Starlink RDOF Assessment

Final Report

Prepared for: Fiber Broadband Association; NTCA – The Rural Broadband Association

Date: February 8th, 2021

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Project Context and Summary Findings

Context and Objectives

- SpaceX has been awarded almost **$900M** of assigned RDOF funds with a commitment to connect **640K** locations across the United States with its incipient Starlink satellite broadband technology
- Cartesian was engaged by the Fiber Broadband Association and the NTCA – Rural Broadband Association to assess the Starlink network, including:
  - Contextual research on Starlink's planned fleet
  - Analyzing network capacity and network demand in committed RDOF locations
  - Identifying implications for the FCC testing framework

Research Findings

- We forecast a **capacity shortfall in 2028:**
  - **56% of RDOF subscribers are congested** in a forecasted low demand scenario
  - More locations will be impacted if RDOF usage is higher, or SpaceX launches fewer satellites by 2028
  - RDOF service could be significantly worse if Starlink capacity is allocated to non-RDOF use cases
- **CAF-style performance testing may fail to detect capacity issues** given the dynamic nature of the Starlink network
- **There are many unknowns** regarding the Starlink service:
  - There is limited information in the public domain
  - SpaceX technical and commercial plans keep evolving
  - The ability to share capacity with non-RDOF users will greatly influence RDOF performance

Source: Cartesian, FCC

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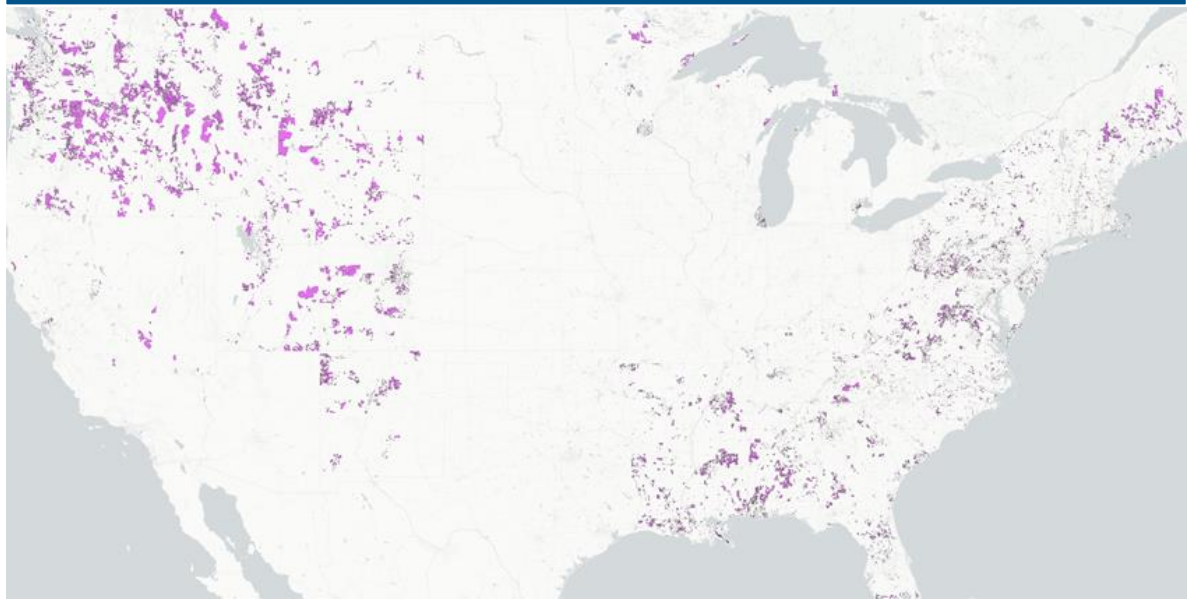
Starlink RDOF Commitment and Planned Fleet

Our analysis is based on Starlink's RDOF commitment and reported satellite fleet specifications

SpaceX Assigned RDOF Locations

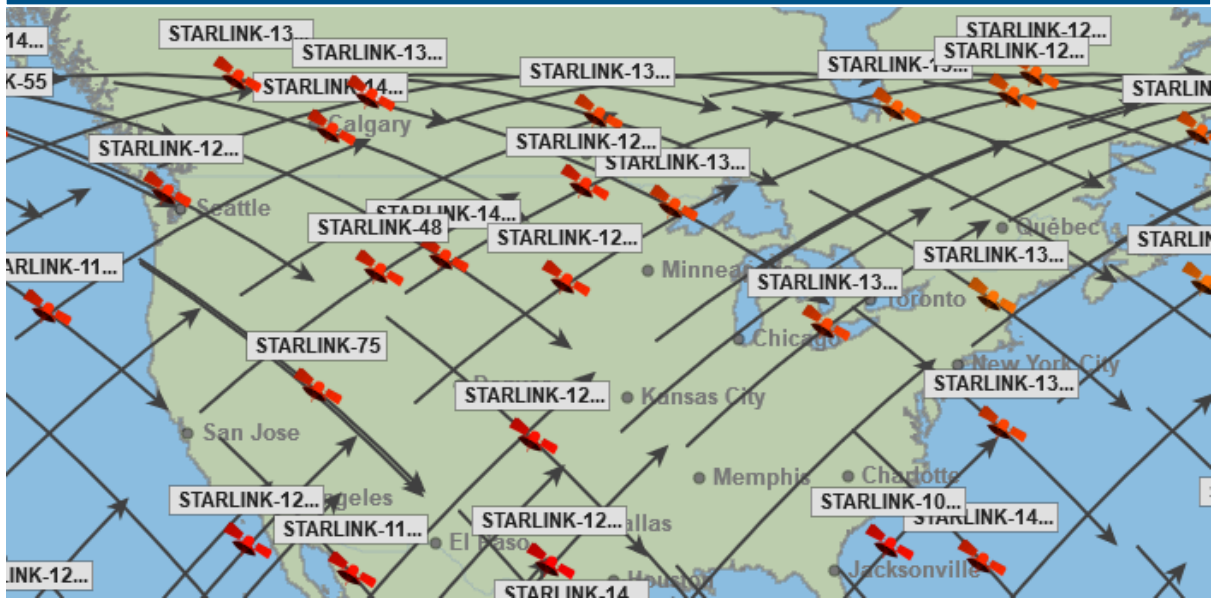


642K Starlink Locations

Top 5 States:	
Pennsylvania	**59.2K** (9.2%)
Virginia	**53.6K** (8.3%)
Washington	**52.1K** (8.1%)
Mississippi	**40.0K** (6.1%)
Alabama	**36.6K** (5.7%)

