# Broadband Technologies Review

## A Technical Assessment of Low Earth Orbit Satellite Broadband

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# Technical Assessment of LEO Satellite Broadband | Introduction

## Context

- LEO satellite technology has evolved rapidly in recent years, with platforms, such as Starlink, offering a step-change in broadband reach and performance compared to earlier geostationary services
- LEO platforms offer widespread coverage, but their availability is constrained by access to spectrum and system capacity, and their performance is constrained due to sharing of limited capacity and other factors inherent to the technology
- Because government policymakers and others want to bring high-speed broadband to rural communities, they are seeking to determine what role LEO platforms, such as Starlink, can play in closing the digital divide
- To inform these conversations, this report assesses the capability of a LEO Satellite platform, such as Starlink, to meet these broadband needs

## Limitations

- This report is based on information available in the public domain in November 2024 with minor updates in January 2025
- Capacity forecasts rely on certain assumptions, e.g. on future spectrum holdings, which may not materialize. In general, we have adopted a conservative approach (i.e., favorable to LEO satellite) in areas of greatest uncertainty
- Similarly, some aspects of Starlink's technology are not generally available in the public domain. Again, we have taken a conservative approach. We would be pleased to update this analysis should any further information be made available

Source: Cartesian





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# Technical Assessment of LEO Satellite Broadband | Key Findings

| | |
|---|---|
| **Capacity** | All broadband networks must address capacity constraints. Satellite platforms are capacity constrained by the satellite hardware and available spectrum. Using Starlink as a LEO capacity case study, we estimate its broadband service (100/20Mbps) can be delivered to 2.0M housing units in the US today. |
| **Subscriber Density** | Subscriber density is relevant for networks that share capacity amongst users – to achieve the 2.0M housing unit capacity, subscribers must be geographically distributed. Today's available spectrum supports approximately 1 housing unit per sq. mile (versus an average of ~30 housing units per sq. mile across the US, and over 10K per sq. mile in urban areas[1]). |
| **Network Improvements** | The capacity of Starlink's network is expected to improve over the next 5 years with increases in fleet size, satellite capacity, available spectrum and spectral efficiency – but spectrum availability will limit the maximum number of housing units it can reach. We estimate that in 2030 Starlink may support up to approximately 3 housing units per sq. mile or 5.5M total US housing units. |
| **Service Performance** | Speed, latency, jitter, and uptime all contribute to overall network performance – LEO technology lags terrestrial networks in these respects. Additionally, LEO consumers typically incur higher fees for equipment (up to $448) and monthly service ($120/mo.) compared to terrestrial services. |

1. Based on Census estimates of 90 people per square mile, assuming ~3 people per housing unit
Note: Findings based on information in the public domain as of time of publication (November 2024)
Source: Cartesian, Census





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# Executive Summary | Study Background

This study evaluates the capability of LEO satellite platforms to provide broadband at scale in the US

| STUDY OBJECTIVES | APPROACH |
|---|---|
| **1 Technical Overview**<br>How do components of a Low Earth Orbit (LEO) satellite platform determine service quality? | Reviewed components of LEO system and associated impact on service quality and identified constraints in shared capacity and coverage areas |
| **2 LEO Serviceability**<br>How many housing units can a LEO satellite platform serve today and in the future? | As a case study for LEO Serviceability, modeled the spectrum and network capacity of Starlink – the largest operational LEO network – to estimate total number of serviceable housing units (HUs) for a LEO network |
| **3 Service Performance**<br>How does LEO satellite network performance compare against fiber and fixed wireless? | Compared network performance aspects of LEO, Fiber and FWA, including speed, latency, jitter, and uptime; assessed how speeds are influenced by capacity and the path to increasing capacity for each technology |

*Our findings are intended to be educational in nature and are based on information in the public domain at time of publication*

Source: Cartesian





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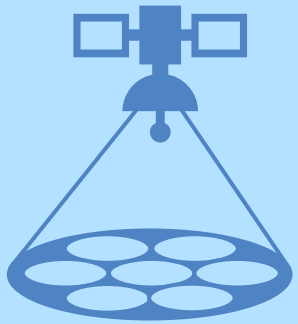
# Executive Summary | Key Findings (1/3)

## 1 Technical Overview



**LEO satellites offer near ubiquitous coverage, but the number of housing units they can serve – both nationwide and within smaller geographic areas – is limited by fleet size, satellite capacity, available spectrum and spectral efficiency**

- Service is broadly accessible from any location that lies under the satellites' orbits and has an unobstructed view of the sky
- The coverage of each satellite is divided into cells of approx. 100 square miles each
- Each cell has a finite capacity that must be shared between the users
- This limits the number of locations that can receive the service level on offer (i.e., higher user density leads to less capacity available per user)

Note: Findings based on information in the public domain as of time of publication (November 2024)
Source: Cartesian





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# Executive Summary | Key Findings (2/3)

## 2 LEO Serviceability: Starlink Case Study

**We estimate Starlink can deliver 100/20Mbps to 2.0M US HUs today, which includes 1.4M existing US subscribers**

- Given 1.4M existing subscribers, we estimate Starlink's network could support up to 0.6M incremental users, including up to 344K BEAD-eligible HUs[1]
- This increases to 5.5M total US housing units by 2030 due to expected increases to fleet size, satellite capacity, authorized spectrum, and spectral efficiency gains
- We forecast Starlink will have 4.2M residential US subscribers by 2030, suggesting available capacity for a further 1.3M subscribers (incl. 670K BEAD HUs)
- Starlink could have capacity for more incremental subs if existing subscriber base is lower than forecasted or if there is less consumer demand on the network[2]
- All estimates assume that served locations are optimally distributed to maximize the capacity utilization of each satellite; in reality, higher density areas will likely experience lower service coverage

1. BEAD estimates assumes network prioritizes least dense areas first, and that no existing subs are BEAD-eligible housing units; 2. See Appendix View '2030 Existing Subs Sensitivities' for more detail
Note: Findings based on information in the public domain as of time of publication (November 2024)
Source: Cartesian





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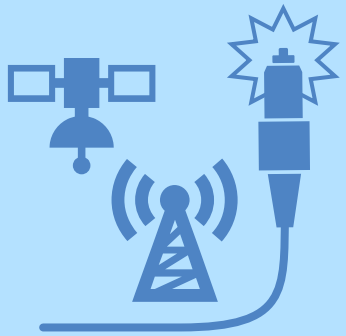
# Executive Summary | Key Findings (3/3)

## 3 Network Performance



**Current LEO technology delivers slower speeds and has worse latency, jitter, and uptime than that achievable on fiber or FWA[1]**

- LEO service performance is uniquely affected by altitude, obstructions (e.g., weather, radio interference), and user density (i.e., sharing of capacity)
- Starlink reports delivering speeds below 100Mbps in large areas of the US, which is below the FCC threshold for broadband (100/20Mbps)
- By 2030, other technologies are expected to be offering broadband services up to 20Gbps (4x current), whereas LEO offerings are only expected to reach 1Gbps

1. While Hybrid fiber-coaxial cable (HFC) is not referenced in this study, it is the most widely deployed terrestrial broadband technology today and also provides far higher speeds and better performance than LEO technology
Note: Findings based on information in the public domain as of time of publication (November 2024)
Source: Cartesian





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# Executive Summary | LEO Serviceability Model Overview

As a case study for LEO capability, our model estimates Starlink's network and spectrum capacity in 2024 and 2030

**LEO serviceability is constrained by available spectrum and total network capacity – we consider both in our analysis:**

## A Spectrum Capacity is modeled by:

1. **Spectrum Allocation:** Radio frequencies used in authorized spectrum bands (e.g., Ku, Ka) for user link connections
2. **Polarization:** Dual polarization doubles capacity for the same amount of spectrum using different orientations (i.e., horizontal and vertical)
3. **Spectral Efficiency:** Measures how efficiently data can be transmitted over the available spectrum, dependent on the chosen modulation scheme and available signal-to-noise (SNR) ratio

## B Network Capacity is modeled by:

1. **Global Fleet Size:** Existing operational satellites *plus* estimated launches per year *minus* estimated end of life satellites per year
2. **Satellites in Range for US:** 5% of Starlink's global fleet is assumed to be within range to provide coverage to the contiguous US
3. **Capacity Per Satellite:** Payload throughput per satellite (Gbps), which varies by Starlink generation

| | | 2024 Year-End Inputs | 2030 Year-End Inputs |
|---|---|---|---|
| Spectrum Capacity (Gbps) | 1 Spectrum Allocation | 2000 MHz | 5100 MHz |
| | 2 Polarization | 1 | 2 |
| | 3 Spectral Efficiency | 3.9 bps/Hz | 4.5 bps/Hz |
| | Max HUs Supported by Spectrum | 114 per cell \| 2.3M overall | 255 per cell \| 5.5M overall |
| Network Capacity (Gbps) | 1 Global Fleet Size | 5,956 | 26,041 |
| | 2 Satellites In Range for US | 298 | 1,301 |
| | 3 Weighted Average Capacity Per Satellite[1] | 50 Gbps | 124 Gbps |
| | Max HUs Supported by Network | 2.0M | 7.3M |

To get serviceable housing units (HUs), the spectrum and network/fleet capacity estimates are compared against the bandwidth needed to deliver a 100/20Mbps service to users at peak demand hours

1. Satellite capacity in the model is calculated at the generation level, weighted capacity per satellite shown in table

Source: Cartesian





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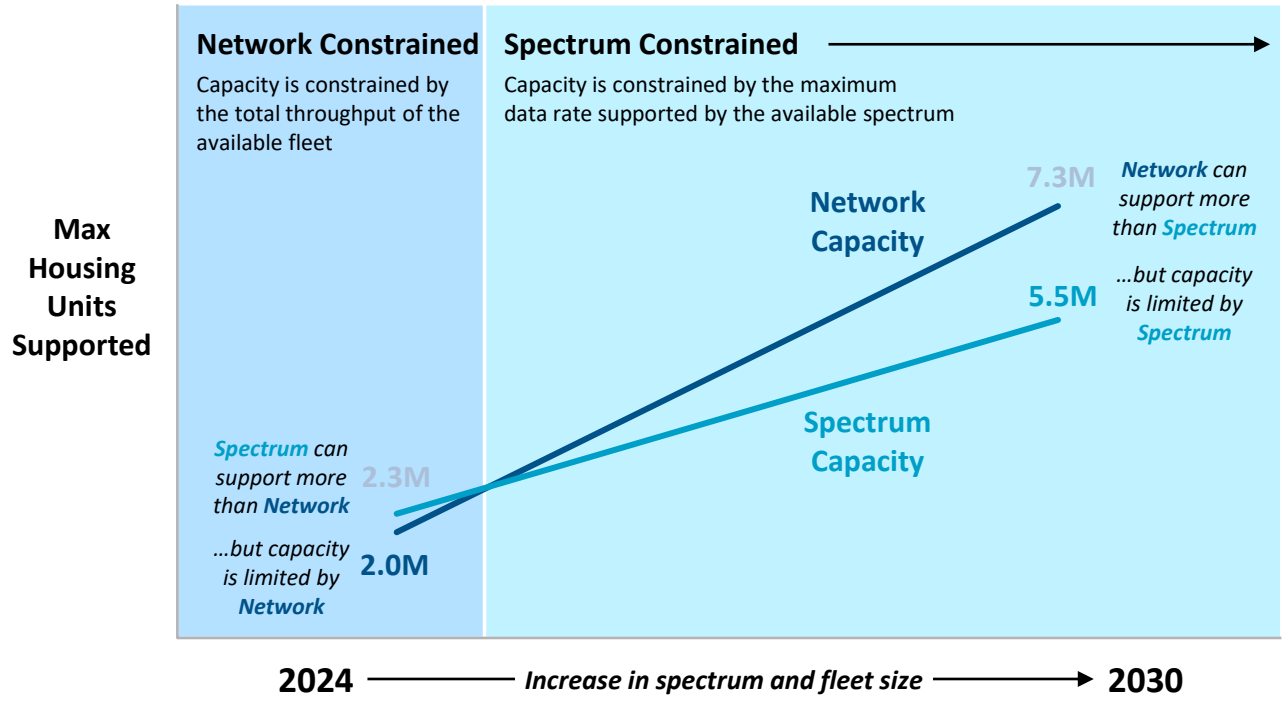
# Executive Summary | LEO Serviceability Key Findings

We estimate how many housing units Starlink's network can support with broadband speeds in 2024 and 2030

## Starlink Housing Unit Capacity in 2024, 2030 Year-End (YE)

*By Capacity Constraint*




The above capacity estimates assume that demand is optimally distributed across the country – uneven geographic concentration of demand would reduce the supportable HUs below this maximum value

## Model Takeaways

| | 2024 YE | 2030 YE |
|---|---|---|
| How many US housing units are serviceable with 100/20Mbps by Starlink? | **2.0M** *Network constrained* | **5.5M** *Spectrum constrained* |
| Approximately how many housing units per square mile can Starlink serve? | 1 HU per sq. mile | 3 HUs per sq. mile |
| What is the estimated number of Starlink residential subscribers in the US? | 1.4M | 4.2M |
| Using the remaining capacity, how many incremental subscribers can Starlink serve?[1] | 0.6M | 1.3M |
| Of the estimated incremental subscribers, how many are estimated to be BEAD-eligible? | 344K *56% of available 0.6M HU capacity* | 670K *52% of available 1.3M HU capacity* |

1. Incremental subs is directly impacted by how many existing subscribers Starlink will have in 2030, see Appendix View '2030 Existing Subs Sensitivities' for sensitivity analysis

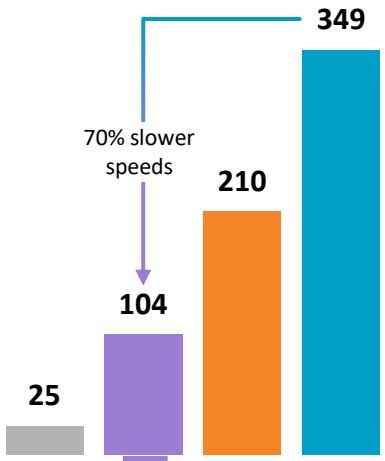
Source: Cartesian, FCC DATA Maps filing as of 12/31/23 accessed 5/28/24

# Executive Summary | Network Performance Key Findings

Fiber and fixed wireless technologies have far better performance than LEO Satellite platforms

## Speeds Received[1, 2]
*Median download speeds received by user*

Mbps

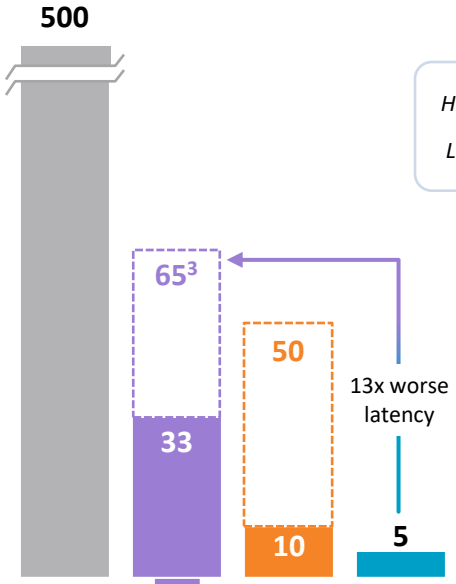



Satellite capacity is shared between users – increasing users can lower speeds

Large files take longer to download on slower connections

## Latency[3, 4]
*Delay in data transmission*

Milliseconds

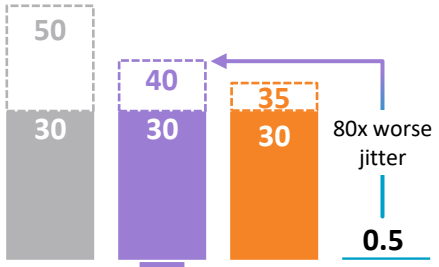



Satellite suffers from higher latency due to longer distance for data to travel

High latency impacts real-time applications and causes slower downloads

## Jitter[5]
*Variability in latency*

Milliseconds

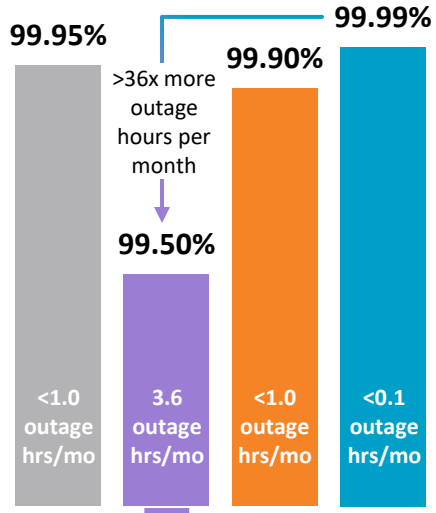



Satellite / user terminals connections are subject to fluctuations in latency

High jitter impacts real-time applications (e.g., video calls may freeze)

## Network Reliability
*Typical network uptime*

% Uptime




Satellites are at risk of atmospheric disruptions, resulting in less uptime

Less reliable connections are less suitable for business-critical applications

1. GEO Satellite speeds based on average of median download speeds of HughesNet and Viasat; 2. Fiber speeds based on average speeds users experience across all plans, not speed tests of fastest speeds offered; 3. Starlink (LEO) latency up to 100+ms in remote areas per Wired.com citing Starlink; 4. 0.005ms/km with assumed 1000km round trip for fiber; 5. LEO based on reports from Starlink customers of 30-40ms jitter values during peak usage hours, down to 10ms under optimal conditions
Source: Ookla, PC Mag, Starlink, M2Optics, CircleID, EngineerIT, Siklu, Businessbroadbandhub, uptime.is.com, BroadbandNow, Cartesian

