“Internet from Space” without Inter-satellite Links?

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ABSTRACT

Buoyed by advances in space technology, several firms are planning satellite constellations to offer broadband Internet service. While these developments are happening quickly, there are also many uncertainties about the design of these networks. A key open question is whether or not they will incorporate direct connectivity between satellites, instead of only ground-satellite connections. We compare the network behavior resulting from the two outcomes of that question. Our analysis shows that inter-satellite links substantially reduce the temporal variations in latency, add greater resilience to weather, and could yield more than 3× the throughput achieved without such links. Thus, whether this one design element pans out could have a large bearing on the performance, reliability, and economics of these networks.

CCS CONCEPTS

• **Networks → Physical links**; *Network performance modeling*.

KEYWORDS

Low Earth orbit satellite, LEO, Internet broadband constellation, inter-satellite link, ground-satellite connectivity, bent-pipe connectivity

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1 INTRODUCTION

Low Earth orbit (LEO) mega-constellations, comprising thousands of satellites, have recently been proposed to offer broadband “Internet from space” [7, 19, 35, 40, 50]. One of the many competitors, SpaceX, has deployed nearly 500 satellites, aiming to start providing service soon [14, 24].

These developments could have a deep and lasting impact on the Internet, extending its coverage to under-served communities, and providing lower latency than present-day fiber for longer distances [5, 20]. While past attempts in this direction failed [4, 9], the new proposals face lower risks due to new technologies that cut their costs, and increase their utility. Recent work [6, 17] identifies three such technologies: satellite miniaturization, reusable rocket boosters, and the ability to set up and maintain high-bandwidth laser connectivity between satellites traveling at high velocity.

We focus on the last key technology above: inter-satellite links (ISLs). Starlink, Kuiper, and Telesat all claim in their regulatory filings that their constellations will feature high-bandwidth laser ISLs [31, 43, 48]. This would enable moving data in space across a series of satellites, along nearly the shortest path, and at the speed of light in vacuum, *c*. Unfortunately, despite the public claims thus far, there is uncertainty about if and when the new constellations will be able to use ISLs. Although Starlink's older filings [47] mentioned 4 silicon carbide components per satellite, which were likely for ISL mirrors [20], SpaceX later announced [22] elimination of those components to ensure complete “burn on reentry” of satellites, without mentioning what would replace them. Starlink's entire current fleet of ~500 satellites does not have components that would enable ISLs [23], making it all-but-certain that they will operate their service initially without ISLs, with long-distance paths bouncing up and down between ground stations and satellites over radio links.

We thus attempt to quantify the utility of ISLs for such constellations: how important are ISLs to the capabilities of such networks, and how do the properties of LEO constellations with and without ISLs differ? Without ISLs, transoceanic distances must be bridged in some other manner than on-land ground stations; following the lead of recent work [5, 29], we use in-flight aircraft to serve as relays in such settings. We then analyze the latencies for end-end network paths and their variations over time, attenuation due to weather, and network throughput under intuitive traffic scenarios.

While prior work argued [21] that absent ISLs, such networks still provide low latency, our findings are more mixed. Indeed, LEO networks without ISLs still provide low latency between many ground locations. However, we quantitatively show that even with dense ground station deployments, there are three very significant downsides to foregoing ISLs:

- The temporal variation in latencies increases substantially: For the median (95^{th}-p) source-destination pair, eschewing ISLs increases latency variation by 80% (422%).
- The network becomes more vulnerable to weather disruption because of transit through satellite-ground links. Having ISLs can reduce the attenuation due to weather by 39% at least 1% of the time.
- The network-wide throughput decreases substantially, by more than two-thirds for the scenarios we evaluated.

Besides the above properties that we analyze quantitatively, we also discuss other drawbacks of ISL-free constellations: requiring ground terminals in unfriendly locations, poorer spectrum use, and limited cross-Equatorial connectivity.

Thus, while ISL-free constellations would still provide significant benefits, adding ISLs would vastly improve network performance,

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reliability, and cost-efficiency. Among the many competing networks, with all else equal, networks that successfully incorporate ISLs will have a sizable advantage.

