A First Look at Starlink's Impact on Internet Equity

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Abstract

Emerging low-earth orbiting (LEO) satellite companies seek to "remove the barriers of connectivity" by providing "fast, affordable broadband to unserved and underserved communities." Still, we lack quantitative analysis of how well existing LEO deployments improve access equity and help close this broadband gap. We take the first step to assess the effectiveness of the largest LEO provider, Starlink, in achieving the connectivity goals of various government programs and initiatives focused on improving Internet access. We use measurements from M-Lab's NDT speed test dataset to measure improvements across two dimensions: performance (how effective is Starlink at achieving performance requirements of existing policies?) and coverage (how does Starlink's coverage address the areas of concern of existing policies?). We observe that as currently deployed, a majority of samples do not meet the performance goals established by the US and EU. On the note of coverage, we find that Starlink is unavailable in low and lower-middle income countries. However, using simulations for what-if analysis, we discover that the use of inter-satellite links (ISLs) can greatly increase coverage by almost 7.4x in areas like Africa. To the best of our knowledge, this paper is the first to explore Starlink through the lens of global policy.

1 Introduction

Closing the broadband gap is an important challenge—one with significant impacts on global welfare. A study conducted by the World Bank and GSMA revealed that the proportion of households in Nigeria below the extreme poverty line dropped by 7 percentage points (corresponding to 2.5 million people) after only two years of gaining broadband coverage [19]. In another study on the impact of Internet technologies on well-being, GSMA reported that mobile phone ownership with Internet access corresponds to a 1.27-point and 1.19-point (out of 10) increase in self-reported quality of life for women and men respectively [25]. Despite the importance of Internet access, much of the world remains unconnected. In fact, only 44% of people in developing countries use the Internet, in comparison to 87% in developed countries [44]. While numerous factors prevent people from accessing the Internet, including laws, education, and affordability, connecting everyone to the Internet is still a physically challenging problem. These challenges include geographic barriers, political instability, natural disasters, and the cost of reaching remote populations. As a result, directly installing fiber cables is simply unfeasible in many locations. Recently, several governments have started exploring how LEO technology can bypass physical barriers by either funding private LEO satellite companies through broadband connectivity programs like BEAD in the US or deploying their own satellite networks such as IRIS^2 in the EU. Hence, we want to understand how Starlink is able to meet the criteria of these broadband subsidy programs and how its deployment covers targeted areas for EU and Chinese satellite initiatives.

As previously stated, the broadband gap is caused by many factors including cost (some people simply cannot afford it), education (some people don't know how to use it), culture (some people are not allowed to use it), and physical limitations (some people simply cannot reach the Internet). We focus on the physical challenges that prevent people from reaching the Internet and evaluate low-earth orbiting (LEO) satellite technology as a solution to bridging this connectivity gap. Today, LEO satellite broadband is a promising direction for closing the physical aspect of the broadband gap, as it is able to overcome many of the infrastructural obstacles of terrestrial deployment. LEO networks are particularly exciting because remote users don't need nearby cell towers or fiber cables for Internet access. Instead, remote users can directly transmit packets to one of thousands of satellites orbiting at low altitudes in space, bypassing the physical challenges of building out the terrestrial infrastructure to connect these regions. Today, LEO network providers make several claims regarding their ability to close the connectivity gap, and several governments are exploring how LEO can help achieve their connectivity goals. We categorize these initiatives into two buckets: (1) government subsidies to support the expansion of broadband offerings, which might reasonably be offered to LEO network providers if they meet certain criteria, and (2) government deployments of national

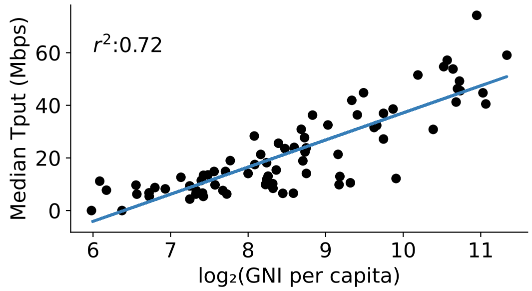


Figure 1: Median of 75th percentile bandwidth per country collected from CloudFlare Radar dataset and gross national income (GNI) per capita.

LEO networks to reach under served regions. We evaluate the key question: *How well is Starlink able to achieve the goals of such policies in regards to both performance and coverage?* We break this question down into two parts.

(1) How effective is Starlink at achieving performance requirements of existing policies? When Starlink falls short, is there any correlation between performance and wealth?
(2) How does Starlink's coverage address the areas of concern, such as low income regions, of existing policies and initiatives?

In both parts, we specifically measure income bias, as initiatives are often designed to address the lack of infrastructure that is most prevalent in regions where providers have low economic incentives. In fact, in preliminary analysis on terrestrial networks using the CloudFlare Radar Dataset[23], we find a strong correlation in Figure 1 between median bandwidth and gross national income. This corroborates the hypothesis that higher income regions generally have better performance.

Understanding these questions from a global perspective is difficult for a variety of reasons. While we want a global view of Starlink and non-Starlink deployments for comparison, we do not have access to a globally deployed testbed for Starlink, nor do we have access to the network itself.

Hence, we rely on Starlink user speed tests from Google's M-Lab NDT dataset. We link this data with US Census and World Bank data to evaluate wealth bias in Starlink performance. For the second question of coverage, we look at the state of deployments today and simulated deployments given the use of inter-satellite links (ISLs) a new technology that should improve Internet access. We discuss this further in § 4. Although in pieces these datasets cannot answer the questions outlined above, by integrating them with one another, we can draw a better picture for the state of Starlink performance and access in regards to global policy.

With regard to performance we find: Starlink performance as deployed does not consistently meet the performance goals of the US and EU, where only 25% and 14% of NDT samples meet the 100 Mbps threshold in these countries respectively. We also find that while performance quality does not appear to be correlated with wealth within country borders, when zooming out to a global view, we find some correlation between performance and wealth. This correlation, however, is weakened due to the unique routing properties of LEO networks that enable less targeted countries to still benefit from the deployments of better-connected regions.

