

# Anyone, Anywhere, not Everyone, Everywhere: Starlink Doesn't End the Digital Divide

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## Abstract

Low Earth Orbit (LEO) satellite constellations, such as Starlink, are increasingly promoted as a solution to the digital divide in rural and underserved communities. In this paper, we take a closer look at the limits of this approach. Using the insight that capacity limitations of LEO-based access networks are driven by peak demand density, we introduce a simple analytical model that brings together real-world demand data with the physical and regulatory limits of LEO satellite networks. Applying our model to broadband demand across the United States, we find that serving the current Starlink constellation size is likely insufficient for covering all un- and underserved locations in the US and we find diminishing returns that disincentivize scaling the constellation to serve the long-tail of these un(der)served locations. We also identify that Starlink's current pricing is likely unaffordable for the majority of these locations, even with existing government subsidies. We argue that LEO constellations, while technologically impressive, are just another piece of the solution, rather than a panacea. New, innovative approaches are still required to end the digital divide.

## CCS Concepts

• **Networks** → **Network performance modeling**; **Public Internet**.

## Keywords

Starlink; LEO satellite networks; LEO capacity modelling; Digital divide; Affordable Internet

## ACM Reference Format:

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## 1 Introduction

Over the last forty years, the rapid spread and growth of Internet use have made equitable access to the Internet an increasingly critical issue. Today, high-quality Internet connectivity supports health, emergency, and education services in locations and among populations that were previously unreachable. However, many people still lack access to high-quality, affordable Internet service.

This gap is referred to as the digital divide. Though it has closed significantly since the term was coined in the mid-1990s [24, 25], considerable usage gaps remain largely due to affordability and digital skills barriers. For example, although mobile broadband networks cover 96% of the world's population, nearly 40% of the world's population lives within coverage but do not use the network; this usage gap has also closed more slowly than the coverage gap over the last decade [11]. Similarly, in the United States, while almost 95% of locations [10] have access to what the US government defines as "reliable broadband" (service that provides at least 100Mbps download speeds and 20Mbps upload speeds) only 73% of households subscribe to these services [22, 44]. These usage gaps increase along predictable lines of socioeconomic marginalization, such as rurality, income, and race, aligning with literature that expands the notion of the digital divide beyond simple accessibility [12, 36].

Given this understanding of the digital divide, we suggest that the true challenge ahead is achieving universal and meaningful Internet access. By meaningful access, we refer to reliable Internet service available at affordable prices and with adequate performance to meet user needs, borrowing from definitions used by digital inclusion advocacy groups



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such as the National Digital Inclusion Alliance [23] and the Alliance for Affordable Internet [42]. By universal, we mean *to all people, in all areas*, just as a national postal service provides universal service to all addresses or universal public education aims to provide schooling to all individuals.

Both private and public sector efforts have targeted these access and usage divides over the years, with some efforts building on research efforts such as WiLDNet [31] and projects supporting community networks [3, 13, 16, 37]. However, a recurring theme we have observed in public discourse is what we refer to as the "silver bullet" approach to addressing the digital divide: a novel technical solution that appears, at least on the surface, to "solve" some aspect of the digital divide, rendering other approaches obsolete. Projects such as One Laptop Per Child (OLPC), Google Loon, or Facebook's Project Aquila exemplify this. Although such efforts have produced novel technical contributions [45] and garnered headlines [21] over the years, none have significantly advanced universal meaningful Internet access. Indeed, Loon and Aquila were canceled after significant private investment [35], and although OLPC continues to exist as a project, it has never achieved its educational objectives [2].

Continuing in this tradition, the technology *du jour* that promises to bridge the digital divide is Internet delivered by low-Earth orbit (LEO) satellite megaconstellations, such as Starlink. These LEO satellite constellations promise to provide last-mile Internet connectivity with high performance and universal connectivity in almost any geographical location. Already, LEO networks have had a significant impact in terms of adoption and have opened new research directions in the networking community [5, 8, 18, 19, 29, 47, 48].

