The Science and Strategy Behind D2C

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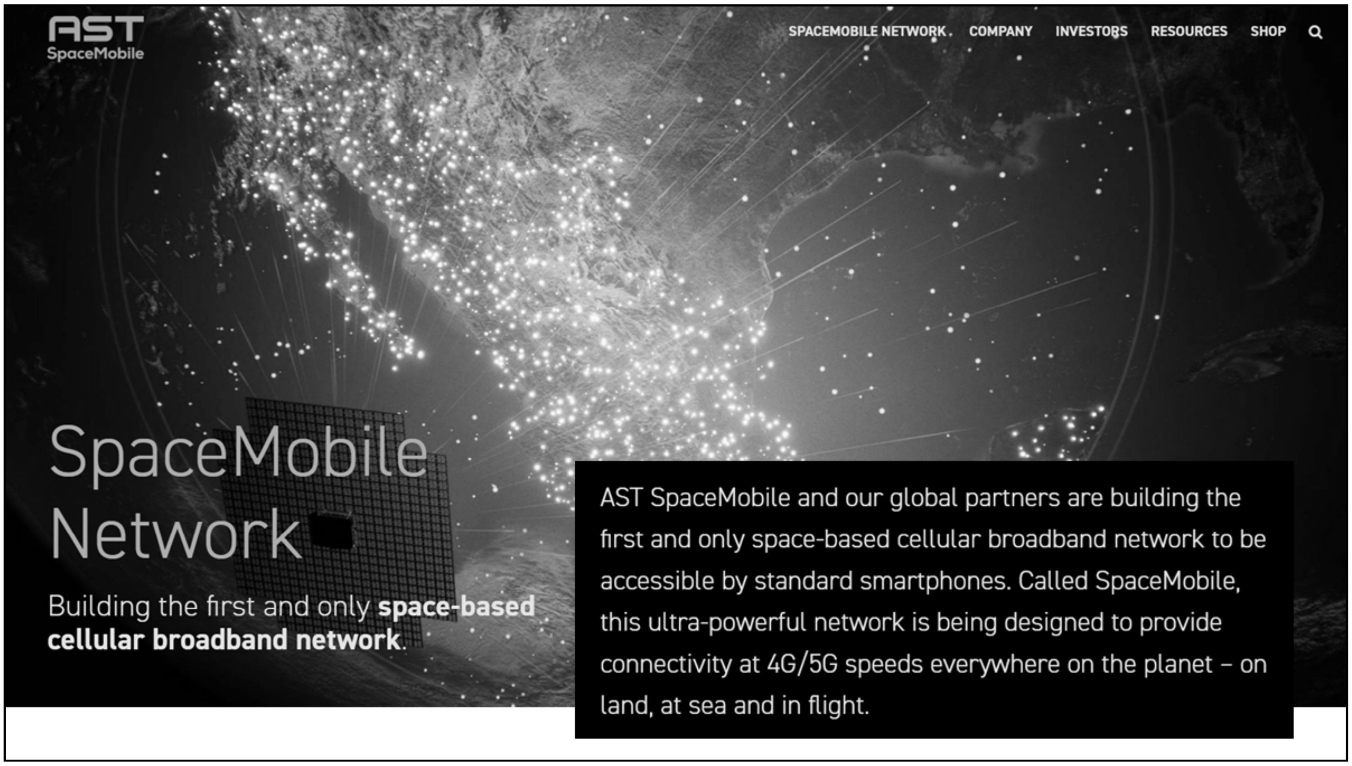
The University of Texas at Austin

TFI Technology Conference | January 22, 2026

A pitched contest is playing out in the skies above us, and in board rooms and R&D labs across the globe. It's a battle for the privilege of connecting your phone directly to a satellite for text, voice, and maybe even broadband data. For me, the two most interesting contenders – the ones with the biggest, most audacious plans – are AST SpaceMobile and SpaceX, with its Starlink constellation. Let's take a closer look direct-to-cell communications.

Contenders

6G @ UT

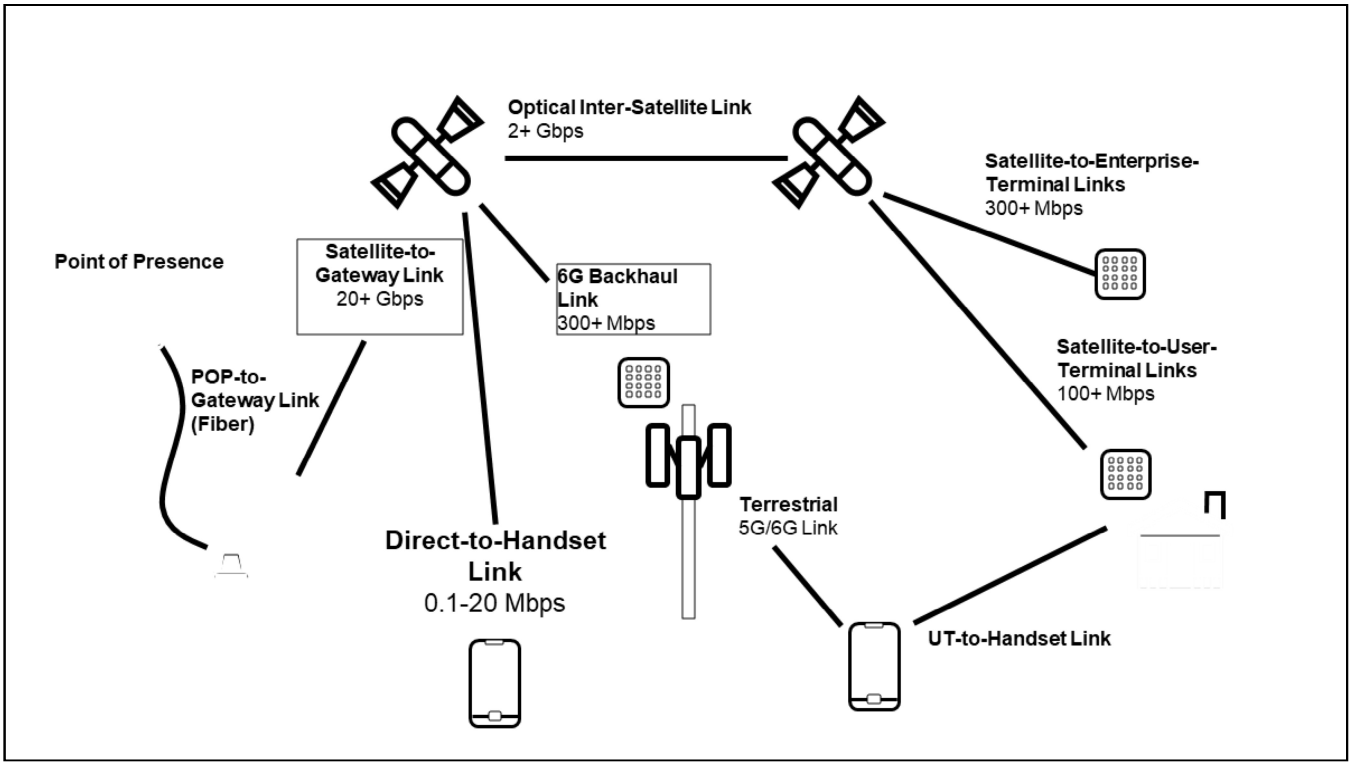


Here is AST SpaceMobile's pitch, taken directly from their website. Notice their explicit reference to broadband and connectivity at 4G/5G speeds.

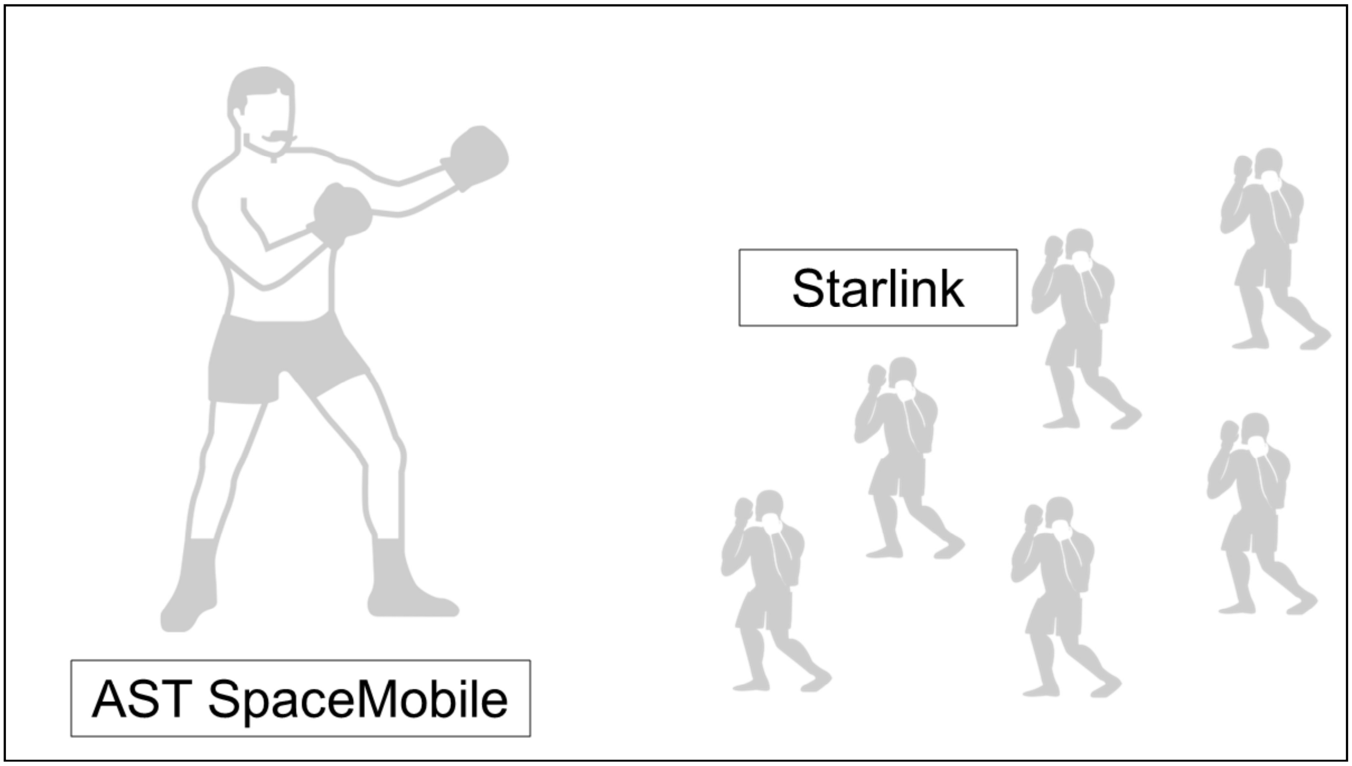
SpaceX's Starlink pitch for D2C is more circumspect, which is surprising for a company headed by Elon Musk.

LEO Broadband

Let’s take a step back and see how this new direct-to-cell service fits into the general architecture of low-Earth-orbit satellite communications.