By Density:	
Urban *(≥500 people/mi²)*	**75.5K** (11.7%)
Rural	**567K** (88.3%)

Starlink Satellite Fleet



Bandwidth and Service	**Throughput/Satellite**	17-23 Gbps
	Coverage/Satellite	~300,000 sq mi
Fleet Configuration	**Planned Fleet Size**	~12,000
	Orbital Inclination[1]	53°
	Orbital Planes	72

[1] Indicates maximum latitude of center of satellite coverage area
Source: Cartesian, FCC, Starlink, In-The-Sky.org

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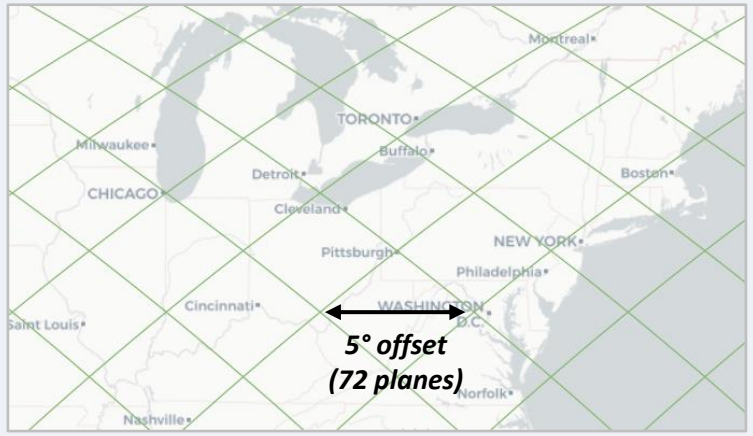
Starlink Capacity Model

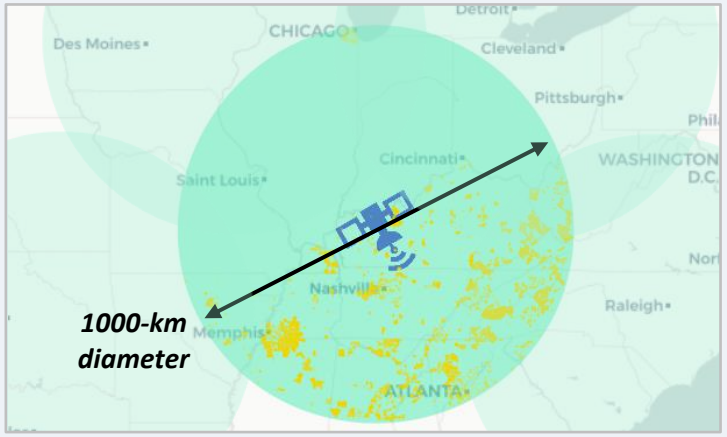
We model Starlink's planned fleet to understand its ability to fulfill the RDOF commitments

1 Create Satellite Fleet Configurations



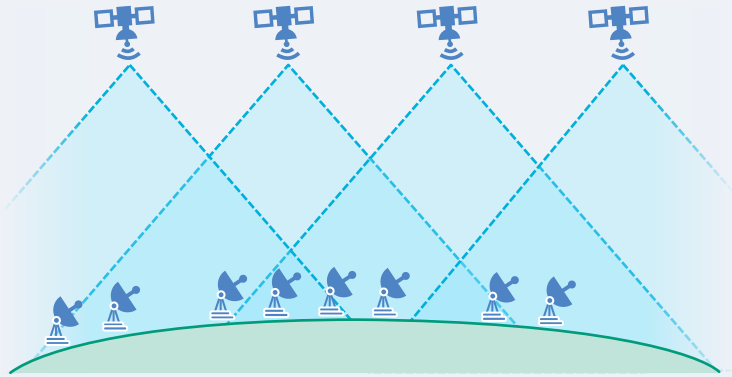
- Define 72 evenly spaced orbital planes at 53° orbital inclination, per Starlink planned fleet configuration
- Allocate 12,000 satellites equally spaced across 72 planes to approximate the Starlink fleet
- Repeat 20 times at random orbital offsets and satellite placements for robust estimates

2 Match Starlink RDOF Locations



- Overlay the RDOF award areas with the satellite locations from step 1
- Identify all RDOF locations within the coverage area of each satellite
- Construct matrix identifying all satellite-RDOF area matches, i.e. how many satellites are available to serve each location

3 Process and Estimate Per-Subscriber Capacity



- Estimate the available capacity of each satellite using publicly-available sources
- Using the matrix from step 2, efficiently allocate satellite capacity to subscribers
- Assume each subscriber can be served by multiple satellites, and attempt to meet the peak-hour demand in each location
- Average across the 20 model runs from step 1

Source: Cartesian

The RDOF Service Commitment

RDOF applicants must design their network to deliver service at the specified bitrate, i.e. 100 Mbps downstream and 20 Mbps upstream for the Above Baseline service

Defining a 100 Mbps Service

FCC RDOF Requirements

Assuming a 70% broadband uptake rate of assigned locations, applicants are required to offer a broadband service which meets the following performance standards for Above Baseline speeds:

"broadband service at actual speeds of at least 100 Mbps downstream and 20 Mbps upstream"

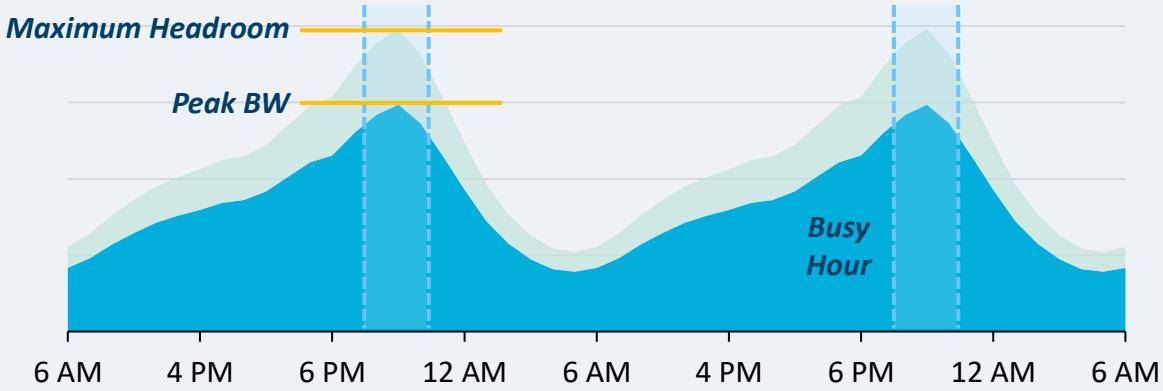
- The FCC has not defined how these requirements should be scaled for contention across the network, accounting for burst demand from the individual subscriber.
- CAF testing requirements have imposed an 80/80 threshold, meaning 80% of testing locations must equal or exceed speed tests of 80 Mbps.