GEO Satellite | LEO Satellite | FWA | Fiber





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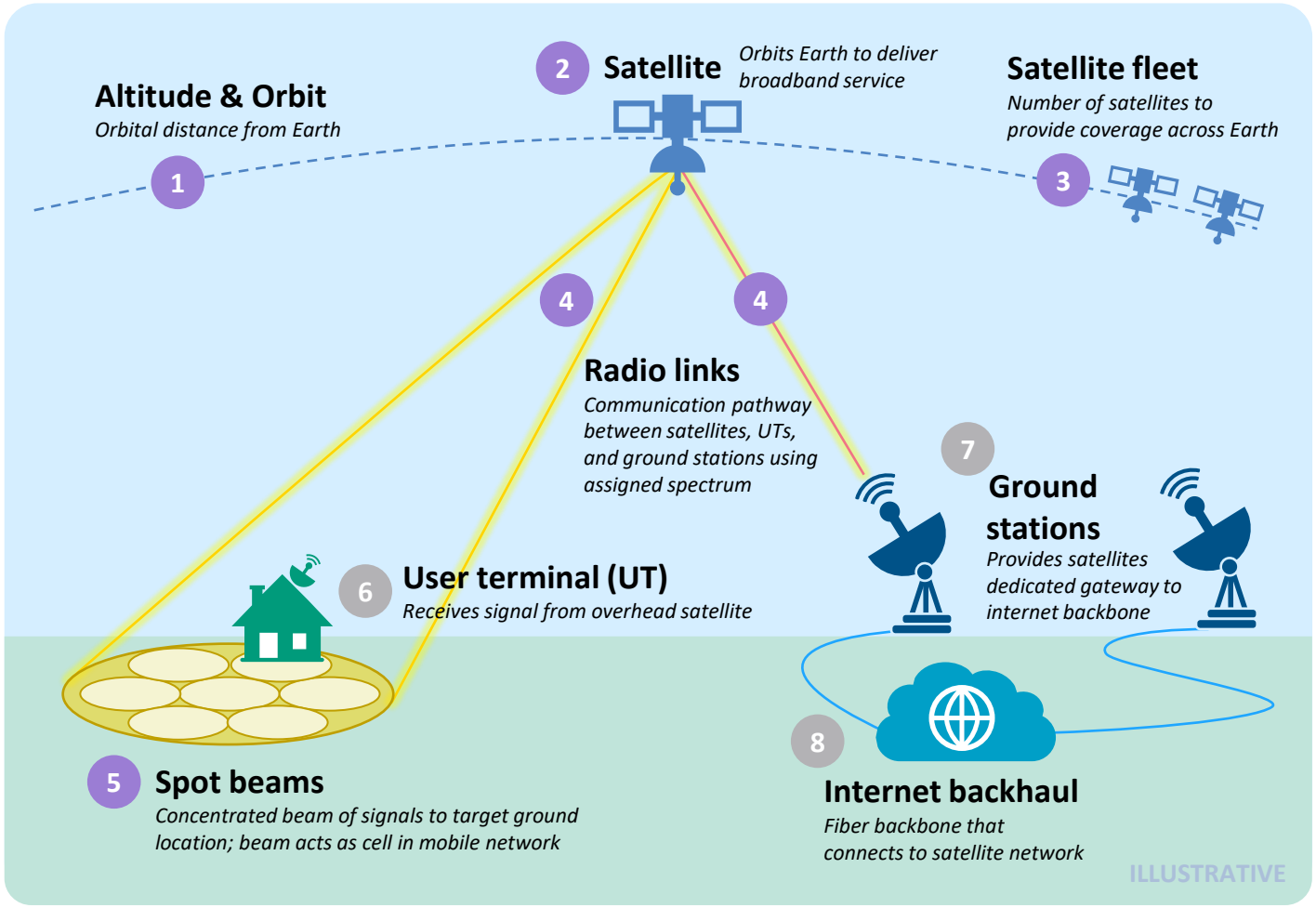
# 1 Technical Overview | How Satellite Networks Work

LEO networks' capacity and performance are affected by numerous technical factors

## Key Factors for LEO Satellite Broadband




**Satellites relay signals between user terminals and ground stations to connect users to the Internet**

1. **Altitude:** Distance from Earth impacts latency and signal strength
   **Orbit:** Determines density in coverage across the Earth
2. **Satellite**: Design determines satellite capacity, spectral efficiency, and number/size of spot beams
3. **Satellite fleet:** Determines network capacity and coverage
4. **Radio links**: Link throughput limited by signal strength, interference, and available spectrum
5. **Spot beams**: Steers capacity received by UTs; satellite capacity dynamically allocated between beams
6. **User terminal:** Design impacts speeds and frequency range
7. **Ground stations:** Direct/indirect connection with satellites impacts latency and capacity satellite can deliver
8. **Internet backhaul:** Connects the ground stations to the Internet

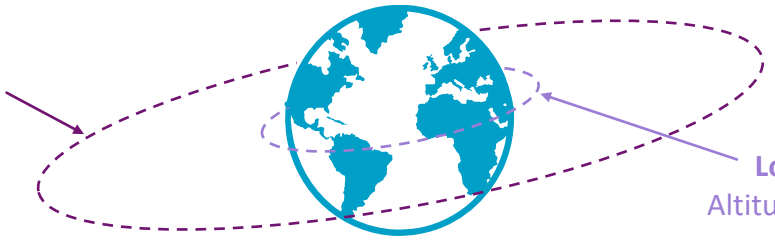
Source: Cartesian

# 1 Technical Overview | Satellite Technology Evolution

LEO satellites deliver much better latency than GEO satellites, but both are capacity constrained

## Satellite Technology

**GEO**
**Geostationary Earth Orbit**
Altitude: 35,786km



**LEO**
**Low Earth Orbit**
Altitude: 300 – 2000km

### Geostationary Earth Orbit (GEO)

Legacy GEO technology, originally developed for broadcasting, adapted for broadband (early 2000s)

**GEO Characteristics:**
- Only a few satellites needed for global coverage
- Each satellite appears in fixed location in sky
- Long development cycle and high cost

**Limitations:**
- Limited capacity, shared capacity across all users
- Real-time audio, video calls suffer due to high latency

### Low Earth Orbit (LEO)

Advances in satellite design and lower launch costs made large LEO fleets viable (late 2010s)

**LEO Characteristics:**
- Fleets of hundreds/thousands of satellites
- Short lifespan due to atmospheric drag
- Better latency for real-time use cases due to lower altitude

**Limitations:**
- Greater capacity, but still constrained by spectrum or platform
- Number of users must be limited to avoid service degradation

### Satellite vs. Terrestrial

**Satellite Advantages**
- High coverage
- Minimal ground infrastructure req.
- Route diversity
- Reach to mobile users (e.g., aviation)

**Satellite Disadvantages**
- High upfront fees
- Long upgrade cycles
- High service terminal fees
- Atmospheric sensitivity

## GEO vs. LEO Specs

| | GEO | LEO |
|---|---|---|
| **Satellite Latency[1]** | 500 - 600ms *vs. fiber 5ms* | 25 - 75ms *vs. fiber 5ms* |
| **Satellite Lifespan** | 15 - 20 years | 5 - 7 years |
| **Development Cycle** | 5 - 10 years | 2 - 5 years |
| **Cost per Satellite[2]** | $100M+ | $200K - $1.0M |
| **Satellites Req. for Global Coverage[3,4]** | 3 | 500 - 1K+ |
| **Cost per Fleet** | $300M+ | $100M - $1B+ |

1. 0.005 microseconds/km with assumed 1000km round trip; 2. Starlink V1 est. cost $200k, V2 Mini est. cost $800k and future V3 est. cost $1.2M per SpaceNews article, based on this we estimate V2 Full Size costs to be around $1M; 3. Three geostationary satellites is enough for near global coverage (ex. poles) per the European Space Agency; 4. Permission has granted by the FCC for Starlink to fly 12,000 satellites. Final cost likely higher as Starlink aims to launch 30K additional satellites (partially approved)
Source: Spacenews.com, European Space Agency, Cartesian





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# 2 LEO Serviceability | Capacity Modeling Overview

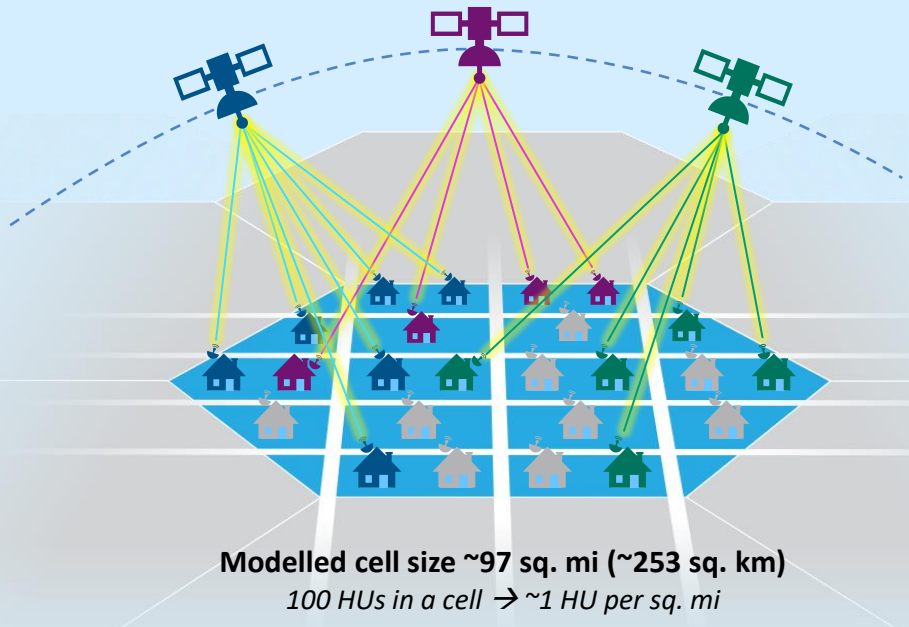
We estimate LEO serviceability using publicly available information for the largest LEO network – Starlink

## Model Overview

### To estimate LEO serviceability, we model Starlink's network capacity and spectrum capacity

Data throughput is limited by the hardware capability of each satellite (i.e., **network capacity**) and locally, the maximum capacity is determined by the spectrum allocated to each cell (i.e., **spectrum capacity**)

**Illustrative Cell**



**Modelled cell size ~97 sq. mi (~253 sq. km)**
*100 HUs in a cell → ~1 HU per sq. mi*

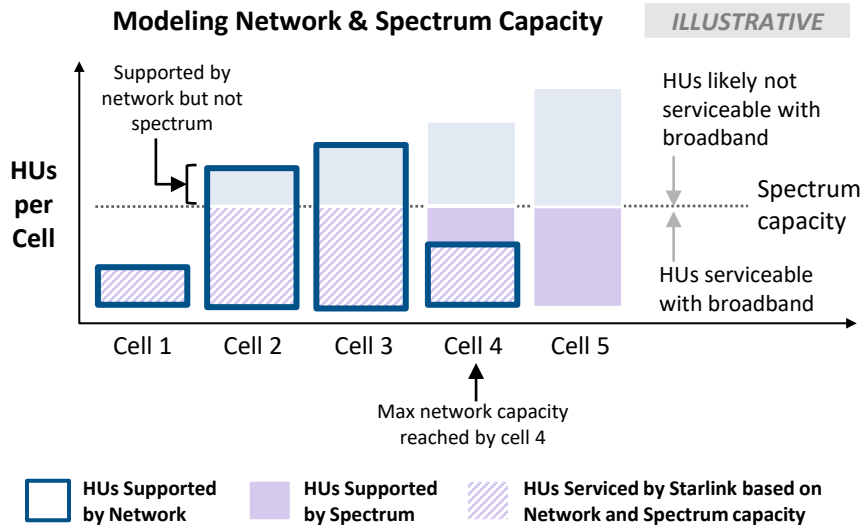
- LEO satellites use a radio plan based on hexagonal cells
- The satellites allocate available radio spectrum between neighboring cells
- The capacity per cell is based on the spectrum allocation; this places a limit on the number of subscribers that can be served in a local area
- There is a finite amount of radio spectrum available for satellite use cases

The model finds the max. subscribers that meet the **network capacity** and **spectrum capacity** limits

## Example Model Simulation

### The two constraints in our model work as illustrated below:

Starlink can deliver broadband to the max number of serviceable HUs per cell (spectrum capacity), up until the max network capacity is reached




- If spectrum capacity (across all cells) exceeds network capacity, the network is ***network constrained***
- If network capacity exceeds spectrum capacity (across all cells), the network is ***spectrum constrained***

Source: Cartesian





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# 2 LEO Serviceability | Findings Overview

We estimate Starlink can provide broadband service to 2.0M US HUs at present, rising to 5.5M by 2030 due to increased fleet size and an assumed increase in authorized spectrum

## KEY QUESTION

**How many US Housing Units (HUs) can Starlink's network support with 100/20Mbps service given estimated network and spectrum capacity constraints?**

## CARTESIAN MODEL FINDINGS[1]

### We estimate Starlink's network can serve up to 2.0M HUs with 100/20Mbps speeds

- **Network Capacity of 2.0M HUs:** In order to achieve the network capacity of 2.0M, subscribers must be geographically distributed as to not exceed spectrum capacity in any given area
- **Spectrum Constraints:** Current spectrum allocations constrain Starlink to 114 HUs per cell (i.e., service group) – or ~1 HU per sq. mile – without risking service speeds below 100/20Mbps
- **Incremental Capacity for Additional Subscribers**: Given Starlink has ~1.4M existing subs, the network can support up to 0.6M additional HUs (of which includes up to 344K BEAD-Eligible HUs), before reaching its total capacity of 2.0M HUs

### By 2030, we estimate Starlink could serve up to 5.5M HUs with 100/20Mbps speeds[2]

- **2030 Model Assumes Network & Spectrum Capacity Improvements**: This estimate accounts for transition to V2 Gen with a fleet of 1.3K satellites over the US at any given time (30K launched globally, 26K active fleet), improved spectral efficiency, dual polarization capabilities, and full usage of authorized Ku/Ka spectrum for UT connections (V & E bands for gateway)
- **Network Capacity of 7.3M HUs**: Starlink's network could support up to 7.3M HUs; however, spectrum capacity caps serviceability at 5.5M HUs (up to 255 HUs per cell – or ~3 HU/sq. mi), beyond which speeds may degrade below 100/20Mbps
- **Limited Capacity for Additional Subscribers**: Forecasting 4.2M subs by 2030, the network could support up to 1.3M incremental HUs (which includes up to 670K BEAD-Eligible HUs) before reaching capacity limits (total 5.5M HUs)

1. Findings based on modeling for contiguous US only; 2. For a hypothetical 1Gbps/500Mbps speed tier, we estimate Starlink could serve up to 4.5M housing units due to spectrum constraints
Source: FCC DATA Maps filing as of 12/31/23 accessed 5/28/24, Starlink, Cartesian





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# 2 LEO Serviceability | Model Approach

Network capacity, available spectrum, and consumer bandwidth are key determinants of LEO serviceability

**To estimate the total housing units (HUs) supported by Starlink, we evaluated the two primary constraints against consumer bandwidth:**

| Model Input: | A Available Spectrum (CONSTRAINT) *Radio frequencies authorized for use by Starlink for satellite communications* | B Network Capacity (CONSTRAINT) *Max amount of data that can be transmitted by entire satellite fleet* | C Consumer Bandwidth *Bandwidth needed to deliver a given speed tier to consumers in a service group* |
|---|---|---|---|
| **Input Considerations:** | • FCC authorizations for spectrum<br>• Intended use of frequency bands for User Terminal connections<br>• Number of channels and polarizations<br>• Spectral efficiency of satellites to utilize avail. spectrum | • Satellite generation<br>• Current mix of generations in orbit<br>• Est. number of operational satellites (less than total satellites)<br>• Number of satellites over the US at any given time | • Speed tier (100/20Mbps)<br>• Est. Quality of Experience (QoE)<br>• Average bandwidth used by consumers at peaks hours |
| **Primary Impact on Model:** | **Used to estimate max serviceable HUs in a cell supported by spectrum** | **Used to estimate max HUs across all cells supported by network** | **Used as input to estimate spectrum & network max serviceable HUs** |
| **Model Steps:** | 1. Calculated Max Capacity per Cell (pg. 17)<br>2. Calculated Serviceable HUs per Cell (pg. 18)<br>3. Aggregated HUs at cell-level using FCC BSL Data<br>4. Determined how many HUs are serviceable by spectrum (pg. 18) | 1. Calculated Max Network Capacity based on fleet size and satellite generation mix (pg. 19)<br>2. Determined how many HUs are serviceable by network (pg. 20) | 1. Determine bandwidth per user at the 100/20Mbps service tier[1] (pg. 18)<br>2. Used bandwidth per user as input to Available Spectrum Step 2 and Network Capacity Step 2 |

1. Based on capacity network engineering formula Note: All model considerations based on publicly available information; may not reflect all factors that impact overall system / spectrum capabilities
Source: Cartesian





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# 2 LEO Serviceability | Model Inputs

Several of the input assumptions change between the 2024 and 2030 modeling scenarios

**We est. increased Starlink spectrum & network capacity by 2030, assuming network improvements which are reflected in modeling components:**

**Model Input:**

## A Available Spectrum — CONSTRAINT

*Radio frequencies authorized for use by Starlink for satellite communications*

**Modeling Components:**

| | 2024 YE | 2030 YE |
|---|---|---|
| **Spectrum Band for User Links (Downlink)** | Ku 2000MHz | ↑ Ku + Ka 5100MHz |
| **Channels (#)** | 8 | 8 |
| **Polarizations (#)** | 1 | ↑ 2 |
| **Spectral Efficiency (bps/Hz)** | 3.9 | ↑ 4.5 |

*Additional authorized frequency bands, dual polarization, and improved spectral efficiency is estimated to result in:*

**Impact on Model by 2030:** **Increased spectrum capacity**

## B Network Capacity — CONSTRAINT

*Max amount of data that can be transmitted by entire satellite fleet*

| | 2024 YE | 2030 YE |
|---|---|---|
| **US Fleet Size (# Satellites)** | 298 | ↑ 1301 |
| **Est. Capacity per Sat[1] (Gbps)** | 50 | ↑ 124 |

*More satellites with higher capacity per satellite is estimated to result in:*

**Impact on Model by 2030:** **Increased network capacity**

## C Consumer Bandwidth

*Bandwidth needed to deliver a given speed tier to consumers in a service group*

| | 2024 YE | 2030 YE |
|---|---|---|
| **Service Tier (Mbps)** | 100/20 | 100/20 |
| **Avg Peak Hr Demand (Mbps)** | 7.4 | ↑ 22 |

*Increased expected consumer demand at average peak hours estimated to result in:*

**Impact on Model by 2030:** **Higher capacity demands**

1.. Satellite capacity in the model is calculated at the generation level, weighted capacity per satellite shown here to provide concept of model input variability
Note: All model considerations based on publicly available information; may not reflect all factors that impact overall system / spectrum capabilities
Source: FCC DATA Maps filing as of 12/31/23 accessed 5/28/24, Starlink, Cartesian

↑ Raises capacity estimate ↑ Lowers capacity estimate





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# 2 LEO Serviceability | A Max Spectrum Available per Cell

The maximum capacity per cell is determined by the spectrum allocation and achievable spectral efficiency