With regard to coverage we find: Starlink availability is still correlated with income, as it is more available in higher income countries. Currently, Starlink is available in only 38.5% and 37.3% of low and lower-middle income countries. We find, however, that up and coming satellite initiatives such as IRIS[2] and Thousand Sails (Qianfan) have the potential to increase Internet access in regions where Starlink is not currently deployed.

Looking towards ISL performance we find: Inter-satellite links (ISLs) have the potential to greatly improve coverage, particularly in lower income countries. We find that ISLs can increase coverage by 6.33x, 4.90x, 2.33x, and 1.37x in low, lower-middle, upper-middle, and high income countries.

Several works have conducted similar wide-scale analysis of Starlink performance [21, 30, 31, 34, 37, 40]. Some have even directly studied Starlink's ability to meet BEAD performance goals [17, 36]. However, as previously mentioned, this study (to the best of our knowledge) is the first to analyze Starlink performance through the lens of global policy. The rest of the paper is organized as follows. In § 2, we provide necessary background on Starlink architecture to give context to its unique properties that could help expand Internet access, followed by a description of methodologies used in this study. In § 3, we discuss the effectiveness of Starlink in achieving performance goals in the US, EU, Australia, and Nigeria. Finally, we discuss Starlink coverage and how it fits into existing initiatives in § 4.

2 Background

In this section, we provide background information on Starlink architecture, its potential to improve Internet access, and methodologies used in our analysis.

2.1 Starlink Architecture

Before digging into the analysis, it is important to detail Starlink architecture, as it has important implications for reachability and performance that are different than terrestrial networks.

Architecture Overview: There are several main components of a Starlink network: user terminals, satellites, and gateways. The user terminals are owned by end users. These

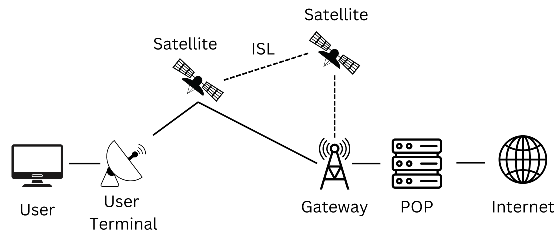


Figure 2: Typical routing path of Starlink network.

devices enable Starlink customers to communicate with satellites in space. Starlink's constellation is made up of thousands of satellites that orbit at roughly 500km above the Earth's surface. Starlink gateways bridge the satellites and terrestrial Internet, as packets are transmitted from space down to a terrestrial gateway. The typical path of a packet is depicted in Figure 2, where data from the client (user terminal) goes up to the satellite, down to a gateway, and then connects to the regular terrestrial Internet. This unique routing architecture has two important implications. The first is that *both* space and ground infrastructure have important roles in improving reachability. If not enough satellites are overhead, even if everyone in the world has access to a user terminal, there may be regions where satellites may simply be out of range. Second, even with perfect satellite coverage, with sparse ground infrastructure, users may not have a gateway that is reachable within one satellite. Unless ISLs are enabled in these regions, users without gateways in range cannot reach the Internet.

Example walkthrough: Let's step through a concrete example for a user downloading a webpage. First, the user must send a GET request to the server that hosts the webpage. The request originates from the user's machine and is locally routed to the user terminal. The terminal then beams the data up to some satellite in space. Once the request is in space, the satellite will either (a) find a nearby gateway and transmit it back to earth, or in the case where a gateway is unreachable (b) transmit the packet to another satellite via ISL. Once the packet is transmitted to the gateway, it can be routed through the public Internet to the server that hosts the webpage. That server will then send back the data for the webpage, and it will traverse the same path in reverse, going from the gateway to a satellite, down to the user terminal, and finally back to the user's machine.

Inter-satellite links (ISLs): Inter-satellite links are particularly relevant to our discussion, as they are a new technology that has the potential to greatly improve Internet coverage. Inter-satellite links are network links that enable satellites in space to send data between one another. These links are powered by long range lasers for data transmission. These inter-satellite links are especially powerful in regions with sparse gateway deployment, such as areas without business incentives in remote or lower income regions. If a user does not have a gateway reachable within one satellite hop, ISLs can forward that user's data to a satellite nearby a gateway, providing connectivity to areas without infrastructure. While this technology is very powerful in improving access, ISLs are still in development, as not all Starlink satellites are outfitted with laser link technology.

2.2 Potential for LEO to Expand Access

In this section, we discuss three key points that set LEO apart from terrestrial infrastructure and why such qualities have promise for increasing broadband access.

Lightweight last-mile deployment: In a terrestrial network, providers must install fiber cables to bring connectivity to a region. Installing fiber cables in rugged terrain (*e.g.* mountains, oceans, etc.) or very remote regions can be very costly. LEO can bypass these challenges, as users simply set up a terminal to connect to Starlink. Hence, LEO provides a lightweight solution for bringing connectivity to remote and rugged terrain.

Resilient to physical and terrestrial challenges: Ground infrastructure is often prone to weather damage or destruction due to natural disasters. Ground infrastructure like cables and towers can even be subject to theft or war damage. These threats can often cause outages during times where Internet connectivity is needed most. Starlink, given most of the infrastructure is deployed in space, is not as susceptible to these threats. As an example, when many terrestrial networks experienced outages during Hurricane Helene, Starlink was deployed to bring Internet access to affected regions[46].

Neighbor effect: Since ground infrastructure has a limited radius of service, the cost of building infrastructure must be justified based on a relatively small number of users per cable or router. Thus, businesses often have low economic incentive to provide service in lower income regions where infrastructure installment can be costly, but few can afford the service. As a result, low income regions are often deprioritized and subject to low speeds or lack connectivity altogether. On the other hand, the return on investment for satellite deployment is shared across all areas under the satellite's footprint, which is very large. Hence, any user which is within a satellite's radius or on a global orbital of dense and wealthy users will have a mode of access. As a result, lower income countries can still reap the benefits of infrastructure deployed in their higher income neighbors.

