Satellites are closer than you think:

A near field MIMO approach for Ground stations (*ArrayLink*)

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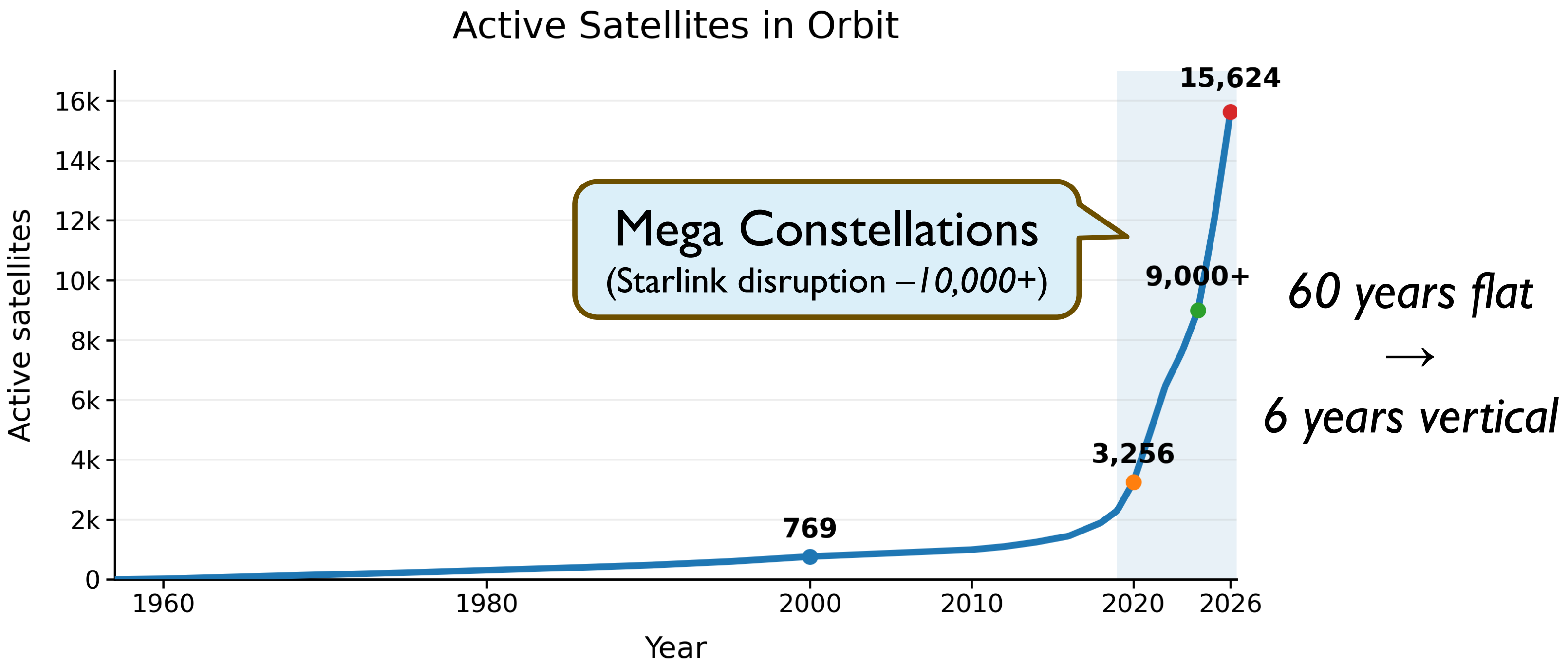
A New Era of Massive Satellite Constellations



Ref: Jonathan McDowell / Planet4589 active satellite statistics; UK Space Agency data points used for 2000, 2010, 2020, 2024.

Satellites are exploding in number…
but can our ground stations keep up?