On the flip-side, we also discuss interesting scenarios where even large, ISL-rich constellations would benefit from additionally using ground relays and terrestrial fiber for transiting some of their traffic. Our work thus calls for a deeper examination of how different types of connectivity, through ISLs, ground relays, and fiber, may complement each other.

2 BACKGROUND

Satellite networks are not new, but existing consumer satellite Internet [26, 51] leverages geostationary orbits (GSO), 35,786 km above the Earth. This leads to high latency, at least 240 ms round-trip. As a result, today, such services are only used in niches where terrestrial connectivity is poor.

The efforts of several companies towards building large low Earth orbit (LEO) satellite constellations to provide Internet access offer a way of side-stepping the limitations of GSO connectivity. Such satellites, instead of using GSO, operate at an altitude of only a few hundred to a few thousand kilometers. The minimum achievable GT-satellite RTT is thus much smaller, and would be comparable to, and often better than, terrestrial last-mile latencies today.

LEO constellation structure: The constellations proposed feature thousands of satellites, each with an orbital period of ~100 minutes. A satellite's orbit is described by its altitude and inclination. The altitude is measured from Earth's surface, and must be under 2,000 km for LEO. The inclination is the angle the orbital plane makes with the Equator as the satellites in the orbit move northward. A large number of orbital planes may use the same altitude and inclination, and cross the Equator at uniform separation from each other. A set of such "parallel" orbital planes is called an orbital shell. The largest proposed constellations feature multiple shells.

For simplicity, we shall restrict our analysis to one shell for both Kuiper and Starlink, corresponding to the first phase of their deployment plans. For Starlink, this shell has 72 orbital planes, with each plane consisting of 22 satellites, an altitude of 550 km, and inclination of 53°. Kuiper's shell consists of 34 orbital planes, 34 satellites per plane, 630 km operating height, and 51.9° inclination. These values are taken from FCC filings [31, 32, 44, 46] by the respective companies.

GT-satellite connectivity: Several networks plan to use radio GT-satellite links [31, 43, 46, 48]. The GT-satellite links are estimated to have up to 20 Gbps capacity [25, 45].

A GT can only connect to satellites within its view, specifically, ones it can see sufficiently above the horizon, as specified by a minimum angle of elevation, e. This angle, together with a satellite's altitude, h, determines each satellite's cone of coverage. For Starlink, $e = 25^\circ$ and $h = 550$ km, implying a coverage radius of 941 km, while for Kuiper, $e = 30^\circ$ and $h = 630$ km, resulting in a coverage radius of 1,091 km.

Each satellite can use its up-down capacity to connect simultaneously to multiple GTs using different frequency bands. For simplicity, we assume that careful frequency management alleviates interference; filings from Starlink and Kuiper state that software-defined frequency management will optimize towards this goal [32, 46].

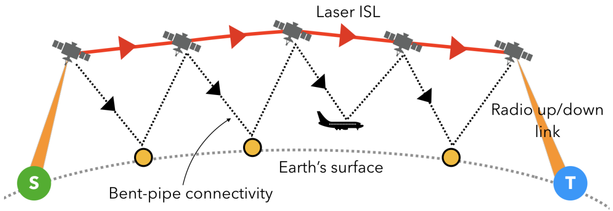


Fig. 1: *ISL-path (solid) versus zig-zag bent-pipe (BP) path (dashed). Smaller circles and an aircraft represent GTs.*

Each satellite is reachable from a GT for a few minutes, after which the GT must connect to a different satellite.

Inter-satellite connectivity: Most planned networks suggest the use of laser inter-satellite links [31, 43, 46, 48] that may achieve capacities of 100 Gbps or higher [3, 20, 23, 36].

ISLs are static point-to-point links between neighboring satellites. Some of the filings indicate that each satellite will form 4 ISLs [47]. A well-known [11, 13, 20, 30, 33, 34, 41, 42, 52] topology consists of each satellite connecting to 2 adjacent satellites in the same orbit, and to 2 satellites in adjacent orbits to form a *+Grid* connectivity pattern. Such satellites travel close to each other, and can remain continually connected. To ensure that ISLs are unaffected by weather, they must not enter the lower layers (~80 km or less) of the atmosphere. For the proposed constellations, the ISLs needed for the +Grid topology easily meet this constraint.