## Spectral Efficiency

Determined by Modulation Scheme & FEC/Code Rate

*Model assumes improvements in V2 sats.*

| Generation: | V1 | V2 |
|---|---|---|
| Modulation[6]: | 16-32APSK | 64QAM |
| FEC: | 75%-90% | 77% |
| Spectral Efficiency: | ~3.5 bps/Hz | ~4.5 bps/Hz |
| Spectral Efficiency: | Calculate weighted avg. by generation per year | |

## Cell

Service area sized as H3 Hexagon Res 5 (~253km$^2$); approximately the same size as Starlink's actual cells

| | 2024 *Current Spectrum[1]* | | 2030 *Expected Spectrum[2]* | |
|---|---|---|---|---|
| | **Downlink** | **Uplink** | **Downlink** | **Uplink** |
| **Available Spectrum** *Frequency range available to user links given authorized spectrum bands* | 2000 MHz | 500 MHz | 5100 MHz | 1500 MHz |
| ÷ | | | | |
| **Channels** *Spectrum is split into 8 separate channels which can be assigned to cells in spot beams* | 8 Channels | 8 Channels | 8 Channels | 8 Channels |
| **Spectrum Per Channel[3]** *Spectrum allocated to each channel; assumes 1 channel per cell* | 250 MHz | 63 MHz | 638 MHz | 188 MHz |
| × | | | | |
| **Number of Polarizations** *By 2030, we assume dual polarization doubles the effective capacity of each cell[4]* | 1 | 1 | 2 | 2 |
| × | | | | |
| **Starlink Spectral Efficiency[5]** *Measures how much data can be transmitted over the available spectrum* | 3.9 bps/Hz | 3.9 bps/Hz | 4.5 bps/Hz | 4.5 bps/Hz |
| **Max Capacity Available Per Cell** *Max theoretical bandwidth capacity available for any given cell* | 964 Mbps | 241 Mbps | 5730 Mbps | 1685 Mbps |

1. Starlink may be operating with more spectrum at present for some V2 Mini satellites; 2. Assumes Starlink is granted permission to use and uses all authorized Ku/Ka bands for user links, in actuality, Starlink may split between gateway and user links; assumes that Starlink does not use authorized V and E bands for user links given commercial infancy of bands and likely required changes to user terminals to support higher frequency ranges; See Appendix view 'Starlink Spectrum Authorizations' for detail; 3.Model does not consider dynamic allocation of capacity across cells; model assumes 1 channel per cell; 4. V2 satellites are expected to use dual polarization with 64QAM modulation; 5. Spectral efficiency is weighted average depending on satellite generation mix for each given year; spectral efficiency has direct impact on Max Capacity Avail Per Cell (see Appendix view 'Spectrum Capacity Components' for detail); 6. Use of more efficient 64-QAM modulation technique will require higher signal-to noise ratios

Note: All model considerations based on publicly available information; may not reflect all factors that impact overall system / spectrum capabilities

Source: ICAIIT, SpaceX FCC Filings, Cartesian





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# 2 LEO Serviceability | A HUs Supportable by Spectrum

Dividing the cell capacity by the bandwidth per user determines the max number of housing units per cell

***What the spectrum can support:***

**How many housing units per cell can be served with 100/20Mbs speed tier given authorized spectrum?**

*Capacity per cell (calculated from available spectrum) determines the max number of users in a cell that can be supported with reliable broadband speeds; this is estimated using a traffic engineering formula, using each cell as a serviceable area[1]*

| | 2024[2] YE | 2030[3] YE |
|---|---|---|
| *Capacity per cell (Mbps)* → **A** **Max Capacity Available Per Cell (Mbps)**<br>*Cell capacity based on spectrum allocation, see previous slide* | 964 | 5,730 |
| − | − | − |
| **QoE Burst (Mbps)**<br>*Headroom maintain Quality of Experience during bursts in demand based on speed tier; we assume 100Mbps to align with broadband definition* | 100 | 100 |
| − | − | − |
| **QoE Ripple[2] (Mbps)**<br>*Capacity to maintain Quality of Experience during short-term ripples in demand. Set at 20% for the 100Mbps Service Tier (20% x 100Mbps = 20Mbps)* | 20 | 20 |
| *Consumer Bandwidth (Mbps per HU) applied against cell capacity* → **C** **Remaining Capacity Per Cell (Mbps)**<br>*Bandwidth capacity required for any given cell after accounting for burst and QoE* | 844 | 5,610 |
| ÷ | ÷ | ÷ |
| **Average Peak Hour HU Demand[3] (Mbps per HU)** | 7.4 | 22 |
| = | = | = |
| *Results in serviceable HUs per cell* → **Max HUs per Cell Supported by Spectrum**<br>*Cell equates to ~97 square miles* | **114 HUs**<br>~1 HU per square mile | **255 HUs**<br>~2.5 HUs per square mile |
| **Max HUs Supported by Spectrum**<br>*HUs per cell (up to 114 in 2024 and 255 in 2030) x Num. Cells* | **2.3M** | **5.5M** |

1. See Appendix View 'Capacity Planning' for detail on calculation/formula; 2. SCTE traffic engineering formula reports that QoE factor to absorb short-term ripples in demand is typically up to 20% to provide reliable service.; 3. See Appendix view 'Consumer Bandwidth & Peak Hour Demand' for detail. Note: All model considerations based on publicly available information; may not reflect all factors that impact overall system / spectrum capabilities

Source: FCC Filings, Satellite Map, The Tesla Space, Teslarati, Starlink Insider, PC Mag, SCTE Broadband Capacity Growth Models (2022), Cartesian





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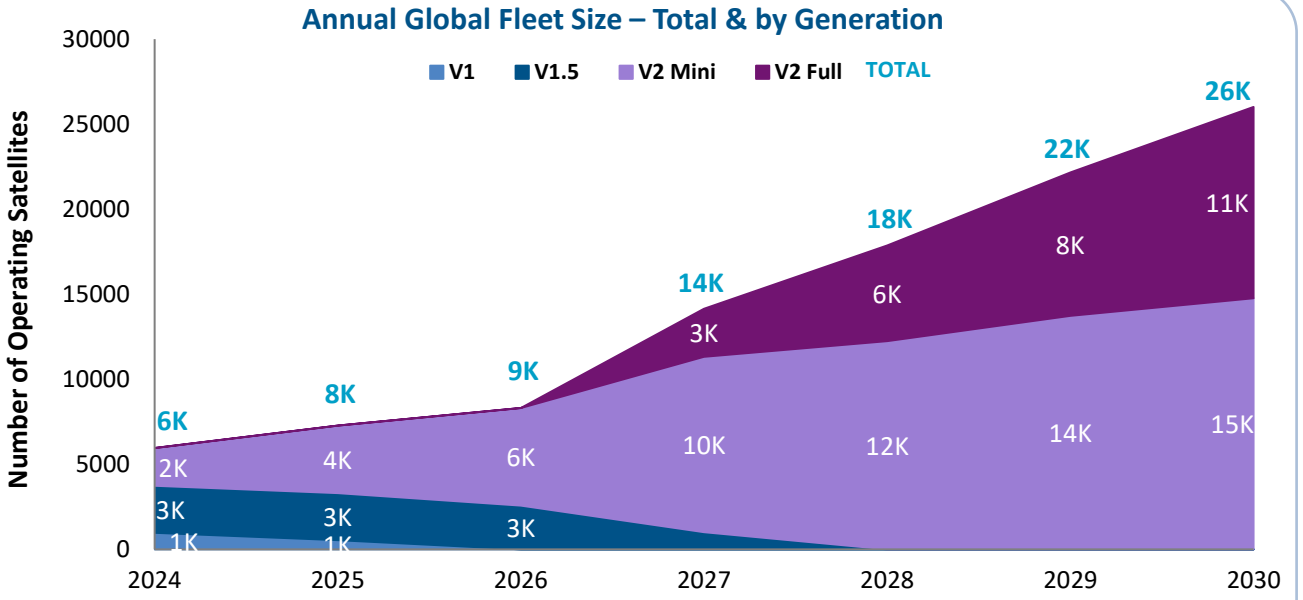
# 2 LEO Serviceability | B Network Capacity per US Fleet

Fleet size and satellite generation determines capacity across the entire network

## 1) GLOBAL STARLINK FLEET BY YEAR

Estimate annual fleet size and make up of satellites covering the contiguous US

**Global Fleet Size:** Existing Active Satellites[1] + Planned Launches[2] − End of Life Satellites[3] = Annual Global Fleet Size




▶ **We assume 5% of global fleet to be available to US based on contiguous US share of total surface area[4]**

## 2) STARLINK DOWNLINK CAPACITY – US FLEET[3]

Estimate total network capacity across all satellites in orbit over US

| Satellite Generation | Satellite Capacity (Gbps) | 2024 YE | | 2030 YE | |
|---|---|---|---|---|---|
| | | Num Satellites | Total Capacity (Gbps) | Num Satellites | Total Capacity (Gbps) |
| V1[5] | 20 | 49 | 983 | 0 | 0 |
| V1.5[6] | 24 | 138 | 3,314 | 0 | 0 |
| V2 Mini[6] | 96 | 111 | 10,613 | 739 | 70,896 |
| V2 Full[7] | 160 | 0 | 0 | 562 | 89,952 |
| **Total Network Cap.** | - | **298** | **14,910** | **1,301** | **160,848** |

Starlink's US fleet theoretically supports up to **14.9 Tbps** over the US at present and **161 Tbps** by 2030. However, this may be constrained by ground station capacity.

1. Active satellites determined by satellites in Operation Orbit, which is more accurate for estimating capacity and lower than the number of total working satellites (~7K). Global fleet includes reported 350 satellites for Direct to Cell (per Starlink Progress Report); 2. Fleet forecasted by splitting remainder of 7.5K (approved by FCC) fleet over 3 years for V2 Minis, remaining 22488 (yet to be approved by FCC) satellites launches distributed evenly 2027-2030, split across V2 Mini and Full Size, see Appendix view 'Global Forecasted Starlink Fleet' for methodology detail; 3. Assumed satellite lifespan of 5 years based on V1 generation, assumes same lifespan for V2; 4. US fleet size estimated based on share of global fleet covering US at any given time, calculated as surface area of contiguous US (excl. AK, HI and territories) plus a 300-500km buffer (due to beams that can cover US from outside US borders) divided by Earth's surface area (5% US share); 5. Satellite capacity est. per Starlink Insider analysis of public filings and assumptions from satellite dimensions/capabilities, posted on 01/16/2024; 6. Starlink satellite capacity estimates per Starlink 2024 Progress Report 7. High end of satellite capacity (140-160Gbps) estimates per Teslarati based on public comments from Elon Musk during 2022 interview. V3 Satellites not included in model due lack of information on satellite capabilities, launch timing, fleet size, etc. 2024 Progress Report claims 1Tbps capacity per satellite (see Appendix View 'Starlink V3 Satellite Generation' for detail), but increased throughput will not impact model outcomes due to spectrum constraints

Note: All model considerations based on publicly available information; may not reflect all factors that impact overall system / spectrum capabilities

Source: FCC Filings, Satellite Map, Jonathan's Space Pages, Teslarati, Starlink Insider, The Tesla Space, PC Mag, Cartesian





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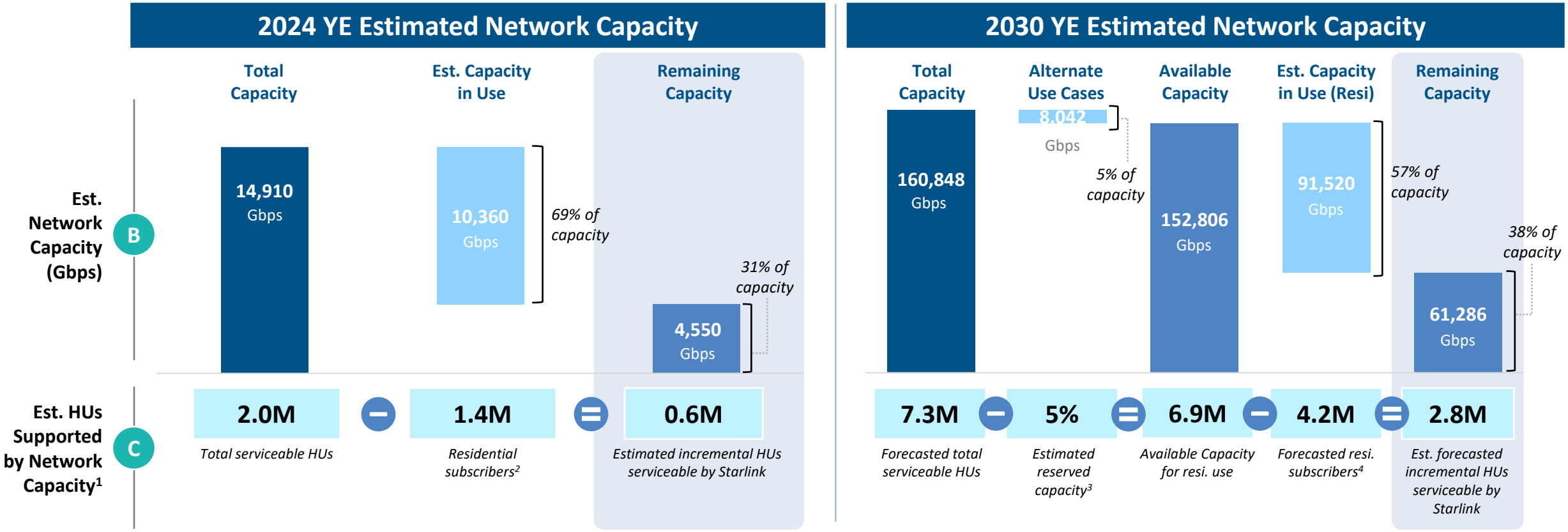
# 2 LEO Serviceability | B HUs Supportable by Network

Dividing the network capacity by bandwidth per user determines the max number of HUs the network could support in the contiguous US (assuming any spectrum constraints were overcome)

***What the system can support:***

**How many housing units can be served with 100/20Mbps speed tier given the network capacity?**

Each satellite has a a given capacity limit; across the system, the total capacity (measured in Gbps) provides an upper limit on the max users at a given speed tier




1. Est. subs calculated assuming each HU demands 7.4Mbps (2024) / 22Mbps (2030) at peak hours on average; 2. 1.4M as of August 2024 reported by Advanced Television, per SpaceX communications to the FCC; total global subscribers of 3.3M per SpaceX; see Appendix View 'Starlink US Residential Subscribers' for detail; 3. Assumes 5% capacity used for alternative use cases (includes aviation, maritime, rail, etc.). See Appendix View 'Alternate Use Cases' for further detail; 4. Morgan Stanley predicted Starlink to have 6M US subscribers by 2040; we estimated 60% of the incremental 4.6M (2040 6M – current 1.4M) to be split evenly across 2025-2030; see Appendix View 'Starlink Subscribers' for detail

Note: All model considerations based on publicly available information; may not reflect all factors that impact overall system / spectrum capabilities

Source: Advanced Television, CommScope, Cartesian, Morgan Stanley, Payload Space





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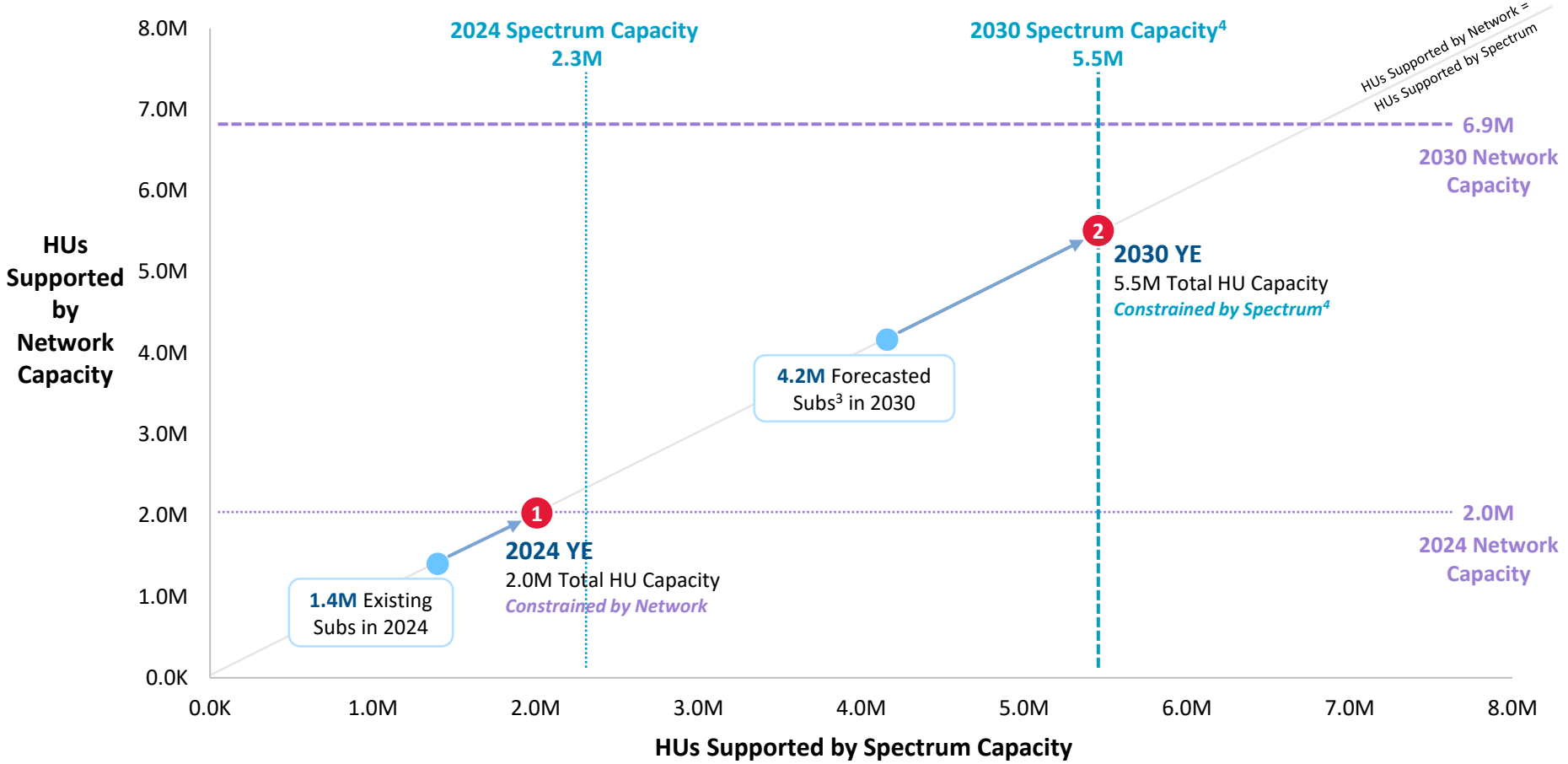
# 2 LEO Serviceability | Model Estimate Results (2024, 2030 Year-End)