2.3 Technical Methodology

We use public performance datasets including M-Lab's NDT service [1], Cloudflare Radar [23], and Ookla speed test data [2]. For socioeconomic data, we pull from World Bank income level classification data [3], the World Bank gross national income (GNI) data [49], and US Census data [4].

We use M-Lab's NDT dataset for download speed test data collected during a 6 month period between May 2024 and October 2024. We further filter this data to samples that use the same congestion control algorithm, BBR, to limit variance. We divide the dataset into non-Starlink and Starlink samples by filtering using AS number and observe 298 unique Starlink vantage points and over 200k unique non-Starlink vantage points. We annotate each vantage point with its World Bank economic classification status [3].

Since direct instrumentation is not possible, we extend an existing LEO network simulator, Hypatia [32], to measure the effect of ISLs on increasing coverage. We load this simulator with a list of gateways from a crowd-sourced dataset [16] and define the satellite orbits based on Starlink's FCC filings [10]. To determine whether a location has coverage, we use the simulator to identify the number of gateways that are reachable within one satellite hop or two satellite hops (using an ISL) for test users.

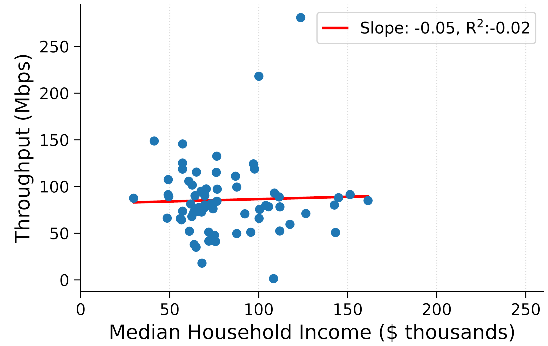
3 Performance

In this section, we tackle two key questions. (1) How effective is Starlink at achieving performanace requirements of government policies in the US, EU, Australia, and Nigeria? (2) Is there correlation between throughput and income? To answer these questions, we look at country-level policies for the United States, European Union, Australia, and Nigeria. We use Starlink speed test data from M-Lab's Network Diagnostic Tool (NDT) speed test dataset to understand how well Starlink meets the requirements set out by these national policies and initiatives for improving broadband access. For the United States and European Union, we additionally analyze the correlation between income and throughput, however, we do not have the data to enable this analysis in Australia and Nigeria.

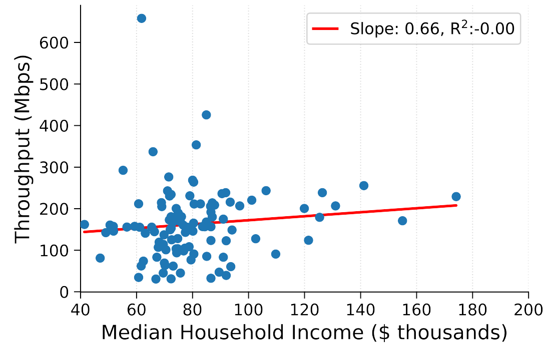
3.1 Country-level Policies

In this section, we zoom into the country-level benchmarks and policies established by the United States, European Union, Australia, and Nigeria.

BEAD in the United States: The Broadband Equity, Access, and Deployment (BEAD) program is a $42.45 billion program administered by the National Telecommunications and Information Administration for investing in network infrastructure and broadband deployment across the country [5]. The program is said to prioritize connecting unserved and underserved locations. Unserved locations are defined by the FCC to be locations with no Internet access or speeds slower than 25 Mbps download and 3 Mbps upload, while underserved locations are locations with broadband speeds



(a) Income by zipcode



(b) Income by county

Figure 3: Average throughput at each distinct Starlink NDT speed test location against average zipcode and county income.

slower than 100 Mbps download and 20 Mbps upload. This analysis is timely given the U.S. Commerce Department's recent considerations to changing the BEAD rules, which currently prioritize fiber providers [26]. Such changes could potentially enable Starlink to tap into BEAD funding. The BEAD program states that grantees must deliver "consistent and reliable download speeds of at least 100 Mbps and upload speeds of at least 20 Mbps" [47]. Thus, we measure the average throughput of Starlink samples to determine whether Starlink's throughput is consistently and reliably meeting the 100 Mbps benchmark.

With 85 NDT samples in the US, we find that only 24.7% of samples have a download speed above 100 Mbps, 61.1% of samples above 75 Mbps, and 85.9% of samples above 50 Mbps. Using the language of the FCC, roughly 75% of Starlink NDT samples in the US exhibit unserved or underserved speeds. We do find, however, that only 4.7% of samples have a download speed less than 25 Mbps. *This data reveals that Starlink meets the BEAD download benchmarks in only 25% of samples observed in our dataset.*

Correlation between income and throughput in the US: We know from prior work that terrestrial networks provide

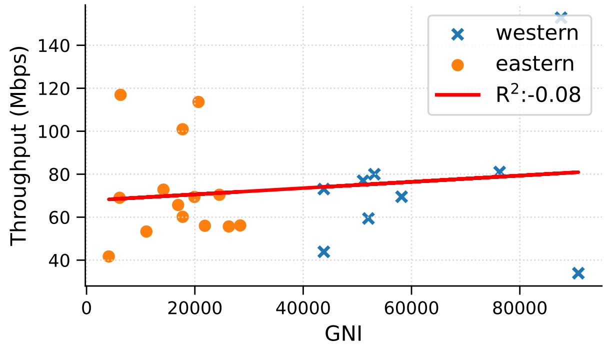


Figure 4: Average throughput at each distinct Starlink NDT speed test location against average country income.

higher performance towards higher income zipcodes. To understand this relationship for Starlink, we used the NDT download throughput measurements along with US zip code and county income data provided by the US Census. As evidenced by Figure 3, we find that within the US, there is no correlation between Starlink download throughput and income. We hypothesize that this lack of correlation can be attributed to the large service regions provided by the satellites and gateways, as well as the expansive network of gateways in North America.