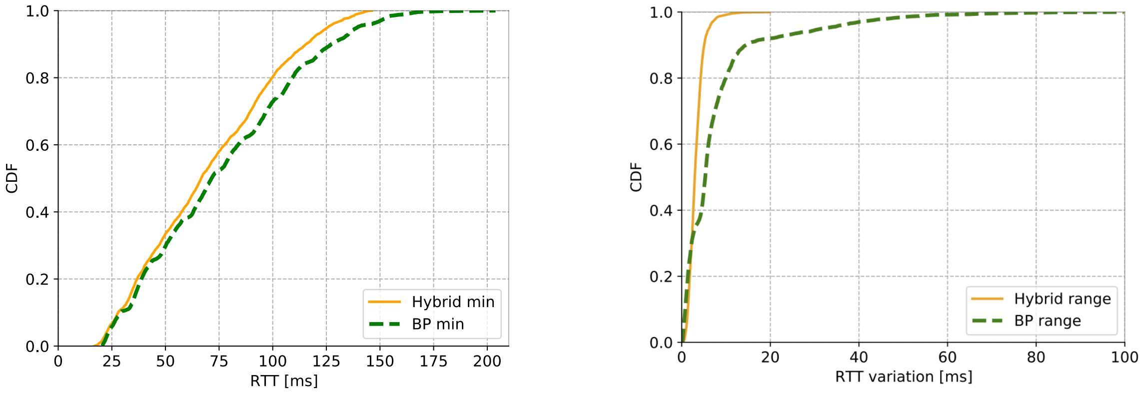
Experimental work has demonstrated 5.6 Gbps ISLs at LEO-LEO satellite distances of 4,900 km, as well as multi-Gbps ISLs at GSO-LEO distances of 45,000 km [15]. Two firms advertise multi-Gbps LEO ISL offerings [37, 49], with plans to soon offer 100+ Gbps [3, 36]. Recent work [8] claims that their production-ready ISL equipment meets the needs of LEO networks in terms of size, weight, and power.

Uncertainty on ISLs: Despite these technology advances and the claims of the to-be operators of LEO constellations, there is substantial uncertainty about whether or not they will successfully incorporate ISLs. None of the hundreds of already deployed Starlink satellites feature ISLs. One hurdle may be the "burn on reentry" requirement that regulators are asking operators to satisfy. Given the large number of proposed satellites, operators are being asked to ensure that *every* component burns up during reentry to the atmosphere, thus not risking injury and damage from de-orbiting satellites. However, the silicon-carbide components that are often used in the mirrors for ISL equipment [20] do not satisfy this requirement — Starlink's filings were amended to exclude mention of these components [22], but it is unclear what they will be replaced with to successfully implement ISLs.

3 BP VERSUS ISL CONNECTIVITY

LEO networks do not need ISLs to provide service. Without ISLs, connections between far-separated GTs bounce up-and-down between satellites and on-path GTs, yielding "bent pipe" (BP) connectivity. Fig. 1 shows BP and ISL connectivity. Besides the natural sources and destinations of traffic as GTs, BP requires additional GTs to *transit* traffic. In particular, across large water bodies, we allow this approach the use of in-flight aircraft as transit GTs.

With exclusively ISL connectivity, the first radio hop between the source GT and a satellite is followed by a series of laser ISLs,



(a) (b)

Fig. 2: *Incorporating ISLs result in (a) lower and (b) more stable RTTs over time than with BP-only connectivity. (a) plots the minimum RTTs seen across city pairs, while (b) plots the RTT variations (i.e., max-minus-min RTT) seen across city pairs.*

and a radio last hop to reach the target GT. Satellites are the only intermediate hops between the two communicating GTs. A *hybrid* approach uses both ISL and BP connectivity in end-end paths.