A Working Definition of a 100Mbps Service

Any subscriber should be able to receive 100 Mbps in peak hours, accounting for the expected usage of other users on the network.

So, we must consider average bandwidth requirements per subscriber at peak hours, and allow for some headroom capacity from the average, for extreme cases.

Hourly Network Downstream Traffic



Hourly downstream traffic of a major US cable broadband provider across February and March 2020*

Key drivers of peak usage at the busy hour:

- Number of users online
- Percentage of network subscribers online
- Devices per location
- Bandwidth demanded per device
- Available speed per subscriber

** Note: Since the COVID-19 lockdown, the busy hour peak has become broader. We expect this effect (longer peak hours) will continue as people spend more time online.*

Source: Cartesian

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Capacity Required per Subscriber

Peak usage demands will continue to grow in the future due to a combination of factors

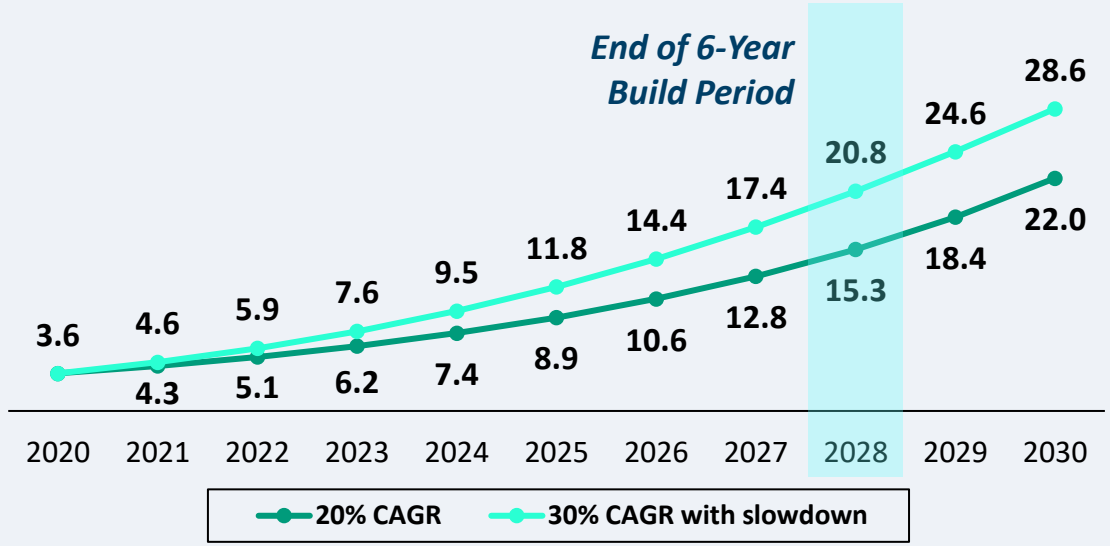
Capacity Required per Subscriber

- Current estimates of average bandwidth usage per subscriber, during peak hours, range from 1.7 to 2.7Mbps
- For RDOF locations, we have uplifted these estimates of peak usage to establish a minimum capacity required of **3.6 Mbps per subscriber** to provide 25% headroom at highest peak usage

Growth in Bandwidth Demand

Online Users	Netflix and other OTT TV services are driving more users online in the busy hour. This effect is **likely to be higher in RDOF areas** where cable TV is not available.
Devices	Cisco forecasts **13.6** networked devices per capita by **2023**, up from **8.4** networked devices per capita in **2018**
Bandwidth per Device	In 2022, Cisco anticipates **22%** of global video traffic to be 4K/UHD, which requires **30-40% more** bandwidth than HD, up from 12% in 2020
Available Speed	100 Mbps is above the current US average; users with faster connections use more data. For example, gigabit accounts for **4%** of connections, but **12%** of all traffic (Openvault, 2020 Q1).

Capacity Required per Subscriber



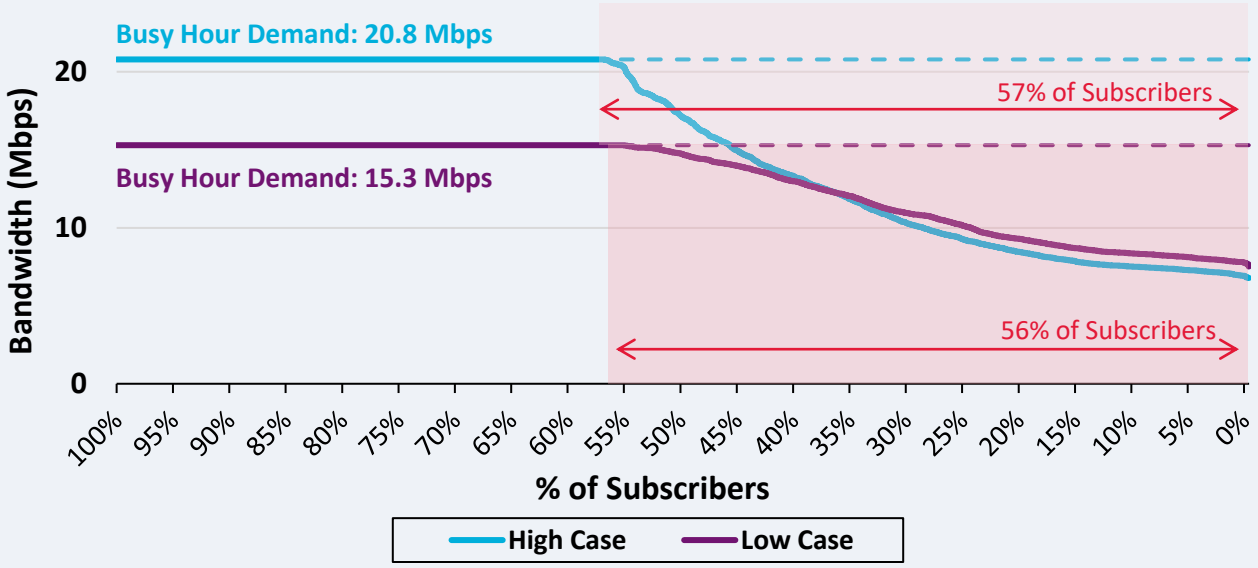
- We have two scenarios for anticipated growth in peak demand per subscriber based on Openvault, Cisco, and Cartesian estimates: a conservative low case with a 20% CAGR; and a high case using Cisco's 30% CAGR, reducing this by 1.5% points each year
- Our model adds 25% headroom to accommodate spikes in demand
- By 2030, the capacity required is 22.0 – 28.6 Mbps per subscriber
- Starlink's 6-year build period is likely to be concluded by 2028; we estimate that capacity required in 2028 to be between 15.3 and 20.8 Mbps
- This average peak demand accounts for users not online in the busy hour