CEBF in the EU: Similar to BEAD, the EU has the Connecting Europe Broadband Fund (CEBF) to provide "equity and quasi-equity to smaller-scale, higher-risk projects, which do not have sufficient access to financing, in (under-served) suburban and rural areas" [6]. Projects that utilize this fund must contribute to Europe's connectivity objectives, which include 100 Mbps networks reaching all European households by 2025 [11]. Hence, we measure the average throughput of Starlink users to evaluate whether Starlink's performance can help contribute to EU-wide connectivity goals and gain support from the CEBF.

Of the samples located in the EU, we find that only 17.4% of them are able to meet this objective of download throughput over 100 Mbps, 30.4% are above 75 Mbps, and 89.0% above 50 Mbps.

Correlation between income and throughput in the EU: When comparing the correlation between income and throughput across the EU, we use the average income level according to country. Based on the scatter plot in Figure 4, we find that there is no correlation in performance according to country income level, as evidenced by an R^2 of -0.08 in Figure 4. Given that western European countries have a higher GNI than those in the east, we compare throughput across eastern vs. western Europe. While we do see that most of western Europe has higher average incomes, we find that this does not translate to a trend in higher throughput for users in western Europe.

Legislated SIPs in Australia: In Australia, statutory infrastructure providers (SIPs) are responsible for supplying wholesale broadband for retailers to then sell to customers across the continent. These SIPs are legally mandated to enable retail providers to supply broadband services with peak download speeds of at least 25 Mbps [18]. While Starlink is currently not an SIP in Australia, people are beginning to question (1) whether the government should continue subsidizing wholesale SIPs given that Starlink is already available and (2) whether Starlink should be eligible to become an SIP itself [24]. Although we cannot directly answer these questions since they are fundamentally political in nature, they lead us to the underlying technical question: Does Starlink meet the technical requirements of SIPs?

We find that 98.4% of Starlink samples in Australia meet the 25 Mbps requirement. Not only does Starlink meet the required throughput for SIPs in a majority of samples today, but in light of recent discussions around increasing the threshold to 100 Mbps [27], Starlink is actually also able to meet proposed future thresholds. Using the new benchmark of 100 Mbps, we find that Starlink meets this peak threshold in 96.9% of samples.

Although this number seems promising when taking the max throughput (since the legislation specifies *peak* download speeds), this number decreases significantly to 42.2% when looking at the average throughput from each location like we do in the US and EU. Thus, we find high variance in the throughput experienced by Starlink users, as we observe a significant difference in average case and peak throughput. This suggests that using peak throughput may be a poor match for LEO's highly dynamic nature and reveals an opportunity to refine policy specifications.

Nigeria's Broadband Plan for 2020-2025: The Federal Ministry of Communications and Digital Economy released the Nigerian National Broadband Plan 2020-2025 [28]. This plan outlines goals for broadband development, particularly delivering data download speeds across Nigeria with a minimum of 25 Mbps in urban areas and 10 Mbps in rural areas. While we find only 4 unique Starlink locations in Nigeria, we find that all 4 samples deliver throughput over 25 Mbps. These results suggest that Starlink is an effective solution in achieving the goals of Nigeria's National Broadband Plan.

3.2 Global Performance

While performance appears to be uncorrelated with wealth within entity borders, as we've seen in the US and EU, in this section, we zoom out to the global scale to analyze whether the same is true in the broader case. We find that while there exists some correlation between income and throughput, we

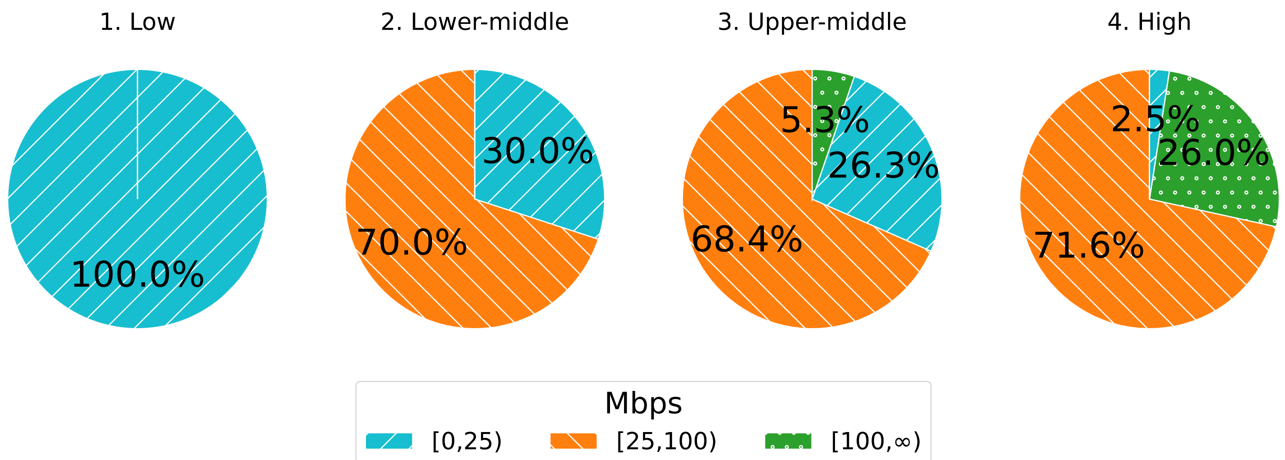


Figure 5: Average throughput at each distinct Starlink NDT speed test location segemented by economic classification.

observe some areas that exhibit the opposite of income bias thanks to the unique service radius of Starlink infrastructure. We describe this neighbor effect in § 3.2.