Starlink is estimated to support up to 2.0M US housing units in 2024 and up to 5.5M housing units by 2030

## Estimated US Housing Units[1,2] Serviceable by Starlink with Broadband Speeds (100/20Mbps)

2024, 2030 Year-End (YE)

**Starlink can serve incremental HUs until *network* or *spectrum* capacity is reached**




### 1 2024 YE Capacity

- Starlink currently has ~1.4M US subs
- We estimate that Starlink can support 2.0M HUs at 100/20Mbps before it reaches the network capacity limit
- This implies potential for 0.6M incremental HUs at 100/20Mbps

### 2 2030 YE Capacity

- Starlink is forecasted to reach 4.2M US subscribers by 2030
- We estimate Starlink can continue adding subscribers until limits of spectrum capacity reached (5.5M HUs)
- This implies potential for 1.3M incremental HUs[5] is at 100/20Mbps

**Est. Existing/Forecasted Subs**
**Est. Total Serviceable HUs**
**Est. Incr. Serviceable HUs**

1. Applied 1.27x multiplier to translate FCC Locations (BSLs) to Housing Units; 2. US Housing Units only include contiguous US (excludes AK, HI and territories); 3. Based on forecasted 4.2M residential subscribers, see Appendix View 'Starlink US Residential Subscribers' for detail; 4. Assumes all assigned Ka/Ku bands used for user terminal connections and V/E bands used for gateway links; 5. Incremental subs is directly impacted by how many existing subscribers Starlink will have in 2030, see Appendix View '2030 Existing Subs Sensitivities' for sensitivity analysis
Source: Cartesian, FCC DATA Maps filing as of 12/31/23 updated 5/28/24





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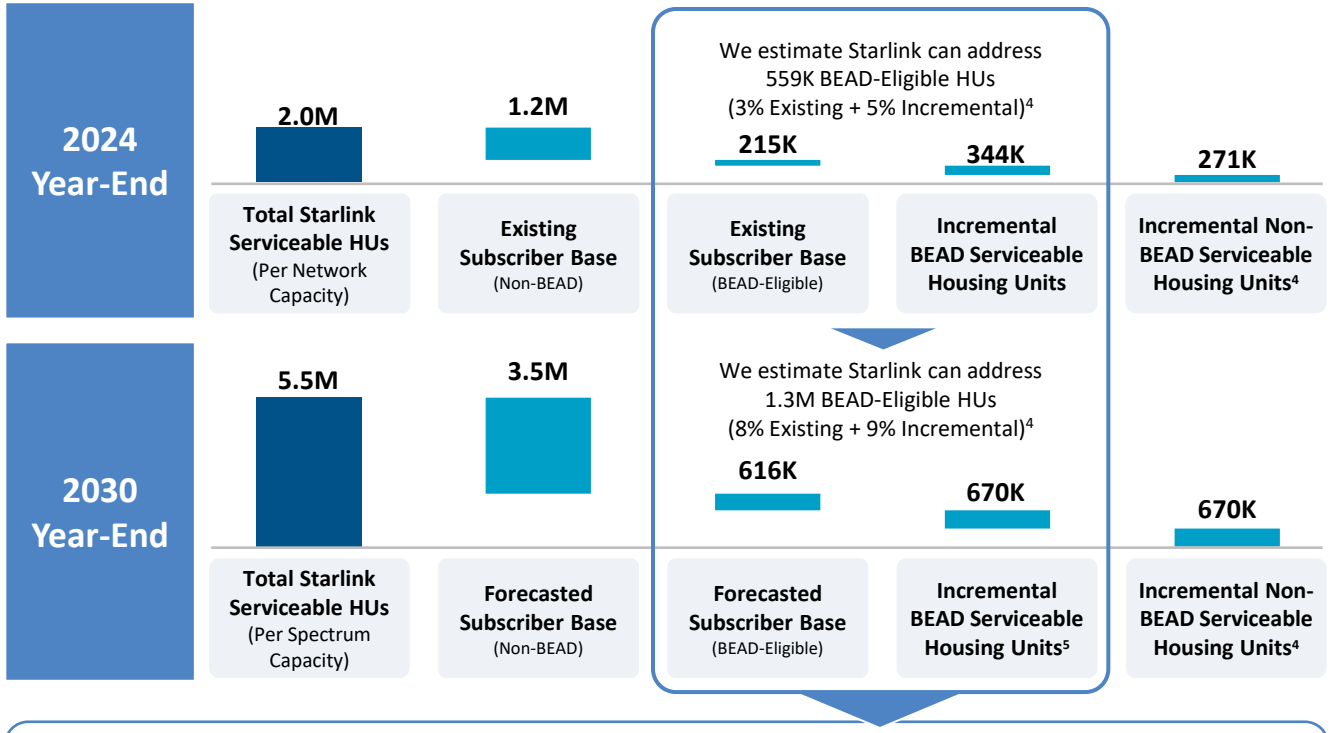
# 2 LEO Serviceability | Estimated Serviceability of BEAD Locations

Due to uneven geographic distribution, we est. 5% of BEAD HUs to be incrementally Starlink serviceable in 2024

## BEAD-Eligible Housing Units

**There are approx. 7.4M BEAD-Eligible housing units in the US[1,2]**

*A BEAD-eligible location is one that does not have access to a low-latency broadband service of at least 100/20Mbps speeds on a wireline or licensed fixed wireless network[3]*



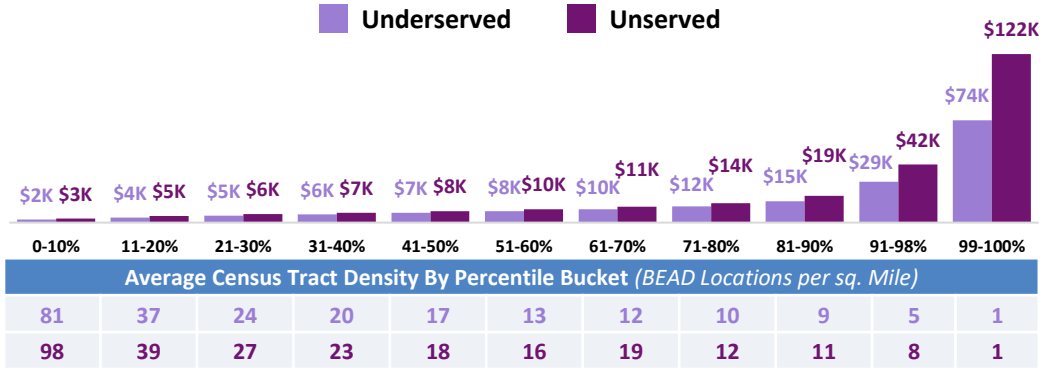

**Due to uneven distribution across cells, only some BEAD HUs are incr. serviceable by Starlink**

Cells in which demand outstrips the spectrum capacity will not have all HUs served at 100/20M

## Deployment for BEAD-Eligible Housing Units

### Fiber Deployment Cost per Location

Segmented by BEAD Location Density[6]




- Fiber deployment costs are highest in areas with low housing density as shown on the chart above
- Standalone FWA deployments are also more expensive in sparsely populated areas
- FWA from mobile networks is limited to areas with cellular/5G coverage

**LEO satellite provides coverage in the most remote locations and may be a more economical solution in these areas than terrestrial networks**

1. Applied 1.27x multiplier to translate FCC Locations (BSLs) to Housing Units; 2. Excludes BEAD-Eligible locations in US Territories, Alaska and Hawaii; 3. By definition, internet subscribers to Starlink – an LEO satellite provider – are BEAD-Eligible, assuming they don't have access to 100/20Mbps+ terrestrial broadband; 4. See Appendix view 'BEAD Serviceable Housing Units by State' (2024 or 2030) to see distribution of existing BEAD sub and incremental BEAD serviceable housing unit distribution by state; 5. In Starlink's best case scenario where they prioritize BEAD housing units and do not account for existing subscriber base, we estimated 3.2M BEAD-eligible housing units, see Appendix view '2030 Starlink Best Case BEAD Serviceability' for details 6. Chart values are average cost per location for each percentile bucket per proprietary Cartesian Fiber Cost Model / Cartesian BEAD Funding National Overview v5.0
Source: Cartesian, FCC





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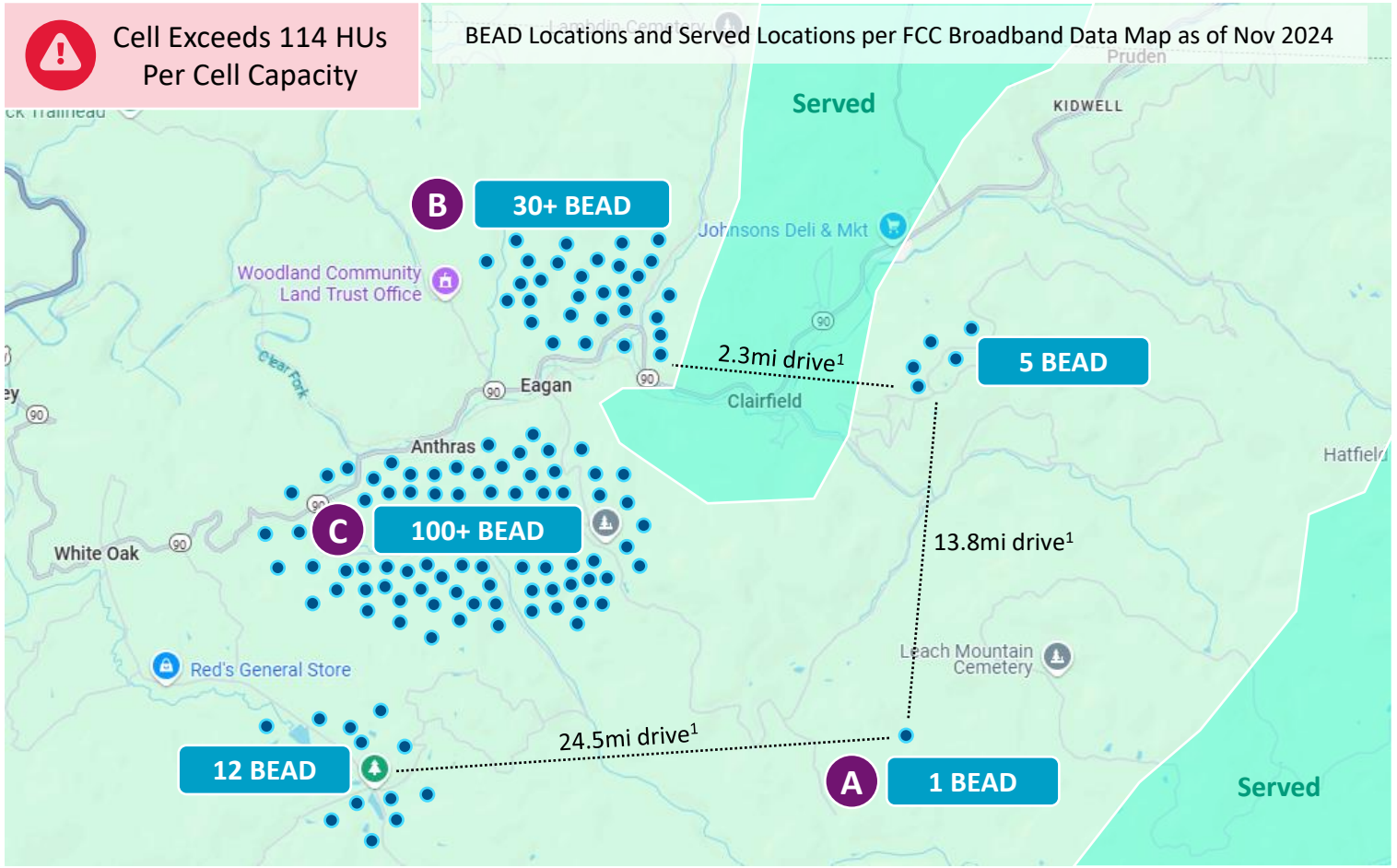
# 2 LEO Serviceability | BEAD Deployment Example

Due to limited capacity, LEO satellite broadband is best positioned for the most isolated locations

## Example Service Area: Near Clairfield, TN

Zip codes 37715, 37729; 42sqmi or 43% of a Cell




## BEAD Location Analysis

### Location density and geographic spread impact terrestrial network deployment costs

**A** **Very Small Cluster, Geographically Isolated**

Isolated BEAD locations that are far from served locations and other BEAD clusters are likely most suited to LEO without exceeding capacity limits.

**B** **Small Cluster, Close to Existing Infrastructure**

Smaller clusters of BEAD locations near served locations may be serviceable with terrestrial technologies due to proximity to existing network

**C** **Large Cluster, Geographically Isolated**

Clusters of BEAD locations that are somewhat isolated may still be economical to reach for terrestrial technology deployment if cluster is large enough

*Using terrestrial technologies when available will preserve LEO capacity for where it is most useful*

1. Drive distance serves as a reasonable proxy for fiber deployment distances

Source: Cartesian, FCC Location Summary Map as of 11/25/2024, Google Maps





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# Contents





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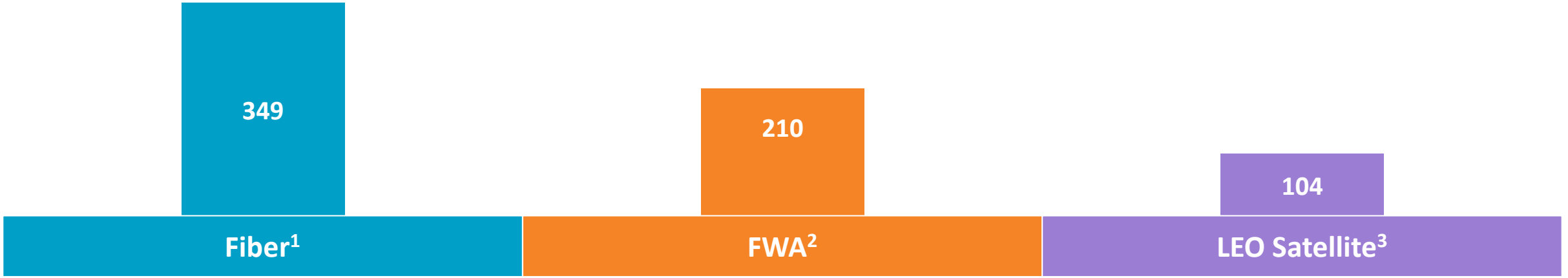
# 3 Service Performance | Typical Consumer Speeds

LEO satellite subscribers currently receive below market speeds compared to other technologies

## Reported Median Download Speeds (Mbps)

*Selected Examples by Technology from US Providers*




**Fiber[1]**

- **Technical Capabilities:** Fiber optic technology delivers very high data rates (multiple Gbps) and low error rates
- **Network Planning:** Fiber networks can be dimensioned to serve entire communities at peak load
- **Reliability:** Fiber is not subject to electro-magnetic interference or drop in performance due to weather

**FWA[2]**

- **Line-of-Sight:** For best performance, requires unobstructed view of tower; trees/foliage can reduce speeds
- **Network Planning:** May encounter congestion in peak hours in dense service areas

**LEO Satellite[3]**

- **User Density:** Cell capacity shared over wide area results in much lower capacity allocated per user
- **Weather:** High radio frequencies are vulnerable to weather (e.g., rain)
- **Line-of-Sight:** For best performance, system requires unobstructed view of sky; trees/foliage can reduce speeds

**As these are median figures, measured speed is lower in half of cases – i.e., often below 100Mbps for LEO**

1. Per Ookla speed test of AT&T Fiber as of June 2024. Based on median speeds users experience across all plans, not speed tests of fastest speeds offered; 2. Per US 5G Median Download Speeds as of Q1 2024, using average of provider median download speeds (T-Mobile ~275Mbps, Verizon ~215Mbps, AT&T ~140Mbps); 3. Based on US Starlink median download speeds from Starlink 2024 Progress Report
Source: Ookla, Starlink 2024 Progress Report, Cartesian





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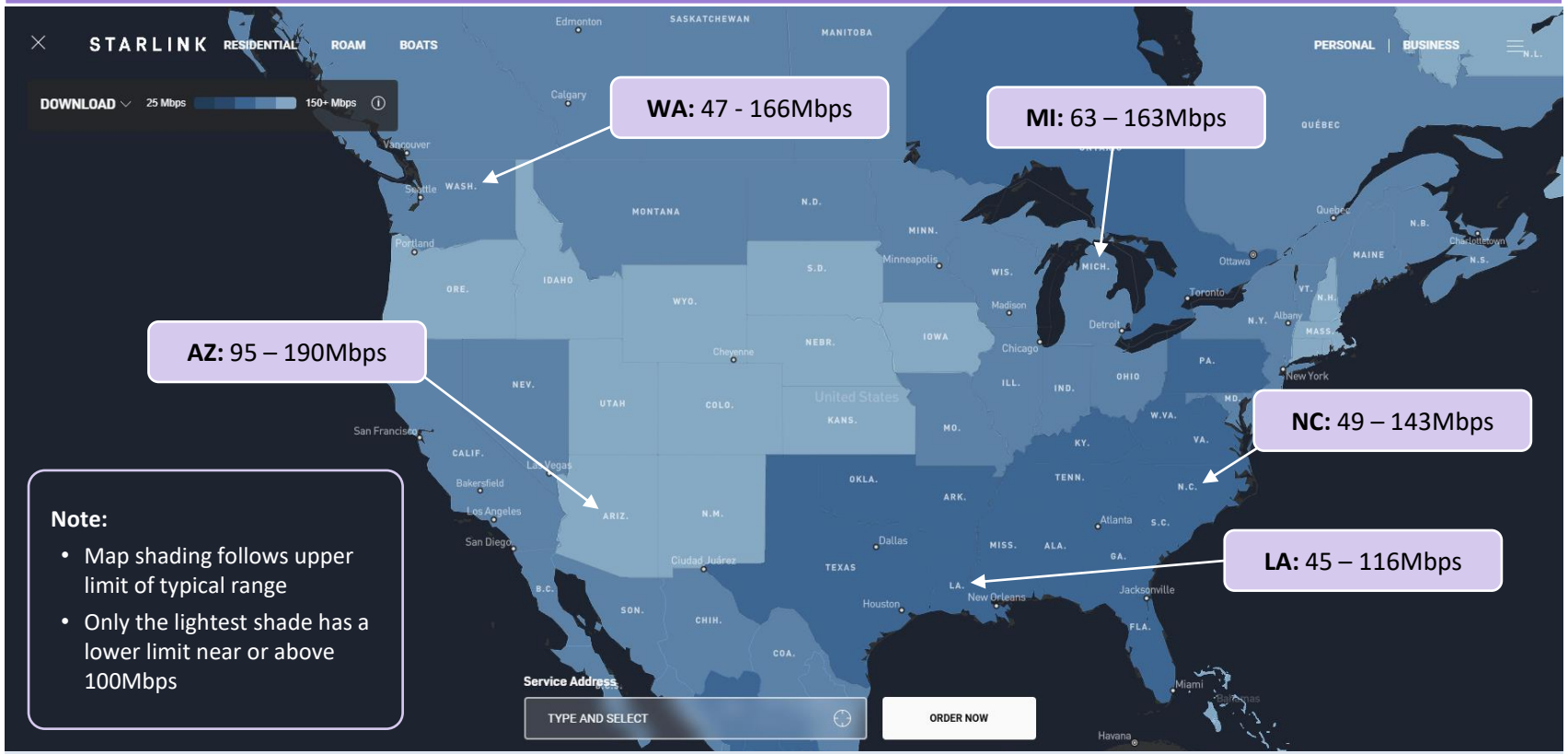
# 3 Service Performance | Starlink-Reported Speeds