The Current Landscape of Satellite Ground Stations

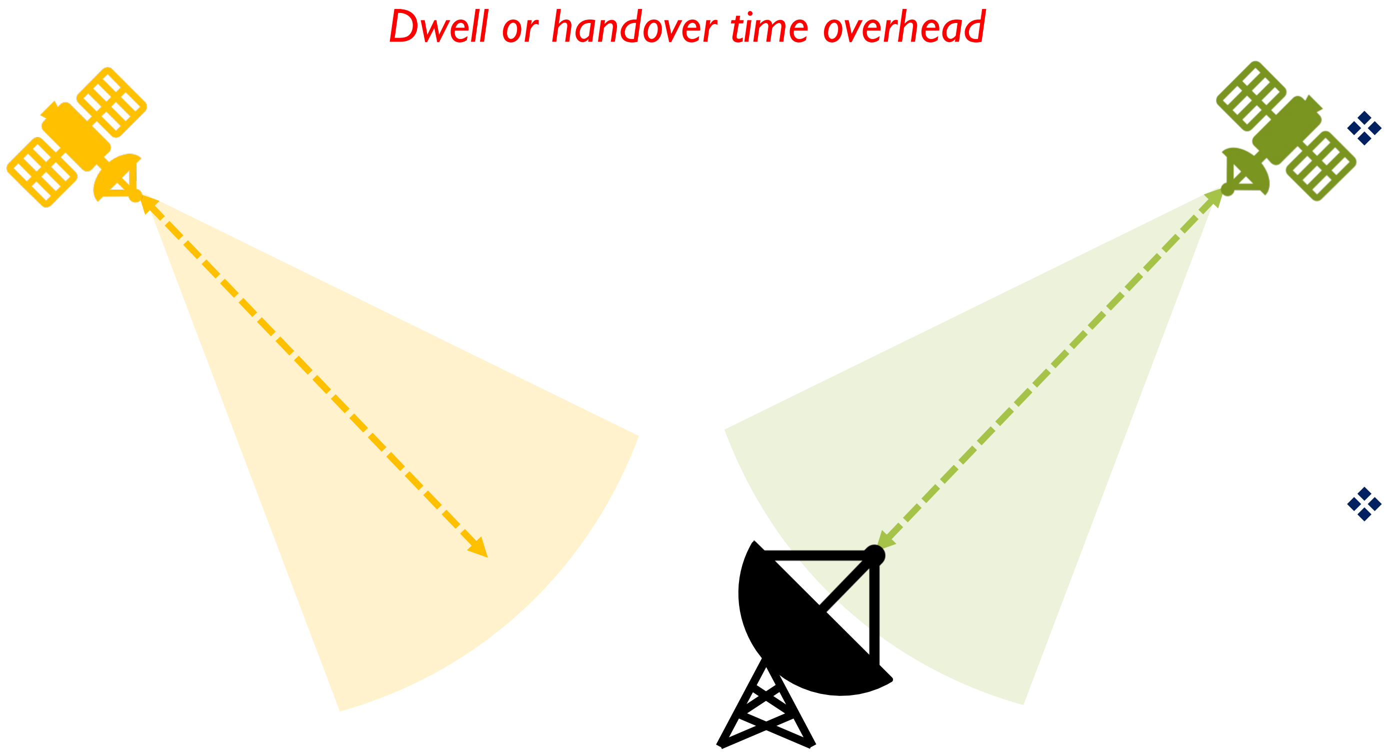
Ground station networks are not scaling at the pace of satellite constellations.

Requirements for Ground Stations

- **High Throughput**
  - Handle Gbps-class data rates per satellite
  - Support high-order modulation
- **Resource Efficient**
  - Fast satellite tracking and seamless handovers → no idle time
  - Spectrum-efficient → support multiple satellites concurrently
- **Scalable**
  - Cost-effective enough to deploy across hundreds of sites

High Throughput	?
Resource efficient	?
Scalable	?

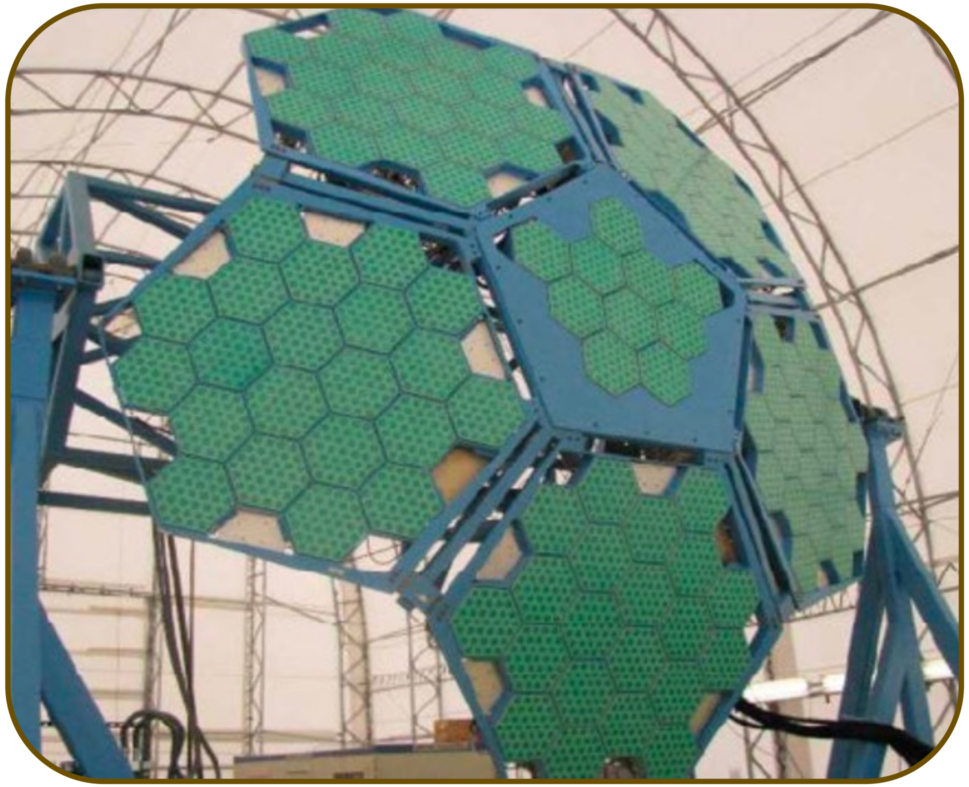
Current solution: Parabolic dishes are not sustainable



- **High-gain Links** ✓
  - Ex: 1.85m Ka-band dish → ~52.6 dBi
  - High-order modulation → peak throughput
- **Resource Inefficient** ✗
  - Mechanical steering 2–5°/s → a few seconds to minutes of idle time per handover (depends on dish size)
  - One satellite at a time → no multiplexing, unused bandwidth is wasted
- **Poor Scalability** ✗
  - Huge CAPEX & OPEX per site (dish, motor, land, fiber backhaul, maintenance)
  - Each site is a full build-out — cost scales linearly with deployment count