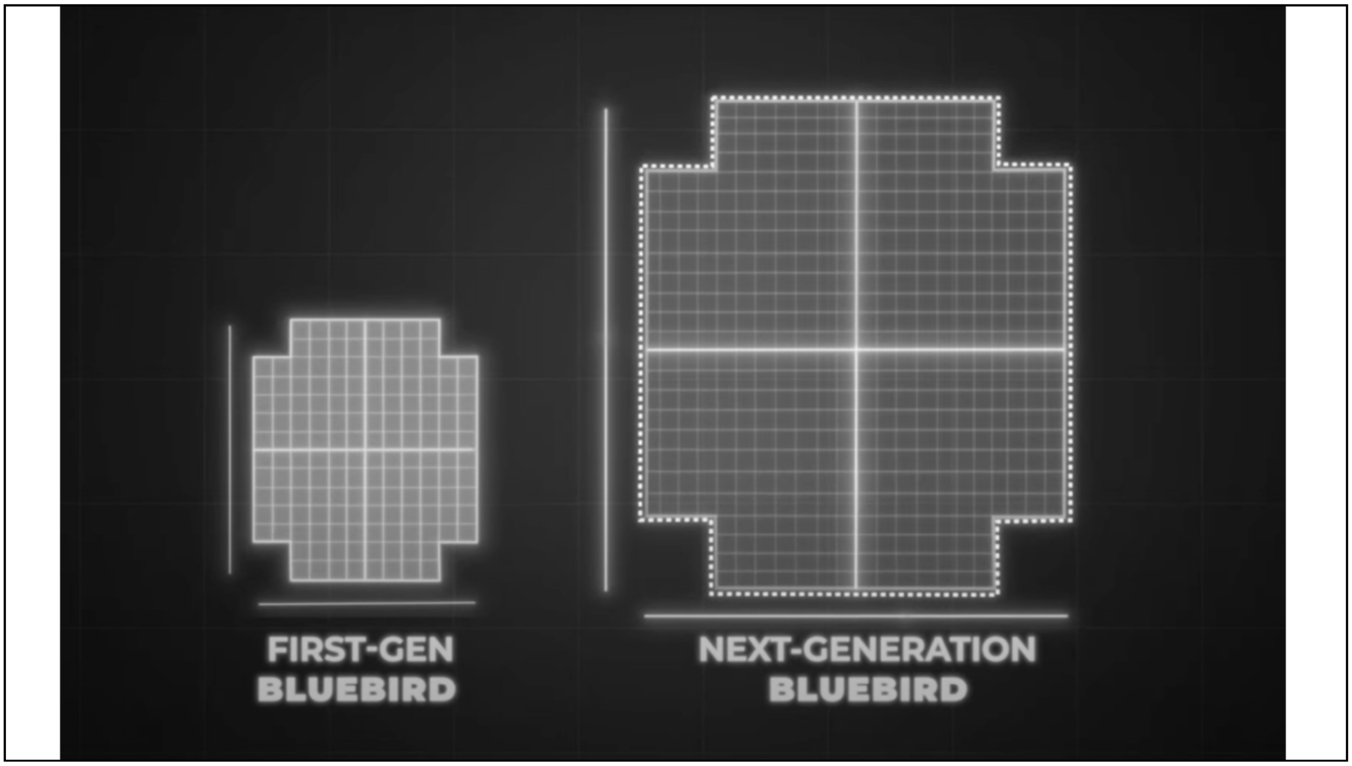
Every broadband LEO network has various points of presence where the satellite network connects to the terrestrial Internet. These POPs are connected to Gateways whose links to overhead satellites are like the wideband backhaul links for terrestrial cell towers. The satellites themselves may be linked in a mesh with their nearest neighbors in the constellation via high-bandwidth optical inter-satellite links. User terminals near the ground are phased arrays with fixed locations, such as a house, or are attached to vehicles, such as an airplane. Connections with less than 30 ms latency to the POP and greater than 100 Mbps throughput are by now common. Fixed or mobile terminals can in turn deliver network access to handsets and other devices over a local wireless network. A promising use case for broadband LEO comms is providing backhaul to cell towers in remote locations where fiber or terrestrial microwave connections are impractical, permitting these towers to service handsets or devices over standard cellular links. The most ambitious proposals for broadband LEO call for direct to handset links with global coverage, low latency, and rates beyond 2 Mbps.



SpaceX already has around 650 D2C-capable SVs (Oct. 2025).

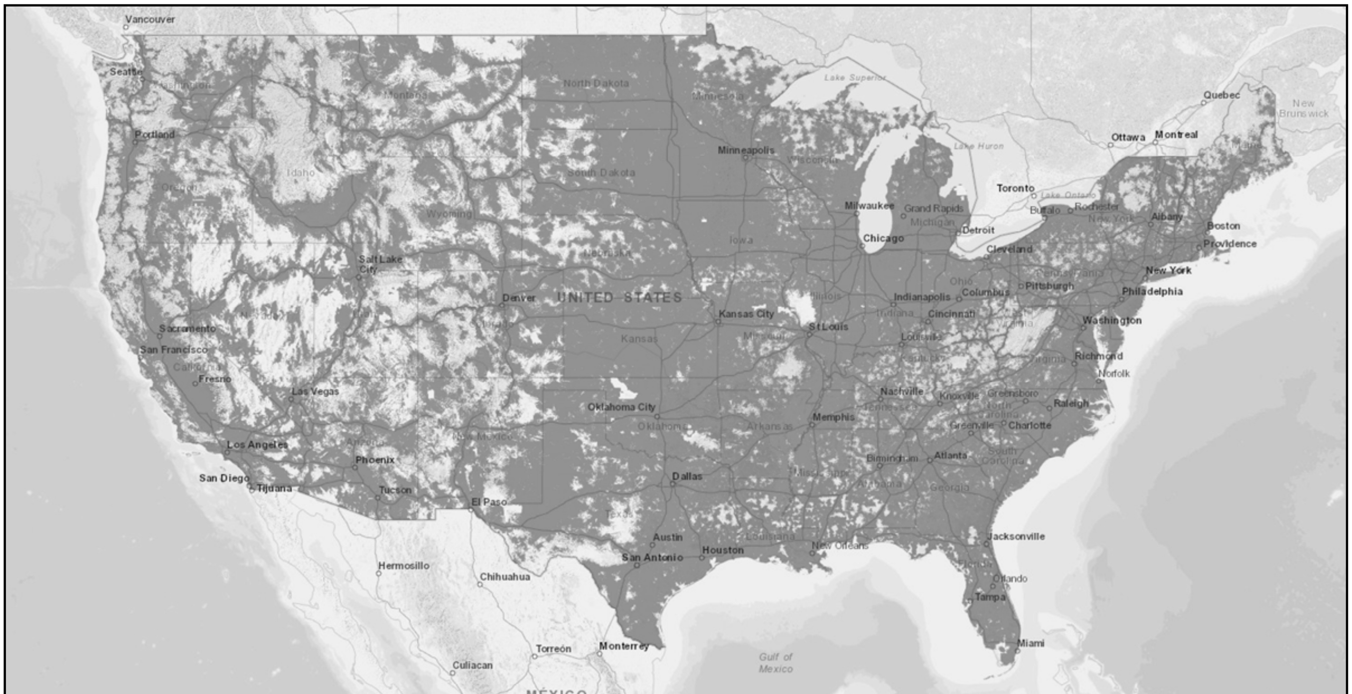
Space deployment allows for enormous arrays even at sub-GHz frequencies.
Bluewalker 3 satellite focuses dozens of ~ 3-deg. beams on surface to support direct-to-

64 square meters. Bluewalker 3. Size of first gen Bluebird. And this is the small one!



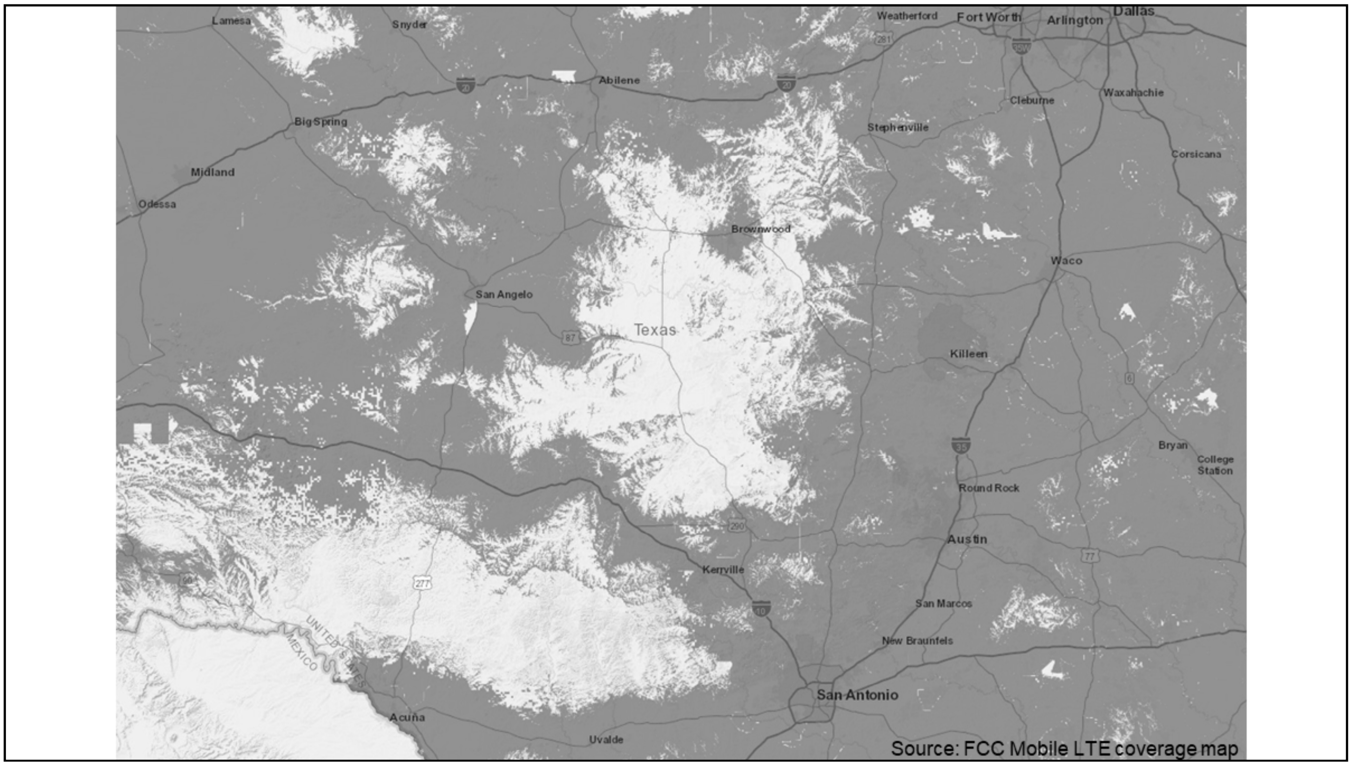
The big one – Block 2 Bluebird -- is 220 m^2, about half the size of a regulation basketball court! I'll admit to feeling proud of the Texas swagger. In what other state of the union could you build a 64-meter-square phased array and have it be the miniature prototype!

But the large size isn't just to show off. There is a sound scientific reason why you want to make the array as big as possible. We'll get to that later on.



Source: FCC Mobile LTE coverage map

Map is outdated, but make my point that the boundary between the haves and the have-nots is highly irregular.



The ragged edge of terrestrial coverage

Case Study

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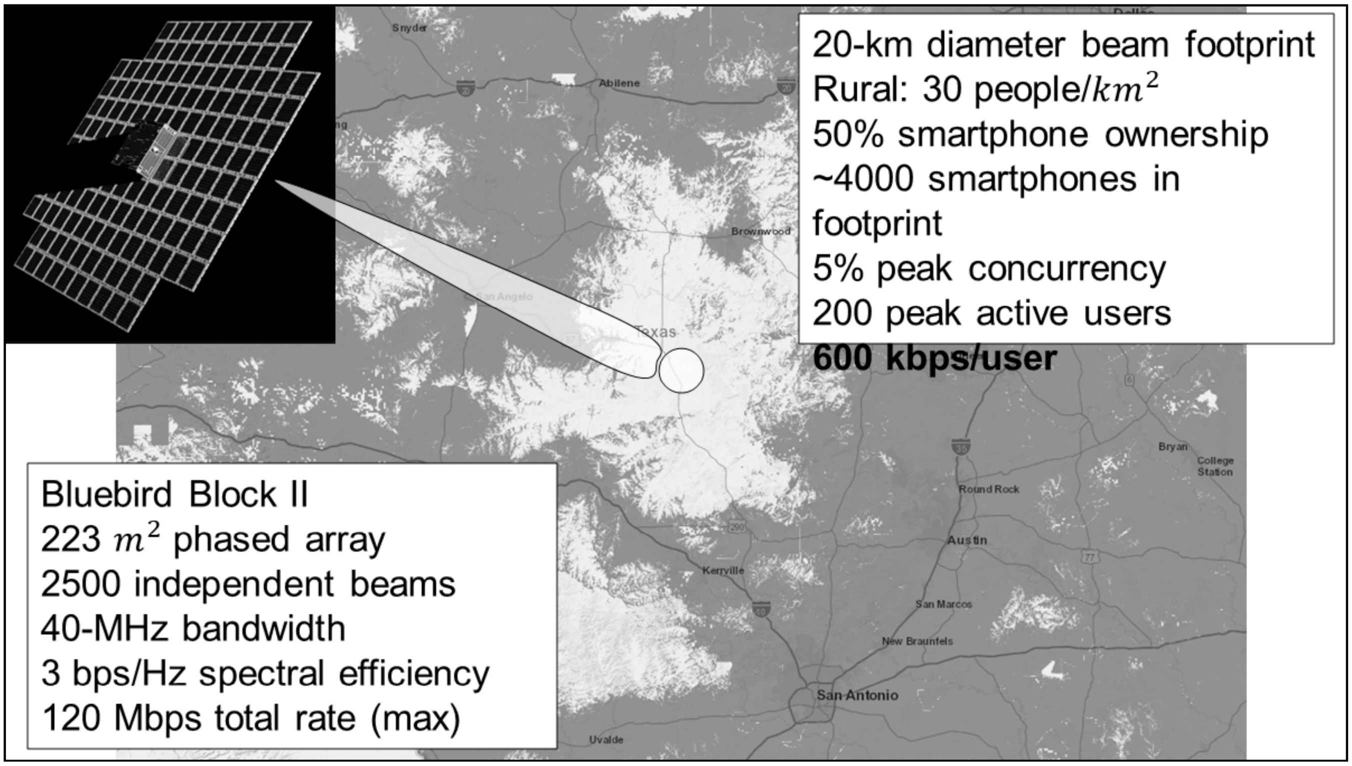
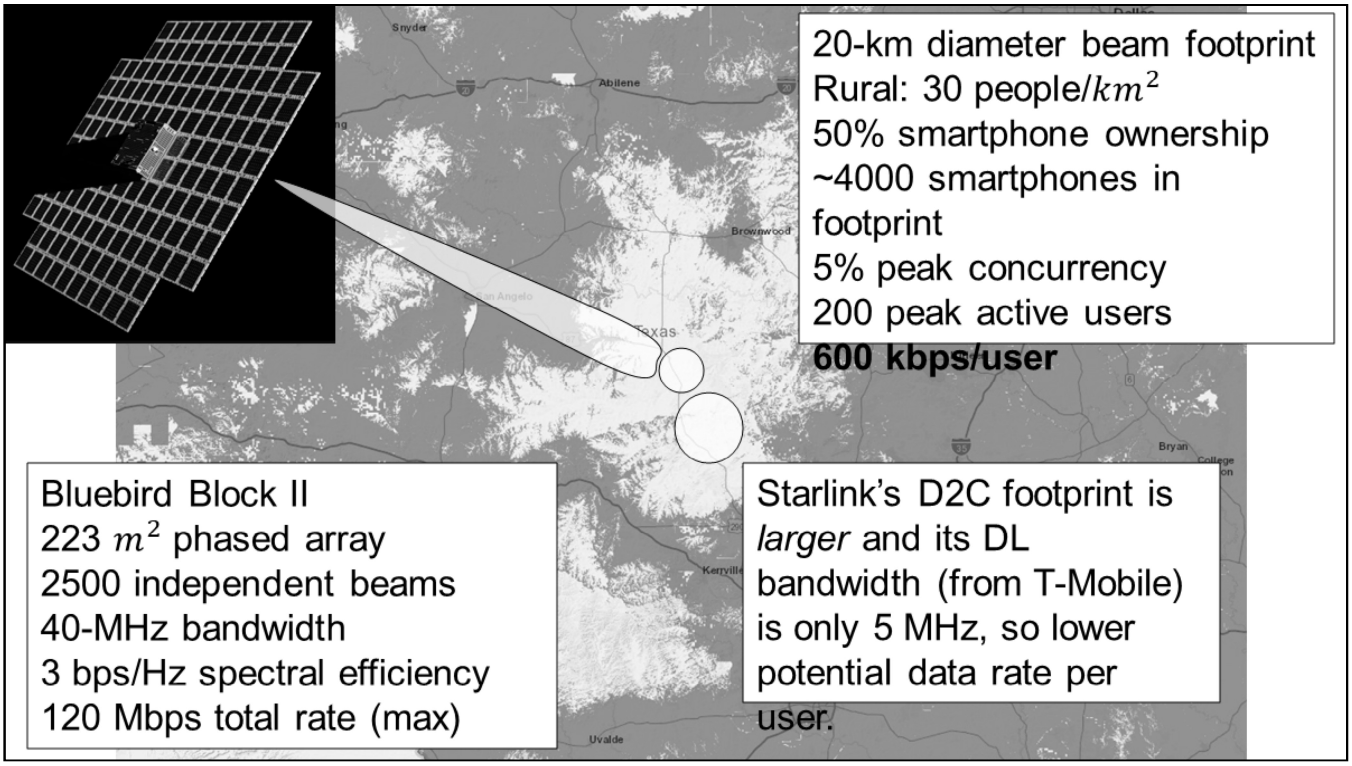