At the same time, we are cautious that the rise of these systems does not shape the discourse as a silver bullet for bridging the digital divide, thereby overshadowing other important efforts working towards universal, meaningful Internet access. LEO constellations may today be able to provide service to *anyone, anywhere* – but it is not clear how they might need to scale to provide service to *everyone, everywhere*, as achieving universal meaningful Internet access would require.

In this work, we examine how Starlink, the only widely available LEO access network, would need to evolve to achieve universal, meaningful Internet access. While the deployment of the Starlink constellation has global implications for Internet connectivity, we note that countries adopt distinct definitions and goals for universal connectivity. With this in mind, we focus our analysis on the United States due to data availability, Starlink's focus on the US market, and recent US regulatory proposals to allow funding for LEO constellations rather than terrestrial infrastructure [26] and leave the analysis of Starlink's impact on other countries' connectivity goals as future work. Specifically, we focus on how Starlink

might scale to serve Internet to all un- and underserved residential locations – as defined by federal "reliable broadband" standards – in the United States. We ask two key questions: (i) does Starlink have sufficient *capacity* to serve all these locations, and (ii) is its residential service *affordable* for these households? We ignore additional demand from users who could choose to use terrestrial Internet, or from mobile users such as those in planes, RVs, or boats. Thus, our analysis is a "best case" scenario, assuming the constellation serves only un- and underserved locations while maintaining full geographic coverage.

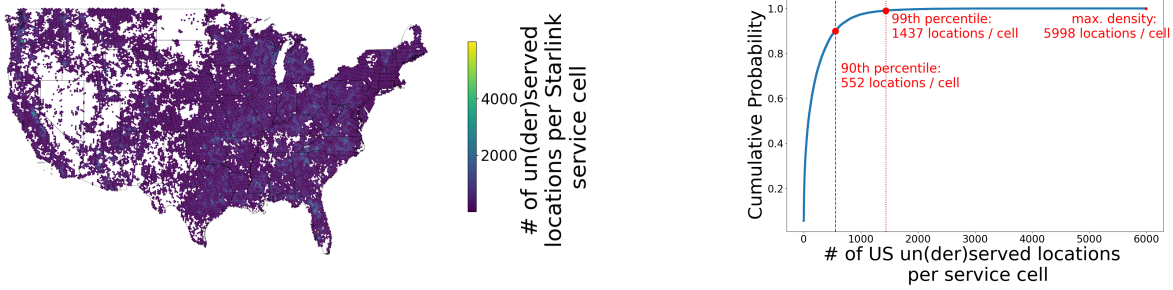
We find that even in this best-case scenario, a LEO constellation of Starlink's current size can only serve these locations by adopting oversubscription ratios 75% higher than federal guidelines, degrading service quality at busy times, and by expanding the constellation size to over 40,000 satellites, which is more than five times the size of the current constellation. Furthermore, adopting standard benchmarks for Internet affordability, we find that 74.5% of un- and underserved locations would not be able to afford the monthly subscription cost of Starlink's standard residential plan. Taken together, these findings suggest both capacity and affordability barriers to the ability of LEO constellations to provide universal, meaningful Internet service.

## 2 Capacity

### 2.1 Scaling LEO access networks

Since their initial deployment, satellite-based access networks have played a crucial role in connecting remote and rural populations to the Internet. On islands and in isolated rural areas, wireless satellite links have provided last-mile connectivity to the Internet backbone, filling the gap in the absence of terrestrial connections such as underwater sea cables, fiber optic cabling, and fixed wireless radio links. However, technological and methodological challenges (such as high latencies associated with geostationary orbit and the high cost of satellite launches) prevented the first generation of satellite networks in the 90s (Iridium, Globalstar, Teledesic) from achieving the performance characteristics of last-mile terrestrial networks.

Recent deployments of LEO satellite mega-constellations have more closely matched the performance of terrestrial access networks while still offering Internet connectivity from "anywhere with a view of the sky." These LEO satellite networks improved upon the performance of traditional geostationary satellite networks by moving networked satellites out of geostationary orbit and into LEO – a difference in orbit height (and associated latency) of approximately 33,000 kilometers – while SpaceX's innovations in rocket launch have driven down the cost of putting satellites in orbit and allowed LEO networks to scale.