Starlink regularly reports delivered speeds below 100Mbps to large areas of the country; this is in line with our modeling that Starlink has limited incremental capacity to widely deliver a 100/20 Mbps service

## Starlink-Reported Download Speeds (Mbps) for Residential Fixed Service Plan[1]

*As of 11/13/2024 per Starlink*




**Geographic variation in speeds delivered likely due to orbital path, fleet size and density, spectrum restrictions, and subscriber location**

## Takeaways

- **Broadband Requirement Not Met:** Considering the ranges provided, Starlink consumers in most states are likely to receive sub-broadband speeds (<100 Mbps)
- **Further Degradation w/ Growing Subs:** These reported speeds reflect service to Starlink's current subscriber base; adding more subs to the network will likely further degrade service in many geographies
- **Gap Compared to Other Technologies:** Adding more subscribers puts Starlink at risk of creating a larger performance gap and even less likelihood to be able to provide 100/20Mbps services

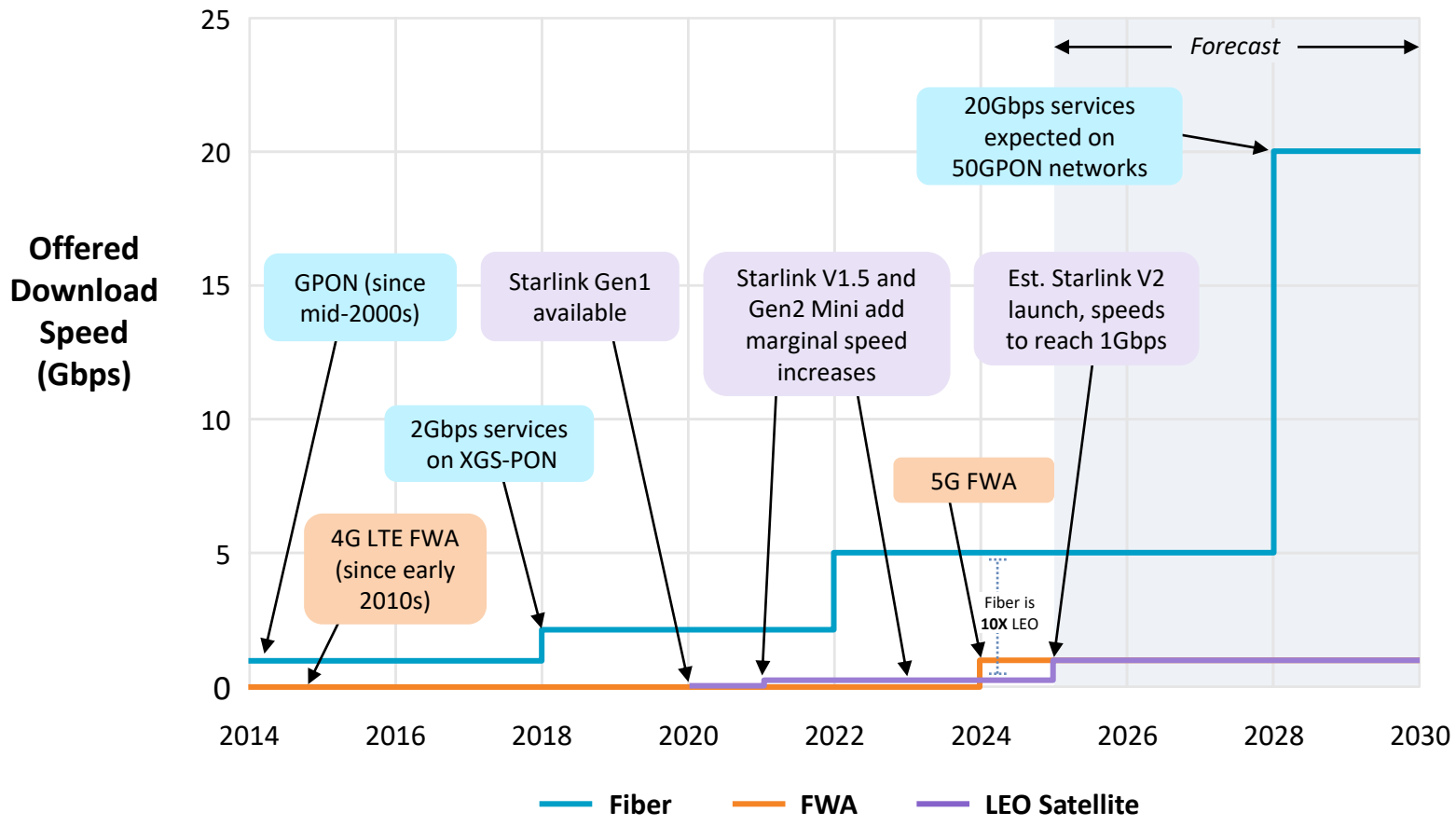
1. Data based on what Starlink claims they deliver; results from Ookla or other independent sources may differ
Source: Starlink speed map as of 11/13/2024 (https://www.starlink.com/map), Cartesian

# 3 Service Performance | Max Consumer Speeds

Fiber outpaces LEO by 10x in max advertised speeds; the gap will continue to widen to 2030 and beyond

## Max Consumer Speeds Offered by Technology (2014 – 2030)

*Based on Expected Technical Advancements*[1]




### Fiber

- 5Gbps services already commercially available
- Speeds will continue to grow at a faster pace due to PON advancements

### FWA

- Speeds of up to 1Gbps available in 2024
- 5G mmWave tech has improved speed, latency, capacity and coverage
- 6G may further improve speeds, specifications mid-development (not displayed in chart)

### LEO Satellite

- Starlink request to FCC claims that 1 Gbps speeds will be achievable with V2 satellite and change to orbital configuration
- Starlink claims they'll be offering 2 Gbps speed tiers in the future (not displayed in chart, timing unknown)
- Expected to also require changes to user terminals

1. Experienced speeds per users may be lower than advertised speeds due to congestion, signal loss, router & equipment limitations

Source: Wired.com, Benton Institute, Cartesian





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# 3 Service Performance | Service Group Capacity Network Planning

Terrestrial technologies have more capacity headroom than our modelled LEO network

## Capacity Headroom By Technology for 100/20 Mbps Offered Speed Tier

Capacity planning typically considers service group capacity, speed tier offered, average peak consumer demand, and number of users per access point, to give the number of users serviceable / Mbps per user

| | LEO Satellite[1]<br>Service Group: Cell | FWA<br>Service Group: Tower Sector | Fiber (XGSPON)<br>Service Group: OLT |
|---|---|---|---|
| **Current Max Capacity[32] (Mbps)** | 964 | 3,200 | 10,000 |
| − **Burst / DS Speed Tier (Mbps)** | 100 | 100 | 100 |
| **QoE Factor** | 20% | 20% | 20% |
| − **QoE Factor (Mbps)** | 20 | 20 | 20 |
| ÷ **Tavg[3] (Mbps)** | 7.4 | 7.4 | 7.4 |
| = **Max Users Per Service Group** | 114 | 416 | 1,335 |
| **Actual Users Per Service Group[4]** | 114 | 100 | 64 |
| **Capacity Headroom vs. Max** | None | 4x | 20x |

**Max Capacity per Service Group:** significantly higher for Fiber and FWA compared to satellite due to shorter distances/stronger signals for FWA and virtually unlimited capacity from optical fibers for Fiber

**Serviceable Users per Service Group:** Higher capacity per service group results in more serviceable users for a given speed tier; FWA and Fiber allow for additional buffer between max and actual users

**Capacity Headroom:** Terrestrial networks are dimensioned with more headroom than LEO, enabling them to better handle unexpected increases in demand

**LEO estimate does not allow for capacity buffer between max and actual serviceable users; running network at maximum capacity increases risk of performance degradation in busy periods**

1. Using Starlink as stand in for LEO, calculated on what spectrum can support per cell; 2. FWA data assumes 80MHz * 10 bps/Hz per link * 4 remote nodes = 3.2Gbps mx theoretical sector capacity per Tarana Wireless G1 vs LEO Whitepaper; 3. Avg demand at peak hours for 2024; 4. FWA data per Nokia reporting that big wireless carriers are seeing close to 100 users per sector
Source: SCTE Broadband Capacity Growth Models (2022), Qualcomm, Cartesian, Tarana Wireless, Nokia





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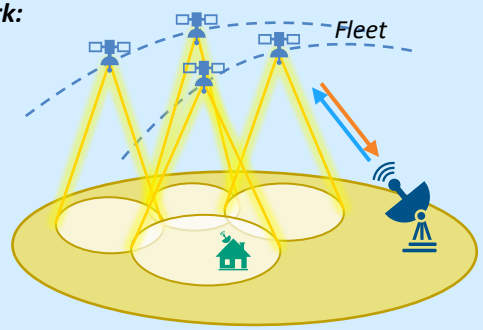
# 3 Service Performance | Capacity Upgrade Path

Increasing satellite capacity requires global fleet upgrades whereas FWA and Fiber can be done on a local basis

## LEO Satellite

***LEO Network:*** ILLUSTRATIVE




**Upgrade paths:**

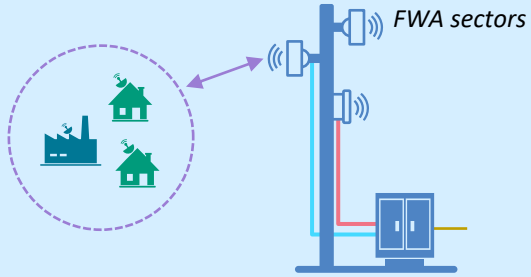
1. Update entire fleet with upgraded capacity; requires global replacement as upgrades cannot be localized
2. Increase number of satellites globally

**Timescale:** Years
**Investment required**: $100Ms

**HIGH EFFORT**

## FWA

***Last Mile Wireless Network:*** ILLUSTRATIVE




**Upgrade paths:**

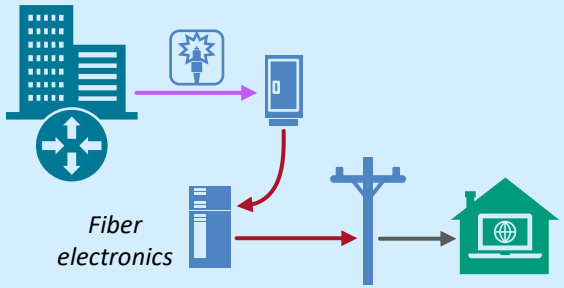
1. Add FWA sectors on existing tower
2. Split the existing cell into smaller cells

**Timescale:** Weeks / Months
**Investment required**: ~$100k per service area

**MEDIUM EFFORT**

## Fiber

***Last Mile Fiber Network:*** ILLUSTRATIVE




**Upgrade paths:**

1. Swap out electronics, able to reuse fiber

**Timescale:** Weeks
**Investment required**: ~$100k per service area

**LOW EFFORT**

**To upgrade capacity across the network:**

Source: Cartesian





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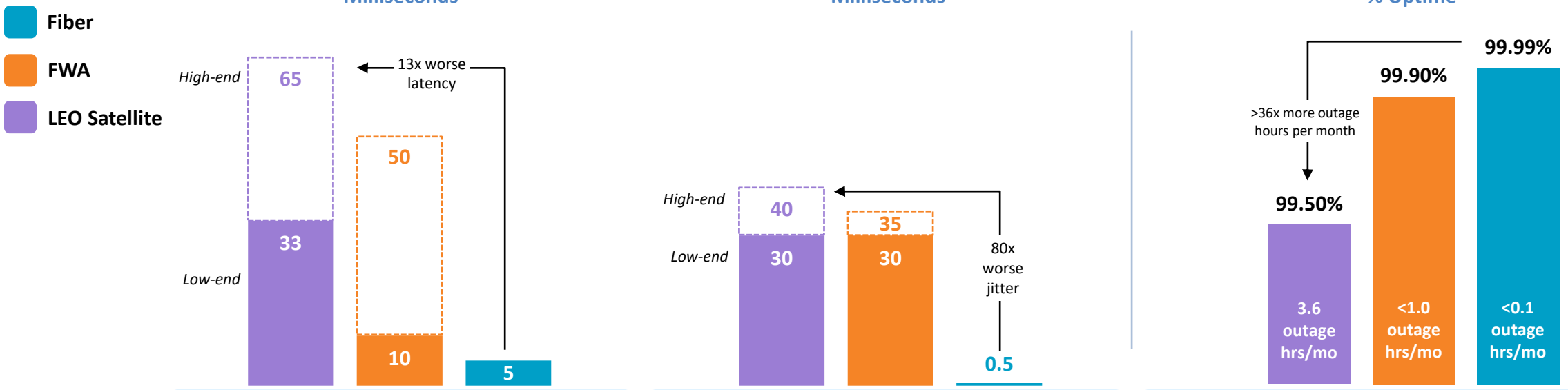
# 3 Service Performance | Latency, Jitter & Uptime

LEO satellite broadband has worse latency, jitter and uptime, which all impact overall service quality

## Estimated Typical Performance by Technology

| | Latency[1,2] – *Delay in data transmission* | Jitter[3] – *Variance in latency* | Network Reliability – *Typical Network Uptime* |
|---|---|---|---|
| | Milliseconds | Milliseconds | % Uptime |




| | | | |
|---|---|---|---|
| **Impact on Consumer:** | **High latency** results in lag for real-time use cases (e.g., gaming) and slower download speeds | **High jitter** results in latency fluctuations, leading to disruptions in voice/video calls, streaming buffers, etc. | **Lower uptime** causes more disruption, meaning connections cannot be relied upon for business-critical applications |
| **Satellite Limitations:** | Data must travel to reach satellites in orbit, causing high latency. Satellite altitude cannot be significantly lowered without encountering greater atmospheric drag. | LEO jitter is largely caused by user terminals switching between satellites as they pass overhead. | Satellite connections are vulnerable to weather (e.g. rain). Outages may also occur due to frequent software updates. |

1. Starlink latency up to 100+ms in remote areas per Wired.com citing Starlink, 2024 Progress Report claims US median latency is 33ms during peak usage hours, while worst-case latency is less than 65ms; 2. Fiber latency 0.005ms/km with assumed 1000km round trip; 3. LEO jitter based on reports from Starlink customers of 30-40ms jitter values during peak usage hours, down to 10ms under optimal conditions
Source: Starlink, teocoaircom.com, M2Optics, CircleID, EngineerIT, Siklu, Businessbroadbandhub, uptime.is.com, Cartesian





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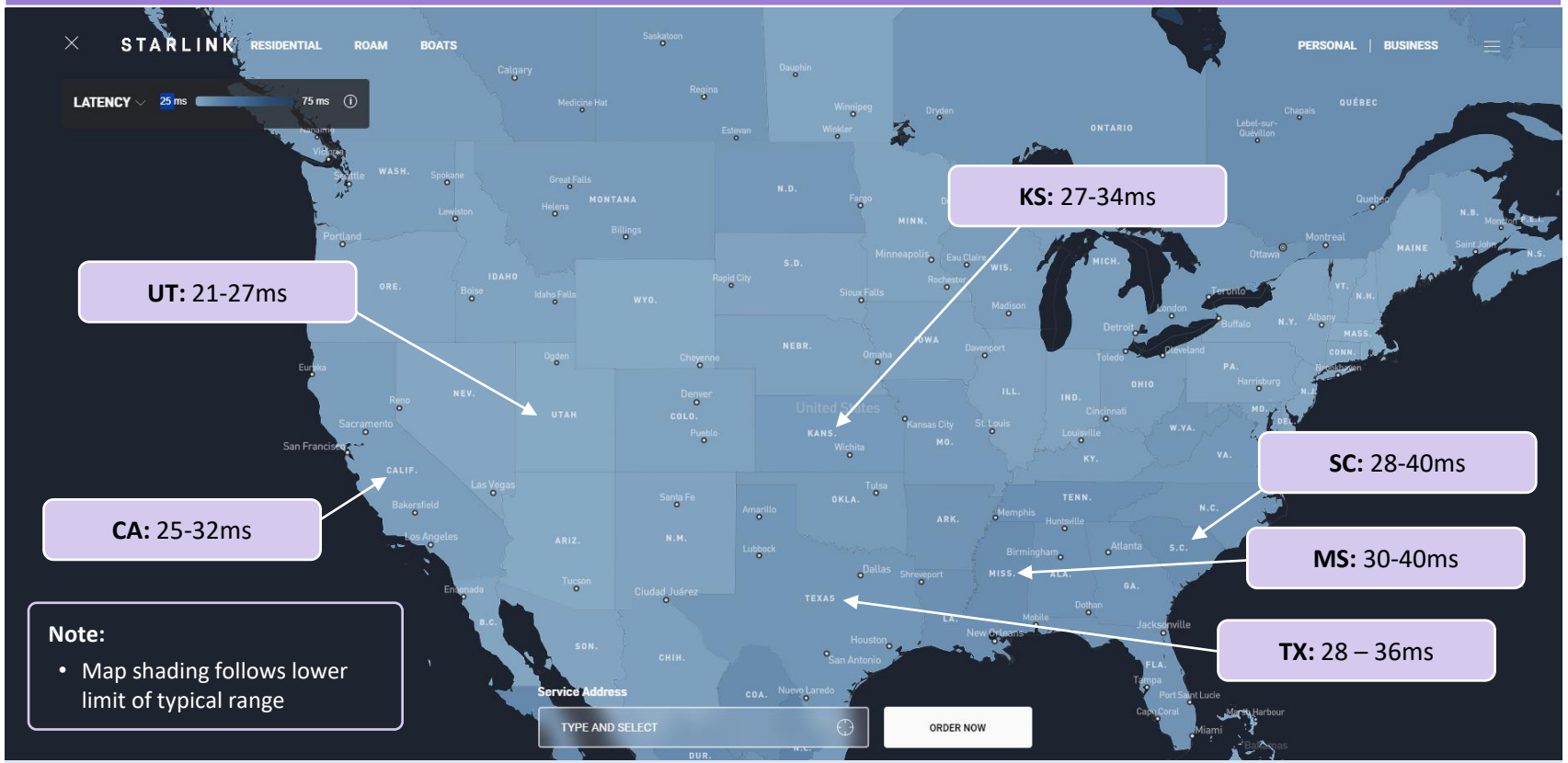
# 3 Service Performance | Starlink-Reported Latency