20-km diameter beam footprint
Rural: 30 people/km^2
50% smartphone ownership
~4000 smartphones in footprint
5% peak concurrency
200 peak active users
600 kbps/user
Bluebird Block II
223 m^2 phased array
2500 independent beams
40-MHz bandwidth
3 bps/Hz spectral efficiency
120 Mbps total rate (max)
Snyder
Abilene
Brownwood
Texas
Bryan
College Station
Round Rock
Austin
Kerrville
San Marcos
New Braunfels
San Antonio
Uvalde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2500 independent beams
40-MHz bandwidth
3 bps/Hz spectral efficiency
120 Mbps total rate (max)
Starlink's D2C footprint is *larger* and its DL bandwidth (from T-Mobile) is only 5 MHz, so lower potential data rate per user.
Snyder
Abilene
Brownwood
Texas
Kerrville
Uvalde
Bryan

Starlink’s and AST’s D2C offerings as planned will not be “broadband” except in special cases where a beam’s whole available bandwidth is devoted to a few customers.

Q: What could we change to get true broadband D2C to many simultaneous customers?

Design Space
&
Constraints

(with focus on downlink)

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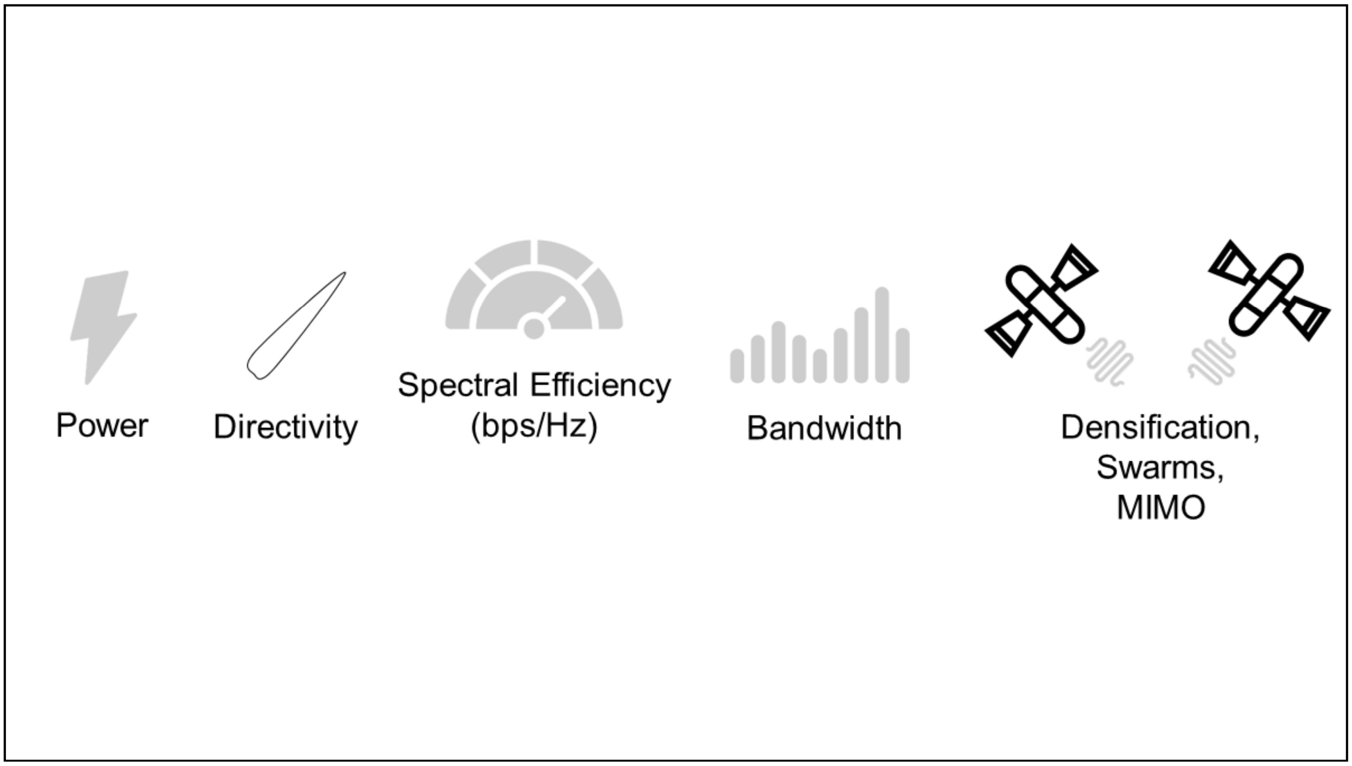
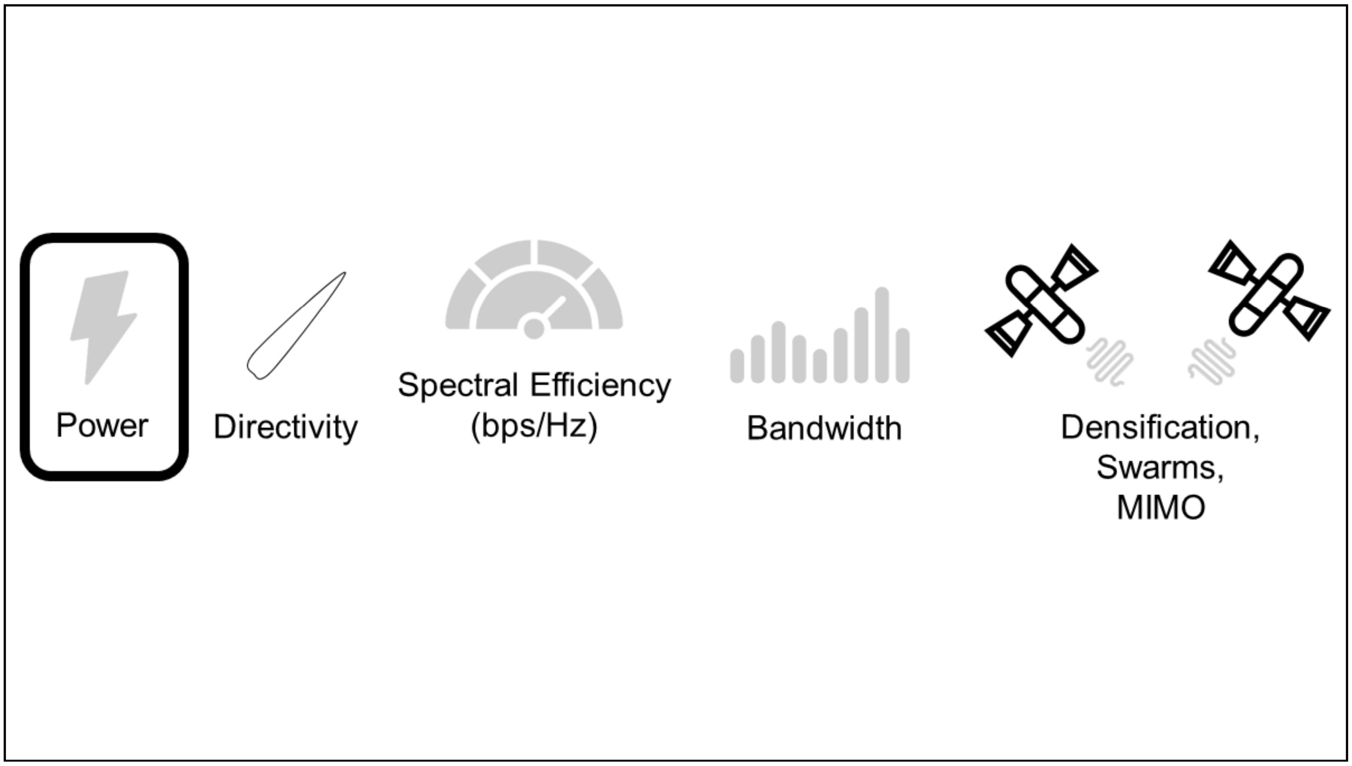
UT