Our goal is to assess the utility of ISLs by comparing networks that are restricted to only BP connectivity to hybrid ones that additionally feature ISLs. A recent effort [21] suggested that BP with a dense-enough deployment of GTs could achieve latencies comparable to constellations with ISLs. Another effort [13] coarsely compared the throughput with and without ISLs, using an extremely lax model, where traffic entering the constellation could exit *anywhere*, treating the entire network as one maximum flow instance with many sources and *one* large sink, instead of imposing any constraints on the destinations of traffic flows. The latter effort also did not account for the possibility of a dense relay deployment, using only tens of terrestrial gateways.

Thus, prior work does not yield a full, clear picture on the utility of ISLs. To address this issue, using models more in line with networking realities, we quantify three network properties with and without ISLs: latency and its variability, network-wide throughput, and resilience to weather. We also discuss other differences we have not yet quantified.

Traffic matrix: The source/sink GTs are located in the 1,000 most populous cities in the world [18]. We only allow traffic between city-pairs separated by more than 2,000 km apart along the geodesic. This minimum distance constraint is used to model the fact that for most nearby city pairs, terrestrial connectivity will provide lower latency, while also being cheaper. Further, to keep the traffic matrix to a tractable size for simulations, instead of running traffic between all pairs of cities, we uniform randomly pick 5,000 city pairs.

Relays for BP: For a conservative view of the utility of ISLs, we use a dense deployment of GTs. The city-GTs serve as both traffic sources and sinks, as well as transit relays. GTs which only transit traffic are placed uniformly every 0.5° on the latitude-longitude grid[1] within a radius of 2,000 km of the cities. In addition to these GTs, to help BP achieve transoceanic connectivity, we use all in-air commercial aircraft as GTs. Note that aircraft-to-satellite radio links are already used in aircraft that offer satellite Internet to passengers. For the positions of such aircraft, we use FlightAware's data [1] for a period of 1 day from 2018. We include only those aircraft as possible intermediate hops which are flying over water bodies [27] to supplement the on-land GTs.

4 LATENCY AND ITS VARIABILITY

LEO satellite networks are highly dynamic. Due to the high velocity of satellites, end-to-end paths and their latencies change continually. Such variations have been pointed out in previous work [5, 20]. We compare the impact of such variations on BP and hybrid connectivity on Starlink.

We simulate the networks for 1 day. At every 15-min snapshot, we find shortest paths between the 5,000 city pairs. Fig. 2 shows the minimum (across snapshots) RTTs and range of RTTs seen over time for both BP and hybrid networks. The min. RTT, in Fig. 2(a), is strictly lower for the hybrid approach, as expected. Along the lines of prior work [21], the differences are small for most city-pairs. There are, however, substantial differences in the tail, the maximum difference being 57 ms. With exclusively BP connectivity, some paths see high latencies due to sub-optimal intermediate hops.

RTT variations reveal larger differences. Across time snapshots, we compute the max-minus-min RTT difference for each city-pair, and show the distribution across city-pairs in Fig. 2(b). The results show that latencies vary much more with BP. While with hybrid connectivity, the maximum range of RTTs across city-pairs over time is under 20 ms, with BP this range is as high as 100 ms. Thus, with hybrid connectivity, RTT stability improves by as much as 80%.

As Fig. 3 shows, with BP, the path between Maceió, Brazil and Durban, South Africa sees an inflation of 100 ms. This is because the density air traffic is much sparser over the south Atlantic than the north. Hence, the path often ends up using aircraft flying over the north Atlantic as intermediate hops. Note that this behavior, as discussed above, not only inflates the RTT of this path significantly, but also makes the heavily used paths over the north Atlantic (due

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[1] This is the highest density of GTs tested in prior work arguing that BP could achieve low latency [21].