Large parabolic dishes achieve **high throughput** but fail on **resource efficiency** and **scalability**

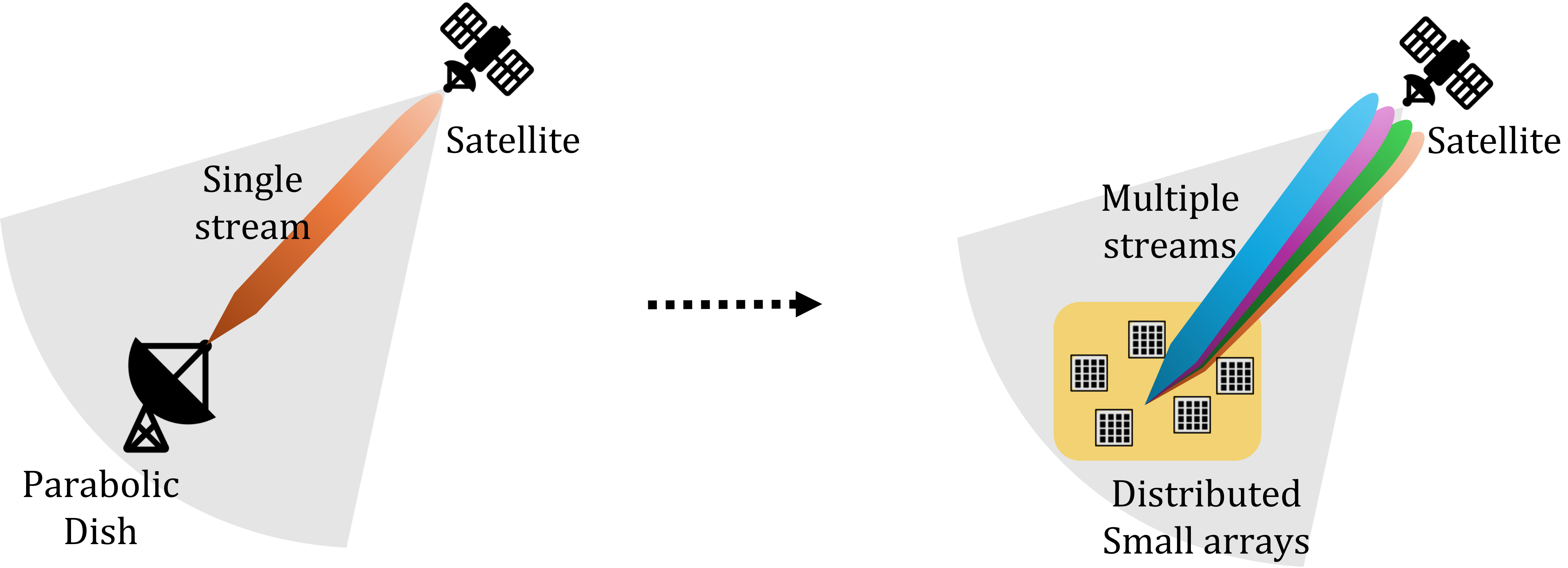
Alternative approach: Large (monolithic) phased arrays



- **Resource efficient ✓:**
  - Electronic steering (no moving parts) → Beam hopping in μs
  - Multi-satellite support → efficient spectrum usage
- **High throughput ⚠ :**
  - Possible, but matching 1.85 m (~52.6 dBi) needs > 50k elements
- **Not scalable ✗:**
  - High power draw, thermal issues, costly manufacturing → impractical to deploy in the field.

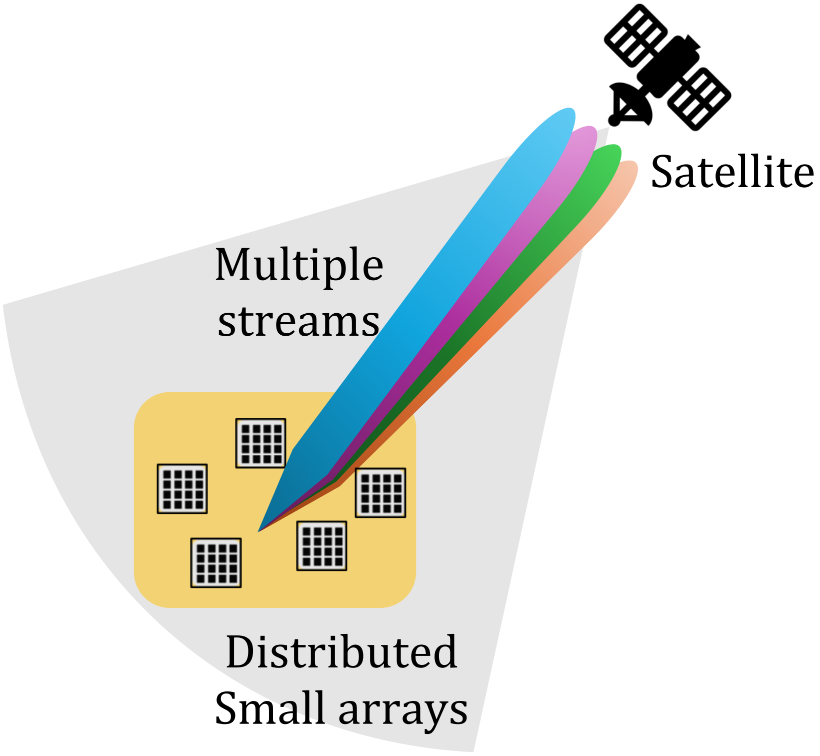
Large phased arrays **address efficiency and throughput**, but gain limits, complexity, and cost make them impractical and **not scalable**.