Power
Directivity
Spectral Efficiency
(bps/Hz)
Bandwidth
Densification,
Swarms,
MIMO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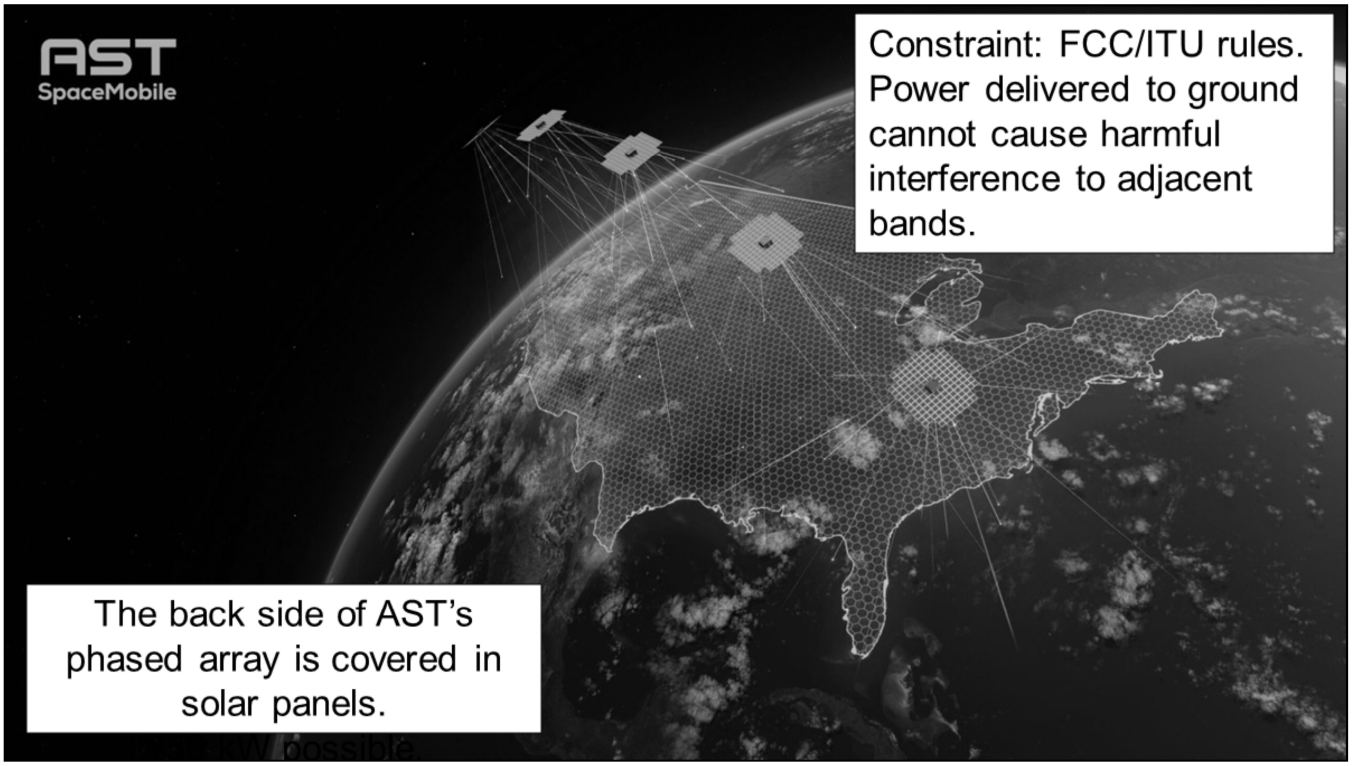
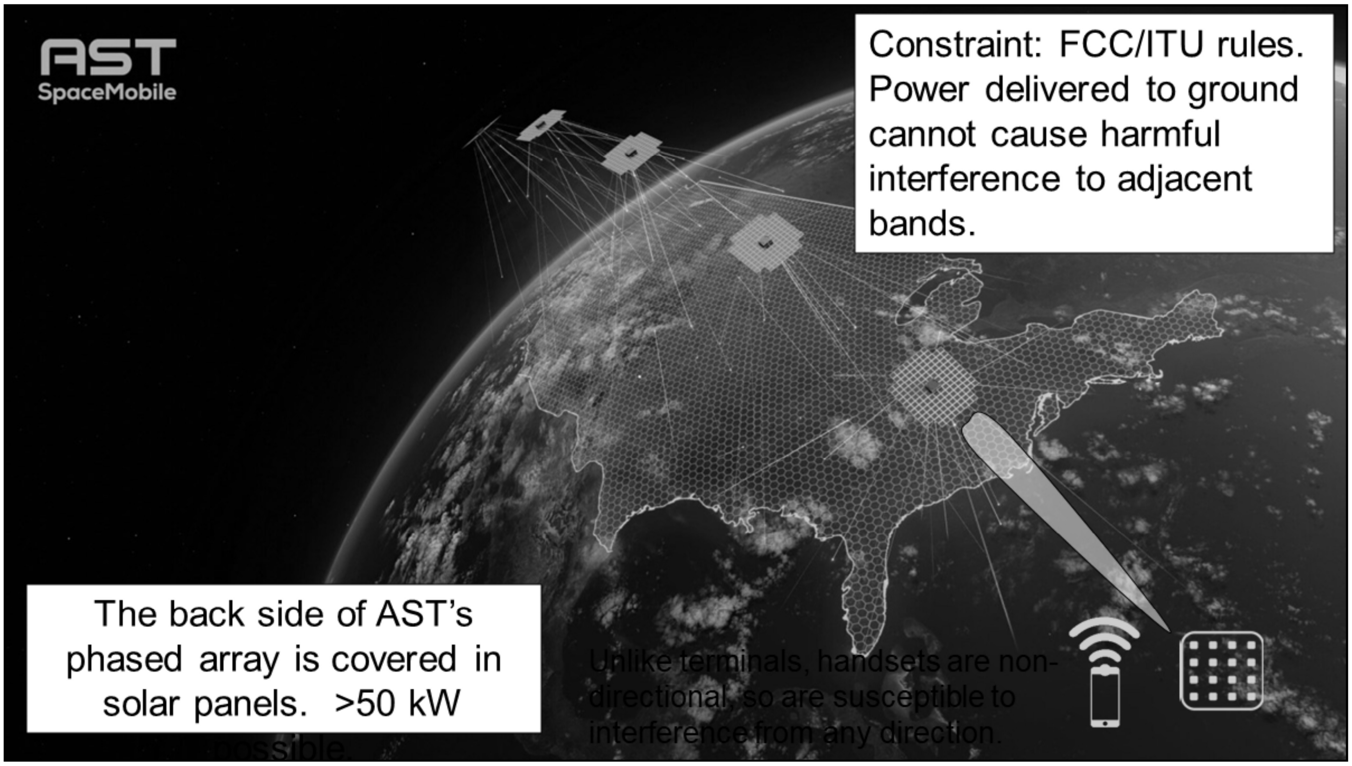


Power flux density limits are the constraint. How much power per kHz per square km?



The notion of effective power flux density, where directivity of the handset it taken into account, is irrelevant in this context: the handsets have such low directivity that good old aggregate power flux density is all that matters.

In 2024, SpaceX requested a waiver to transmit at 9.4 dB higher PFD than the FCC SCS framework allows.

AT&T and Verizon fought back, citing harmful interference.

In March 2025, the FCC granted SpaceX's waiver request.

Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of	)	
Space Bureau and Wireless Telecommunications Bureau Seek Comment on Filings of SpaceX and T-Mobile Requesting to Establish Supplemental Coverage from Space	)	GN Docket No. 23-135; ICFS File Nos. SAT-MOD-20230207-00021, SAT-AMD-20240322-00061
Application for Authority for Modification of the SpaceX NGSO Satellite System to Add a Direct to Cellular System	)	Call Sign: S3069

ORDER

Adopted: March 7, 2025 **Released: March 7, 2025**

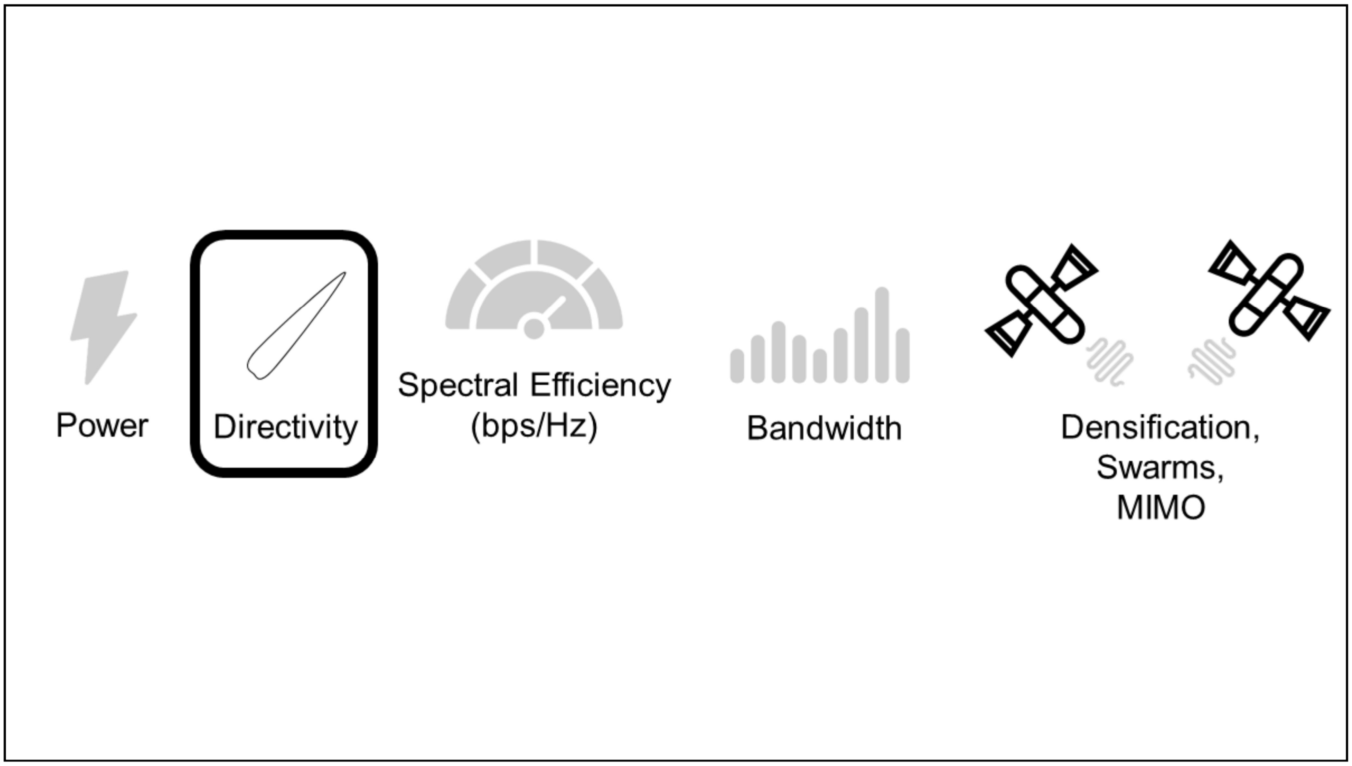
By the Chief, Space Bureau, and the Acting Chief, Wireless Telecommunications Bureau:

I. INTRODUCTION

1. By this Order, the Space Bureau and Wireless Telecommunications Bureau conditionally grant the request of Space Exploration Technologies Corp. (SpaceX) for waiver of section 25.202(k)(1) of the Commission's rules, thereby permitting aggregate out-of-band emissions (OOBE) in the United States at a power flux density (PFD) level up to -110.6 $dBW/m^2/MHz$.[1] SpaceX asserts that the public interest is supported by allowing a waiver of the established PFD to this level, which "will protect adjacent band networks from harmful interference while ensuring that consumers and first responders can use an increasingly robust set of features even in the most challenging circumstances," and will avoid placing artificial caps on the number of satellites used to provide supplemental coverage from space for terrestrial networks.[2] For the reasons discussed below, we find that there is good cause to grant SpaceX's waiver request, subject to the conditions outlined herein, including requiring that SpaceX address any harmful interference to adjacent band terrestrial wireless networks or else cease operations under the waiver.

II. BACKGROUND

2. In March 2024, the Commission issued the *Single Network Future: Supplemental*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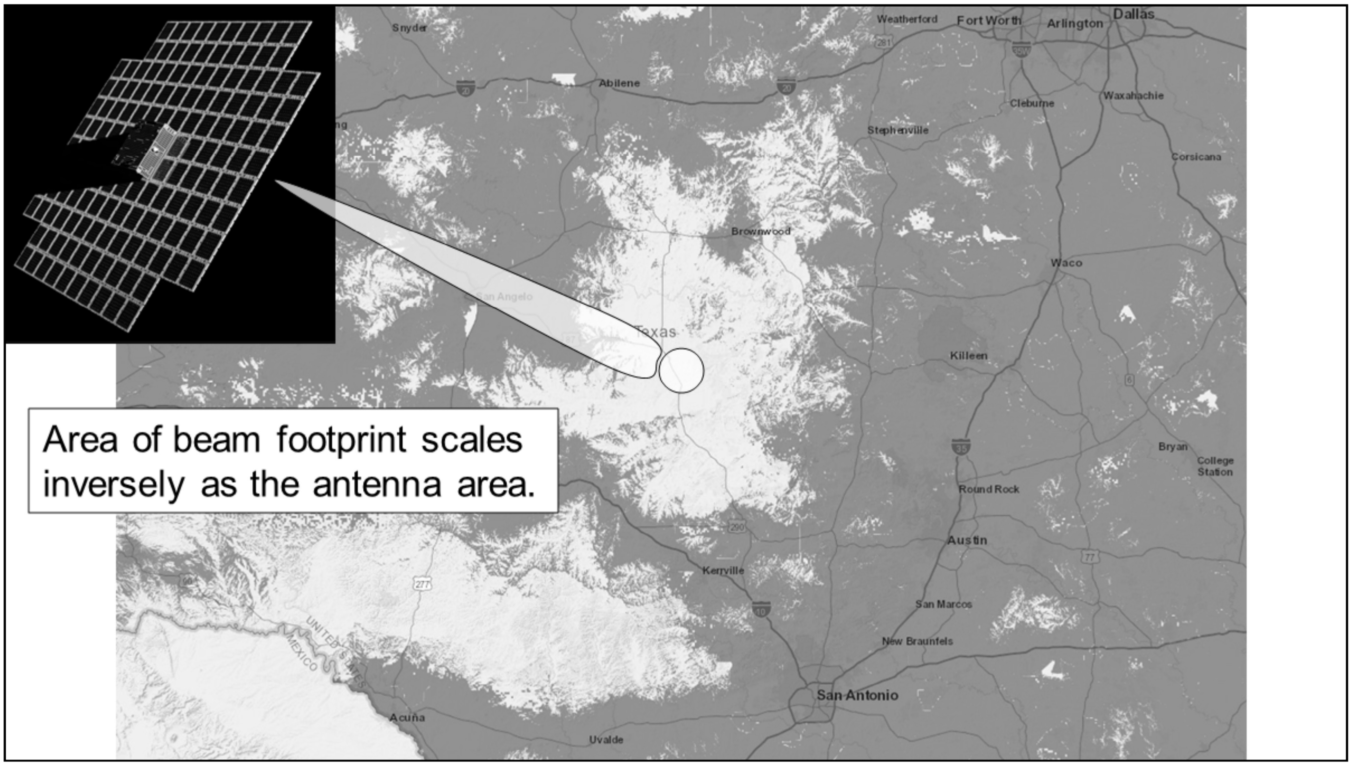
Densification,
Swarms,
MIMO