Source: Cartesian, Cisco, Openvault

Capacity Allocation to Subscribers

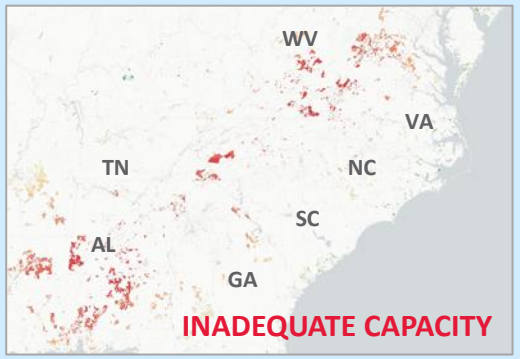
Modeling peak usage and Starlink's network capability shows that Starlink may fail to provide enough bandwidth to over half of all subscribers at peak hours

Bandwidth Allocation to Subscribers During Peak Demand (2028)



- We modeled Starlink's best possible share of subscribers fully served under the low case and high case capacity requirements of **15.3** and **20.8 Mbps** respectively – customers receiving less **will experience service degradation**
- **56%** of subscribers in the low case, and **57%** of subscribers in the high case, will experience service degradation during peak times
- The median capacity allocation is **14.7 – 17.1 Mbps**, and **25 – 29%** of subscribers receive less than 10 Mbps during peak times

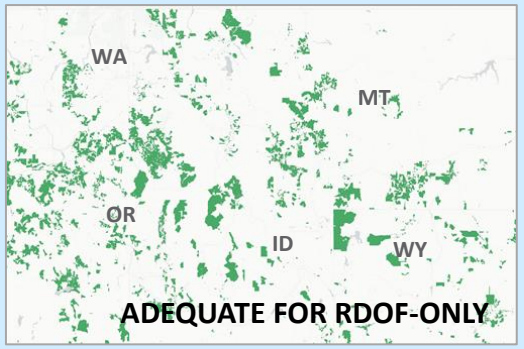
Areas of High and Low-Capacity Coverage



Eastern US

Washington DC, Richmond and Knoxville

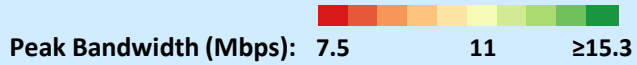
- Eastern states contain the highest densities of Starlink's RDOF subscribers
- Even with satellites over the ocean serving few other locations, subscribers have an allocated peak bandwidth of around **8 Mbps** – falling short of the 15.3-20.8 Mbps required



Mountain West

Montana, Wyoming and Washington

- RDOF subscribers in the northwest are spread over a large area
- The capacity requirement is met due to low population density and the higher satellite density in northern latitudes



Extending service to non-RDOF customers would further reduce allocated capacity per RDOF subscriber

Source: Cartesian, Openvault

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Starlink Capacity for RDOF

Our model indicates that Starlink's fleet would not have enough capacity to meet expected demand, particularly in the Eastern US, even given favorable assumptions

Modeling Assumptions and Key Results

We have made several assumptions in our model which are optimistic about the future state of the Starlink fleet:

- The base case of our model assumes Starlink is able to meet its goal of **12,000 satellites** before the mandated RDOF completion date
- Our model assumes that Starlink will optimize its satellite coverage by:
  - Prioritizing uplinks from ground stations to satellites that few other users can connect to
  - Allocating capacity to attempt to satisfy RDOF requirements in all areas before distributing surplus capacity
- Our model assumes all subscribers within range of a satellite can connect to that satellite, and does not account for terrain and other serviceability considerations
- The throughput capacity of a single satellite is set at **20 Gbps** per previous SpaceX public statements – other filings imply that the maximum capacity could be only **10 Gbps**
- Our model assumes that all Starlink satellites will be authorized to use its full licensed spectrum at all altitudes – it is possible Starlink may not gain approval for a certain portion of its satellites to be at a low enough altitude to support our assumed **500-km coverage radius**

Our model shows that with these assumptions, in our base case at fleet completion, 56-57% of RDOF subscribers may not receive enough bandwidth to avoid service degradations at peak hours – further modeled scenarios for the Starlink fleet are covered on slide 12

Source: Cartesian, FCC

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Impact on RDOF Locations from Non-RDOF Commercial Broadband

The base case assumes that all Starlink capacity is used for RDOF subscribers. In reality, Starlink will serve broadband users outside of RDOF, leading to a lower peak allocation per RDOF subscriber.

Starlink Commercial Broadband Expansion

- We anticipate Starlink will offer a commercial broadband service outside of RDOF areas in order to better monetize its satellite fleet
- Starlink's Better Than Nothing Beta program launched an initial trial service the U.S. and Canada in 2020[1]
- We considered how usage from non-RDOF broadband customers could impact the service quality in RDOF areas
- Our model focused on potential demand from states where SpaceX has been assigned RDOF locations

Methodology:

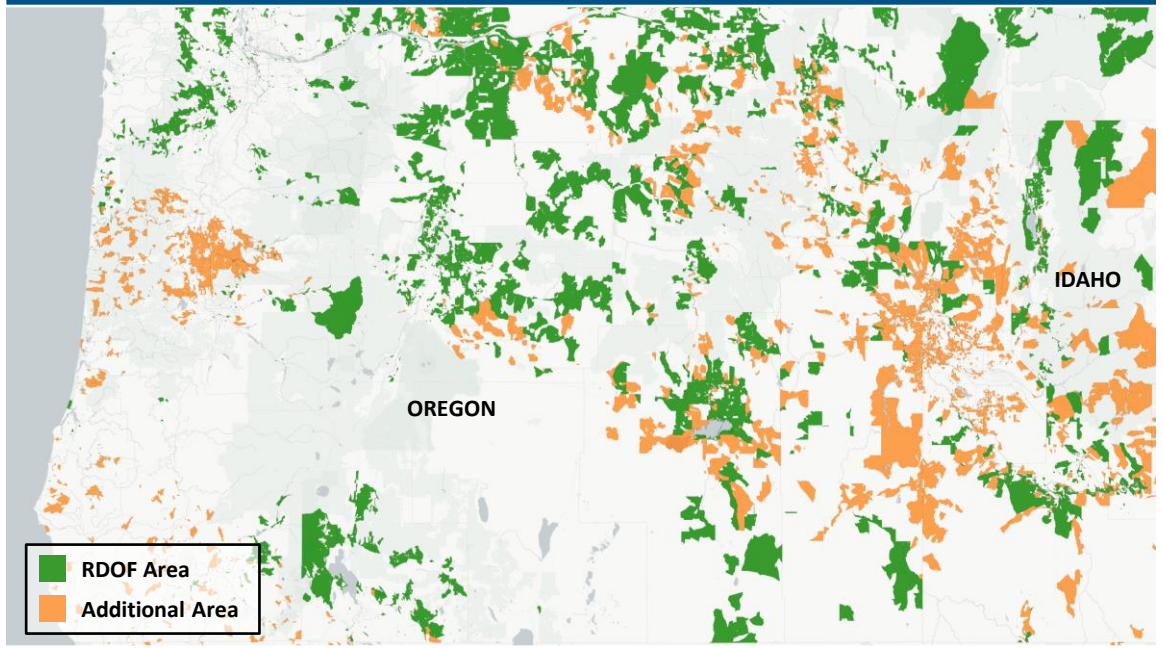
We targeted areas that were not RDOF eligible, where Starlink would have best chance of competing with existing providers:

- Customers currently only receive 25-50 Mbps broadband
- Population density is no greater than 500 per square mile

We have assumed that Non-RDOF subscribers are offered the same 100Mbps service and have the same bandwidth demands on the network

Network capacity is shared evenly across all subscribers on the network

Potential Non-RDOF Expansion Areas in Oregon



	RDOF Areas	Expanded Areas	
Locations in Footprint	643K	1.0M	
Broadband Uptake	70%	10%	20%
Subscribers	**450K**	**101K**	**202K**

1. Starlink Mobile App, via CNBC
Source: Cartesian, FCC, CNBC

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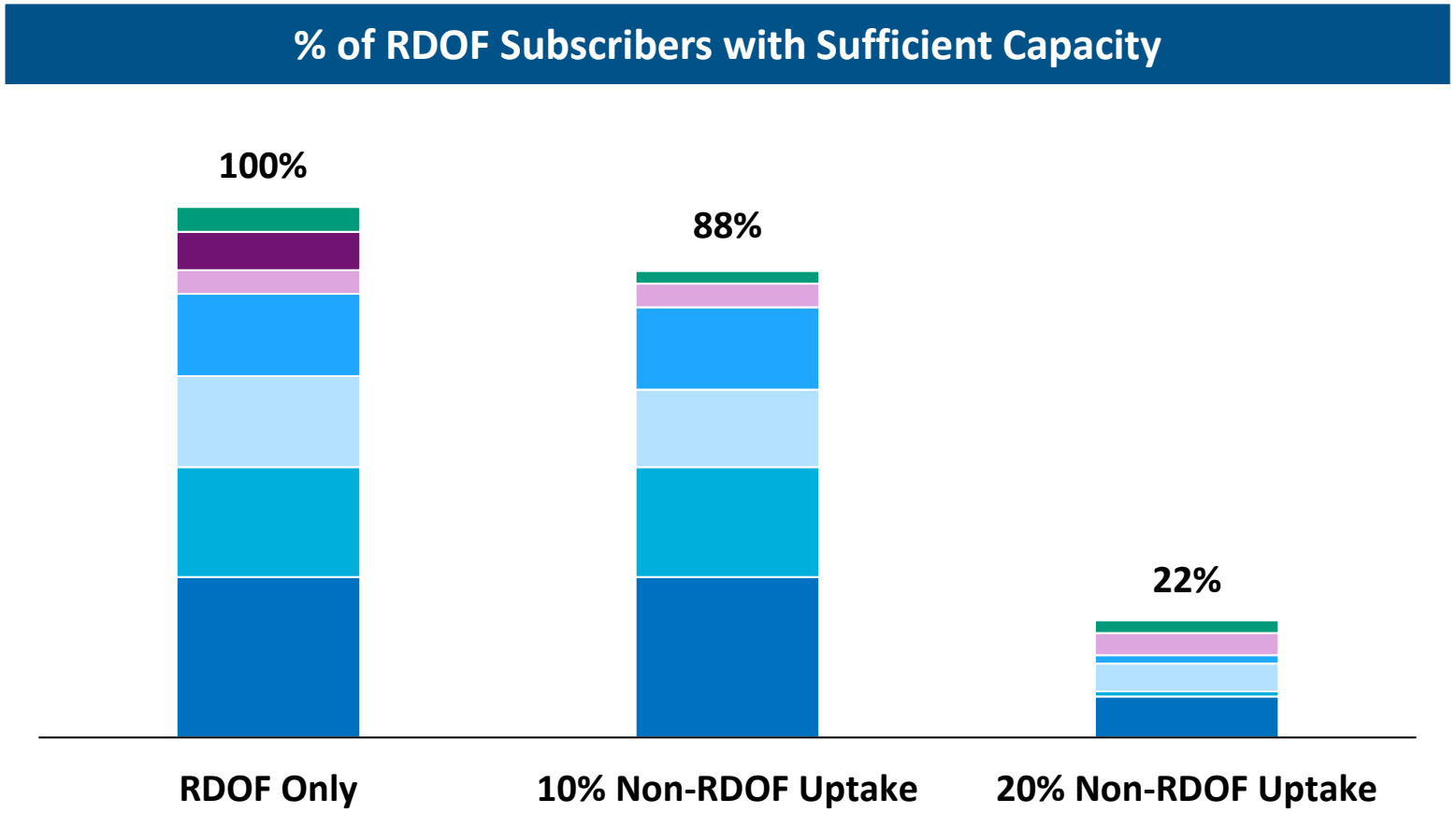
Non-RDOF Commercial Broadband Impact: Midwest and Western States

In the high demand scenario, there is insufficient capacity to support non-RDOF customers in rural areas alongside the RDOF commitment

Selected States	RDOF Subscribers
All Locations	450K
Michigan	6K
Illinois	9K
Wyoming	5K
Idaho	19K
Montana	21K
Oregon	25K
Washington	36K
Total	*121K*



RDOF subscribers in these states receive the required 20.8 Mbps allocation in the RDOF-only scenario but lose out when non-RDOF subscribers are added to the network

Source: Cartesian, FCC

Non-RDOF Commercial Broadband Impact: Eastern US

Eastern States are not allocated sufficient bandwidth in the RDOF-only base case. The gap becomes even larger when non-RDOF broadband is considered.