**Figure 1: Distribution of locations within the United States that are unserved or underserved by current Internet service provider offerings.**

However, moving to the LEO orbit introduced a new challenge: satellites no longer remain above a fixed spot on the Earth's surface, so users on Earth cannot continuously send and receive traffic to a single satellite as traditional GEO satellite users do. LEO satellite networks, therefore, must be deployed in constellations of thousands of satellites. User terminals (UTs) pass user traffic to whichever satellite in the constellation is overhead at transmission time, and the overhead satellite is responsible for passing user data to terrestrial ground stations (and consequently the Internet).

We identify two scaling properties that are inherent to this architecture and not typically seen in other access technologies:

**Property 1 (P1): High costs to serve small geographical areas; low costs to scale to (certain) additional geographical areas.** With traditional terrestrial technologies, scaling the footprint of an access network is proportional to the size of the geographical area to be covered (e.g. the cost of installing fiber to a set of homes depends on the distances between homes and the network backbone). In contrast, for LEO access networks, connecting a single location requires a high-cost deployment of an entire satellite constellation to ensure the user terminal on Earth always has a viable link to one of the satellites in the rotating constellation. However, once this constellation is in the air, it is essentially zero cost to serve additional locations that have a line-of-sight to the overhead constellation. Such locations can even be on the other side of the globe.

**Property 2 (P2): Peak bandwidth demand density, not total bandwidth demand of the network, determines LEO constellation size.** P1 states that connecting even a single user necessitates deploying an entire LEO constellation. This implies that once the network reaches its peak bandwidth capacity, serving any additional demand requires densifying the constellation. Flipping this logic, we arrive at P2: the number of satellites in a LEO constellation is determined by peak user demand. Note that in practice, the

“peak demand” of a constellation's user base varies depending on the size of the geographical area into which users are grouped, as well as the strategies used to serve these geographical areas with the satellite constellation. We provide further analysis of this in the sections that follow.

While P1 and P2 highlight the structural scaling constraints of LEO constellations, it is essential to note that systems like Starlink employ advanced beamforming techniques that enable dynamic reallocation of capacity across geographic regions [28]. This flexibility enables operators to partially mitigate localized peak demand without resorting to full constellation densification immediately. However, such adaptive techniques are ultimately limited by physical and regulatory constraints on spectrum reuse and beam overlap (e.g., FCC polarization restrictions). Thus, while beamforming softens the hard edges of P1 and P2, the underlying scaling dynamics remain a dominant architectural constraint.

## 2.2 Modeling Starlink Operation

Starlink connects terrestrial user terminals (UTs) to the Internet by transmitting user traffic from UTs to orbiting overhead satellites, which have constantly shifting views of the Earth's surface. As such, two key tasks of the Starlink system are: (1) ensuring that each user terminal on the ground is connected to an overhead satellite at all times via wireless channel and (2) ensuring that each satellite is connected to a ground station at all times, either directly via wireless channel (i.e., in a bent-pipe configuration) or indirectly via inter-satellite link (ISL) to a satellite that possesses its own direct wireless link.

To achieve these tasks, Starlink divides the Earth's surface into bounded regions (cells), grouping user terminals and gateways based on their geo-location. Each cell with at least one user requires at least one “spot beam” on it at all times to ensure continuous connectivity for its user(s). Antennas on the satellites produce these spot beams, which serve as wireless channels for data transfer. Each satellite has a fixed number of these spot beams that it can form, which translates to a fixed number of cells that can be served by each

satellite. As the satellites orbit the Earth, they constantly replace their spot beams on the Earth’s surface as old cells exit the satellite’s field of view and new cells enter [28].

**2.2.1 US Households without Reliable Broadband.** The FCC’s National Broadband Map [10] is the authoritative source of broadband availability in the United States. This map provides a record of the maximum service speeds offered by ISPs at every location in the US that might be served by broadband (e.g., a house). A location is considered “served” if an ISP reports providing service of at least 100Mbps download and 20Mbps upload speed; all other locations are considered “unserved” or “underserved”. The FCC builds this map using coverage data self-reported by ISPs. Although a public challenge process exists to correct false claims, prior work indicates that ISPs may exaggerate their coverage; as a result, we expect this map to *undercount* the number of locations that lack reliable broadband in the US. Figure 1 maps the spread of un(der)served locations in Starlink service cells across the United States.