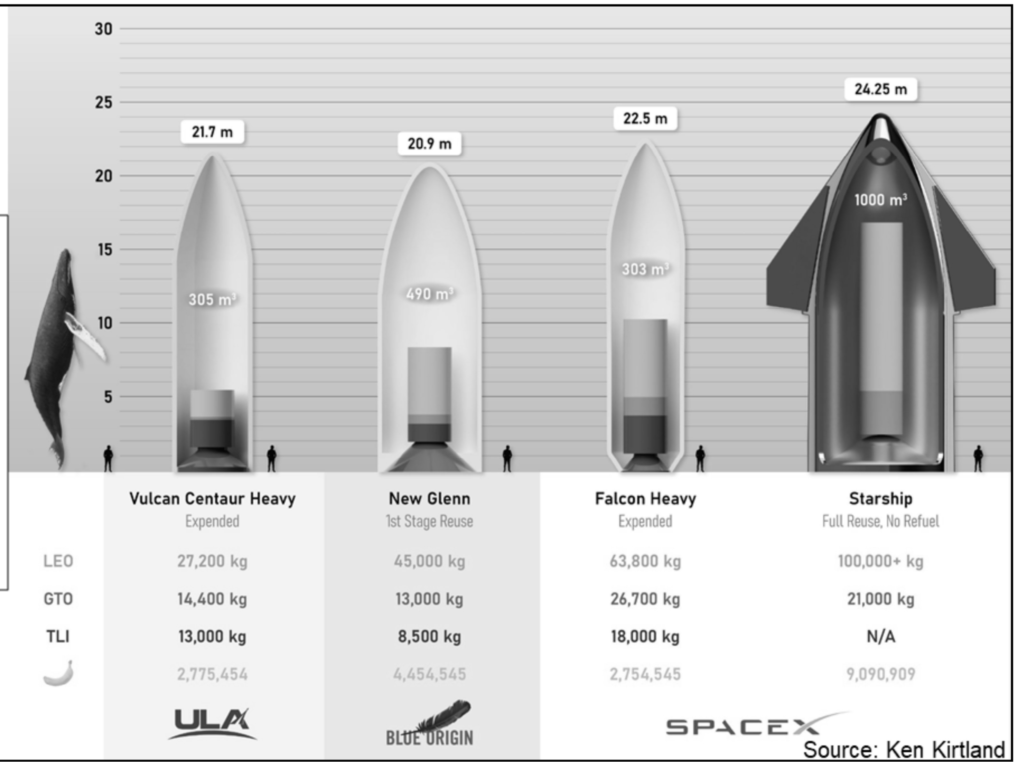

Area of beam footprint scales inversely as the antenna area.
Snyder
Weatherford
Fort Worth
Arlington
Dallas
Abilene
Cleburne
Waxahachie
Stephenville
Corsicana
Brownwood
Waco
Texas
Killeen
Bryan
College Station
Round Rock
Austin
Kerrville
San Marcos
New Braunfels
San Antonio
Acuna
Uvalde

Space deployment allows for enormous arrays even at sub-GHz frequencies.
Bluewalker 3 satellite focuses dozens of ~ 3-deg. beams on surface to support direct-to-

Who wants to play half court ball? What prevents us from going to a full basketball court size?

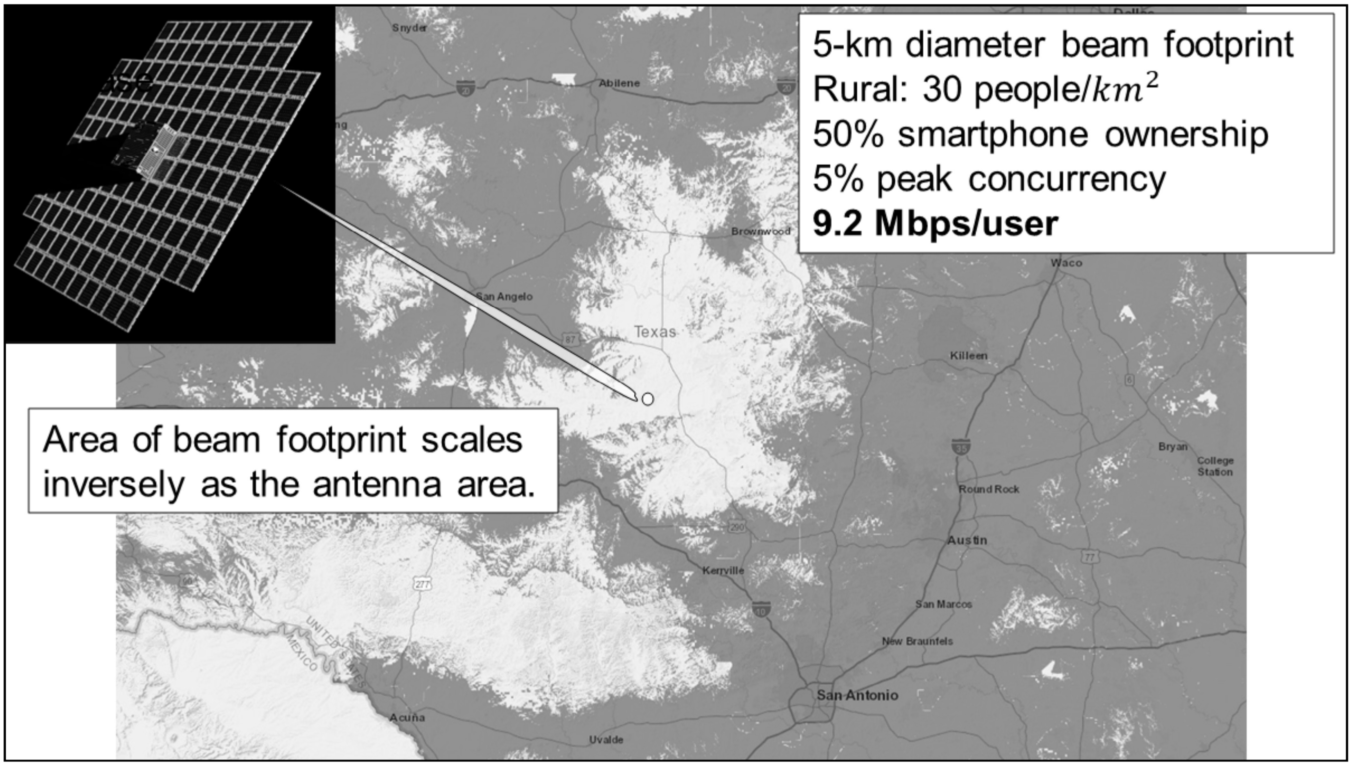
And since it's Texas, let's play football. What about football field size antenna?

Constraint: Launch fairing volume. The largest conceivable phased array over next ~10 years could only be ~16x the area of the Bluebird Block II.

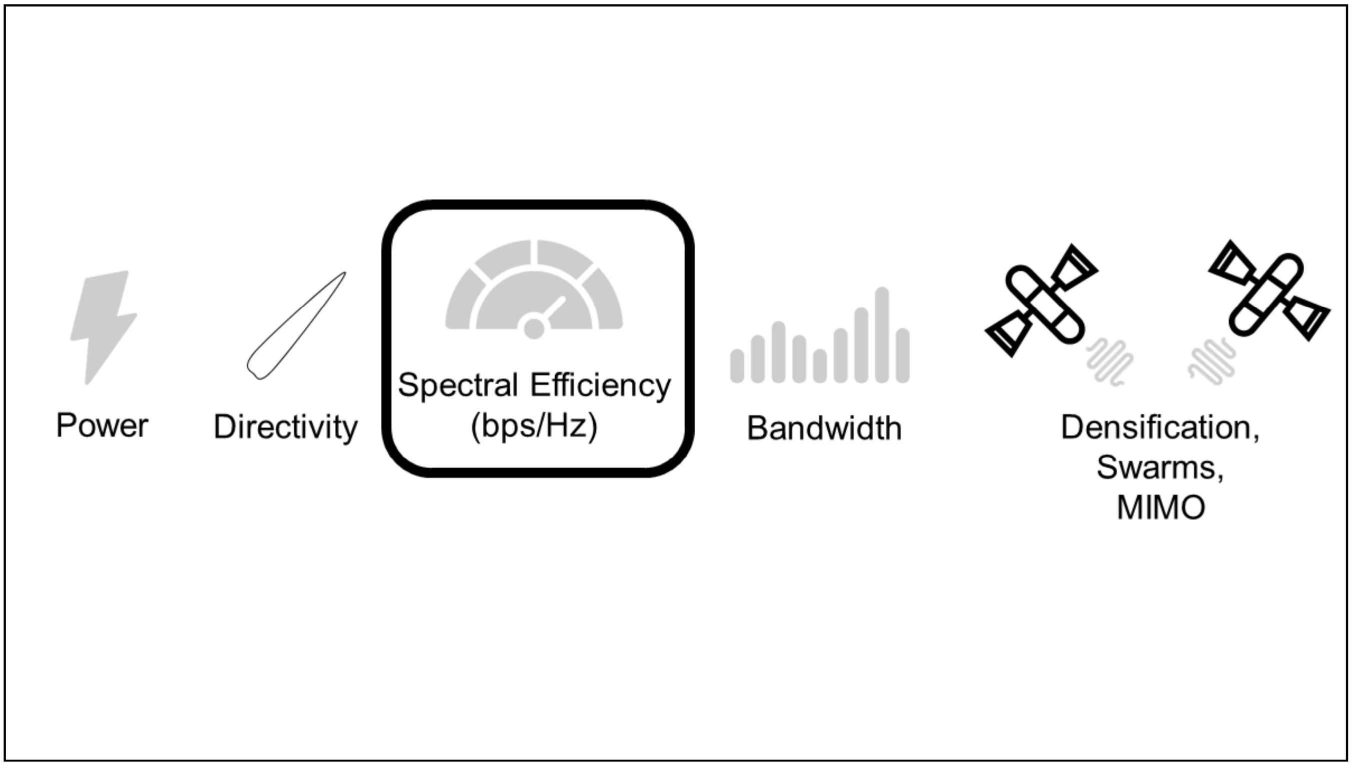


Source: Ken Kirtland

New Glenn is big enough to deploy 8 Block 2 BlueBird SVs at a time. On Falcon 9 (not pictured), with the 5.2 meter fairing diameter, they can fit 4 Block 2s at a time. Starship could fit 16 if all 1000 m^3 were devoted.



Would be ¾ size of football field (excluding end-zones)!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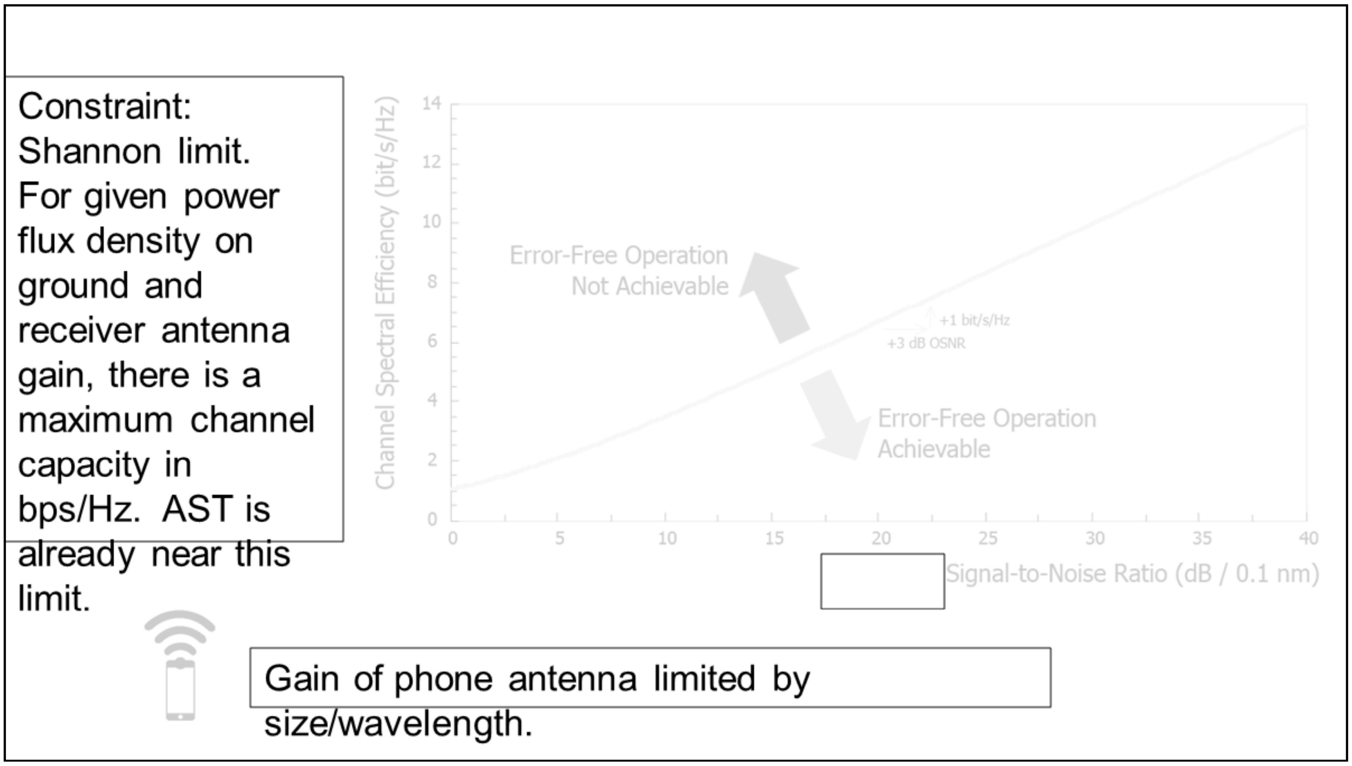

You will not break this limit. Not with end-to-end AI.