State	RDOF Subscribers	Median Peak Allocation (Mbps)		
		RDOF-Only (Low Demand)	RDOF-Only (High Demand)	High + 10% Extra Uptake
Alabama	26K	8.2	7.3	5.4
Virginia	38K	8.6	7.6	6.2
West Virginia	7K	8.7	8.1	6.3
Mississippi	27K	9.0	8.3	6.3
Georgia	16K	9.3	8.3	6.1
North Carolina	14K	9.1	8.7	6.6
Maryland	4K	10.9	9.8	8.2
Pennsylvania	41K	12.0	11.4	9.5
Tennessee	8K	11.5	11.5	8.0
Peak Allocation Requirement to Avoid Congestion (Mbps)		15.3	20.8	20.8

Subscribers in these states do not receive the required allocation, even in the RDOF-only scenarios

Source: Cartesian, FCC

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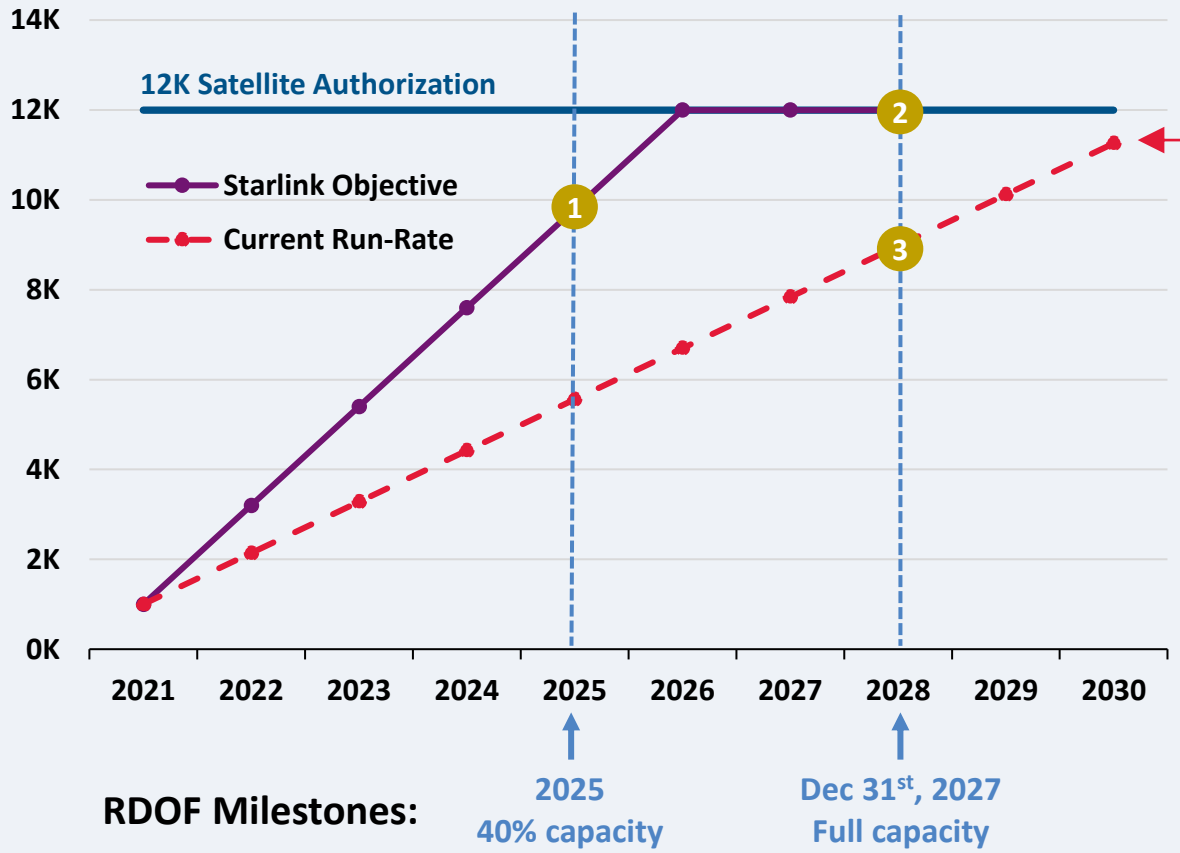
Sensitivity Analysis – Fleet Size

In addition to the commercial broadband impact, we have modelled alternative scenarios based on how Starlink's capacity will evolve over time against the RDOF Milestones

Satellite Numbers: SpaceX Plans versus Current Run-Rate



Alternative forecast based on Current Run-Rate

SpaceX launches 48 times every year[1], 40% of which are provisioned for Starlink[2], releasing 60 satellites at a time.

Model Scenarios and Sensitivities

1. Base Case (2025) – 10K Satellites and 40% Locations
2. Base Case (2028) – 12K Satellites and 100% Locations
3. Slower Launch (2028) – 9K Satellites and 100% Locations

We also model a case in which the satellite count is increased by 10% to 13.2K satellites

1 2021 stated launch volume target for Falcon 9 rocket
2 Assuming consistent with 2020 launches
Note: Alternative forecast would still allow Starlink to meet its satellite license obligations.
Source: Cartesian, SpaceX

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Summary of Results

The model indicates that Starlink will be unable to meet demand in 2028, particularly if they miss their target for satellite fleet size

Base Case Scenario: Percent of RDOF Locations where Demand is Met

Scenario	2025	2028	2030
Low Demand Case (20% CAGR)	100%	44%	43%
High Demand Case (30% CAGR with slowdown)	100%	43%	16%

We estimate Starlink will be able to meet the 40% RDOF build target in 2025 – however, the network will face a capacity shortfall by 2028 as more subscribers are added.

The model indicates that between 56% and 57% of RDOF subscribers will not be fully served in 2028.

Sensitivity Analysis for 2028

Scenario	Low Demand Case	High Demand Case
Commercial Broadband (5% Other Rural Take-Up)	43%	40%
Slower Launch Rate (9K Satellites)	0%	0%
10% More Satellites (13.2K Satellites)	45%	43%

Sensitivity analysis reveals that the number of underserved subscribers will be higher if Starlink serves other users or is late in its launch schedule.

Source: Cartesian

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Beyond Fixed Broadband

Starlink is exploring many other potential use cases. We have not modeled the impact of these on RDOF.