Our Approach: Distributed phased arrays *(ArrayLink)*



Transforming satellite ground stations:
From large dishes to smaller distributed phased arrays.

ArrayLink: Scalable Architecture with Higher Throughput



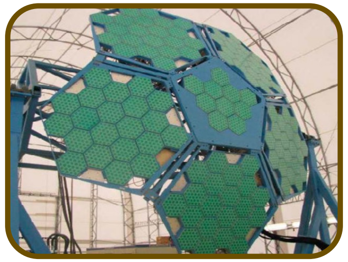
- **Scalable Design ✓**
  - Practical and cost-efficient **with a few panels**
  - Trade a small amount of gain to significantly reduce the number of phased-array panels.
- **Higher Throughput ✓**
  - Near field effect with **distributed panels**
  - Enable multiple simultaneous streams in line-of-sight channels with near field to match or exceed single high-gain link capacity.
- Resource efficient ✓
  - Inherent use of phase array panels avoids mechanical steering and support multiple satellites

ArrayLink trades a small amount of beamforming gain for **scalability**, then recovers and exceeds the **throughput** using near-field MIMO.

ArrayLink: Satisfies all three requirements

Ref: www.satellitetoday.com/connectivity/2017/10/18/orbit-provide-satellite-tracking-ground-stations-endurosat/

Ref: He, Guolong, et al. "A review of multibeam phased array antennas as LEO satellite constellation ground station." IEEE Access 9 (2021).



Phased array ref: https://www.extreme-waves.com/satcom

Requirements	Parabolic dishes	Large (*Monolithic*) arrays	**ArrayLink** *(this work)*
High Throughput	✅	⚠️	✅
Resource efficient	❌	✅	✅
Scalable	❌	❌	✅

ArrayLink: Dish-class gain and multi-stream throughput without large dishes or monolithic arrays.

Roadmap for the Rest of the Talk

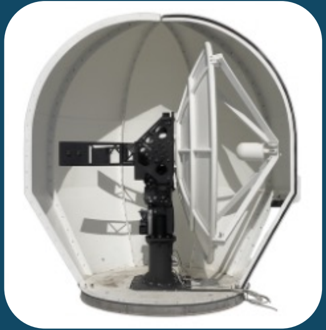
1. Enabling Dish-Class Gain

2. Enabling Multiple streams

3. Evaluations

Challenge-1: Dish-Class Gain in a Practical Design

- **The Problem**
  - Achieving high gain is critical (e.g., SpaceX 1.85 m dish → 52.6 dBi)
- **Naive Approach**
  - Use commercially available phased-array terminals (e.g., 1024 elements → 36.1 dBi) and coherently combine multiple terminals to enable high-gain links.
  - However, to reach 52.6 dBi, we would need at least 45 such panels



SpaceX ground station dishes (ka band):
- 1.85m → 52.6 dBi
- 1.47m → 49.5 dBi

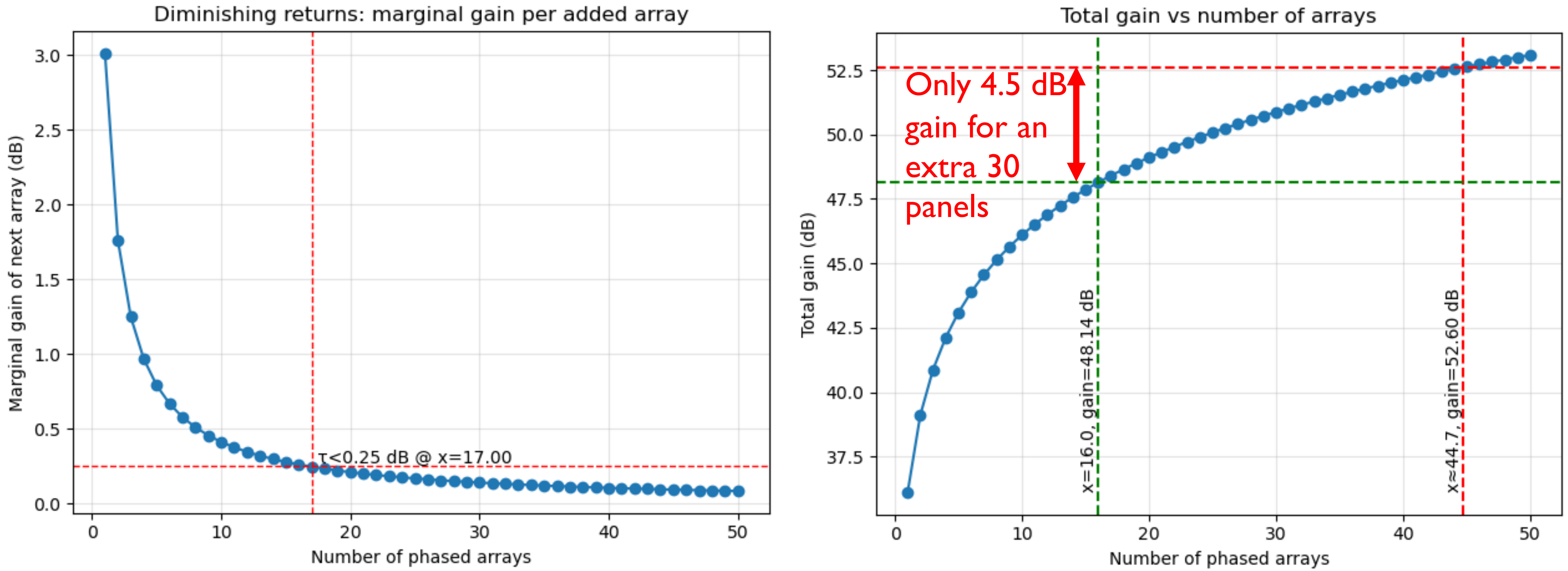
Ref: https://fcc.report/IBFS/SES-LIC-20200428-00458/3872480.pdf, https://fcc.report/IBFS/SES-AMD-20230525-01127