Not by increasing tariffs.

NOT IN A BOX. NOT WITH A FOX. NOT IN A HOUSE. NOT WITH A MOUSE.

You might object, saying: "But the signals are coming from different directions! We can exploit spatial diversity!" Not with a phone's antenna. You'd need higher frequencies to support directivity.


Power
Directivity
Spectral Efficiency
(bps/Hz)
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Densification,
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MIMO

Mobile Satellite Services (MSS) spectrum

Upper Mid-Band (FR3) spectrum

Terrestrial cellular spectrum (under SCS)

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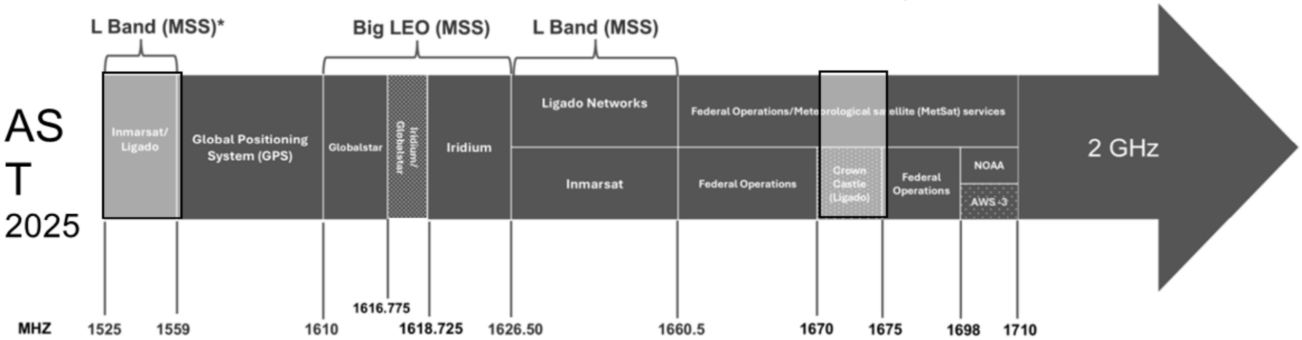
Terrestrial cellular spectrum (under SCS)

L Band Allocations – U.S.

Constraint: Most already allocated to credible (if not efficient) users.



Opportunity: Financial difficulty and regulators pressuring inefficient users to sell spectrum to others who will load it more.

Ligado → AST SpaceMobile (45 MHz)

* Currently under regulatory and legal scrutiny.

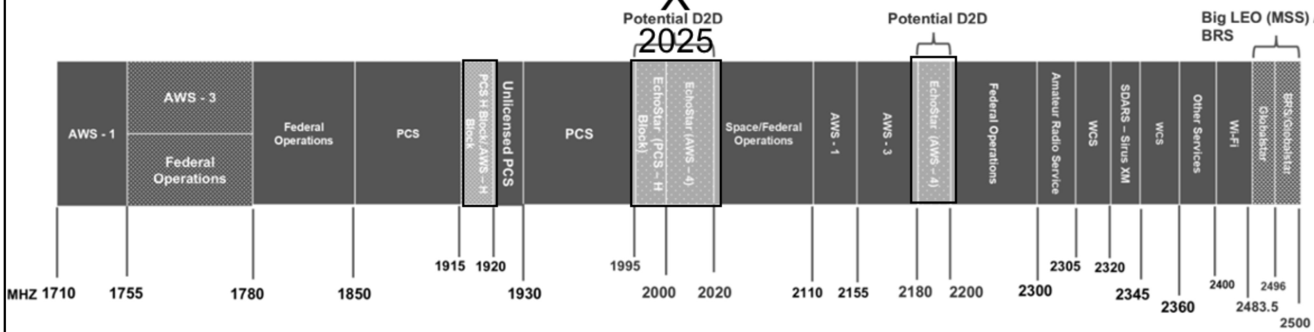
-- Represents shared spectrum

-- Represents terrestrial use spectrum

Source: Company Filings, Press Release, Summit Ridge Group, LLC and TMF Associates, Inc. analysis

Upper L Band, 2 GHz and S- Band Allocations – U.S.

Space X 2025



Opportunity: Financial difficulty and regulators pressuring inefficient users to sell spectrum to others who will load it more.

-- Represents shared spectrum

-- Represents potential D2D spectrum

EchoStar → AT&T (50 MHz) and SpaceX (50 MHz)

Source: Company Filings, Press Release, Summit Ridge Group, LLC and TMF Associates, Inc. analysis

Mobile Satellite Services (MSS) spectrum

Upper Mid-Band (FR3) spectrum

Terrestrial cellular spectrum (under SCS)

Perhaps most interesting:

* 7.125 – 8.4

* 12.7-13.5, currently controlled by NASA, FCC is considering for expanded use, including mobile broadband.

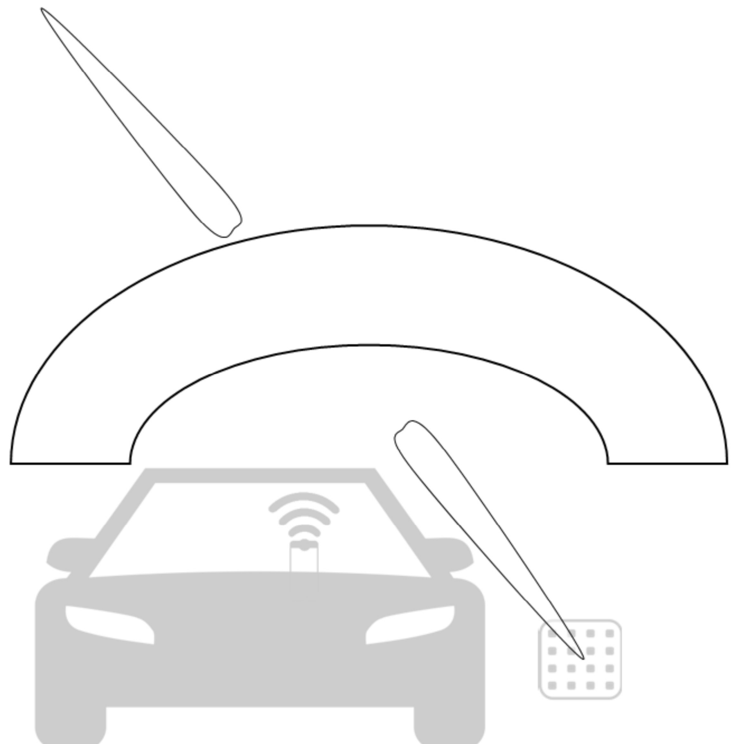
Constraints:

FSS band spectrum sharing depends on UE directivity, which handsets and IoT devices lack.

Atmospheric losses

Poor penetration

7.125 – 8.4 GHz, WRC-27 agenda item, most interesting for D2D in FR3.