Correlation between income and throughput at country level: We break down the download throughput of each economic category in Figure 5. From this chart, we find that there is a correlation between economic classification and download throughput. We find that in low-income countries, 100% of samples have throughput that would be considered "unserved" according to the US FCC, or less than 25 Mbps for download throughput. We also find that speeds over 100 Mbps are only found in upper-middle and high income countries, with 5.3% and 26% of samples in upper-middle and high income countries meeting this threshold respectively.

This trend becomes more apparent when we group samples by country and plot the average throughput of all samples in a country against their average gross national income in Figure 6. In this figure, we notice a log-linear trend between a country's average download throughput and gross national income with an $R^2 = 0.39$ with outliers and $R^2 = 0.65$ without. While this does not indicate a strongly correlated relationship, it does suggest that Starlink performs better in wealthier countries. Still, we find that there are strong outliers where Starlink throughput is much higher in countries that we'd expect to do poorly based on income. This signifies a deviation from our prior assumptions about lower income countries being left behind.

Neighbor Effect: Despite a clear correlation between wealth and throughput, we find several outliers above the regression line, suggesting that some countries perform far better than expected at their income level. We call this the neighbor effect. We highlight these outliers above as points of interest because they demonstrate Starlink's effectiveness

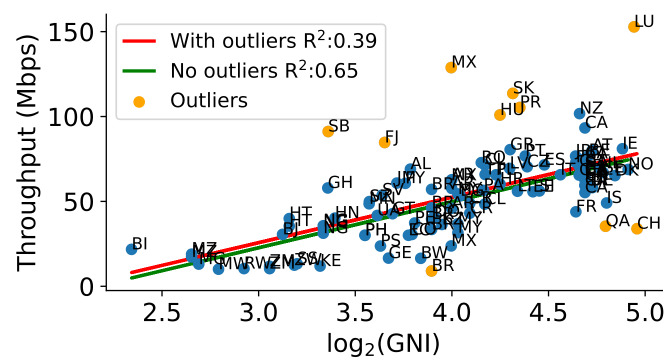


Figure 6: Average throughput at each distinct Starlink NDT speed test location against location's average county income.

at reaching places that are typically not the most profitable. This neighbor effect allows countries proximate to wealthier regions to piggyback off of the infrastructure that is placed to target denser communities. We see this phenomenon in the Solomon Islands and Fiji, which are outliers far above the regression line. In these cases, LEO technology enables users in these remote islands to benefit from the well-connected infrastructure in Australia. Since the service radius of satellites is large, users can transmit packets directly up to space and down to Sydney, Australia rather than traversing sparse local infrastructure and long sub-sea cables to reach an Internet exchange point. This is important on the note of equity because it reveals that Starlink's large service radius enables LEO network providers to reach people that aren't targeted (even when unintentional). While the data suggests that Starlink performance is correlated with wealth, we find that LEO networks have unique properties that enable less-targeted,

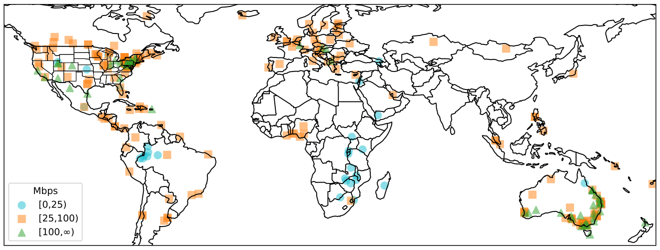


Figure 7: Average throughput at each distinct location of Starlink NDT speed tests.

lower income regions to benefit from infrastructure deployed to profit from wealthier regions.

4 Coverage

In this section, we explore the key question: How does Starlink's coverage address the target areas of existing policies or initiatives? We view coverage through the ITU/UNESCO Broadband Commission's stated goal of achieving 65% Internet user penetration in all low and middle income countries [7]. Through this view, we first observe that current and planned Starlink deployments are unlikely to reach most countries in these categories. However, we find that with the help of ISLs, coverage can greatly improve in these countries. We also find hope in the intersection between Starlink's current deployment and proposed government-backed LEO networks in the EU and China. In the first part of this section, we look at coverage from the perspective of Starlink alone, followed by analysis of alternative government-backed LEO networks.

4.1 Starlink Coverage

In this section, we dive into how Starlink's coverage is supporting the Broadband Commission's goals of increasing connectivity in low income countries. We end this section with exploring how Starlink's ISL technology can help improve connectivity, specifically in low income countries.

What is Starlink's coverage in low and middle income countries? As previously stated, one of the broadband advocacy targets of the Broadband Commission is to increase penetration to 65% in 100% of low and middle income countries.

We turn to Starlink's availability data to see where service is available for low and middle income countries. As seen in Figure 8, Starlink is only available in less than 40% of low and lower-middle income countries, with availability at 49.1% and 61.2% in upper-middle and high income countries. While planned deployments can help reach these goals, we are aware that many challenges can pose as blockers to deployment, including non-infrastructure challenges like regulatory approval and politics. Historically, we observed that of the 33 countries indicated as "Planned" in 2024, 14 of them were able to meet their target launch dates. This data suggests that even if Starlink could provide Internet access in 100% of the countries it is available, this coverage is only available in a fraction of the Broadband Commission's targeted countries.

To what extent is Starlink currently expanding connectivity? In this section, we explore to what extent is Starlink currently expanding connectivity by addressing the question: Is Starlink being used in regions where alternate connectivity forms do not exist? To answer this question, we analyze whether Starlink is often being used as the sole provider in super remote regions. Two challenges of this analysis are determining (1) where Starlink users are located and (2) where alternative connectivity options are available. To answer these questions, we use the locations of Starlink NDT speed tests and Ookla speed test datasets. We acknowledge that the use of speed test locations introduces sampling bias [33] and offer this analysis as a qualitative study to develop an initial understanding of Starlink's main use cases.