Kuiper user terminal panels < $500 (ka band)

Need to reduce the panels to make it more practical and scale efficiently

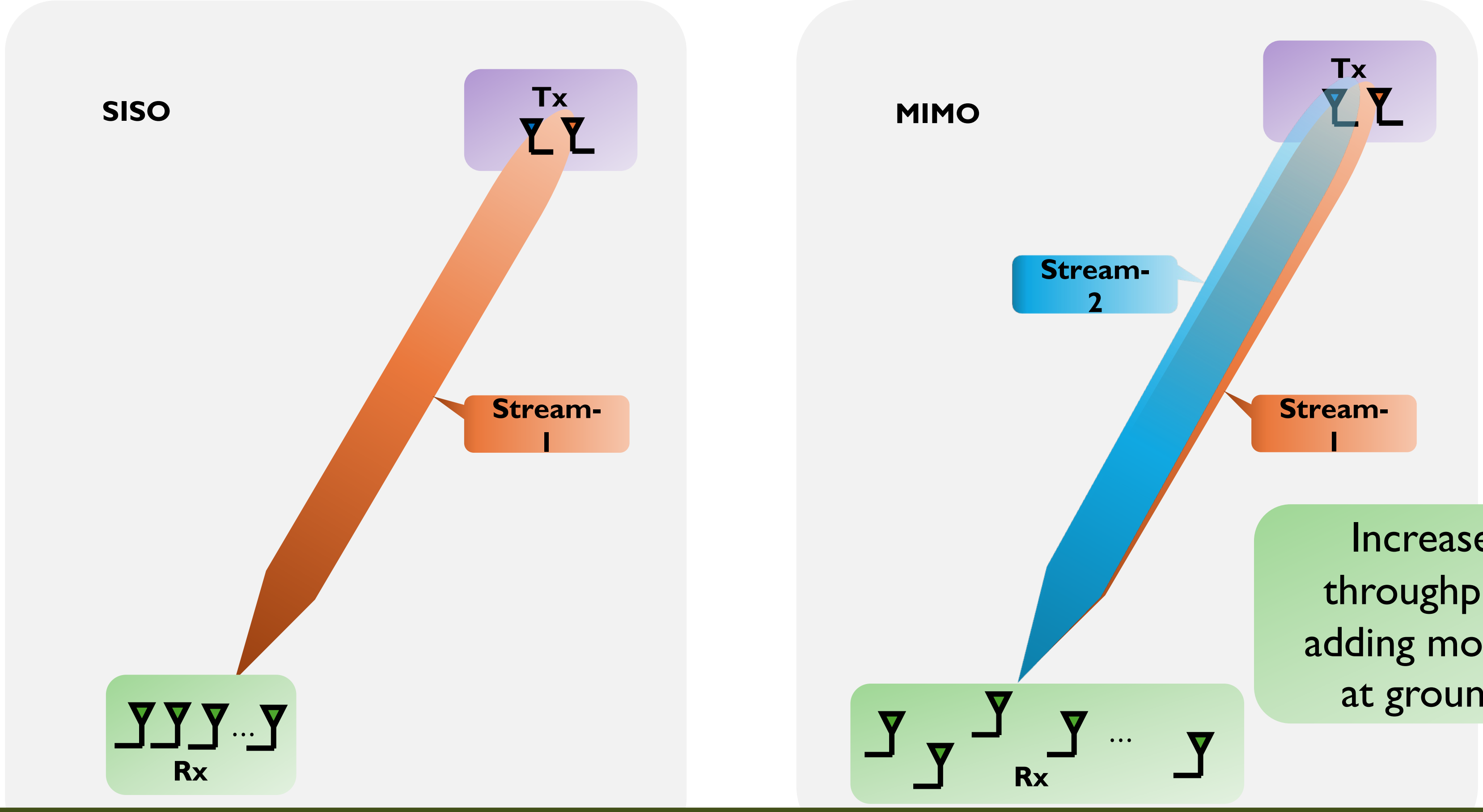
Making ***ArrayLink*** design practical

- Tradeoff between gain and no of phased arrays/cost



Trading 4.5 dB gain reduces required arrays from 45 panels to just 16.