Starlink reports latency of between 20-40ms to many areas of the country

## Starlink-Reported Latency (ms) for Residential Fixed Service Plan[1]

*As of 11/15/2024 per Starlink*




**Starlink latency varies geographically due to factors including the distribution of ground stations, network congestion, and internet connectivity**

## Takeaways

- **Lowest Starlink Latency Still High:** Considering the ranges provided, consumers are likely to receive latency in the 20 – 30ms range at best
- **Further Congestion w/ Growing Subs:** Adding more subscribers to the network will increase the chance of congestion during peak hours, further increasing latency

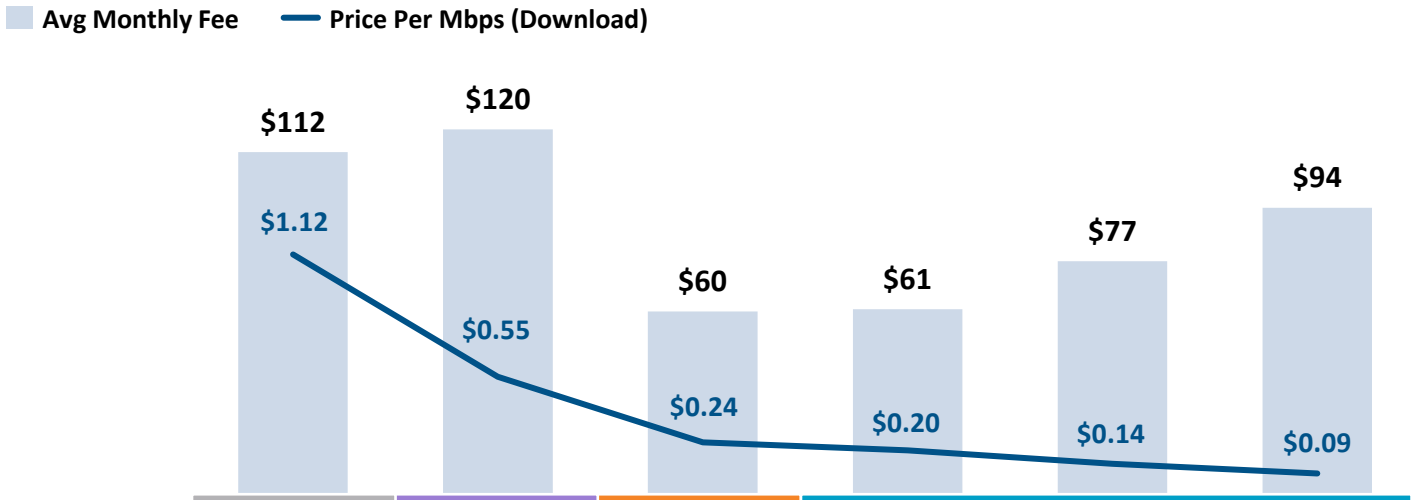
1. Analysis based on Starlink claims; metrics represent the 20th to 80th percentile of real user data
Source: Starlink speed map as of 11/15/2024 (https://www.starlink.com/map?view=latency), Cartesian

# Service Performance | Service Pricing and Performance

Upfront and recurring fees for fiber and fixed wireless are much lower than for LEO broadband services

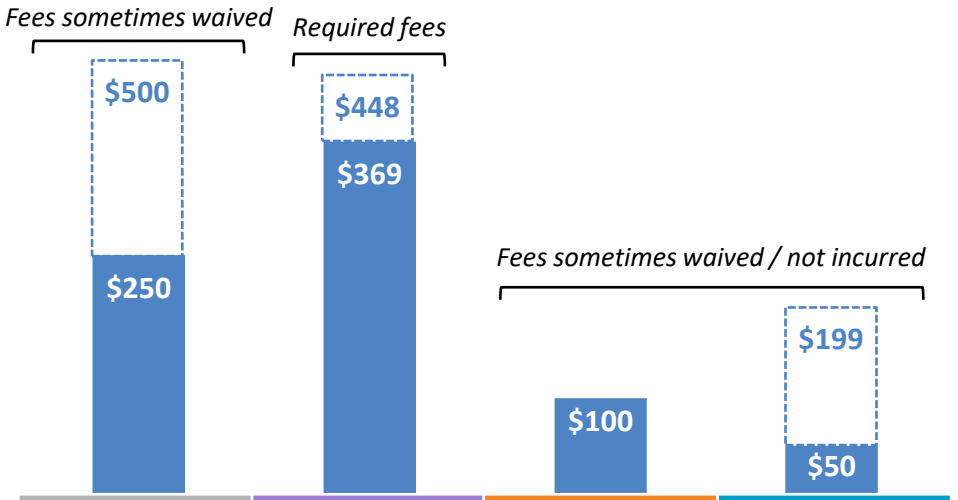
## Service Pricing by Technology

### Average Monthly Fee and Price per Mbps




| | GEO Satellite[2] | LEO Satellite[1] | FWA[3] | Fiber[4] | | |
|---|---|---|---|---|---|---|
| Typical Speed Tier Offered (Mbps) | 100/5 | Up to 220/20[1] | 245/30 | 300/300 | 500/500 | 1000/1000 |

### Non-recurring / Upfront Fees




| GEO Satellite | LEO Satellite[1] | FWA | Fiber |
|---|---|---|---|
| • $250-$300 Equipment<br>• $200 Pro Install *(fee can be lower or waived)* | • $349 Standard kit<br>• $20-$99 Shipping | • $100 Antenna Set-Up *(not a cost for all FWA providers)* | • $50-$100 Activation Fee *(fee is often waived)*<br>• $99 Pro Install *(not incurred if self-install)* |

**Fiber service tiers are a more economic option for broadband consumers, getting symmetrical and more reliable speeds for cheaper than satellite**

**Users face higher upfront one-time fees to access satellite services compared to terrestrial broadband options**

1. Based on advertised Starlink speeds and pricing as of October 2024 for residential service; 2. Based on advertised HughesNet and Viasat speeds and pricing; 3. Based on advertised T-Mobile, Verizon, and AT&T FWA speeds and pricing ($50-$70) as of October 2024; 4. Based on advertised Verizon, AT&T, Optimum, and Frontier fiber pricing as of November 2024 and sample of smaller fibers providers (Ziply, Pella, Seamless, Five Area, Fiber by Central Florida, Ozark, Fort Dodge, Sonic.net) as of December 2024
Source: Cartesian, Provider Websites, CircleID





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# Appendix

## Model Inputs & Assumptions

- Model Assumptions
- Starlink Spectrum Authorizations
- Global Forecasted Starlink Fleet
- Starlink V3 Satellite Generation
- Alternate Use Cases
- Starlink US Residential Subscribers
- Consumer Bandwidth & Peak Hour Demand
- Capacity Planning

## Model Results

- BEAD Serviceable Housing Units by State (2024)
- BEAD Serviceable Housing Units by State (2030)
- Starlink Best Case BEAD Serviceability (2030)

## Model Sensitivities

- Spectrum Capacity Components
- 2030 Existing Subs Sensitivities
- Model Assumptions & Sensitivities

# Appendix | Model Assumptions

The model inputs and calculations contain several important assumptions

## MODEL ASSUMPTIONS

### A Available Spectrum

*CONSTRAINT*

- Service group is a H3 Hexagon Res 5 cell, which is similar in size to Starlink's cells
- Model assumes one dedicated channel per cell based on co-frequency restrictions (Nco = 1), does not account for spatial multiplexing
- 2024 YE model assumes Ku bands for user links; 2030 model assumes Ka/Ku bands for user links
- Certain geographies have restricted spectrum; as a simplifying assumption, the model ignores this additional constraint
- 2024 YE model assumes one polarization based on current UT capability; 2030 YE model assumes full use of dual polarization
- Model assumes improved spectral efficiency by 2030 YE based on expected shift to all V2 satellites in fleet[1]; however, potential for lower spectral efficiency in higher frequency bands

### B Network Capacity

*CONSTRAINT*

- Model does not account for geographic variation in satellite density (and therefore capacity) determined by orbital path
- Model does not reflect typical network operator capacity threshold of 70% - 80%; model assumes total capacity allocated
- Model assumes Starlink will get FCC approval to launch all 29,988 requested satellites
- Assumed satellite capacities for V2 Full are based on anecdotal reports; V3 considerations expanded upon in Appendix
- For simplicity, model only accounts for contiguous US (excl. AK, HI, and territories) in sizing fleet and serviceable cells/HUs
- Model does not account for improvements in satellite lifespan (5 years assumed)

### C Consumer Bandwidth

- Model assumes same consumer speed tier in 2024 and 2030 (100/20 Mbps), not accounting for changes in consumer behavior towards higher speed tiers
- Model assumes Starlink will serve all existing/incremental subs with broadband speeds (100/20Mbps); does not account for differences in speeds delivered
- Model assumes that Starlink subscribers have a similar peak hour bandwidth demand to other US broadband users
- Assumes 100% network utilization at peak demand across all serviced HUs
- Model assumes QoE Ripple factor of 20% to deliver a reliable customer service[2]; this is assumed to not change by 2030 YE

*All model considerations based on publicly available information; may not reflect all factors that impact overall system / spectrum capabilities*

1. V1 satellites are assumed to have spectral efficiency of 3.5 bps/Hz and V2 satellites are assumed to have spectral efficiency of 4.5 bps/Hz (based on Modulation and FEC rates of each generation); 2. SCTE traffic engineering formula reports that QoE factor to absorb short-term ripples in demand is typically up to 20% to provide reliable service.
Source: FCC DATA Maps filing as of 12/31/23 accessed 5/28/24, Starlink, Cartesian





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# Appendix | Starlink Spectrum Authorizations

A Available Spectrum

## We assume Starlink will utilize both Ku and Ka authorizations for user links by 2030

| Band | Authorized or Conditionally Approved *As of Oct 2024* | | | | Requested Spectrum Modifications *Per SpaceX FCC Filing Oct 11, 2024*[1] | | | | Expected Future Spectrum Allocation | | | | Cartesian Assumptions for Spectrum Capacity Modeling[7] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ku | 10.7 – 12.7 GHz | FSS | User | DL | 10.7 – 12.7 GHz | FSS | **+ Gateway** | DL | 10.7 – 12.7 GHz | FSS | User + GW | DL | 10.7 – 12.7 GHz | FSS | User | DL | 2024, 2030 |
| | 14.0 – 14.5 GHz | FSS | User | UL | 14.0 – 14.5 GHz | **+ MSS** | **+ Gateway** | UL | 14.0 – 14.5 GHz | FSS + MSS | User + GW | UL | 14.0 – 14.5 GHz | FSS | User | UL | |
| Ka | 17.3 – 17.7 GHz[4] | FSS | Not Assigned | DL | | | | | 17.3 – 17.7 GHz[4] | FSS | Not Assigned | DL | | | | | |
| | 17.7 – 17.8 GHz[4] | FSS | Not Assigned | UL | | | | | 17.7 – 17.8 GHz[4] | FSS | Not Assigned | UL | | | | | |
| | 17.8 – 18.6 GHz[2] | FSS | Gateway | DL | 17.8 – 18.6 GHz[2] | FSS | **+ User** | DL | 17.8 – 18.6 GHz[2] | FSS | User + GW | DL | 17.8 – 18.6 GHz[2] | FSS | User + GW | DL | 2030 |
| | 18.8 – 19.3 GHz[2] | FSS | Gateway | DL | 18.8 – 19.3 GHz[2] | FSS | **+ User** | DL | 18.8 – 19.3 GHz[2] | FSS | User + GW | DL | 18.8 – 19.3 GHz[2] | FSS | User + GW | DL | |
| | *19.7 – 20.2 GHz[2,3]* | *FSS* | *Unspecified* | DL | *19.7 – 20.2 GHz[2,3]* | **+ MSS** | **+ User + GW** | DL | *19.7 – 20.2 GHz[2,3]* | FSS + MSS | User + GW | DL | *19.7 – 20.2 GHz[2,3]* | FSS | User + GW | DL | |
| | 27.5 – 29.1 GHz[2] | FSS | Gateway | UL | 27.5 – 29.1 GHz[2] | FSS | **+ User** | UL | 27.5 – 29.1 GHz[2] | FSS | User + GW | UL | 27.5 – 29.1 GHz[2] | FSS | User + GW | UL | |
| | 29.5 – 30.0 GHz | FSS | Gateway | UL | 29.5 – 30.0 GHz | **+ MSS** | **+ User** | UL | 29.5 – 30.0 GHz | FSS + MSS | User + GW | UL | 29.5 – 30.0 GHz | FSS | User + GW | UL | |
| V<br>*Gen2 Only[6]* | 37.5 – 40.0 GHz | FSS | *Unspecified* | DL | 37.5 – 40.0 GHz | FSS | **+ User + GW** | DL | 37.5 – 40.0 GHz | FSS | User + GW | DL | 37.5 – 40.0 GHz | FSS | Gateway | DL | |
| | 40.0 – 42.0 GHz | FSS | *Unspecified* | DL | 40.0 – 41.0 GHz[5] | **+ MSS** | **+ User + GW** | DL | 40.0 – 41.0 GHz[5] | FSS+ MSS | User + GW | DL | 40.0 – 41.0 GHz[5] | FSS | Gateway | DL | |
| | 47.2 – 50.2 GHz | FSS | *Unspecified* | UL | 47.2 – 50.2 GHz | FSS | **+ User + GW** | UL | 47.2 – 50.2 GHz | FSS | User + GW | UL | 47.2 – 50.2 GHz | FSS | Gateway | UL | |
| | 50.4 – 51.4 GHz | FSS | *Unspecified* | UL | 50.4 – 51.4 GHz | FSS | **+ User + GW** | UL | 50.4 – 51.4 GHz | FSS | User + GW | UL | 50.4 – 51.4 GHz | FSS | Gateway | UL | |
| E | 71.0 – 76.0 GHz | FSS | Gateway | DL | 71.0 – 74.0 GHz | **+ MSS** | **+ User** | DL | 71.0 – 74.0 GHz | FSS + MSS | User + GW | DL | 71.0 – 74.0 GHz | FSS | Gateway | DL | |
| | 81.0 – 86.0 GHz | FSS | Gateway | UL | 81.0 – 84.0 GHz | **+ MSS** | **+ User** | DL | 81.0 – 84.0 GHz | FSS + MSS | User + GW | DL | 81.0 – 84.0 GHz | FSS | Gateway | DL | |

GW = Gateway / Backhaul links

Approved for License request; not currently authorized for Starlink

DL User Model Inputs

DL Downlink (space to Earth)

UL Uplink (Earth to space)

1. SpaceX FCC filing requests use of listed authorized bands for FSS and MSS use; additionally, SpaceX requests FCC to permit use of all authorized Ku, Ka, V, and E band frequencies (except frequencies solely dedicated to TT&C) for either gateway or user-links;
2. Subject to EPFD limits to protect GSO operations; 3.Per FCC Filing 03/29/2018, NGSO operations on secondary basis to GSO operations, SpaceX to accept interference from GSO operations in this band; 4. Per FCC Press release 09/24/2024, 17.3 – 17.8 GHz will be open to NGSO FSS services; 17.3 – 17.7 GHz on co-primary basis with GSO, 17.7 – 17.8 GHz on co-primary basis with GSO and unprotected basis with terrestrial fixed services; 5. 40.0 – 40.5 GHz globally, 40.5 – 41.0 GHz on secondary basis in Region 2; 6. V band authorized for 7.5K V2 Gen satellites only; model assumes this includes V2 Mini satellites; 7. Starlink was approved to use portions of T-Mobile's network for MSS per FCC filing on 11/26/24, model assumes Starlink will utilize T-Mobile spectrum for MSS, dedicating own spectrum to FSS
Source: FCC Filing SATMOD2024101100224, FCC Filing SAT-LOA-20161115-00118, FCC Public Notice Report No. SAT-01768, Cartesian





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# Appendix | Global Forecasted Starlink Fleet

B Network Capacity

## We forecast Starlink's global fleet through 2030 YE, assuming approval for all requested launches

**Global Fleet Size Calculation[1]:** Existing Active Satellites in 2024 Year-End + Annual Planned Launches through 2030 − Annual Decommissioned Satellites = Annual Global Fleet Size by 2030

**Active Satellites as of 2024 YE[1]**

| | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | Total Active Satellites in 2024 YE |
|---|---|---|---|---|---|---|---|
| V1.0 | 27 | 415 | 541 | - | - | - | 983 |
| V1.5 | - | - | 185 | 1,561 | 1,016 | - | 2,762 |
| V2 Mini | - | - | - | - | 870 | 1,341 | 2,211 |
| V2 Full | - | - | - | - | - | - | - |

**Forecasted Launches by 2030 YE**

| | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|
| V1.0 | *Discontinued* → | | | | | | |
| V1.5 | *Discontinued* → | | | | | | |
| V2 Mini | - | A 1,763 | 1,763 | 4,574 | 2,811 | 2,811 | 2,811 |
| V2 Full | - | - | - | B 2,811 | 2,811 | 2,811 | 2,811 |

**End of Life / Removed**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| V1.0 | C 27 | 415 | 541 | - | - | - | D - |
| V1.5 | - | - | 185 | 1,561 | 1,016 | - | - |
| V2 Mini | - | - | - | - | 870 | 1,341 | 1,763 |
| V2 Full | - | - | - | - | - | - | - |

**Assumes all requested 29,988 satellites will be approved by the FCC:**

- A Currently approved 7,500 satellites launch by 2027 (2,211 already launched, remaining 5,289 spread evenly across 2025-2027)
- B Remaining 22,488 requested will be split evenly across V2 mini and full size, from 2027-2030

**Assumes 5-year lifespan of all generations:**

- C All active satellites launched from 2019-2024 will reach end-of-life by 2024-2029
- D Similarly, all forecasted launched satellites from 2025 will reach end-of-life by 2030

**We apportion 5% of Starlink's global fleet to serve the contiguous US based on the share of surface area, inclusive of a 300 – 500km buffer[2]**

1. Only active/operational satellites are considered as they are the ones providing service; 2. Buffer accounts for service delivered from satellites located outside US borders.
Source: FCC Filings, Satellite Map, Jonathan's Space Pages, Cartesian





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# Appendix | Starlink V3 Satellite

The current information available on Starlink's V3 satellite does not change the conclusions of this study

Starlink's 2024 Progress Report announced that they plan to deploy a more advanced satellite – V3 Starlink Satellite – which has greater throughput than the V2 Full Size. Based on the information available, the new satellite will not overcome Starlink's spectrum constraint and the forecast serviceability for 2030 still stands.