Identifying areas with Starlink connectivity: Given the security concerns of geolocating Starlink users, no publicly available dataset reveals this ground truth. The closest dataset [45] provides information at too coarse a granularity to be useful for our analysis[1]. Given the lack of public data sources, we approximate the location of Starlink users using the coordinates in the NDT sample dataset, geolocated by M-Lab using MaxMind [39].

Our approach annotates a location as including Starlink if our NDT dataset contains a sample from a Starlink user at said location. To address known limitations of the geolocation granularity, we expand our analysis to M-Lab's recommended level [8], *i.e.*, county level, by defining the Starlink user's location to be a 25km radius around the provided coordinates. We opt for a 25km radius ($\sim 2000km^2$), which is slightly larger than the US median county size of $\sim 1600km^2$ [22], to be conservative.

Identifying areas with alternative connectivity: We create a new method, rather than relying on Internet provider coverage maps, because of known bias [35], *i.e.*, they significantly overestimate coverage. Our approach approximates (and underestimates) non-Starlink coverage using Ookla's Q42024

[1][45] aggregates the data into 1 degree longitude by 1 degree latitude bins, removing bins with fewer than 10 samples, which eliminates samples in remote areas

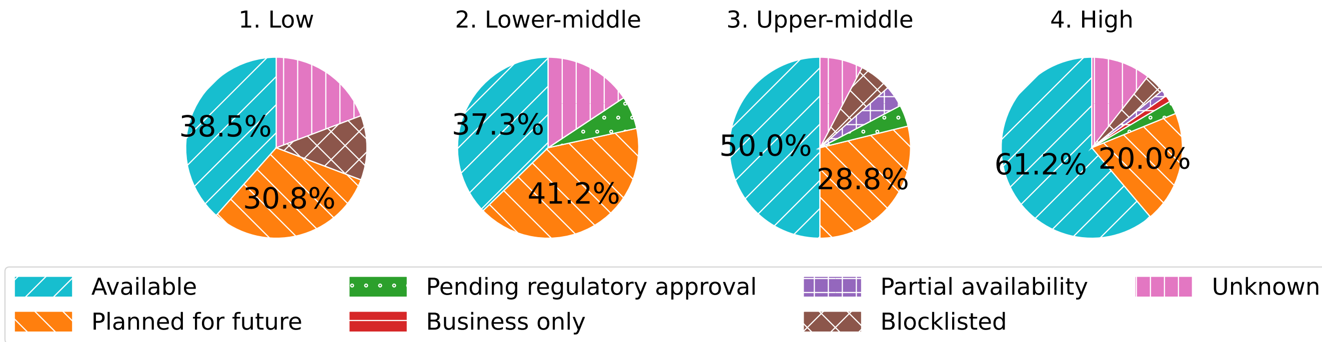


Figure 8: Reasons for Starlink availability in regions according to income classification.

speed test data, which details the number of speed tests taken per $0.37km^2$ tile. We state that the $0.37km^2$ tile has non-Starlink coverage if there exists a 'mobile' speed test in that tile. We use 'mobile' tests as opposed to 'fixed' since Ookla groups Starlink samples into the 'fixed' dataset. For each Starlink datapoint, we determine whether it is within 25km of a $0.37km^2$ Ookla tile with coverage.

Results: Of the 298 unique Starlink user locations in our dataset, 96.6% of them fall in regions with alternative connectivity options, despite our model of non-Starlink coverage providing a lower bound on where alternative connectivity exists. This data corroborates the hypothesis that Starlink is mainly being used for last mile or better connectivity rather than as a sole provider for very remote regions. Hence, we do not have strong evidence that LEO is greatly improving coverage in regions where alternative forms of connectivity do not exist.

How can Starlink improve coverage in these countries with ISLs? While we find Starlink has limited availability in low and middle income countries and find little evidence that Starlink is vastly improving coverage, our simulations reveal that Starlink's new technology, inter-satellite links, can have significant impacts on increasing coverage, particularly in these lower income regions. To quantify the impact of inter-satellite links on coverage, we use a LEO simulator, Hypatia, loaded with Starlink's architecture. We leave the details of the simulator to Appendix A. Using the simulator, we tested a number of evenly spaced users by tiling the globe into 5 degree steps of latitude and longitude to achieve appropriate global coverage. We place a test user in each tile to see whether they are one satellite or two satellite hops (using an ISL) away from a gateway[2]. We determine that land is "covered" if a gateway is reachable within one or two satellite hops.

We find that ISLs have a biased effect on lower income countries highlighted in Figure 9. Utilizing ISLs reveals an enormous benefit for lower income countries. When enabling two satellite hops, land coverage increases 6.33x, 4.9x, 2.33x, and 1.37x for low, lower-middle, upper-middle, and high income countries respectively. This is likely due to gateway deployment being more sparse in these regions, so users must rely on ISLs to gain connectivity to reach a downlink from space. These results highlight Starlink's promise in boosting coverage in lower income countries through the use of ISLs. One important aspect to note in Figure 9 is that there are several mechanisms beyond just infrastructure that prevent users from reaching Starlink. While ISLs have the potential to expand Starlink in many low income countries, Starlink must first gain regulatory approval to become available to customers in many countries. Hence, we acknowledge that