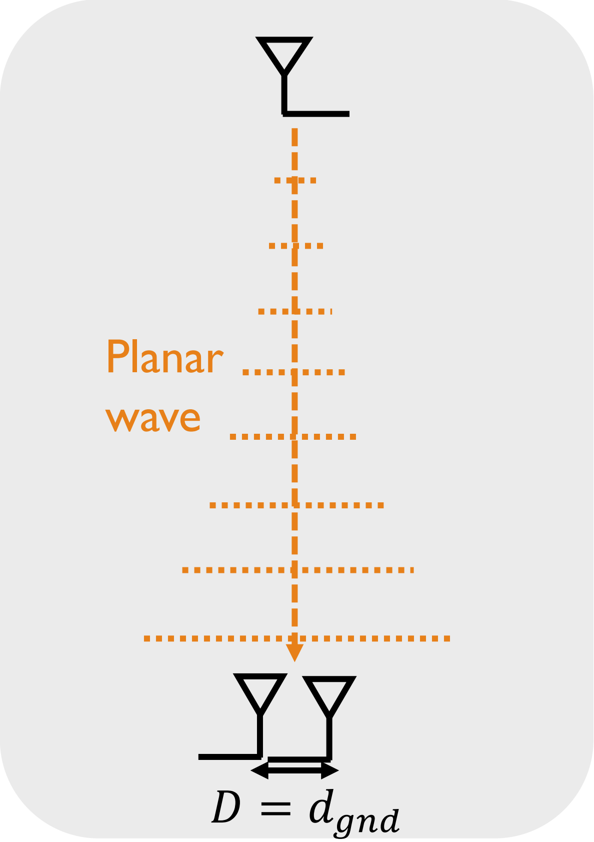
Challenge-2: Enabling multiple streams to boost throughput

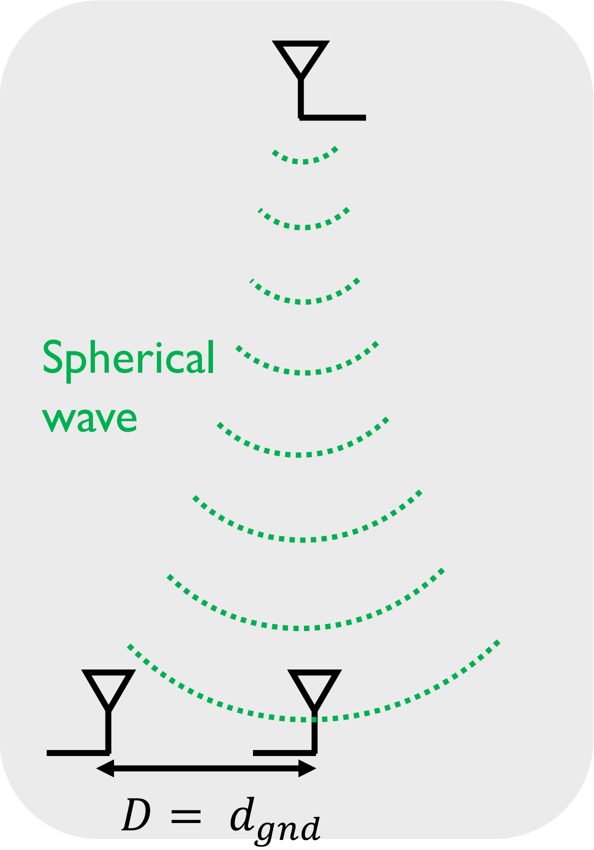


Increases overall throughput without adding more antennas at ground station.

How to do we enable multiple streams in a line-of-sight scenario?

Key Insight – Increasing antenna spacing at ground station brings Satellites from Far-Field to Near-Field