 **Military**	• **Existing testing relationship:** As of May 2020, the US Army is evaluating the suitability of Starlink broadband for military use cases • **Unknown network impact:** Whether Starlink will utilize the same network as for residential broadband is unknown
 **Commercial**	• **Existing Testing:** SpaceX has submitted a request in FCC filings to test their network terminals aboard planes • **Industrial use cases:** SpaceX has already been in talks with oil and gas exploration companies to deploy Starlink broadband in the field
 **Non-Fixed Broadband**	• **Vehicle broadband:** Elon Musk has suggested vehicles could be outfitted with Starlink connectivity to provide broadband to consumer vehicles and mass transit

Source: Cartesian, SpaceNews, Inverse

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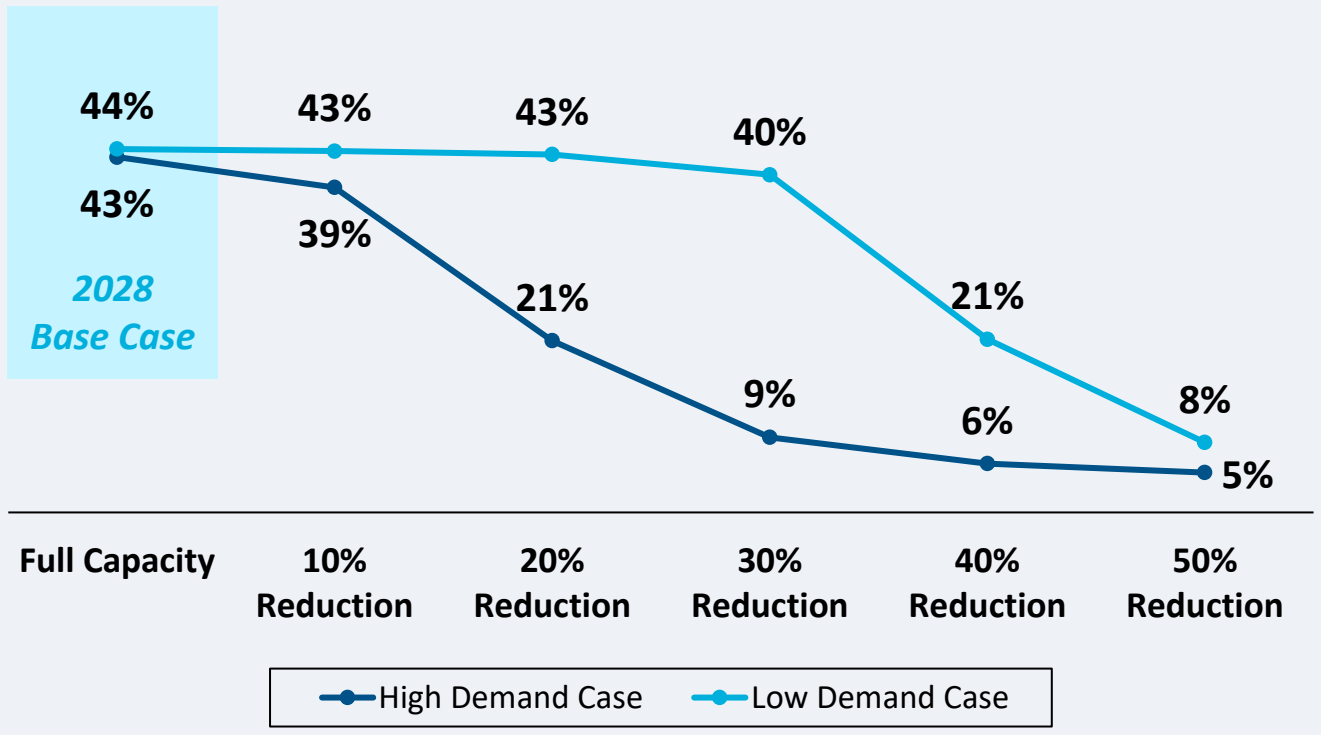
Impact on RDOF Locations from Other Use Cases

We have modeled the effect of reducing the satellite capacity available to RDOF areas, in order to estimate the potential impact of Starlink expanding its network beyond RDOF fixed broadband

Subscribers Fully Served During Peak Hours



Findings

- In both scenarios, allocating Starlink capacity to non-RDOF usage has a material impact on the RDOF service
- In the low demand scenario where peak bandwidth grows at a slower pace, Starlink maintains a similar share (c.40%) of subscribers fully served until at least 30% of capacity is allocated to non-RDOF uses
- In the high demand scenario, the share of fully served subscribers immediately decreases, and moderate amounts of capacity reduction result in large numbers of subscribers no longer being fully served

In the scenario where 50% of average satellite capacity is allocated to non-RDOF network users, only 5-8% of subscribers receive sufficient bandwidth allocation during peak hours