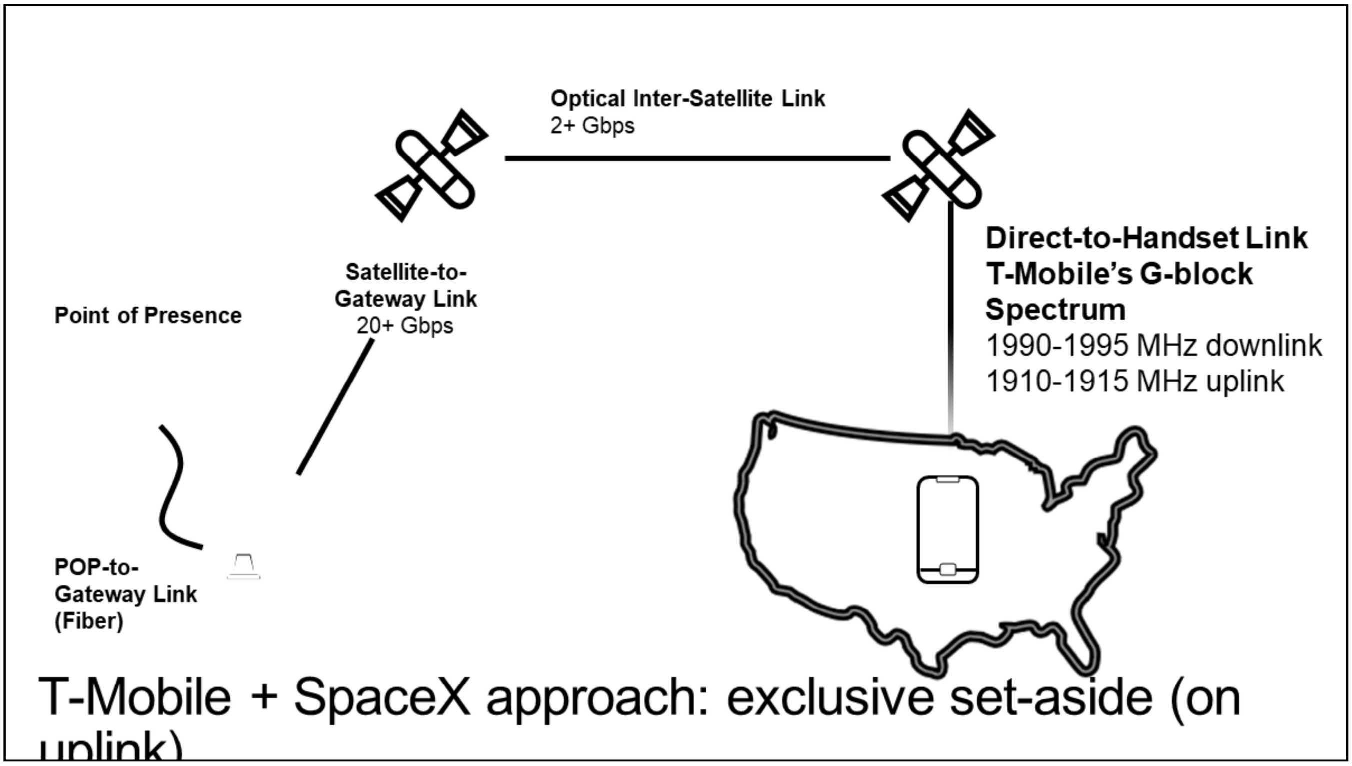


Mobile Satellite Services (MSS) spectrum

Upper Mid-Band (FR3) spectrum

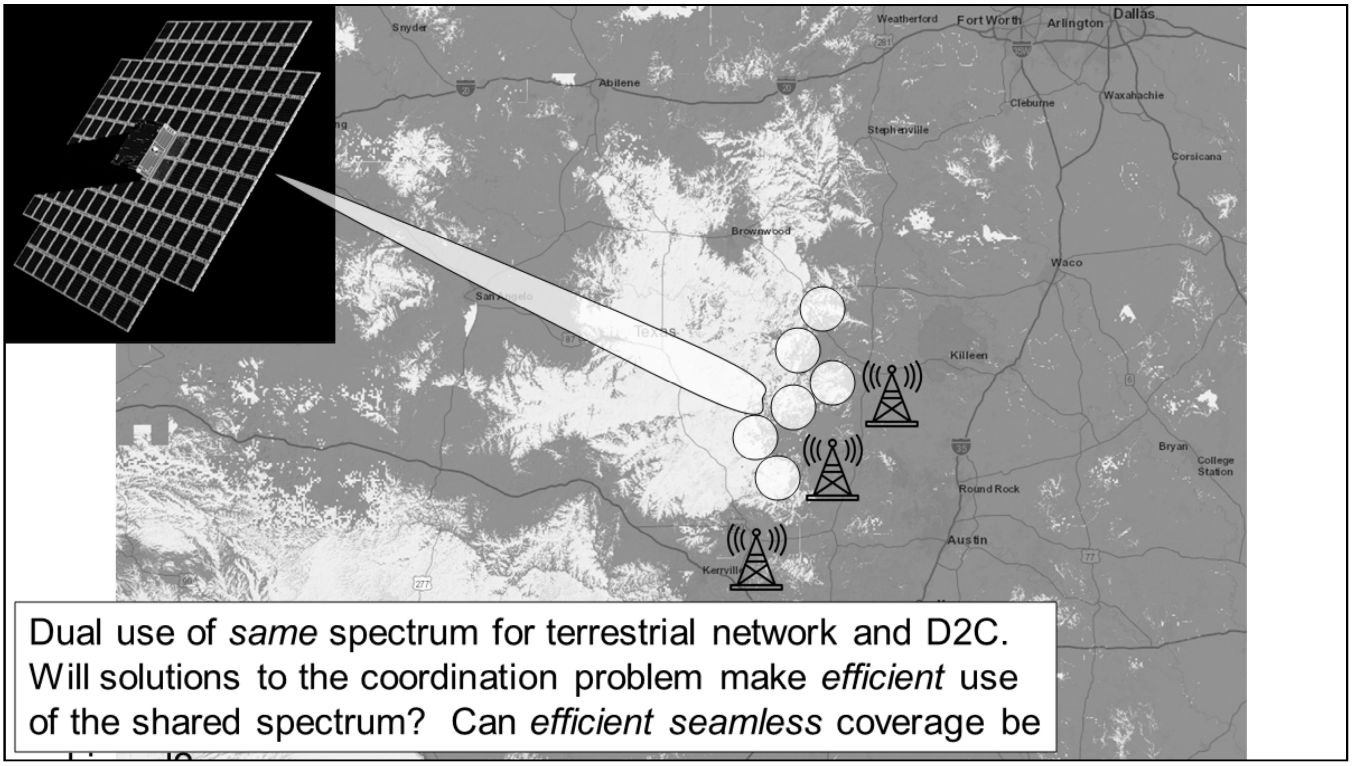
Terrestrial cellular spectrum (under SCS)

Q: Set aside terrestrial spectrum exclusively for D2C, or dual-purpose it for both terrestrial network and D2C?

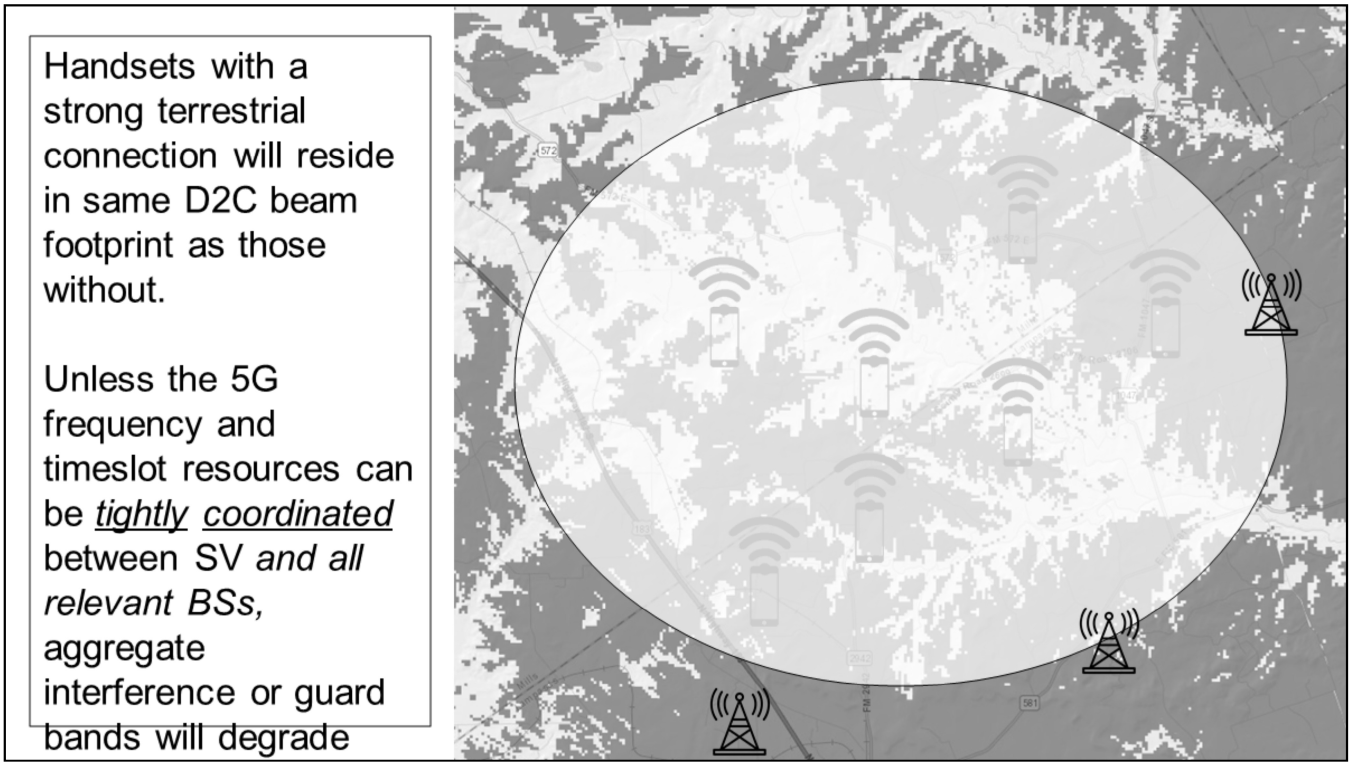


Aurora Insights: The joint announcement by the two companies also included an open invitation to cell carriers around the world to join the program. While T-Mobile owns exclusive rights to the 1910-1915/1990-1995 MHz band in the U.S., neither T-Mobile nor Starlink currently have a license to operate in this band in other countries. Following the announcement by T-Mobile and SpaceX, our satellite data confirmed that this frequency band (1910-1915/1990-1995 MHz) is currently being used in other areas of the world.

But other mobile network operators are *extremely reluctant* to follow T-Mobile in setting aside any of their precious terrestrial spectrum for exclusive D2C use.



We assume FDD for both TN and SN.



As with femtocells: “For 3G CDMA femtos, the dominant method for interference coordination has been power control strategies [77]–[79] and/or reserving a “femtofree” band where macrocell users can go to escape cross-tier interference when it arises. “

Might have to reserve D2C-free bands too.

“4G LTE femtocells offer more tools for interference coordination including backhaul-based coordination, dynamic orthogonalization, subband scheduling, and adaptive fractional frequency reuse. How to best exploit these techniques is an active area of research [28], [80]–[83] and is the subject of two papers in this special issue [41], [84].”

Orthogonal resources to macrocell.

Working with D2C is arguably *easier* than working with femtocells.

“Perhaps the most difficult aspect of femtocell mobility is that femtocells are not typically directly connected into the core network where mobility procedures are usually coordinated. The lack of a low delay connection to the core network can result in significant handover signaling delays.” Would be same for D2C – maybe even worse!

“Ralph de la Vega, AT&T President, reported in June 2011 they recommended against using femtocells where signal strength was middle or strong because of interference problems they discovered after widescale deployment.[16]”

And remember, Femtos were pretty strong relative to D2C, which needs whisper quiet.

Separate channels obviously.

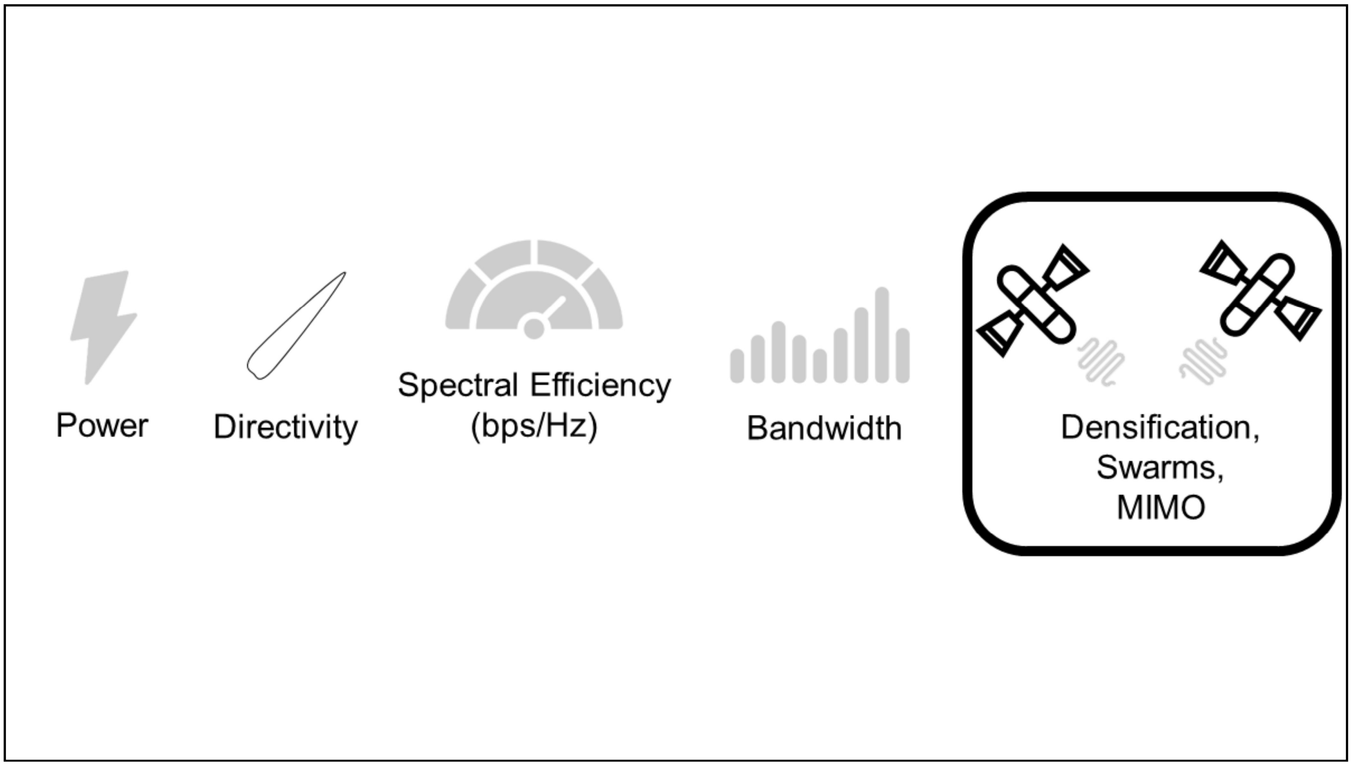
Wifi offloading killed the femtocell it seems. Especially with Wifi 7.

The UE tells the BS what satellites it can sense on separate channels. The UE hears the satellites’ synchronization bursts. Has some sort of identifier. The UE has to report the identity of the satellite it can hear.

In the other direction, it must report the identity of the tower it can hear. There will have to be orthogonal components for the towers and the SVs.