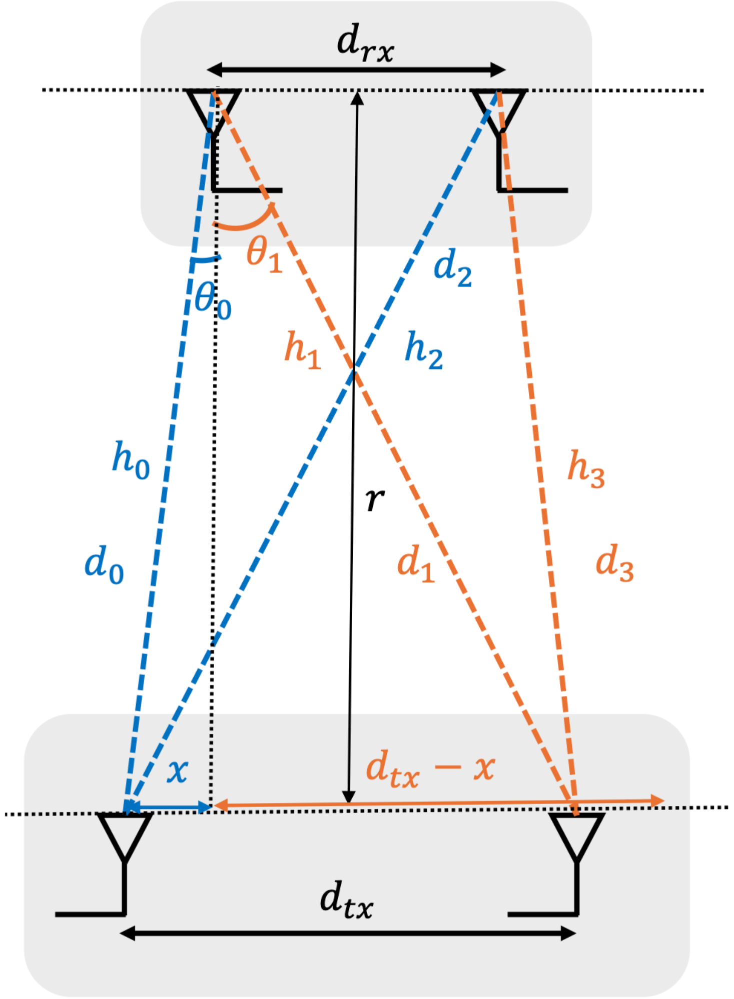


Fraunhofer distances at 28 GHz (Ka band, $\lambda \approx 0.01m$):

$D = 0.1\ m$	$\frac{2D^2}{\lambda} \approx 2\ m$
$D = 1\ m$	$\frac{2D^2}{\lambda} \approx 200\ m$
$D = 10\ m$	$\frac{2D^2}{\lambda} \approx 20\ km$
$D = 100\ m$	$\frac{2D^2}{\lambda} \approx 2000\ km$
$D = 1000\ m$	$\frac{2D^2}{\lambda} \approx 200000\ km$

Increasing antenna spacing enlarges aperture, bringing satellites into the near-field and creating channel diversity.

Key Insight - Singular values dependency on Phase Spread



$$H = \begin{pmatrix} h_0 & h_1 \\ h_2 & h_3 \end{pmatrix}, \text{where } h_i = \beta_i e^{-j2\pi \frac{d_i}{\lambda}}$$

- When $\beta_i \approx \beta$, The singular values σ_1 and σ_2 depend only on the phase spread Δ:

$$\sigma_{1,2} = \sqrt{\left(2 \pm 2 \left|cos\left(\frac{\Delta}{2}\right)\right|\right)}$$

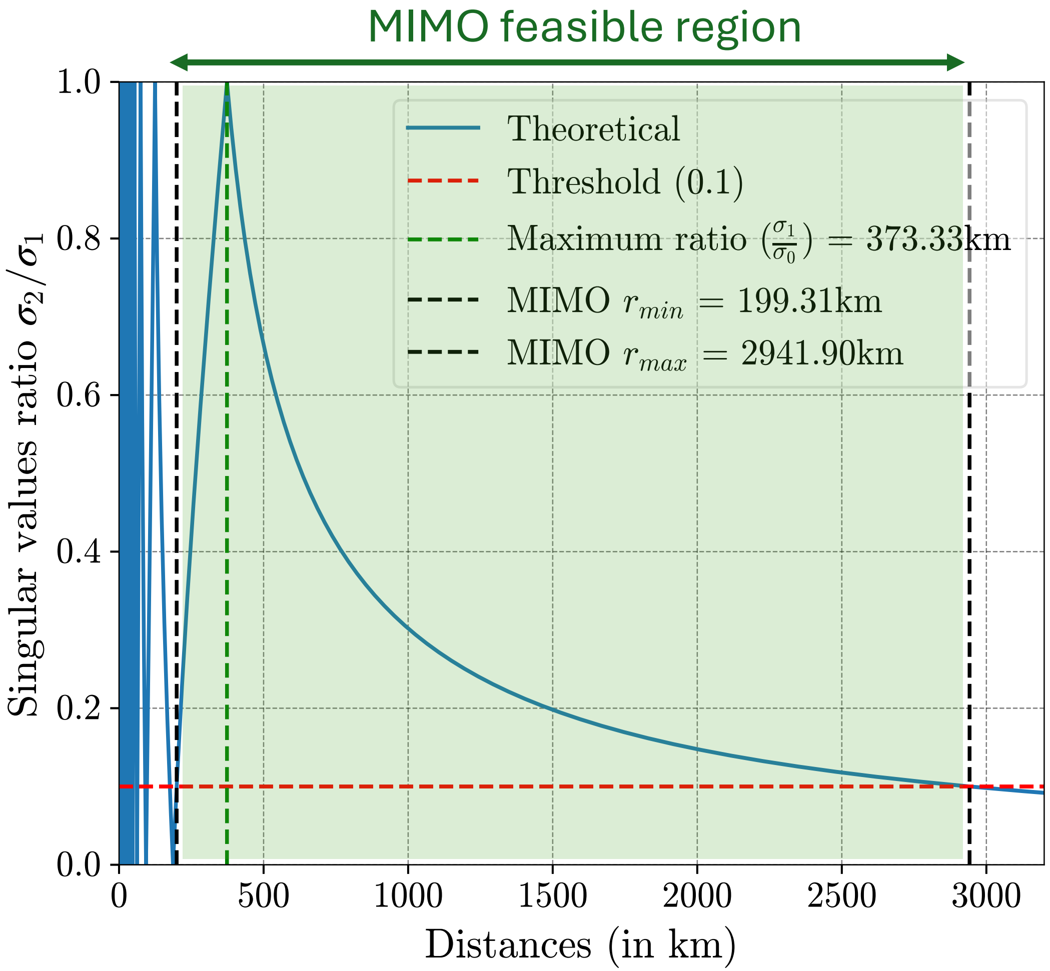
- Phase spread Δ is defined as

$$\Delta = \frac{2\pi}{\lambda} d_{tx}[(-(d_0 - d_1) + (d_2 - d_3)].$$

$$\approx \frac{2\pi}{\lambda} d_{tx}\left(\frac{x}{r} + \frac{d_{rx} - x}{r}\right)$$

$$\boldsymbol{\Delta = \frac{2\pi}{\lambda}\left(\frac{d_{tx} d_{rx}}{r}\right)}$$