In the following sections, we assume that Starlink aims to provide global coverage (in the US). Still, there is no demand on the network outside that derived from our dataset – that is, the calculations that follow represent a “best case scenario” for Starlink in which the constellation provides full geographical coverage to all service cells in the US (each US cell must have one beam on it at all times), but demand is determined by the un(der)served locations in our dataset (only cells containing  $> 0$  un(der)served locations determine whether a beam’s capacity is sufficient to provide coverage to the cell).

### 3 Limits of Starlink’s Capacity

From this model of operation, we can examine Starlink’s ability to meet the bandwidth demand required to fill the existing gaps in Internet access across the United States. As discussed in 2.1, Starlink’s limitations are driven by the service cells with the highest bandwidth demand. Thus, evaluating Starlink’s limitations requires information about the format of Starlink’s terrestrial planning cells, the demand for bandwidth of cells of interest, and the number and capacity of the spot beams emitted by satellites. We have all of this information. Previous work has identified that boundaries for these cells are likely taken from the H3 Geospatial Indexing System [19]. From the National Broadband Map, we can calculate the number of un(der)served locations, and therefore bandwidth demand, for each cell. In Starlink’s filings with the FCC, we can find characterizations of their spot beams.

**3.0.1 Is Starlink constrained by spectrum?** Applying this data to our model of operation, we first ask whether the spectrum Starlink uses across its constellation to form wireless channels has enough capacity to meet peak cell demand. From

Starlink’s Schedule S filings [39], we know that Starlink can use 3850 MHz of spectrum to serve downlink traffic to UTs on Earth (see Table 1). According to recent work estimating the efficiency of Starlink spectrum to be  $\sim 4.5$  bits per Hz [33], this channel width supports throughputs of  $\sim 17.3$  Gbps.

| Band (GHz)                  | # Beams        | Usage                  |
|-----------------------------|----------------|------------------------|
| 10.7–12.75 (2050 MHz)       | 4              | Downlink to UTs        |
| 19.7–20.2 (500 MHz)         | 8              | DL to UTs              |
| 17.8–18.6 (800 MHz)         | 8              | DL to UTs / GWs        |
| 18.8–19.3 (500 MHz)         | 4              | DL to UTs / GWs        |
| 71–76 (5000 MHz)            | 4              | DL to GWs              |
| <b>Total to UTs / Cells</b> | <b>24 / 28</b> | <b>3850 / 8850 MHz</b> |

| Parameter                  | Value                  |
|----------------------------|------------------------|
| UT downlink spectrum       | 3850 MHz               |
| Spectral efficiency        | $\sim 4.5$ bps/Hz [33] |
| Max per-cell capacity      | $\sim 17.3$ Gbps       |
| Peak Cell users            | 5998 users             |
| FCC throughput requirement | 100/20 Mbps (DL/UL)    |
| Peak Cell DL demand        | 599.8 Gbps             |
| Max DL oversubscription    | $\sim 35:1$            |

**Table 1: Starlink Single Satellite Capacity Model**

From our data on un(der)served locations, we see a maximum of 5998 residential locations for a single cell. In order to meet federal definitions of Internet service, each of these locations requires 100 Mbps downlink / 20 Mbps uplink capacity; this yields a demand of 599.8 Gbps for our cell with the most un(der)served locations. While 17.3 Gbps is clearly insufficient for serving this demand on paper, it is common practice among Internet service providers is to “oversubscribe” their network – that is, many service providers offer Internet speeds to customers that they could not fulfill if every customer in the network tried to use that speed at the same time. Here, Starlink can fulfill the single-cell demand of 599.8 Gbps with a maximum channel capacity of 17.3 Gbps if it adopted a 35:1 oversubscription ratio for this cell.