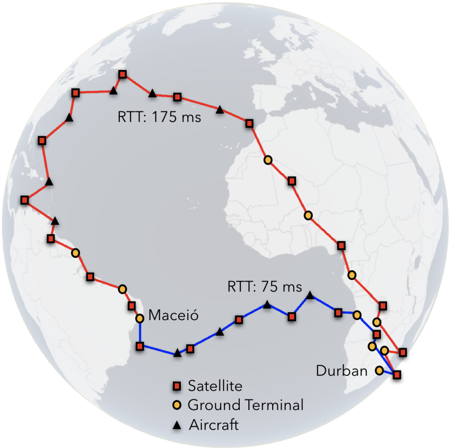

Fig. 3: *The path between Maceió, Brazil and Durban, SA changes a lot depending on aircraft availability.*

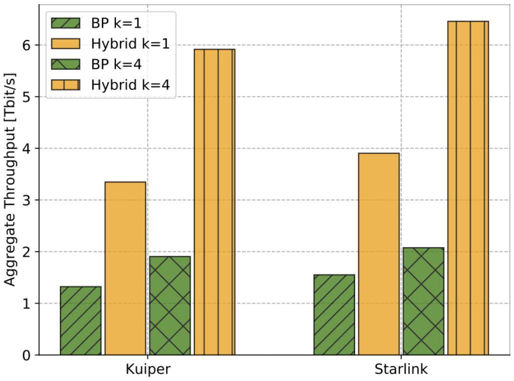

Fig. 4: *Aggregate throughput for* 5,000 *city pairs, with traffic sent along k edge-disjoint shortest paths per pair.*

to busy routes between north America and Europe) even more congested.

RTT variations result in varying quality of experience for latency-critical applications. For intance, past work [2, 10] has shown how QoE in gaming deteriorates not only with higher latency, but also with higher latency variations.

5 NETWORK-WIDE THROUGHPUT

The network's throughput will determine how much revenue the operator can obtain while offering low-congestion connectivity. We thus compare the aggregate throughput offered by LEO networks with BP-only connectivity and hybrid connectivity. With BP, all traffic needs to be routed via up/down radio links, using up more constrained capacity at these links, instead of using higher-capacity ISLs. For experiments in this section, we use floodns [28] which simulates routed flows in a network.

We evaluate the throughput of both approaches on Starlink and Kuiper. We first show results with each GT-satellite link having up- and down-link capacities of 20 Gbps, and ISLs of 100 Gbps, and later, with different ratios of these capacities. We use the same 5,000 city-pairs, and for each pair, we route over the k edge-disjoint shortest paths, with $k = 1$ and 4.

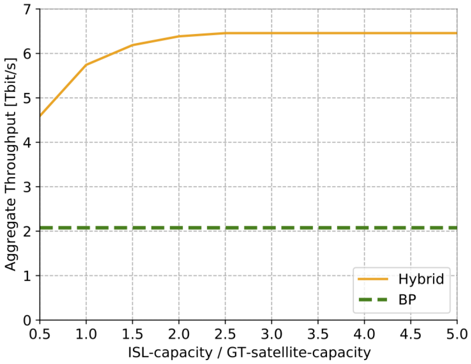

Fig. 5: *Starlink's throughput with varying ISL capacities.*

We find a max-min fair allocation of link capacities to flows in order to find out the aggregate throughput of the system. Traffic between each city-pair uses k sub-flows, each along one of the k edge-disjoint shortest paths. These sub-flows are treated independently by the simple max-min fair-share algorithm [38], which iteratively and greedily finds the most congested link in the network, and shares the bottleneck link capacity fairly among the competing flows. Note that because of edge-disjoint paths used for sub-flows, sub-flows of one flow do not compete with each other. The exploration of superior routing schemes is left to future work.

Fig. 4 shows the achieved aggregate throughput. For only shortest-path routing ($k = 1$), the hybrid approach achieves more than 2.5× higher throughput than BP for both Starlink and Kuiper, while with $k = 4$, this improvement is even larger, at least 3.1×. Also noteworthy, is that the improvement from using multiple paths, instead of just the shortest, is larger for the hybrid approach: 1.65× and 1.76× for Starlink and Kuiper, compared to 1.34× and 1.44× for BP.