THE UNIVERSITY OF TEXAS AT AUSTIN

RADIONAVIGATION LABORATORY


Power
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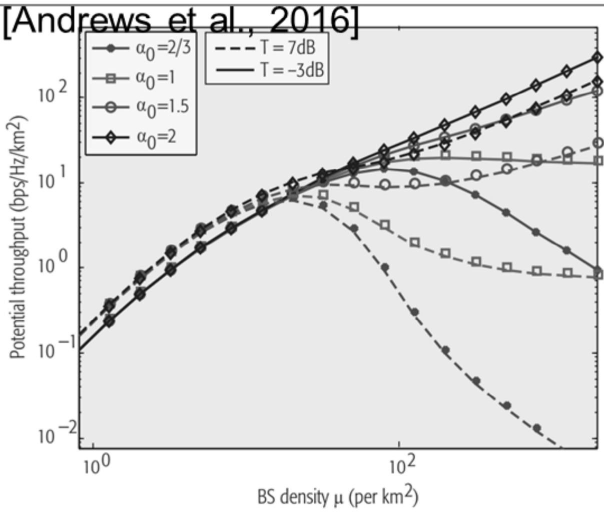
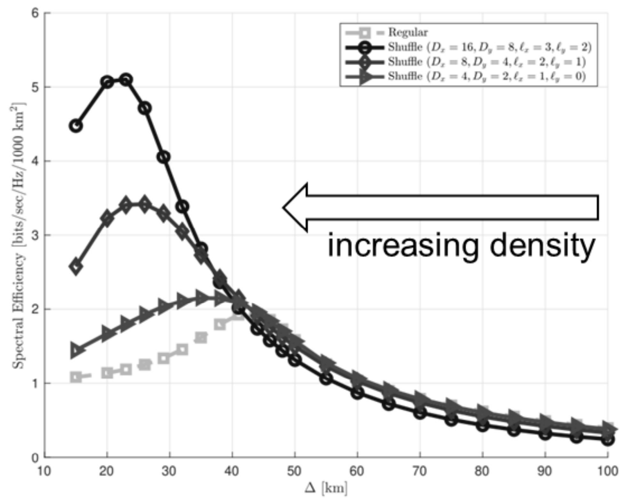
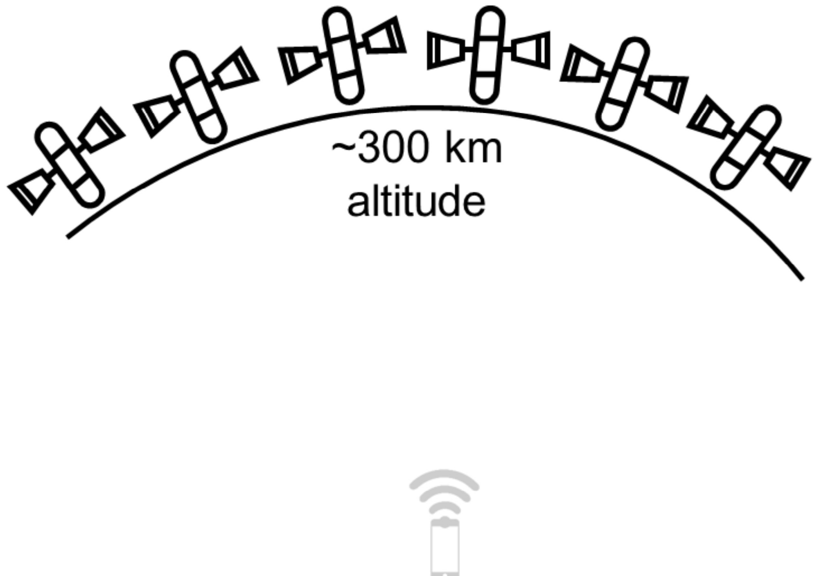
Area spectral efficiency increases quasi-linearly as a function of base station density for *terrestrial networks.*
[Andrews et al., 2016]



This is not the case for satellite networks, which exhibit peaks in ASE and degradation with further densification [Ozturk et al., 2025]

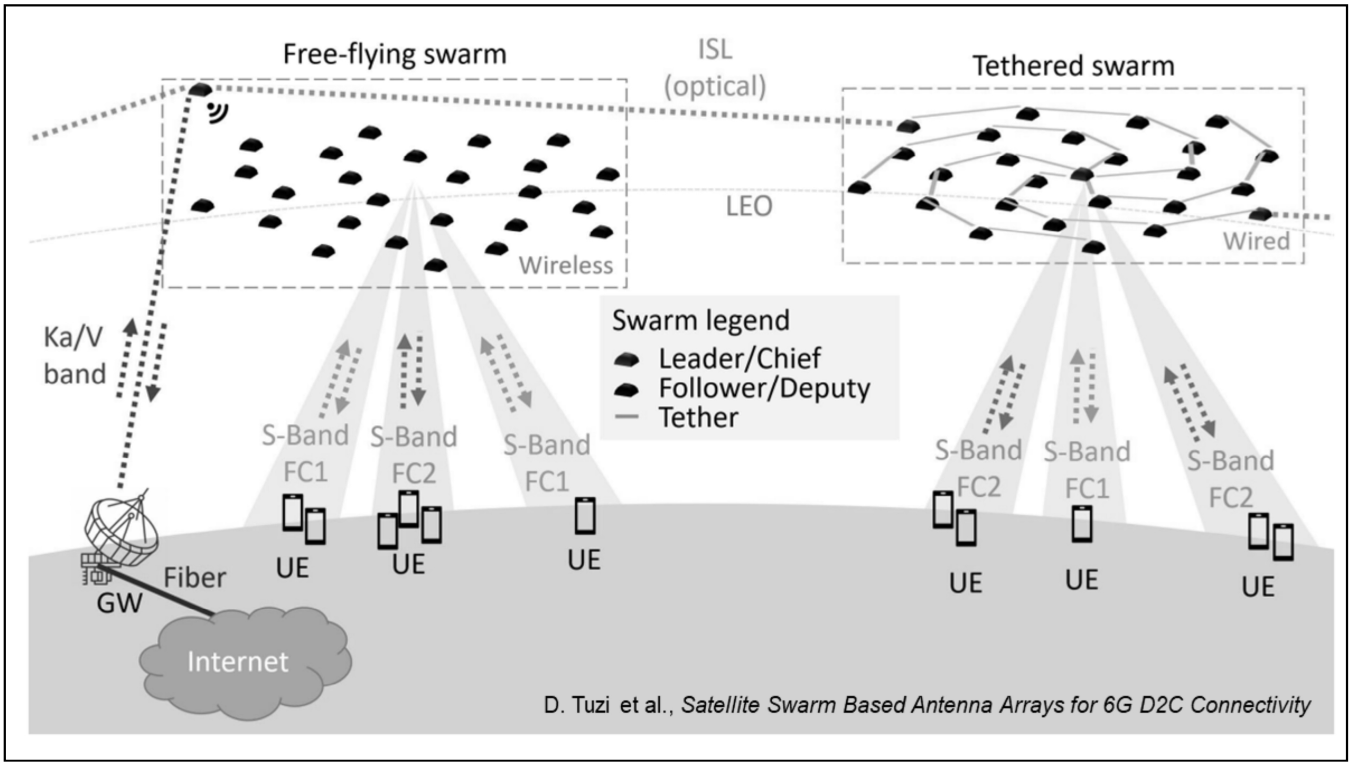


Intuition: Orbital mechanics and atmospheric density bound the benefit of satellite densification with low-gain antennas: No matter how dense the constellation, satellites cannot economically be closer than ~300 km from users.



Takeway: Constellation densification *reduces* area spectral efficiency after critical point.

But this assumes that satellites are not coordinating at the carrier phase level …


Free-flying swarm
ISL
(optical)
Tethered swarm
LEO
Wireless
Wired
Ka/V
band
Swarm legend
Leader/Chief
Follower/Deputy
Tether
S-Band
FC1
S-Band
FC2
S-Band
FC1
S-Band
FC2
S-Band
FC1
S-Band
FC2
UE
UE
UE
UE
UE
UE
Fiber
GW
Internet
D. Tuzi et al., Satellite Swarm Based Antenna Arrays for 6G D2C Connectivity

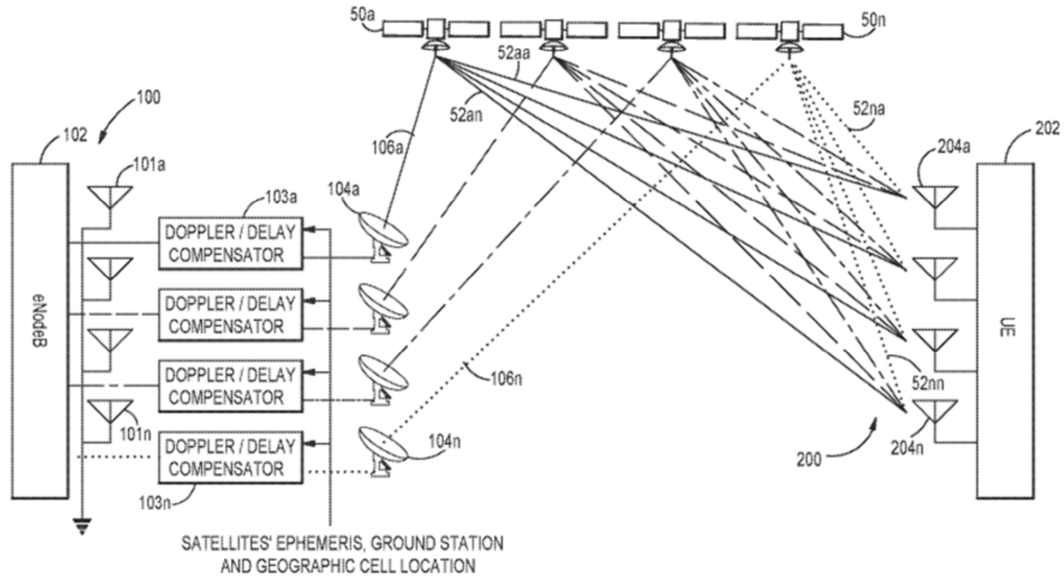
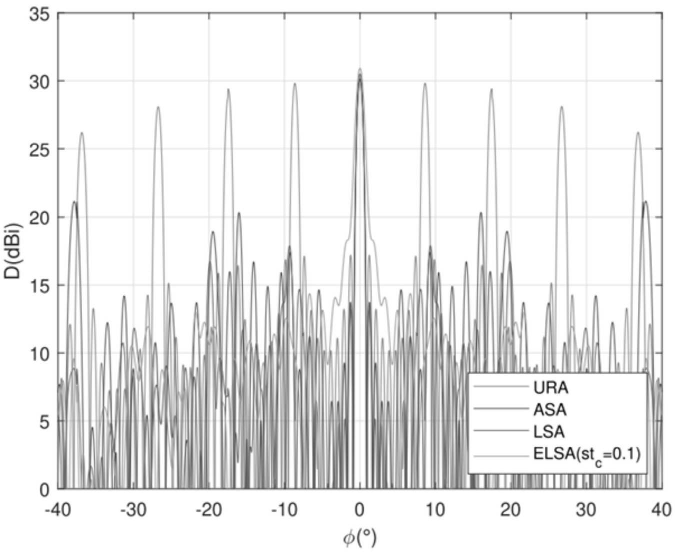
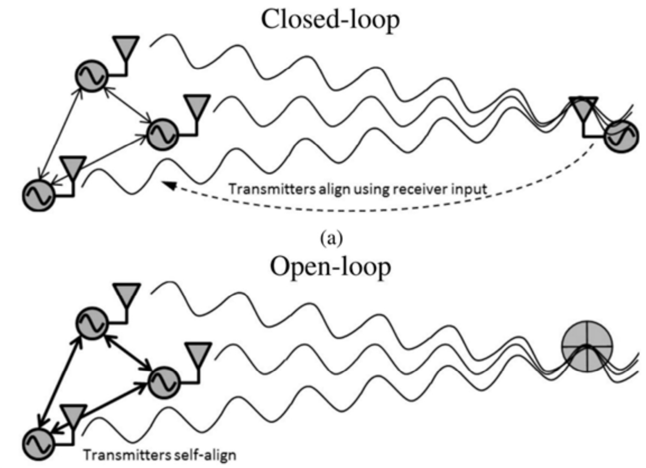


FIG. 2 MIMO USING FOUR SUBSTANTIALLY SEPARATED SATELLITES

AST SpaceMobile 2021 U.S. patent application





Fractional-wavelength synchronization and controlled positioning across the array are significant technical challenges.

D. Tuzi et al., *Satellite Swarm Based Antenna Arrays for 6G D2C Connectivity*

Constraint: Unless satellites in swarm are packed very close together (within a few multiples of the wavelength), prominent grating lobes will appear in

Conclusions

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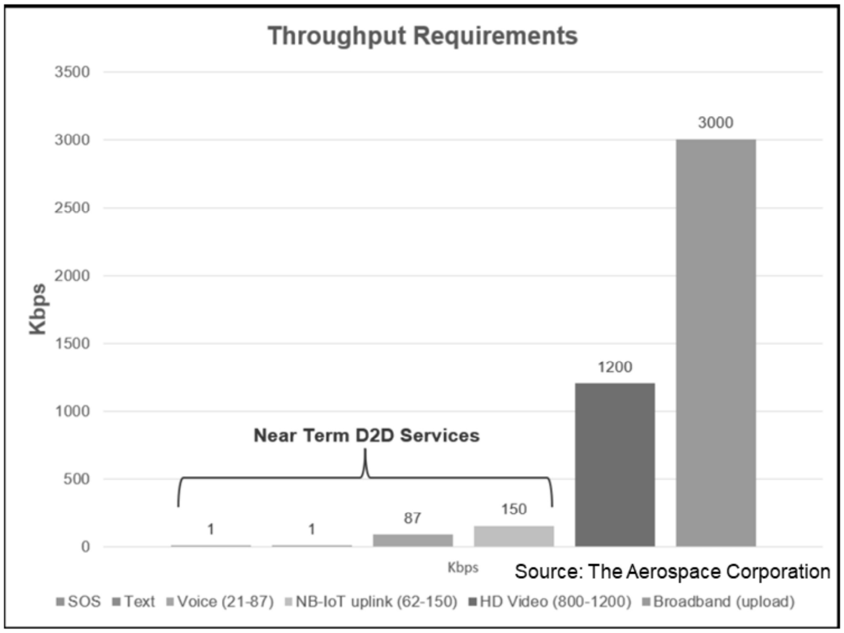
D2C will only exceed 3G rates (~3 Mbps) under special circumstances but will nonetheless be revolutionary.



Much can be done with 3 Mbps!

6G

@

UT