This is a high oversubscription rate, which would likely result in many users in this particular cell not receiving 100/20 service from Starlink. However, given the long-tail of cell densities (see Fig. 1), the proportion of all Starlink subscribers affected by this level of oversubscription is relatively small. While there is no limit to maximum allowable oversubscription rates for satellite Internet providers, the FCC recently mandated that terrestrial unlicensed fixed wireless providers cannot exceed subscription rates of 20:1. If they were to adopt this maximum rate, Starlink could serve 99.89% of total locations (all but 5128 locations). Alternatively, Starlink could choose to simply serve all locations, with 22,428 locations (0.48% of total) served at rates higher than 20:1. We call the latter a “full service deployment” scenario.

| Beamsread factor | Constellation size (full service) | Constellation size (max. 20:1 oversub.) |
|------------------|-----------------------------------|-----------------------------------------|
| 1                | 79287                             | 80567                                   |
| 2                | 40611                             | 41261                                   |
| 5                | 16486                             | 16750                                   |
| 10               | 8284                              | 8417                                    |
| 15               | 5532                              | 5621                                    |

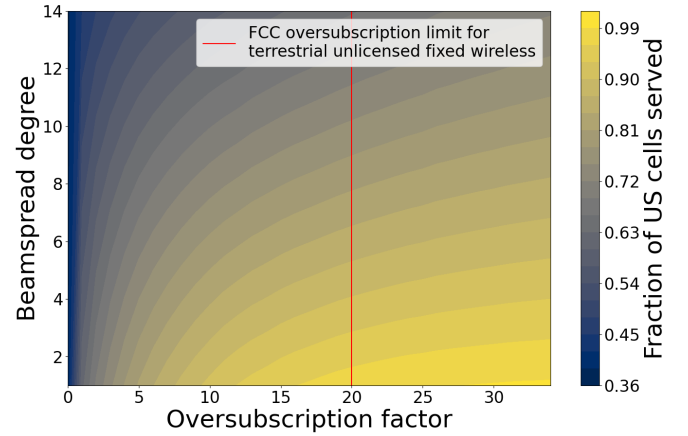
**Table 2: Predicted constellation size for various beam-spread scaling factors.**

**Finding 1 (F1):** Starlink can overcome the limits of its spectrum allocations either by allowing high (35:1) oversubscription rates across its footprint with 22,428 locations subject to such rates) or by choosing to serve at most 99.89% of total un(der)served locations at an acceptable level of oversubscription (maximum of 20:1).

**3.0.2 Calculating required constellation size from peak demand.** We proceed to derive how many satellites would be required to support either deployment scenario presented in **F1**. Given the geometrically symmetrical nature of the LEO satellite constellation, calculating the number of satellites in the constellation overall from the number of satellites at any location is relatively straightforward. The critical calculation thus becomes finding the number of satellites over the terrestrial region that consumes the greatest bandwidth, as this point determines the overall constellation size, per **P2**.

This turns out to be a difficult point to find. Satellites serve user bandwidth requirements by directing spot beams of varying channel capacities from their antennas to terrestrial cells. As such, whether a cell needs more than one spot beam depends not just on its raw bandwidth demand, but also on the bandwidth demands of other cells being served by the same satellite. Beam spreading, or the use of a single beam to cover multiple cells, also introduces another degree of complexity into the capacity allocation problem [32]. Serving multiple cells with a single beam allows satellites to serve more cells than the number of beams it can form; however, it also effectively decreases the channel capacity used for each cell served by the same beam, which changes the threshold after which using additional beams to serve the same cell is required. Lastly, 16 of the 24 Starlink satellite spot beams are used to serve both gateways and user terminals (UT) flexibly (Table 1). Determining when these beams are used for gateway or UT traffic adds yet another layer of complexity.

