, i.e., the minimum RTT jumps in a step-wise manner in certain intervals. Upon close inspection and investigation, it corresponds to the satellite-GS reconfiguration interval every 15 seconds, as mentioned in Starlink FCC filings [17] and a patent granted to Starlink [18], globally synchronized at 57, 12, 27 and 42 second off each minute, as discovered by other researchers too [15]. Such min-RTT changes, often in 10, 20 or even 50 milliseconds, are way above the change of propagation delay of visible satellites, but are indeed caused by the changing GS associated with the satellites and the need to tunnel back to the home PoP, as we showed in Fig. 1. Delay spike and packet loss occur at such handovers, and consequently affect network protocols and applications.[3]

3) Uplink and downlink correlation: As shown in Fig. 5, with a time-synchronized cloud VM collocated with the Starlink PoP, we can conduct IRTT measurement in 10ms intervals for up (i.e., from UT to VM) and down (VM to UT) links separately, and compare with the RTT measurement at the same time. It is clear that Starlink's up and downlink are symmetric in terms of the satellite-GS tunnel traversed, where the uplink and downlink OWD jumps in sync in the same direction. Moreover, the downlink, which is dominated by the satellite to UT link, has more distinct patterns in media access grouping and banding, while the uplink is more randomized due to the poll-randomize-grant operation discussed in Starlink's patent.

The periodic delay spike (due to link-layer buffering when the physical link is temporarily unavailable during the satellite-GS handover without "make-before-break" at the UT side) and packet loss affects TCP throughput considerably due to premature timeouts (when the link delay jumps up) and excessive duplicate acknowledgments due to packet reordering (when the link delay jumps down), which triggers TCP to reduce its congestion window repeatedly. For a single TCP flow, its achievable throughput is much lower than the advertised

[3]Starlink started to mitigate this issue in 2024, reaffirming its sub-20ms RTT target when the UT and GS are seen by the same satellite, i.e., no ISLs.

capacity, even for the downlink shown in the last plot of Fig. 5, as measured by iPerf3 and reported in 100ms intervals.[4] Note that we used CAKE smart queue management (SQM) at the OpenWRT router in Victoria, so the uplink throughput is regulated to have an uplink OWD even lower than the downlink for some interactive applications such as online gaming. However, uplink still suffers more loss events and downlink has a higher throughput overall due to a higher physical capacity and less user contention.

4) Active and inactive dish correlation: On the other hand, inactive dishes give us additional opportunities to measure the access link and infer those with the same GS and PoP. Inactive dishes have a lower priority than the active ones, and can be forced to change to different gateways during the same measurement session (i.e., changing 172.16.y.* addresses). Regardless, we still can perform access RTT measurement at link, network, transport and application layers even though IRTT and iPerf3 are not possible currently. As shown in the lower portion of Fig. 4, inactive dishes have a higher RTT than the active dishes with the same PoP and GS. In addition, Active dish 2 has a lower RTT than Active 1 due to a higher user priority. Nevertheless, inactive dishes can provide a performance bound for the active dishes in the same cell.

B. Inter-Sat Link Performance

Inter-satellite links (ISLs) provide Internet access to users who are faraway from GSs, e.g., in the middle of an ocean. We measured the SAN performance of a Starlink user in the middle of the Indian Ocean, 5,000+km away from the nearest GS, initially with the global and now regional roaming, with a Rwandan IP address associated with the Lagos PoP. As shown in Fig. 3 and 4, the ISL introduces much more delay, delay variation (jitters) and packet loss. However, the ISL performance has been greatly improved from May to August 2023, likely due to more satellites becoming available.

Currently, Starlink ISL always routes toward user's home PoP first, regardless its destination. For example, the packet from the Lagos user to a Perth user arrives at Lagos first, and then London, New York City, Denver, Los Angeles, Sydney and finally Perth with an RTT above 500 milliseconds, instead of crossing the Indian Ocean directly with ISL for an RTT below 100 milliseconds. The IPv4 packets have to be tunneled back to Lagos to be NAT'ed. However, with public IPv6 addresses, packets can go toward the destination directly if Starlink can adjust and improve its ISL routing strategies.

C. GS-Sat-GS Performance

In September 2023, Starlink also opened the first community gateway (CG) in Dutch Harbor, Alaska. CG is a mini GS with a local distribution network. Unlike individual user dishes for each household, the CG aggregates and distributes user traffic through the mini GS. Compared to UT-Sat links with electronically steered phased array antennas in Ku bands, GS-Sat links use parabolic antennas in Ka bands. Due to user

[4]The throughput shown in Fig. 5 is also affected by the reporting interval.

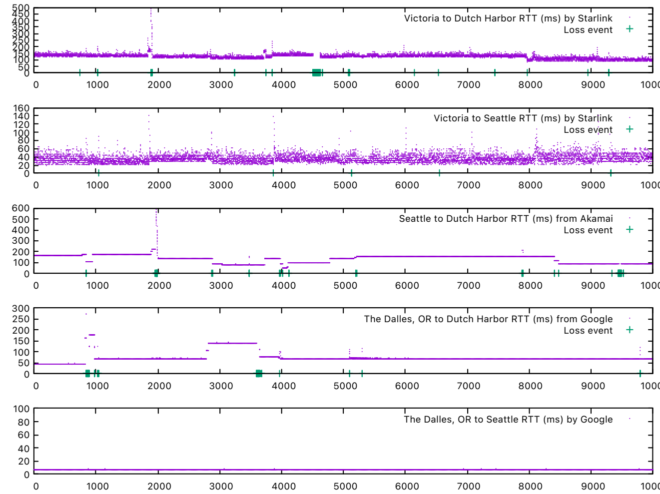

Fig. 6. Starlink community gateway performance.