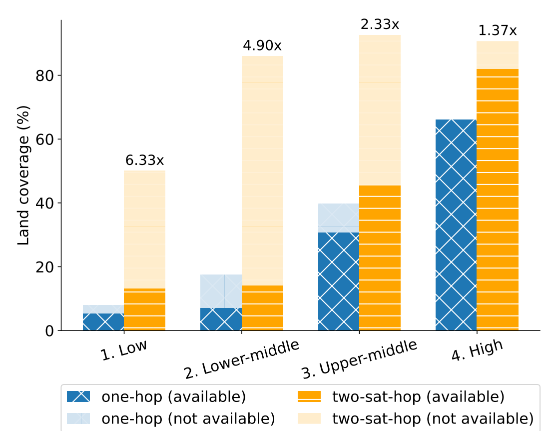
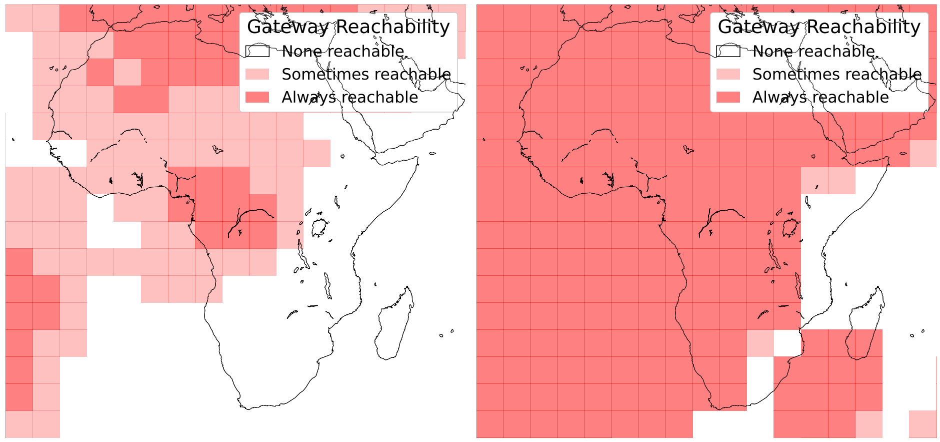


Figure 9: Impact of ISLs on coverage of countries where 'available' denotes points where Starlink has launched.

[2]While ISLs are technically capable of connecting a chain of several satellites, we offer this preliminary analysis using only one single ISL to simplify our analysis.



(a) One satellite hop (No ISLs) **(b) Two satellite hops (Single ISL)**

Figure 10: Simulated Starlink African coverage map.[3]

there are several factors beyond infrastructure that prevent Starlink from being accessible to more users.

4.2 Coverage of Government-Funded LEO Projects

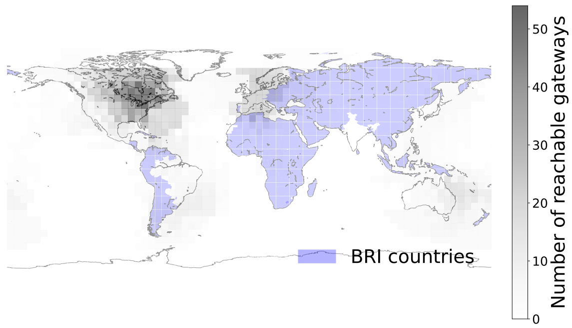
In this section, we project forward and explore how LEO networks from the EU and China may contribute to global coverage, particularly in lower income countries. While the EU has explicitly stated its areas of interest, we use prior Chinese government initiatives to predict the coverage of China's Starlink competitor, Thousand Sails.

IRIS^2 in the EU: The EU has launched plans for their own LEO satellite network to provide secure connectivity across the EU. One of the specific goals outlined by this project is to "put an end to dead zones in Europe as well as the whole of Africa using the constellation's North-South orbits"[9]. However, when looking at Starlink availability in prior sections, we have found that much of Africa remains uncovered. Based on the 2025 availability data, Starlink has only launched in 20/57 (3̃5%) of African countries. In order to understand Starlink's potential impact in these countries, particularly with inter-satellite link technology, we use the same custom simulator previously mentioned. We leave the details of the simulator to Appendix A.[3]

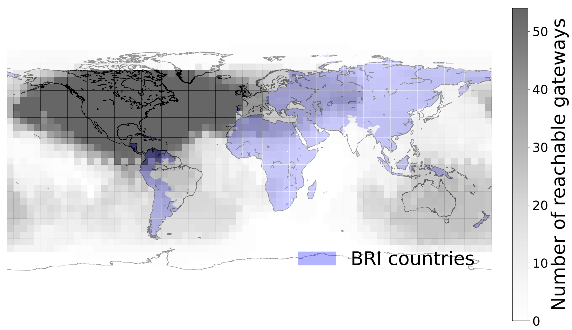
Using the Hypatia simulator, we consider a region to be "connected" if a user in that given location is able to reach a gateway using one or two satellite hops. We define three classes of connectivity: 'None reachable' (when no gateways are reachable from that location at all), 'Sometimes reachable' (when a gateway is reachable but based on satellite dynamics, there are periods where no gateway is reachable), and 'Always reachable' (when a gateway is always reachable from the simulated user's location). We find that ISLs are highly effective in improving reachability, increasing the 'Always reachable' land area from 11% with no ISLs to 81% with enabling two satellite hops. Thus, while IRIS^2 can certainly contribute to the connectivity efforts set out by the Broadband Commission, we find that Starlink already has the potential to boost connectivity over the same target regions through the use of ISLs. It is again important to note that access is limited for reasons beyond technology. Looking back to Figure 8, we see that portions of low and lower-middle income countries are either blocklisted or pending regulatory approval. Hence, we acknowledge that while ISLs can help boost connectivity, there may be additional blockers that prevent users from fully taking advantage of Starlink's technology.

Thousand Sails in China: Recently, China has released Thousand Sails, which has been marketed as a competitor to Starlink [20]. In order to understand how Starlink is related to the goals of Thousand Sails, we use the Belt and Road Initiative (BRI) countries [48] as a proxy for Thousand Sails' target countries. While the BRI countries are an overestimation of what we'd expect in Thousand Sails, we believe it serves as a reasonable proxy since Thousand Sails belongs to China's Space Information Corridor, which aims to provide and improve service for BRI countries [38]. Based on this assumption, we find a potential bifurcation in the market given the current Starlink deployment and BRI countries. As currently deployed, Starlink covers only 52% of BRI countries while BRI countries make up only 43% of Starlink's covered countries. This diversion is depicted in Figure 11. In this

[3]This simulation used 2024 gateway data. Since this data was collected, additional gateways have been deployed in South Africa and Kenya, potentially increasing the coverage described in this section.