Despite these challenges, we recognize that with a few simplifying assumptions, we can make a strict lower-bound estimate on the size of the constellation required to serve all un(der)served locations in the United States. FCC filings indicate that 4 beams are required to serve a single cell with the full 17.3 Gbps capacity. In both the "full-service" and



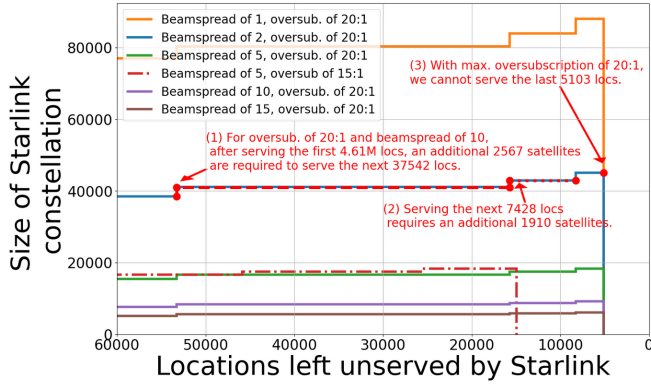
**Figure 2: Impact of beamsreading and oversubscription on fraction of US cells served**

"maximum oversubscription of 20:1" deployment scenarios, we know that 4 beams are required to serve the peak demand cell. From here, we make the generous assumption that no other cell around the bandwidth-neediest cell requires more than one spot beam in calculating our lower bound of total constellation size. This assumption means that the satellite serving the bandwidth-neediest cell can serve at least 20 other cells, with the exact number depending on the degree of beam spreading adopted by the constellation. Given some degree of beam spread, we can work backwards from the "satellite density" at the geographical location of the peak demand cell to determine the overall constellation size required to support that cell. Table 2 shows calculated constellation size required for varying degrees of beam-to-cell spreading and for the two deployment scenarios outlined in **F1**, while Figure 2 illustrates the number of cells that could be served for varying beamsread values and maximum oversubscription rates. Together, the results of Fig. 2 and Tab. 2 tell us that to cover all cells in the US, Starlink needs to adopt a low beamsread with an adequately high oversubscription rate. If Starlink wishes to serve all US cells while staying within the bounds of acceptable oversubscription rates, it must adopt a beamsread factor less than 2 – which correlates to a constellation size of over 40,000 satellites.

**F2:** Starlink's current 8000 satellite deployment would require high degrees of beamsreading and high oversubscription rates to serve all US cells. To stay within acceptable levels of oversubscription, Starlink would need to deploy more than 32,000 additional satellites to achieve a beamsread factor that ensures coverage of all US cells.

We conclude by noting that Starlink may simply avoid serving the long tail of users to reduce constellation size. Fig. 3 explores this strategy and shows how constellation sizes changes with varying number of locations per cell served at





**Figure 3: Constellation size required to serve varying number of un(der)served locations for fixed oversubscription and beamspread factors.**

a fixed oversubscription rate of 20:1 and for different beamspread scaling factors; note the stepped behavior corresponds to how a reduction in constellation size is only possible once a beam is freed from serving a peak cell in our model.

**F3:** The long tail of cell density introduces significant diminishing returns that disincentivizes Starlink from serving the long-tail of users. In our model, connecting the final  $\sim 3000$  locations requires deploying from a couple hundred to a couple thousand of additional satellites.

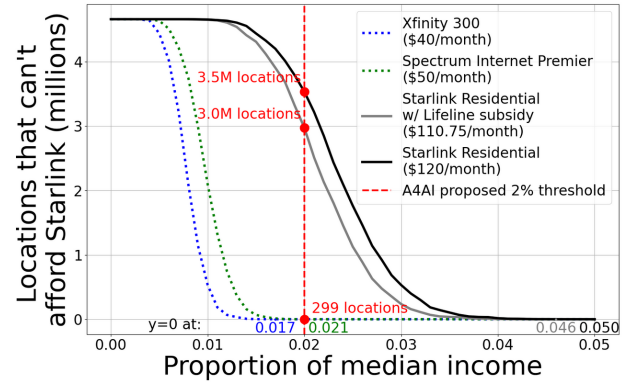
Together, F2 and F3 motivate our titular observation: while LEO networks might serve anyone, anywhere, they can not easily simultaneously serve everyone, everywhere.

#### 4 Affordability

Achieving universal meaningful Internet access requires service to be both available and affordable. One widely-adopted threshold for "affordability" is that Internet service should not cost more than 2% of a household's monthly income; this guideline has been adopted in the UN Broadband Commission's 2025 Targets [1, 6] and has been used by the FCC as a benchmark [9, 43].