Source: Cartesian, FCC

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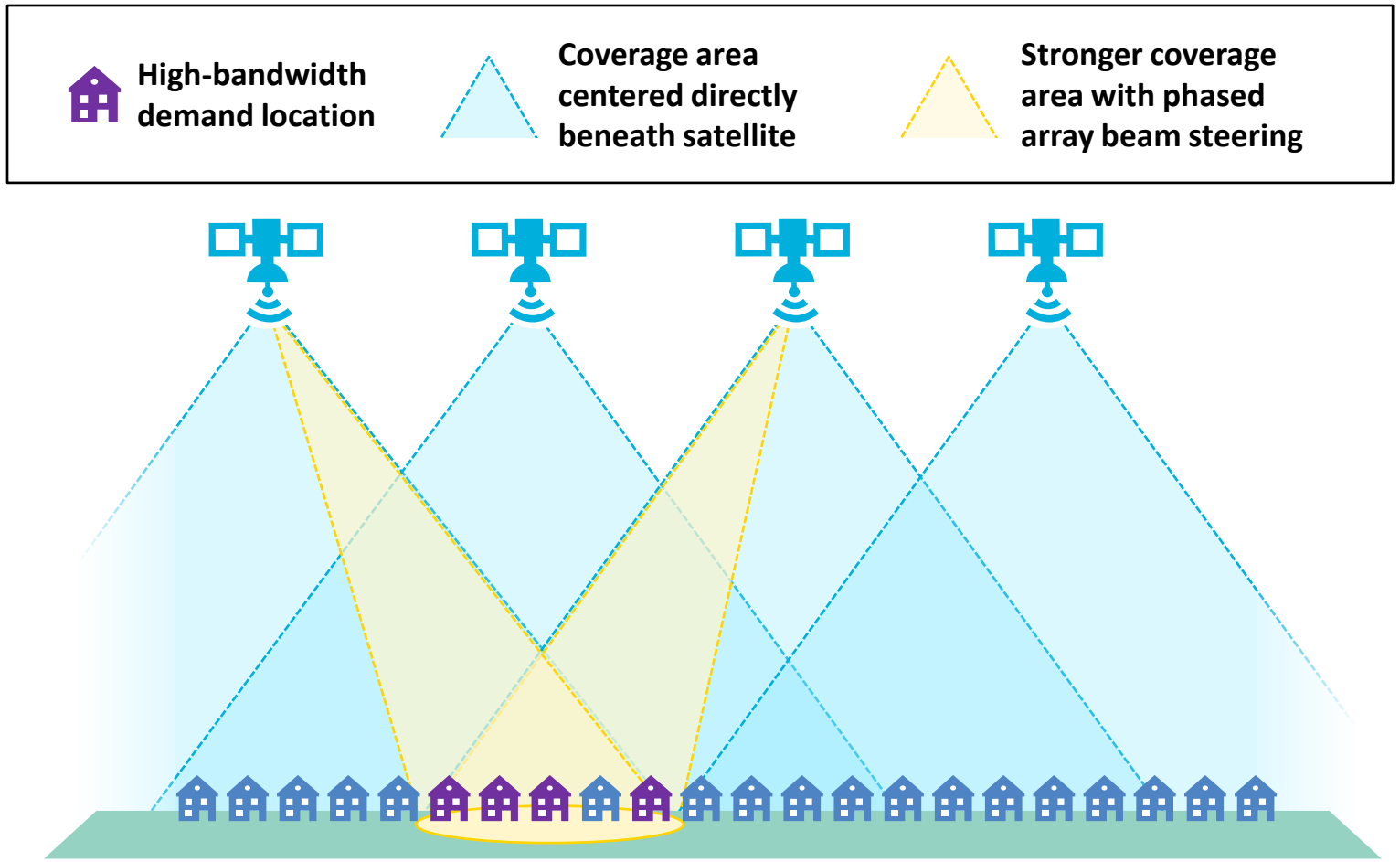
Dynamic Satellite Coverage

Starlink satellites are equipped to shift coverage as needed to densify signal strength in certain areas



Starlink is capable of dynamically allocating satellite coverage to areas where it may be beneficial to increase coverage density

Research Findings

- Starlink's satellites are equipped with multiple phased array antennae, which allow the fleet to dynamically allocate satellite capacity as needed:
  - Capacity can be steered towards areas of greatest demand
  - Capacity may also be temporarily assigned for a period of time
- We anticipate this dynamic coverage capability will play a role in supporting an RDOF network despite high expected oversubscription
- However, the dynamic nature of the network raises important questions for the RDOF application process and the FCC's performance testing program

Source: Cartesian, FCC

FCC Long-Form Application

Form 683 appears to be better suited to a terrestrial network application. There is a risk that potential future issues could be missed if the assessment does not fully consider the nuances of LEO satellite networks.

Application Item	Description	Considerations for Starlink Assessment
State-to-State Network Design	Applicants must submit state-by-state network designs	• Starlink's orbiting network is not aligned to state boundaries • Ground capacity is not fixed as satellites transit overhead, and satellite spot beams can be dynamically repositioned
Engineer Certification	Network designs must be certified by a professional engineer	• Unlike a terrestrial fixed network, Starlink can be reconfigured after deployment • Starlink network may deviate over time from the design submitted in the long-form application

Source: Cartesian, FCC

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CAF Testing Overview and Limitations

The CAF testing methodology may need to be altered to properly test Starlink's network

CAF Testing Overview	
Sampling Methodology	• Up to 50 locations in each state • Selected at random from RDOF areas • Sample updated every 2 years
Testing Methodology	• Speed tests are conducted once an hour between 6PM and 12AM • Latency tests are conducted once a minute in the same period
Testing Criteria	• 80% of Locations must record speeds above 80 Mbps • 95% of locations must record latency at or below 100 ms

Testing Implications

- The CAF testing methodology appears to have been designed with static, terrestrial networks in mind
- A single Starlink satellite has a coverage area that is far larger than the typical serving area of a CO or other terrestrial network node
- As previously noted, the Starlink network design is not fixed, and capacity may be dynamically reassigned
- From this, it follows that testing a small sample may be inadequate to reveal capacity constraints (and service degradation) elsewhere on the network

Source: Cartesian, FCC

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Conclusions

Our model indicates that Starlink will face a capacity shortfall in 2028; however, the RDOF performance test may not detect whether targets have been missed

- We forecast a capacity shortfall in 2028
- RDOF service quality is at further risk if Starlink allocates capacity to non-RDOF use
- The FCC may find it difficult to ensure that Starlink complies with the RDOF terms:
  - Starlink's future business plans are continuously changing
  - The network is highly flexible and could deviate from the design in the long-form application
  - The RDOF performance tests may not detect whether targets have been missed

Recommendations

We recommend that the FCC mitigates potential RDOF risks in its upfront assessment and ongoing monitoring

1. The long-form assessment should stress test the network design under a range of realistic 10-year scenarios for service take-up and usage in the peak hour

2. Risks arising from uncertainties in the evolution of proposed networks should be mitigated through contract, e.g. a minimum capacity commitment to RDOF

3. RDOF performance testing should be designed to cater for highly reconfigurable networks:
   - Blind testing with a larger sample size could be introduced
   - Testing could also be complemented by regular audit of operational KPIs

Starlink Evaluation

A thorough assessment of Starlink's design will need to consider many factors beyond the scope of our model

Category	Parameter	Cartesian Model
Traffic	RDOF Subscribers	Estimated from household adoption in RDOF areas
	RDOF Busy Hour Demand	Estimated from public data
	Other Broadband Demand	Unknown, illustrative 5% scenario used
	Non-Broadband Demand	Not assessed
	Busy Hour Headroom	25% spare capacity
Hardware Capacity	Satellite Quantity	12,000 satellites
	Satellite Distribution	Evenly spaced, 72 orbital planes at 53° inclination
	Satellite Max. Throughput	20Gbps
	Ground Stations Quantity	Ground station capacity constraints not assessed
	Ground Stations Location	
	Ground Station Max. Throughput	
Radio Network Capacity	Satellite – Ground Station Capacity	Radio network capacity constraints not assessed
	Satellite – Subscriber Capacity	
	Spot Beam Quantity, Size, and Configurability	
	Spectrum Allocation and Usage	
	Link Budgets	
	Topography	

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