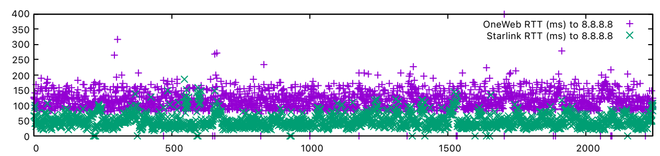

Fig. 7. OneWeb vs Starlink RTT to 8.8.8.8.

aggregation, GS-Sat-GS links have much less user contention, amid similar satellite-GS handover behaviors, as shown in Fig. 6. The first plot is from the Victoria dish to Dutch Harbor, thus over UT-Sat-GS and GS-Sat-GS links, and the second plot is just for the first segment. To avoid the impact of user contention on the UT-Sat-GS link, we also measure the access performance from a VM hosted by Akamai in Seattle and another VM hosted by Google in The Dalles, OR, USA. The fiber connection from The Dalles to Seattle introduces a very stable RTT around 6 milliseconds and zero packet loss, and the RTT to Dutch Harbor from Akamai in Seattle and from Google in The Dalles is quite stable except the minimum RTT fluctuation in handover periods. There are two GSs in Seattle that can reach Dutch Harbor in parallel for PoP resiliency, and the Victoria dish and Akamai share the same GS gateway, so their RTTs are also correlated, while Google's RTT to Dutch Harbor is relatively independent as it uses another GS.

V. Further Discussion

A. Starlink vs Other LEO Networks

In addition to Starlink, OneWeb also has started offering business services around the world [2]. With much fewer satellites at higher altitudes in polar orbits and currently much fewer ground stations and PoPs, OneWeb consequently has a higher latency than Starlink. As we can observe in Fig. 7, OneWeb RTT to Google's public DNS server (8.8.8.8) has similar behaviors as Starlink, i.e., delay spike and packet loss happen when satellite handover occurs. However, OneWeb demo site has two dishes following a "make-before-break" handover approach with sweeping instead of spotting beams used by Starlink to jump between many more consumer dishes, so its delay spike and packet loss are less dominating than Starlink. Nevertheless, satellite and possibly GS and PoP handover is still a challenge to LEO networks, likely for Telesat and Kuiper too, where the former similarly focuses on business users while the latter also on consumer ones.

B. Predicting Sat-GS Handover

Thus the ability to predict Sat-GS handovers is very important to improve LEO network performance. For Starlink, currently we can know for sure when the next Sat-GS handover happens (i.e., 57, 12, 27 and 42 seconds after each minute), but we do not know which satellite it will use and the corresponding GS, or whether the minimum RTT is to increase or decrease. Previously, Starlink dish's gRPC interface exports user's service cell ID, satellite ID and gateway ID, however, this feature has disappeared in newer firmware updates. We have found that the construction of the obstruction map can indicate the location of the communicating satellite from the dish's viewpoint where its azimuth and elevation information is available through the gRPC data [19], [20], as well as the GPS location, and by correlating with the public two-line element (TLE) satellite orbital data, one can figure out the satellite ID again, which has been adopted by [15].

Figuring out the landing GS is much more challenging, even though the GS location is known in most countries. The UT-to-GW latency can give a hint if the feasible GSs are far apart geographically. However, such inference may not be conclusive in an area where both the satellites and GSs are densely distributed. We appeal to Starlink and other LEO satellite network companies to make more technical information available to the research community and their users. Given the likelihood to roam between different LEO networks in different countries around the world, certain standardization is also necessary as terrestrial mobile communication systems. A reliable prediction can considerably improve application performance, as indicated in our recent work [13], [14].

C. An Emerging Global Testbed

In [5], we appealed to the Starlink user community to host more RIPE Atlas probes behind their dish, and to the research community to federate their dishes into a global testbed similar to Planetlab. Currently the public Atlas probes behind Starlink dishes have increased to about 70 but still in less than 20 countries, which is behind Starlink's global coverage. All our three Starlink dishes are accompanied by RIPE Atlas probes, and we are participating in an emerging global testbed [21], where we encourage other Starlink users and researchers to participate as well. In addition, we are committed to public dataset release and have already started doing so.

VI. Conclusions

In this paper we continued our previous effort on exploring the Starlink access, core and backbone networks, and focused on the performance of Starlink satellite access network between user terminal, satellites and ground stations around the world. By devising both inside-out and outside-in measurement approaches and techniques applicable to both active and inactive dishes, we can significantly increase the measurement capability. Performance evaluation reveals Starlink's globally synchronized Sat-GS scheduling, media access control and user contention. The future work shall better predict LEO satellite and possibly ground station handover in addition to handover time, and incorporate such information to improve network protocol and application performance, besides improving the inter-satellite link routing and integration with ground infrastructures for a space-air-ground-aqua network envisioned by the 6G mobile communication system.

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