Starlink's Residential plan – their only plan that offers fixed broadband that meets the "reliable broadband" definition – costs \$120/month, ignoring one-time antenna and equipment costs. Few subsidies for monthly service cost exist in the US; the most common is the Lifeline program, which provides a \$9.25/mo subsidy for Internet service to households earning below 135% of the Federal poverty limit. Thus, even with Lifeline support, a household must earn at least \$66,450 per year for Starlink's service to fall under the 2% affordability threshold. Nationally, this accounts for between 52.4 and 64.6 million households [40].

However, many of these households are served by other ISPs and have access to lower-costs service plans. For example, two of the US's largest ISPs, Xfinity and Spectrum, offer



**Figure 4: Un- and underserved locations unable to afford service.**

speeds up to 300 and 500Mbps for \$40 and \$50 per month respectively [7, 34]. The more salient question is whether un- and underserved locations can afford Starlink service; i.e., even if Starlink had capacity to serve all of these households, how many could afford to use it?

To estimate this, we consider the median income reported in the US Census for each county, and assume that locations within a county have household incomes equal to the median. Figure 4 shows that, even with Lifeline subsidy, nearly 3 million un- or underserved locations are unable to afford Residential Starlink service: regardless of the capacity of the network, these households are unlikely to benefit from the service.

**F4:** Based on median income, 3.5M of 4.7M un(der)served locations cannot afford Starlink's Residential plan, while widely-available, comparable plans from other ISPs are affordable to all residents for  $> 99.99\%$  of these locations.

#### 5 Related Work

Previous work has explored the scaling behaviors of LEO constellations, albeit from different perspectives. Chen et al. identify "uneven demand" that arises due to the uniform density of LEO satellite networks but non-uniform distribution of LEO users as a key physical scaling limitation of LEO constellations [8]. Others have proposed multi-party LEO satellite architectures (MP-LEO) as a solution for more efficiently supporting operators who wish to provide localized coverage [29] and multi-tenant LEO constellations for providing direct-to-cell service at lower capital costs for mobile LEO network operators. Further work has explored security, resilience, and performance limitations of LEO constellations [5, 18, 47, 48]; in this work, we focus on *current* LEO access network deployments and scrutinize the implication of the above scaling behaviors on their ability to provide universal and meaningful Internet across the United States.

## 6 Discussion

Steve Song, a longtime advocate for affordable Internet connectivity, proposed an analogy for thinking about building towards universal and meaningful Internet access of filling a jar with stones [38]: each technology, business model, and regulatory approach for building and sustaining access networks is a different size stone. Using large stones fills the jar quickly, but leaves many gaps. Filling in these gaps requires smaller stones and stones of different shapes.

LEO constellations like Starlink represent a new type of stone for building towards the goal of filling the jar of universal meaningful Internet access, filling in gaps that prior approaches have failed to address. Yet at the same time, it is just another stone: gaps will remain, and people will remain unconnected. Although LEO presents exciting innovations and research opportunities, it does not invalidate continued efforts to innovate in other forms of access networks, particularly those that leverage novel access technologies and architectures [30, 41, 46], new models of access to spectrum [27] or infrastructure sharing [4, 20], or community-based [14, 15, 17] and municipal approaches to connectivity.

In this work, we sought to characterize the shape of Starlink's stone using the latest data on unconnected locations. Though provisioning satellites to serve locations within the US has consequences for connecting locations outside the US, we limit our evaluation of Starlink's capacity to a single country, as varying definitions of meaningful Internet connectivity across different countries complicate a standardized evaluation. With the insight that capacity limitations of LEO-based access networks are driven by peak demand density, we find that current spectrum use limits Starlink's coverage of the densest regions of users without relying on high rates of oversubscription and propose a lower-bounding model of Starlink operation that indicates that (1) the current constellation is likely insufficient for covering all remaining un(der)served locations in the US and (2) diminishing returns makes serving the last thousands of users significantly more expensive. We conclude by identifying that outside of capacity, affordability is a major barrier to universal, meaningful Internet access that Starlink may be unlikely to overcome at its current pricing.

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