## Public Information on V3

*Per Starlink 2024 Progress Report*

- **Downlink Capacity Per Satellite:** 1 Tbps
- **Uplink Capacity Per Satellite:** 160 Gbps
- **Satellites Per Launch:** 60

## Unknown Information on V3

- **Launch Frequency / Overall Fleet Size of V3:** used to determine network capacity
- **Timing of Deployment:** uncertain timing of when V3 satellites will be incorporated in fleet
- **Modulation and FEC Rates:** used to determine spectral efficiency

**Although V3 satellite capacity will increase Network Capacity, the serviceability forecast is unchanged as due to 2030 spectrum constraints**

Source: Starlink 2024 Progress Report, Cartesian





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# Appendix | Alternate Use Cases

B Network Capacity

We estimate 5% of Starlink's network capacity will be dedicated to alternate use cases by 2030 and hence unavailable for fixed broadband subscribers

## EXAMPLE STARLINK USE CASES

**Aviation**

- Starlink is certified on 20 aircraft models
- They installed service to 450 aircraft globally, and now on contract for installation on over 2,000 additional aircraft

**Maritime**

- Starlink Maritime connects more than 75k vessels globally
- This includes more than 300 cruise ships, serving over 10M cruise passengers annually

**Rail**

- Starlink is beginning to improve internet connectivity to train passengers
- Expansion in the rail industry began with Florida Brightline, Starlink's first passenger rail system

Source: Starlink 2024 Progress Report, Cartesian





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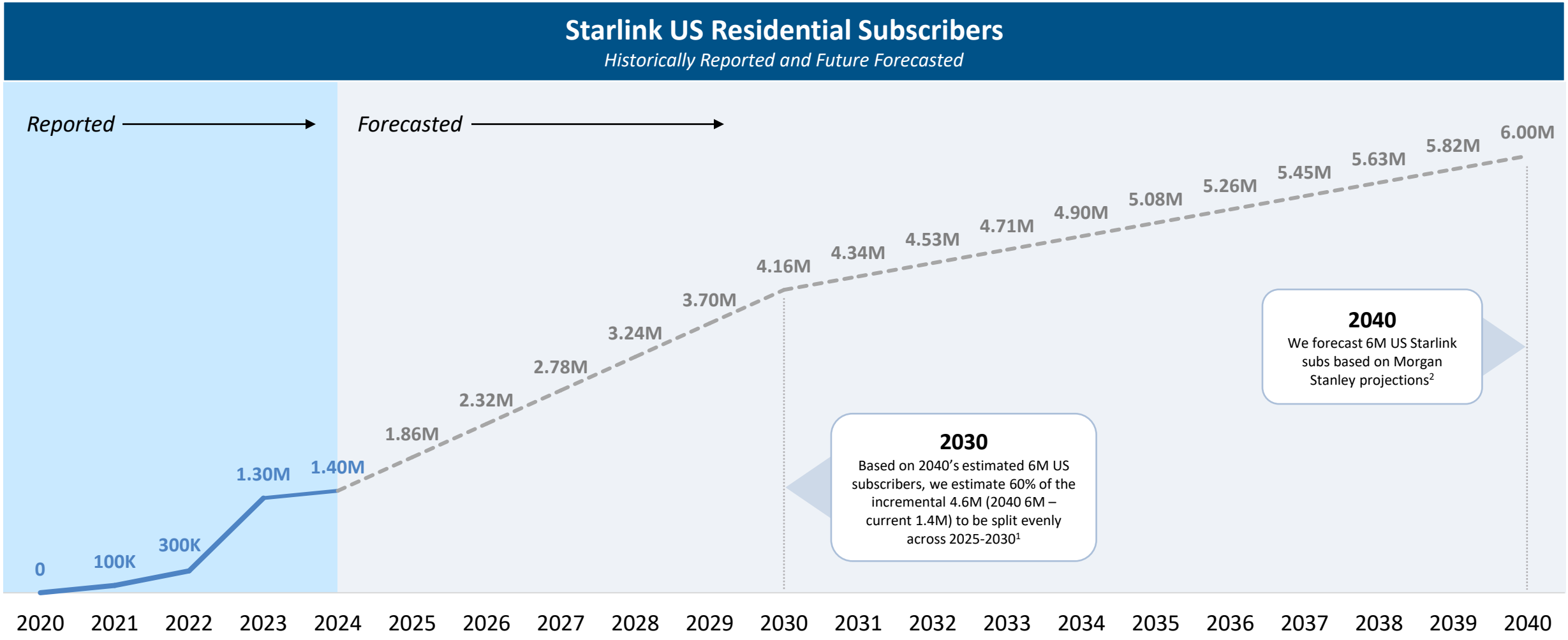
# Appendix | Starlink US Residential Subscribers

B Network Capacity

We forecast annual Starlink US subscriber counts using currently reported numbers and industry estimates




1. We frontload more (60%) forecasted subs in the next 5 years to account for more potential growth in upcoming years and further global expansion in subsequent years. Remaining 40% to split evenly across 2030-2040
2. Morgan Stanley predicts that by 2040 Starlink will have 15M-80M subs globally (midpoint of 32M). We expect non-US subs to grow faster than US subs, assuming US Share of 20%, or 6M subscribers

Source: Cartesian, Historytools.org (2021 Reported), Advanced Television (2022-2024 Reported), Economist/Morgan Stanley





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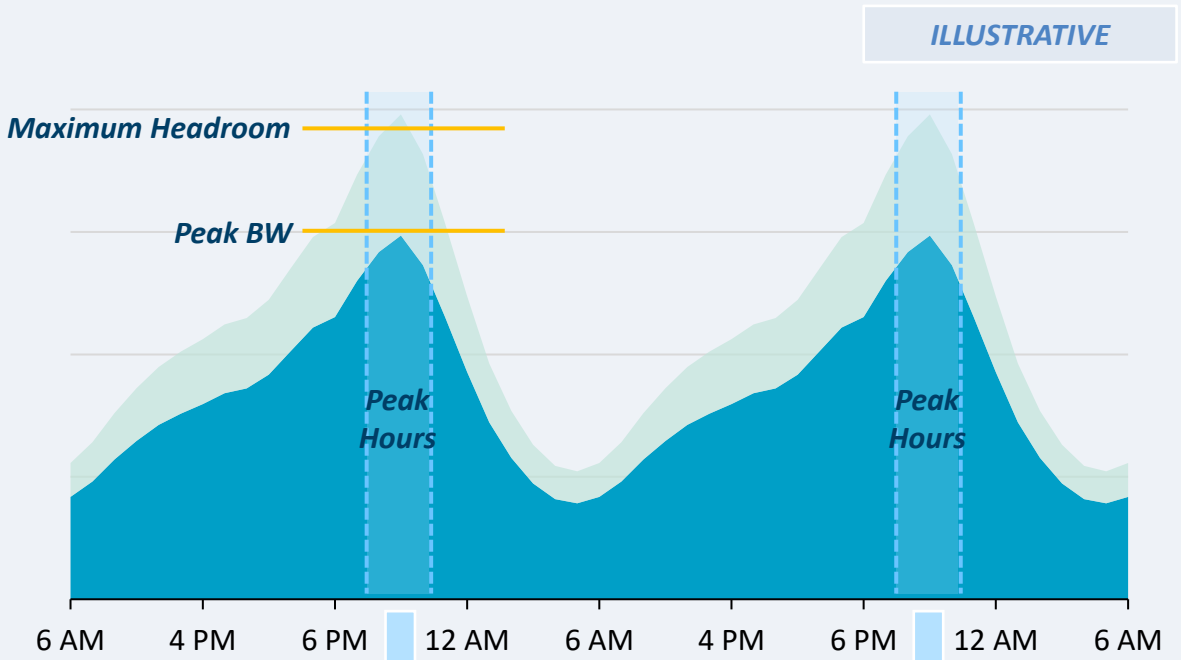
# Appendix | Consumer Bandwidth & Peak Hour Demand

C Consumer Bandwidth

Our capacity model reflects how much consumer bandwidth is required at peak hours

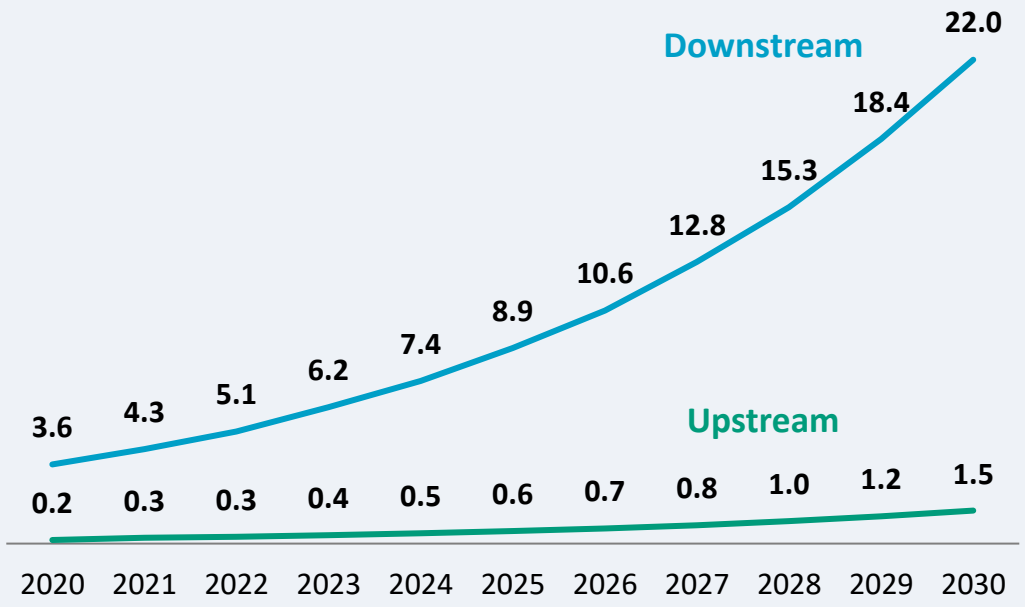
## Hourly Average Downstream Consumer Bandwidth Usage




Capacity model requires available capacity to accommodate for average consumer demand in peak hours (~7pm - 11pm)

## Average Consumer Demand at Peak Hours by Year

2020 – 2030




Average consumer demand at peak hours increases over time with increased video streaming, new applications, etc.

Source: Cartesian (Download Speeds), CommScope (Upload)





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# Appendix | Capacity Planning

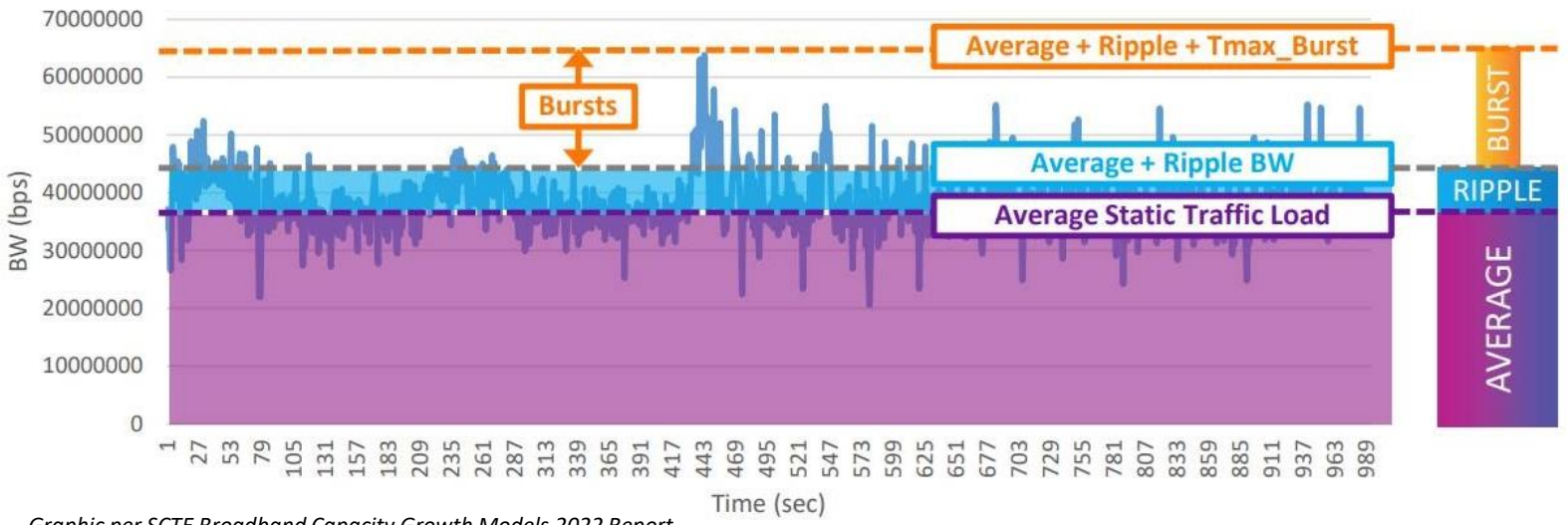
C Consumer Bandwidth

We estimate the number of HUs supported at 100/20Mbps speeds using a capacity engineering approach

## Broadband Traffic Engineering Approach

*SCTE, Cable Labs, and NCTA (2022)*

### BW vs Time




*Graphic per SCTE Broadband Capacity Growth Models 2022 Report*

Burst accounts for sudden, extreme spike in bandwidth usage, caused by high-demand events or simultaneous usage

Ripple accounts for natural fluctuations in bandwidth usage, caused by variations in user activity (20% of average bandwidth load)

## Mbps per User

| | Starlink[1] |
|---|---|
| Capacity (Mbps) | 964 |
| DS Speed Tier (Mbps) | 100 |
| Ripple Factor | 20% |
| Ripple (Mbps) | 20 |
| Tavg[2] (Mbps) | 7.4 |
| Max Users | 114.1 |
| Max Users (rounded) | 114 |
| Available Mbps per User | 8.5 |

1. Calculated on what spectrum can support per cell; 2. Avg demand at peak hours
Source: SCTE Broadband Capacity Growth Models (2022), Cartesian





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# Appendix | Starlink Serviceable BEAD Housing Units by State (2024 YE)

Model Results

## Including existing users, we estimate Starlink currently has capacity to serve ~559K BEAD housing units

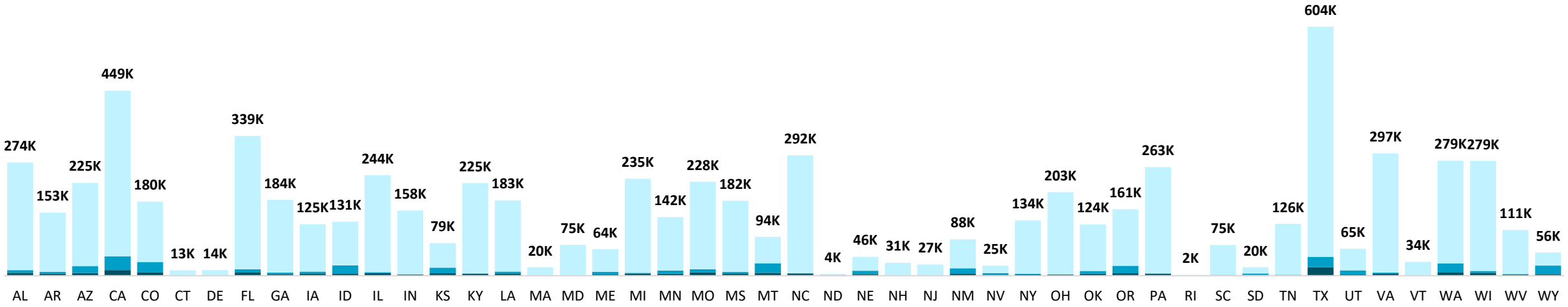
***BASE CASE***
*Starlink continues to serve existing customer base with BEAD as an add-on*

**2024 BEAD Housing Units[1,2] by State (Contiguous US Only)**
*BEAD-Eligible Housing Units Served and Serviceable by Starlink*

*215K Total Est. Existing Starlink Subs that are BEAD HUs* + *344K Total Est. Incremental Starlink Serviceable BEAD HUs*

- Est. BEAD-Eligible HUs in Existing Subscriber Base
- Est. Incremental BEAD HUs Serviceable by Starlink
- Est. BEAD HUs not Serviceable by Starlink

To model Starlink's existing base, subscribers are evenly distributed across all cells (1.4M subs across 29K cells / 48 existing subs per cell), then apportioned within each cell to BEAD/non-BEAD in proportion to the mix of HUs in each cell. Remaining capacity is then used to determine the potential for incremental BEAD HUs serviceable by Starlink in each cell.[3]




**Most states estimated to have <10% of their BEAD-Eligible Housing Units serviceable by Starlink**

Serviceable incremental housing units – including BEAD – vary significantly by state, due to **(1)** uneven distribution of BEAD locations across the country, **(2)** how many housing units the spectrum can support in a cell, which is dependent on housing unit density and **(3)** what share of housing units in a cell are modelled to be existing Starlink subscribers

1. Applied 1.27x multiplier to translate FCC Locations (BSLs) to Housing Units; 2. Excludes BEAD-Eligible locations in US Territories, Alaska and Hawaii; 3. Starlink serviceability model assumes prioritization of cells from least to most dense
Source: Cartesian, FCC





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# Appendix | Starlink Serviceable BEAD Housing Units by State (2030)

Model Results

By 2030, we estimate Starlink could serve ~1.3M BEAD housing units if BEAD is prioritized over other user groups