We also examine the impact of the relative capacities of GT-satellite links and ISLs. We fix the GT-satellite link capacity at 20 Gbps, and vary ISL capacity from 0.5×–5× of this. Fig. 5 shows Starlink's throughput with $k = 4$. Even with an ISL capacity of 0.5× GT-satellite link capacity, the hybrid approach, with its greater path diversity, increases throughput by 2.2× compared to BP. With $k = 4$, the aggregate throughput does not improve for ISL capacities beyond 3×, this is an artefact of the routing scheme we use; with more efficient routing and traffic engineering, we can expect larger improvements overall, as well as a continued increase with higher capacity ISLs. A routing scheme that minimizes the maximum utilization, for example, can offer higher throughput, albeit at the cost of increased latency.

Besides the use of scarce GT-satellite capacity for transit in addition to only sourcing and sinking traffic, another reason BP fairs poorly on throughput is that at any time, it is unable to utilize a large fraction of the satellites for networking at all. For Starlink, we find that across a day, the number of satellites that are entirely disconnected from the rest of the network varies between 25.1% and 31.5% of all satellites.

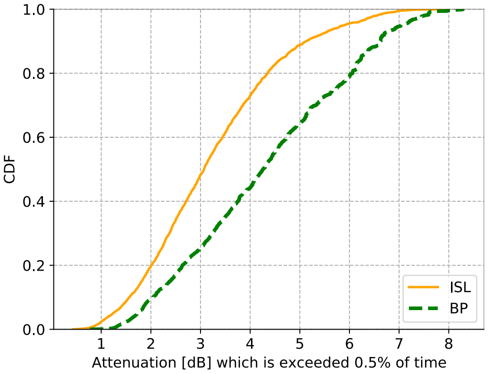

Fig. 6: *Attenuation is much higher for BP connectivity.*

6 RESILIENCE TO WEATHER

We use the *ITU-Rpy* [12] library to measure the attenuation for GT-satellite paths. The library implements ITU recommendations to model atmospheric attenuation due to rain, cloud, gaseous cover, and tropospheric scintillation in slant paths. Attenuation due to path loss is not considered, reflecting the assumption that the link design accounts for that.

For each of the 5,000 city pairs, we find the shortest paths using Dijkstra's algorithm. Next, we find the worst attenuation seen across all links in the path. Note that for BP paths, this is the worst attenuation seen across all links of the zig-zag path bouncing between the satellites and GTs. For paths consisting of ISLs, this value is either the first or last hop attenuation, whichever is worse. For calculating the atmospheric attenuation along BP and ISL paths, we use different up-link and down-link frequencies for Starlink (14.25 GHz and 11.7 GHz respectively; Ku-band) which are within the ranges specified in their FCC filing [43]. For the ISL paths, we exclude GTs as intermediate hops, in order to quantify the maximum improvements in attenuation possible with ISLs. If such intermediate hops through GTs are used, the attenuation of the path would be the worst link attenuation across all the up/down radio links used along the path. Note that this model and the experiments in this section (exclusively) assume that the signal for BP-paths uses error correction and regeneration at each GT; otherwise, the multiplicative impact of attenuation would be prohibitively high.

Attenuation across city-pairs: For each city-pair, we compute the 99.5^{th} percentile attenuation across time. This percentile corresponds to more than 7 minutes a day, and almost 2 days every year. We compute a distribution (across city-pairs) of this 99.5^{th} percentile attenuation. Fig. 6 shows that the attenuation is much higher for BP; the median with ISLs is more than 1 dB lower. This translates to an 11% reduction in received power. This number would be even higher for Ka-band communication (intended for use for larger terrestrial gateways), which is affected more by weather conditions [39]. Higher attenuation has to be dealt with by appropriate design for modulation and error correction schemes (MODCOD) [16], and trades off bandwidth for reliability.

Attenuation along one example path: For more insight into why BP suffers more from attenuation, we use an example end-end path between Delhi and Sydney[2]. We pick this city-pair because the path between them covers the tropical region, which experiences high annual precipitation [53]. Fig. 7 shows a random time, at which the BP-path uses 2 aircraft and 4 on-land GTs as intermediate hops. The heat-map depicts 99.5^{th} percentile attenuation across south-east Asia. Although both end-points, Delhi and Sydney, are in low attenuation areas, BP ends up using intermediate hops in regions with higher attenuation. In contrast, the ISL path avoids this entire high-attenuation region. This is evident in Fig. 8, which plots the attenuation along the path. At least 1% of the time, the BP attenuation is 5 dB (44% reduction in received power on the affected link) while ISL attenuation is 2.2 dB (32% reduction in received power on the affected link). Thus, ISL connectivity can reduce the attenuation due to weather by 39% (56% received power with BP versus 78% received power with ISL) at least 1% of the time.