(a) One satellite hop (No ISLs)



(b) Two satellite hops (Single ISL)

Figure 11: Simulated Starlink coverage over BRI countries.

figure, we see large portions still uncovered by Starlink infrastructure in China, Russia, and Africa. This suggests that the conjunction of Starlink along with Thousand Sails could bring connectivity to a vast majority of countries, advancing the Broadband Commission's goal of global connectivity.

We find however, that simply looking at the number of reachable gateways within one or two satellite hops is not a fair comparison for connection quality. In Figure 11, we see the Atlantic Ocean has several reachable gateways, but upon deeper inspection, many of these connections are via two satellite hops. We know from Starlink's website that using ISLs leads to poorer connection quality as their website states, "You can expect Starlink's typical high speed internet with brief periods of intermittent service and high latency" in areas serviced by ISLs. As a result, we generate a new mapping to distinguish the quality of these connections. Using the number of reachable gateways as a proxy for connection quality, we generate a map of Starlink connection quality in Figure 12. We define connection quality on a scale from 0

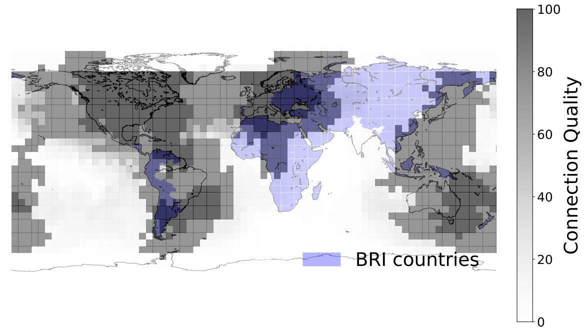


Figure 12: Simulated Starlink connection quality over BRI countries.

to 100. A location is given a score of 100 if over 5 gateways are reachable within one satellite. We choose a threshold of 5 gateways to capture resilience to failures and network congestion when users have multiple gateway options. A score of 75 is given if at least 1 gateway is reachable within one satellite and $min(50, \# \textit{ gateways within two satellite hops})$ for the remaining locations. This *min* function enables us to distinguish locations that may simply have several gateways reachable only via ISL, such as in the middle of the Atlantic Ocean. Based on our estimation for connection quality, we find good connection quality particularly around North and South America, Europe, and Australia. This corroborates the hypothesis that Thousand Sails could help bridge connectivity in regions like China and Africa where connection quality is not as strong.

5 Prior Work

It is well-established that providing ubiquitous Internet access is an important goal [43]. However, we know from prior work that Internet access at the terrestrial level is biased towards wealth as shown by Paul et al. [41] and Iyengar and Bergman [29]. Recently, Starlink, along with other LEO providers, have claimed to help bridge the connectivity gap [13–15], and we seek to measure how well they can in practice. While prior work has measured Starlink performance from a geographically diverse lens such as Izhikevich et al's study of Starlink quality of experience on Netflix [30], our analysis, to the best of our knowledge, is the first to explore Starlink from the lens of global policy. Although there are many Starlink measurement papers [21, 30, 31, 34, 37, 40], we explore new dimensions of analysis including the impact of Starlink's unique routing architecture on Internet access equity and the efficacy of ISLs in improving Starlink coverage. Recent work has even explored Starlink's ability to meet BEAD goals [17, 36]; however, we extend this analysis to various country-level and global policies.

6 Conclusion

We explore Starlink's performance and coverage through the lens of global policy. On the note of performance, we find that Starlink, as currently deployed, does not consistently meet the performance requirements set in place by the US and EU, but shows great promise in Australia and Nigeria. While performance does not seem to be correlated with wealth within the US and EU, we do find some correlation at the global scale. This correlation, however, is weakened with the neighbor effect, where lower income, less targeted regions are able to still benefit from infrastructure in nearby richer regions. On the note of coverage, we find that while Starlink is still unavailable in a vast majority of lower income countries, ISLs have the potential to greatly increase coverage in these regions. We also find that alternative, government-backed initiatives like Thousand Sails in China may potentially help fill in Starlink's coverage gaps to bridge the connectivity gap globally. While Starlink as currently deployed has not yet solved the connectivity gap, we find great hope in achieving global Internet access through the deployment of ISLs and additional LEO deployments from China and the EU.

A Hypatia Description

A.1 Off-the-shelf Hypatia

Hypatia takes as input the the coordinates of terrestrial gateways, and the following parameters describing a single shell of satellites: mean motion revolutions per day, altitude, number of orbits, number of satellites per orbit, and inclination degree. From these coordinates and parameters, the simulator generates two-line element (TLE) sets to describe each satellite's orbital motion. At each timestamp, the simulator uses Ephem to simulate satellite dynamics, and outputs an `ns` graph of connected satellites and gateways for packet-level simulation. Hypatia assumes a static mesh grid of ISLs where each satellite has 4 links: two to immediate neighbors in the orbit and two to satellites in the adjacent orbit.

A.2 Hypatia Extensions

To run our analysis, we extended Hypatia's dynamic state algorithms to process constellations with satellites of different altitudes for a more realistic analysis of the current and planned Starlink constellations. We also implemented a new dynamic state algorithm, *calculate_reachable_gateways*, to extract the number of reachable gateways from input coordinates. Finally, we updated the constellation parameters to support Starlink's Generation 1 constellation with 5 orbital shells based on the FCC filings [12].

A.3 Gateway locations

Our gateway dataset is derived from a snapshot of a crowd-sourced dataset [16] from 2024. We further filtered this dataset by including only gateways marked "Live" or "[Under] Construction". While we acknowledge the bias that may exist in the crowd-sourced gateway dataset, we made our best effort to validate the lack of gateways in countries by cross-referencing this dataset with online Starlink simulators [42]to maximize our coverage based on publicly available data.

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