***BASE CASE***
*Starlink continues to serve existing customer base with BEAD as an add-on*

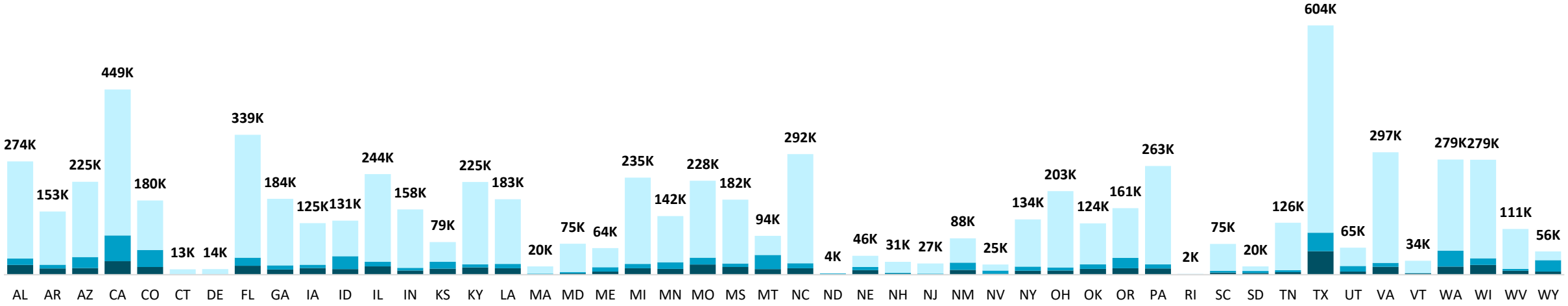
## 2030 BEAD Housing Units[1,2,3] by State (Contiguous US Only)

*BEAD-Eligible Housing Units Served and Serviceable by Starlink*

*616K Total Est. Existing Starlink Subs that are BEAD HUs* + *670K Total Est. Incremental Starlink Serviceable BEAD HUs*

- Est. BEAD-Eligible HUs in Forecasted Subscriber Base
- Est. Incremental BEAD HUs Serviceable by Starlink[3]
- Est. BEAD HUs not Serviceable by Starlink

To model Starlink's future base, anticipated subscribers in 2030 are evenly distributed across all cells (4.2M subs across 29K cells / 142 existing subs per cell), then apportioned within each cell to BEAD/non-BEAD in proportion to the mix of HUs in each cell. Remaining capacity is then used to determine the potential for incremental BEAD HUs serviceable by Starlink in each cell.[4]




**Most states estimated to have <10% of their BEAD-Eligible Housing Units serviceable by Starlink**

Serviceable incremental housing units – including BEAD – vary significantly by state, due to **(1)** uneven distribution of BEAD locations across the country, **(2)** how many housing units the spectrum can support in a cell, which is dependent on housing unit density and **(3)** what share of housing units in a cell are modelled out to be existing Starlink subscribers

1. Applied 1.27x multiplier to translate FCC Locations (BSLs) to Housing Units; 2. Excludes BEAD-Eligible locations in US Territories, Alaska and Hawaii; 3. Assumes all current BEAD-eligible housing units will remain BEAD-eligible in 2030 (i.e., assumes there will be not deployment to these housing units by 2030) 4. Starlink serviceability model assumes prioritization of cells from least to most dense
Source: Cartesian, FCC





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# Appendix | Starlink Best Case BEAD Serviceability (2030)

Model Results

We also modelled a hypothetical scenario where all Starlink capacity is allocated to BEAD HUs

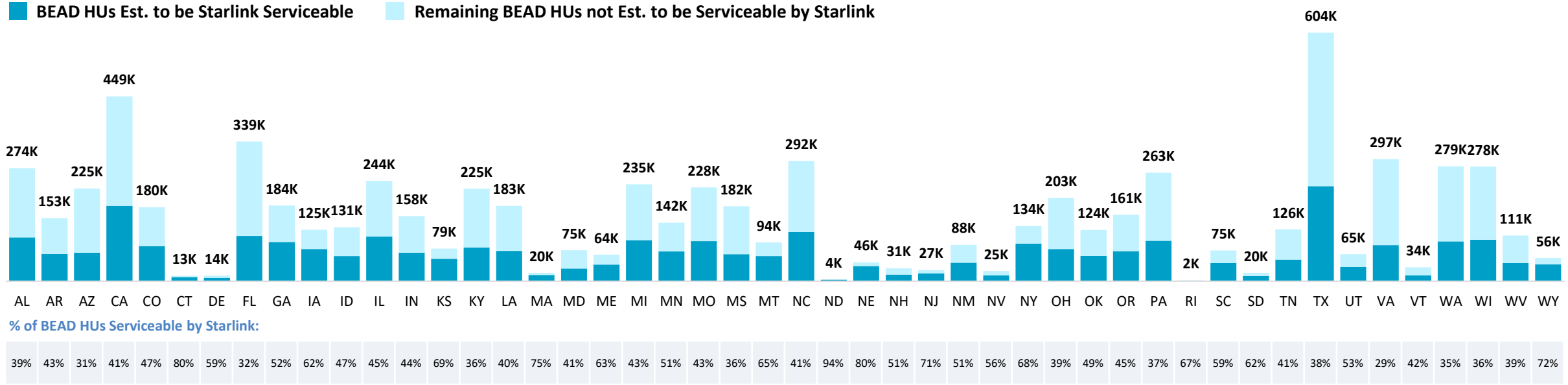
***STARLINK BEST CASE***
*Entire capacity allocated to BEAD*

## 2030 BEAD Housing Units[1,2] by State (Contiguous US Only)

*BEAD-Eligible Housing Units Serviceable by Starlink (Assuming No Other Starlink Users)*

***3.2M Total Est. Starlink Serviceable BEAD HUs***

Assumes that up to 255 BEAD housing units in each cell will be serviceable by Starlink (i.e., no capacity allocated to other users in cells with BEAD HUs); BEAD housing units beyond the maximum cell capacity of 255 will not be serviceable by Starlink




**If all capacity is allocated to BEAD, at least 30% of BEAD-Eligible Housing Units estimated serviceable in most states**

In this hypothetical scenario where Starlink's entire capacity is allocated to BEAD-eligible housing units, we estimate that 3.2M of these housing units could be served in 2030 (~43% of BEAD HUs). The figure is far lower when other Starlink use cases are accounted for.

1. Applied 1.27x multiplier to translate FCC Locations (BSLs) to Housing Units; 2. Excludes BEAD-Eligible locations in US Territories, Alaska and Hawaii; 3. Starlink serviceability model assumes prioritization of cells from least to most dense
Source: Cartesian, FCC





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# Appendix | Model Assumptions and Sensitivities

Model Sensitivities

The model results are dependent on several assumptions; changing these will impact serviceability

| Model Assumption | | 2024 YE | 2030 YE | Additional Sensitivity | Impact on Capacity 2024 YE | Impact on Capacity 2030 YE |
|---|---|---|---|---|---|---|
| **Allocated Spectrum** | Spectrum Bands | Ku | Ku + Ka | Inclusion of V and E spectrum bands in user terminal spectrum allocation | ↑ | ↑ |
| | FSS vs. MSS Allocation | FSS | | Allocating add. spectrum to MSS would reduce available spectrum for internet service | ↓ | ↓ |
| | Spectrum Sharing | No Sharing | | Spectrum may need to be shared with other LEO providers (e.g., OneWeb) | N/A | ↓ |
| | Spectral Efficiency | 3.9 bps/MHz | 4.5 bps/MHz | Spectral efficiency could be lower than claimed | ↓ | ↓ |
| | Polarizations | 1 | 2 | If dual polarization is already in use currently, max capacity could be higher | ↑ | N/A |
| **Satellite Fleet Capacity** | Fleet Size (US Coverage) | 298 (5% of global) | 1302 (5% of global) | Fleet size could be much smaller in reality, depending on what the FCC approves | N/A | ↓ |
| | Generation Mix | 0% V2 Full | 43% V2 Full | Starlink could focus on having higher share of V2 Full Size / lower share of V2 Mini | N/A | ↑ |
| | Capacity Use | 100% | | Starlink may limit capacity usage to 70-80% of theoretical maximum | ↓ | ↓ |
| | Commercial Use | 0% | 5% | Starlink may have a higher share of capacity dedicated to commercial use | ↓ | ↓ |
| | Nco=1 | *N/A* | *N/A* | Limit to one co-frequency per cell could be lifted or worked around due to tech advancements | N/A | ↑ |
| | Altitude | *N/A* | *N/A* | Starlink could get approved for lower altitude of their satellites and would need more satellites for nationwide coverage | ↑ | ↑ |
| **Consumer Bandwidth** | Consumer Pattern | Usage resembles other internet subs | | Starlink consumer demand at peak hours could be lower than the average internet user | ↑ | ↑ |
| | Consumer Demand at Peak Hours | 7.4 Mbps | 22 Mbps | The growth rate of consumer demand at peak hours may flatten out by 2030, resulting in lower consumer demand | N/A | ↑ |
| | Service Tier | 100/20 Mbps | | Higher speed tiers (e.g., 1000/500Mbps) could reflect consumer trends | ↓ | ↓ |
| **Serviceable HUs** | Existing Subs | 1.4M | 4.2M | US Starlink subs could be higher than est. 1.4M current subs and forecasted 4.2M subs | ↓ | ↓ |
| | | | | US Starlink subs could be lower than est. 1.4M current subs and forecasted 4.2M subs | ↑ | ↑ |
| | BEAD Deployment | Priority of Incremental Subs in least dense cells | | Starlink may not prioritize least dense cells, impacting the # of serviceable BEAD HUs | ↓ | ↓ |

Source: Cartesian





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# Appendix | Sensitivity to Spectral Efficiency

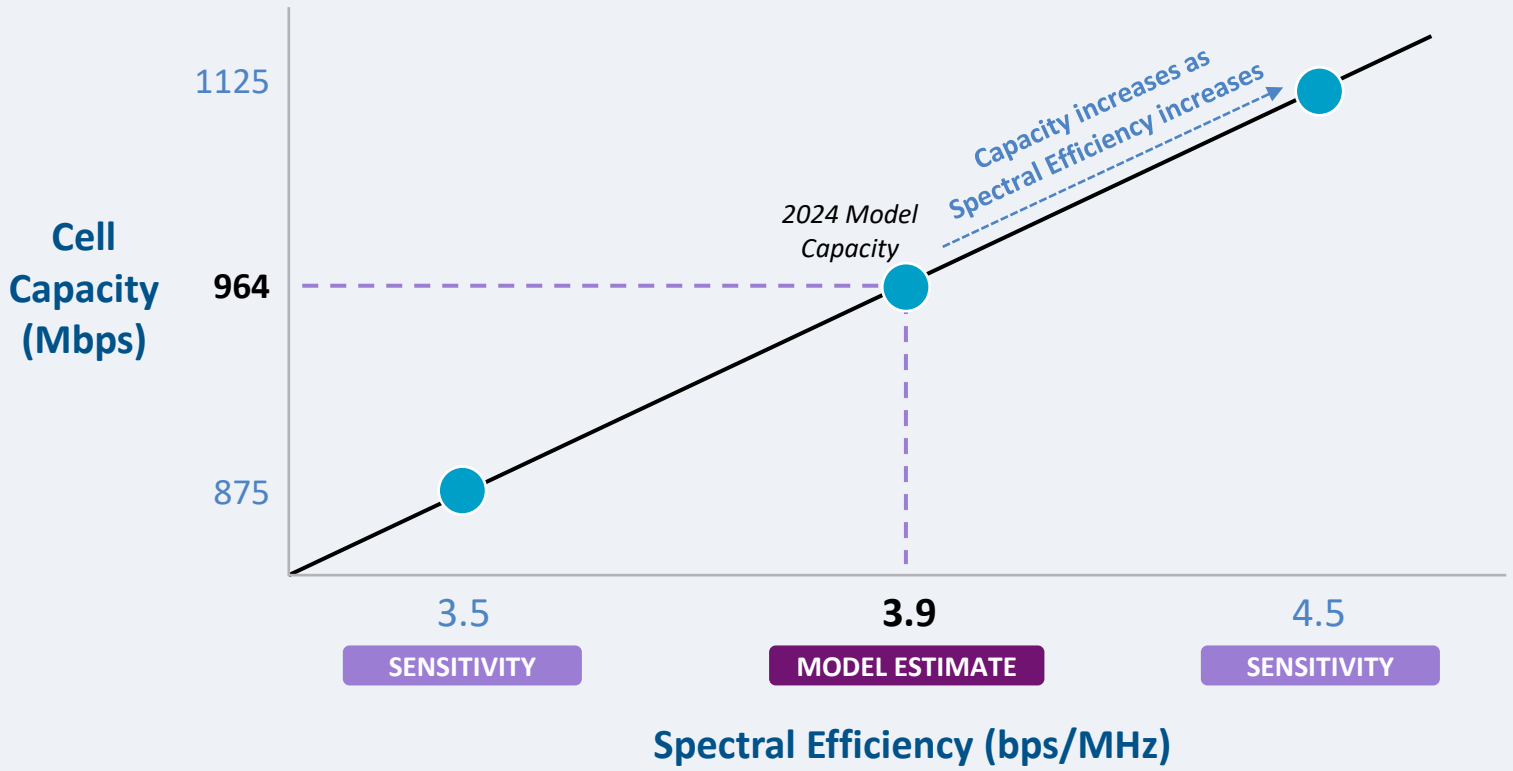


In practice, Starlink may achieve greater or worse spectral efficiency than our model assumption

## A 2024 YE Available Spectrum Calculation

| | Downlink |
|---|---|
| Available Spectrum | 2000 MHz |
| | ÷ |
| Channel Split | 8 Channels |
| Spectrum Available Per Channel[3] | 250 MHz |
| | × |
| Number of Polarizations | 1 |
| | × |
| **Starlink Spectral Efficiency** | **3.9 bps/Hz** |
| **Max Capacity Available Per Cell** | **964 Mbps** |

## Cell Capacity & Spectral Efficiency Sensitivity




**Max theoretical bandwidth per cell is dependent on spectral efficiency and available spectrum; Max theoretical bandwidth per cell directly impacts the max housing units per cell supported by spectrum, which ultimately impacts the total housing units supported by spectrum**

Source: Cartesian

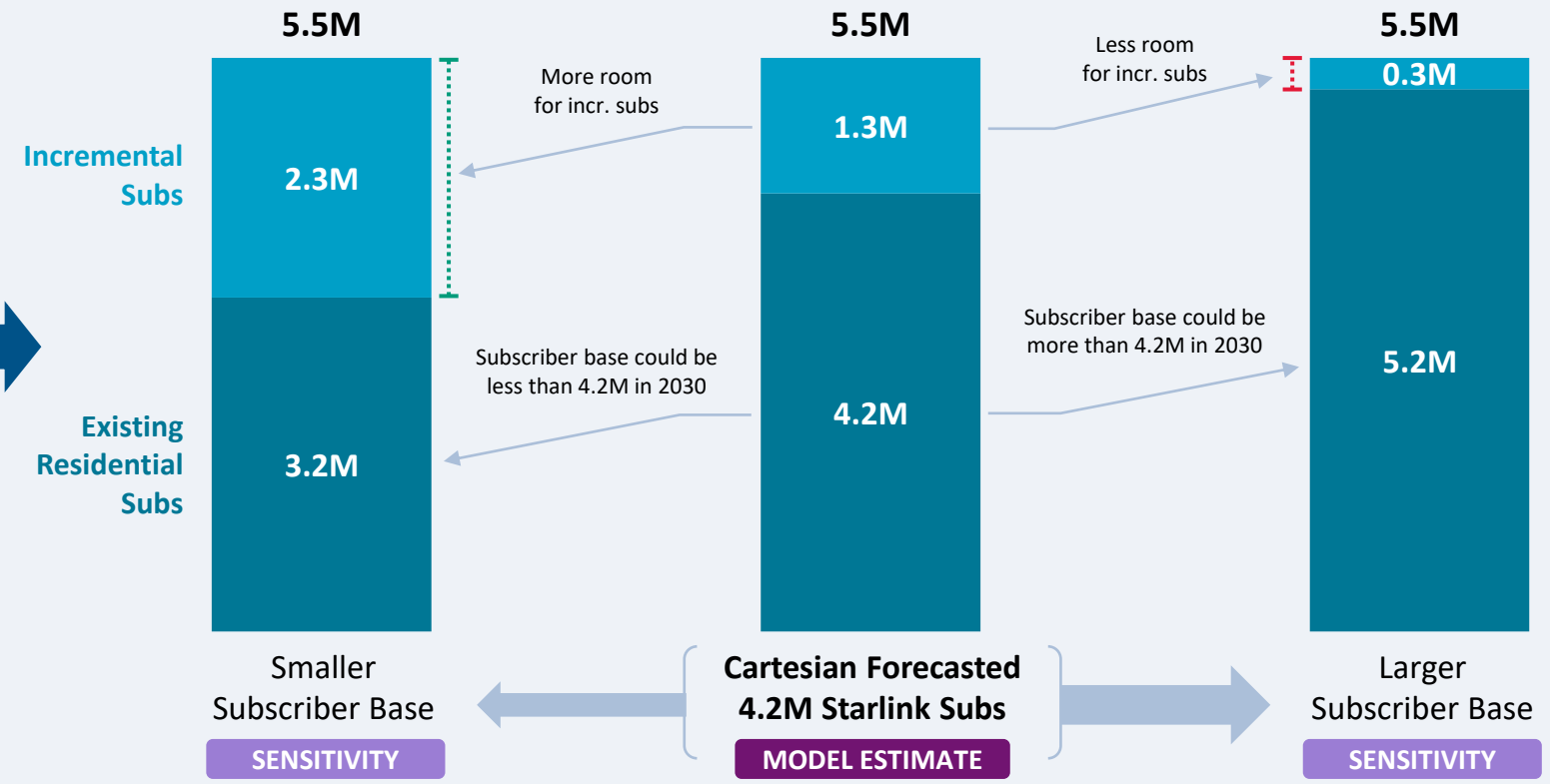
# Appendix | Sensitivity to 2030 Subscriber Forecast



If Starlink exceeds the modeled subscriber forecast for 2030, it will have less capacity for incremental subs

## A 2030 Year-End Existing Residential Subscriber Base Sensitivities

| | 2024 YE | 2030 YE |
|---|---|---|
| Is Starlink's serviceability constrained by network or spectrum capacity? | Network | Spectrum |
| Due to capacity constraints, how many US housing units are serviceable by Starlink? | 2.0M | 5.5M |
| What is the estimated number of Starlink subscribers in the US? | 1.4M | 4.2M |
| Using the remaining capacity, how many incremental subscribers can Starlink serve? | 0.6M | 1.3M[1] |




**The capacity to add incremental subscribers is determined by Starlink's subscriber base in 2030; if its more than our forecasted 4.2M subscribers, there will be less room for incremental subscribers, and if its less then there will be more room for incremental subscribers**

Source: Cartesian