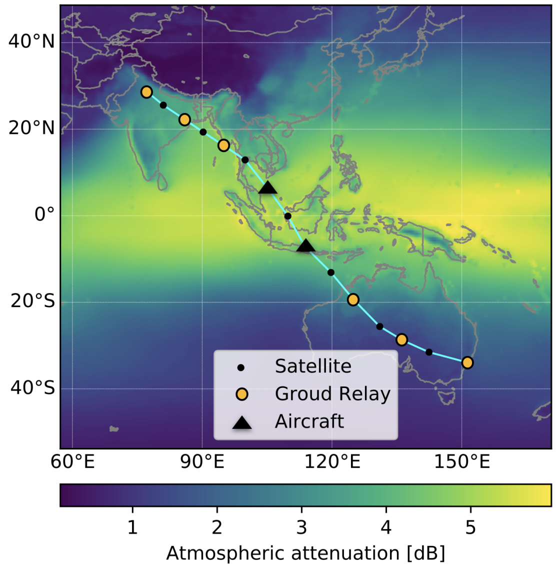

Fig. 7: *Delhi-Sydney path with 2 aircraft and 4 GTs.*

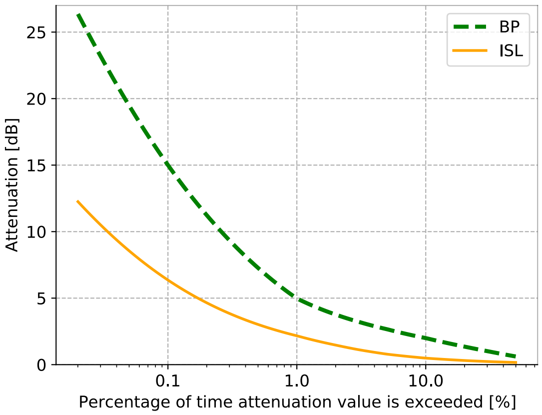

Fig. 8: *Impact of Attenuation on Delhi-Sydney path.*

7 OTHER BENEFITS OF ISLS

We quantitatively compared BP and ISL connectivity across three network properties, showing that constellations with ISLs would

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[2] Delhi-Sydney is not among the 5,000 randomly picked city-pairs.

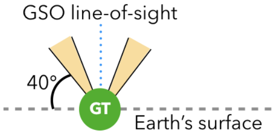

Fig. 9: *GSO arc-avoidance: at the Equator, only satellites in the small shaded regions of elevation are reachable.*

have a substantial edge on latency, throughput, and reliability. However, there are several other aspects where ISLs offer improvements, which we have not yet quantified.

Crossing unfriendly territory: BP connectivity between certain sources and destinations is bound to require GTs in countries and regions that an operator would like to avoid either because the topography is challenging for construction and maintenance, or for political reasons. ISLs side-step this issue, crossing such unfriendly territory entirely in space.

Spectrum efficiency: For Ka- or Ku-band radio spectrum operation, companies need licenses from bodies like FCC and ITU. The spectrum is shared among multiple interested parties. In contrast, thanks to the narrow beams and negligible interference issues, inter-satellite laser connectivity is unlicensed [54]. Thus, with ISLs, interference and spectrum contention only arise at the sources/sinks of data.

GSO arc-avoidance: GSO satellites fly above the Equator, and operate in the same frequency bands sought for LEO communication. Thus, LEO Satellites, when crossing the lower latitudes near the Equator, must avoid interference with GSO satellites. Both Starlink and Kuiper explicitly note in FCC filings [31, 43] that they would address this by only allowing up/down-links with at least a minimum angular separation from the bore-sight of a GSO base station. For Starlink this angle of separation is 22°, while Kuiper mentions that this angle would gradually increase from 12° to 18° over deployment. The consequent reduction in the field-of-view from a GT is illustrated in Fig. 9 for Starlink with the 40° minimum angle of elevation planned for its full deployment.

With BP, any traffic between the northern and southern hemispheres would use GTs near the Equator. Thus, the impact of the reduced GT field-of-view will be much higher on BP than on ISL connectivity, as for the latter, only sources and destinations in the Equatorial region will be affected.

8 WHEN ISLS ARE NOT ENOUGH

While ISLs are a highly valuable enhancement for a constellation, there may be room to creatively augment ISL-enabled constellations with not just BP, but also terrestrial fiber. We briefly pose two ideas in this direction, with a quantitative evaluation left to future work.

BP augmentation: As noted in §2, the largest planned constellations seek to deploy multiple *shells*, each shell comprising satellites at one altitude and inclination. Cross-shell ISL connectivity is non-trivial: because of the different satellite trajectories across shells, such links will not be as long-lived as those within a shell, and thus require frequent teardown and setup [6]. In fact, Starlink's filings [44] only indicate 4 ISLs per satellite, which are likely to all be used within one shell, thus leaving no free ISLs for cross-shell connectivity. Of course, being able to use paths through multiple shells would increase path diversity, thus decreasing latency and increasing network throughput. In the absence of cross-shell ISLs, BP connections could be used sparingly as "transition points" between shells. Fig. 10 shows one such path between Brisbane and Tokyo which achieves lower latency by using an intermediate BP connection to switch traffic between 2 shells operating at inclinations of 53° and 90°.

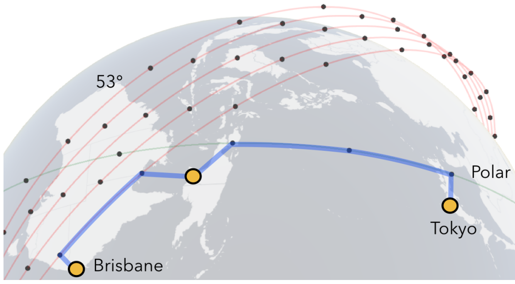

Fig. 10: *Brisbane-Tokyo path using a GT to switch between* 53° *inclined and Polar orbits to achieve lower latency.*

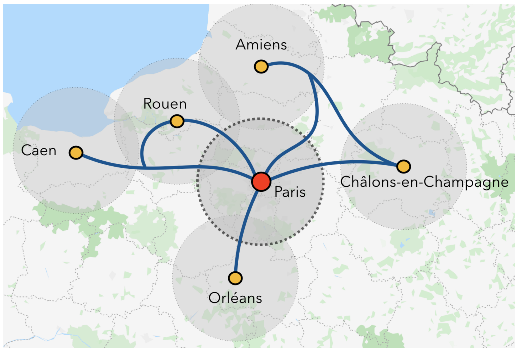

Fig. 11: *Increased satellite-connectivity for Paris, by leveraging GTs located in nearby cities over high-bandwidth fiber.*

Fiber augmentation: The ground-satellite connectivity at large metros like New York, Delhi, Paris, and London, could easily be congested by high demand. However, each of these metros has several smaller cities nearby, with good terrestrial fiber connectivity to the metro. These smaller cities could potentially augment the metros' ground-satellite connectivity by having some of the metro's traffic transit to them through fiber, and benefiting from the smaller cities' satellite connectivity. Such "distributed GTs" could thus allow more efficient use of contended ground-satellite spectrum. Fig. 11 shows the potential for this using the rough existing fiber connectivity between Paris and 5 nearby cities along with the (approximate) cone of satellite visibility for each city.

9 CONCLUSION

If the newly proposed constellations fail to incorporate ISL connectivity, they will still provide valuable connectivity improvements, especially in under-served regions, using bent-pipe connectivity. However, this would be a compromise on several counts, resulting in higher and more variable latencies, lower network throughput, lower resilience to weather, the necessity of ground terminals in unfriendly locations, poorer spectrum efficiency, and limited cross-Equatorial connectivity. However, there are also surprising opportunities for BP connectivity, and even terrestrial fiber, to augment an ISL-enabled constellation to improve its performance.

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