MIMO bounds for stable min and max region



$$H = \begin{pmatrix} h_0 & h_1 \\ h_2 & h_3 \end{pmatrix}, \text{where } \mathrm{h_i} = e^{-j2\pi\frac{d_i}{\lambda}}$$

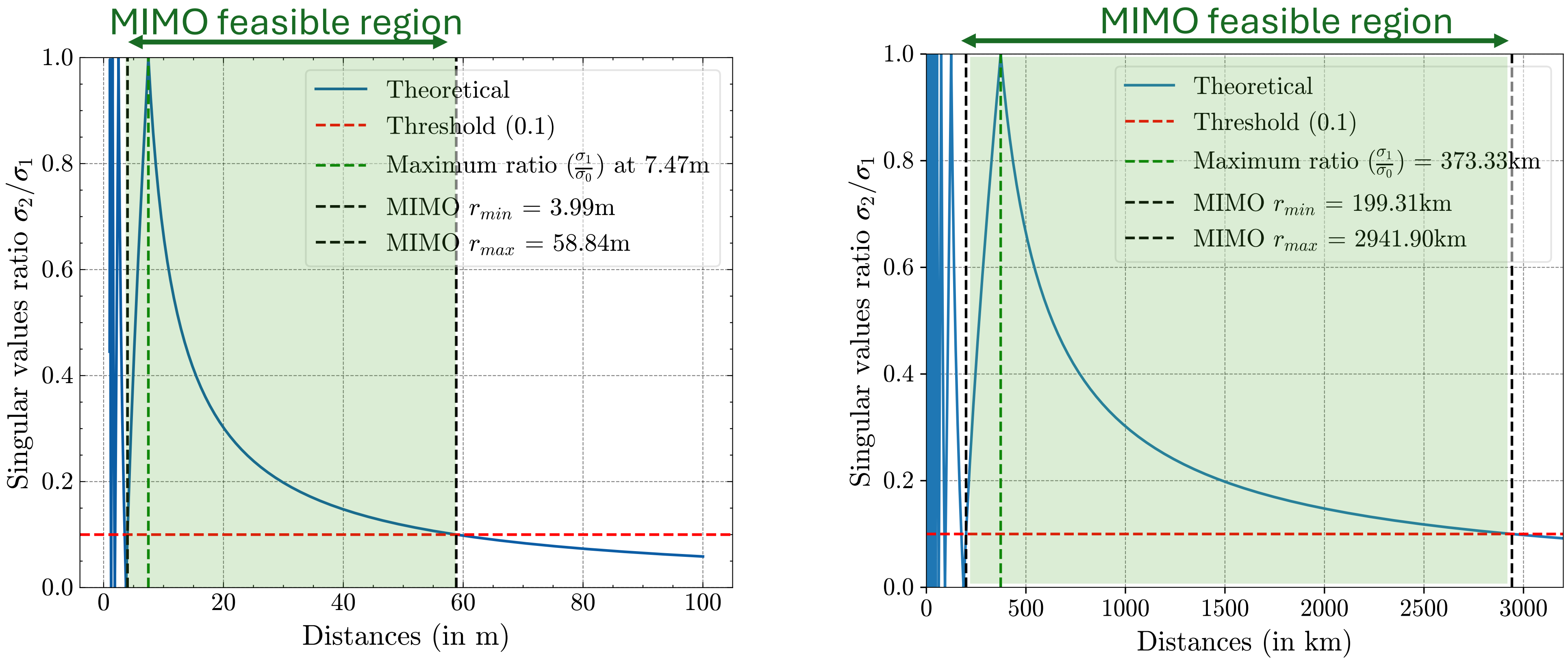
$$\sigma_{1,2} = \sqrt{\left(2 \pm 2\left|cos\left(\frac{\Delta}{2}\right)\right|\right)},\ \Delta = \frac{2\pi}{\lambda}\left(\frac{d_{tx}d_{rx}}{r}\right), \frac{\sigma_2}{\sigma_1} = tan\frac{\Delta}{4}$$

Given, threshold $\tau = min\frac{\sigma_2}{\sigma_1}$ to enable MIMO

$$r_{min} = \frac{\pi}{2\tan^{-1}\left(\frac{1}{\tau}\right)}\frac{\boldsymbol{d_{tx}d_{rx}}}{\boldsymbol{\lambda}}$$

$$r_{max} = \frac{\pi}{2\tan^{-1}(\tau)}\frac{\boldsymbol{d_{tx}d_{rx}}}{\boldsymbol{\lambda}}$$

MIMO bounds for stable min and max region

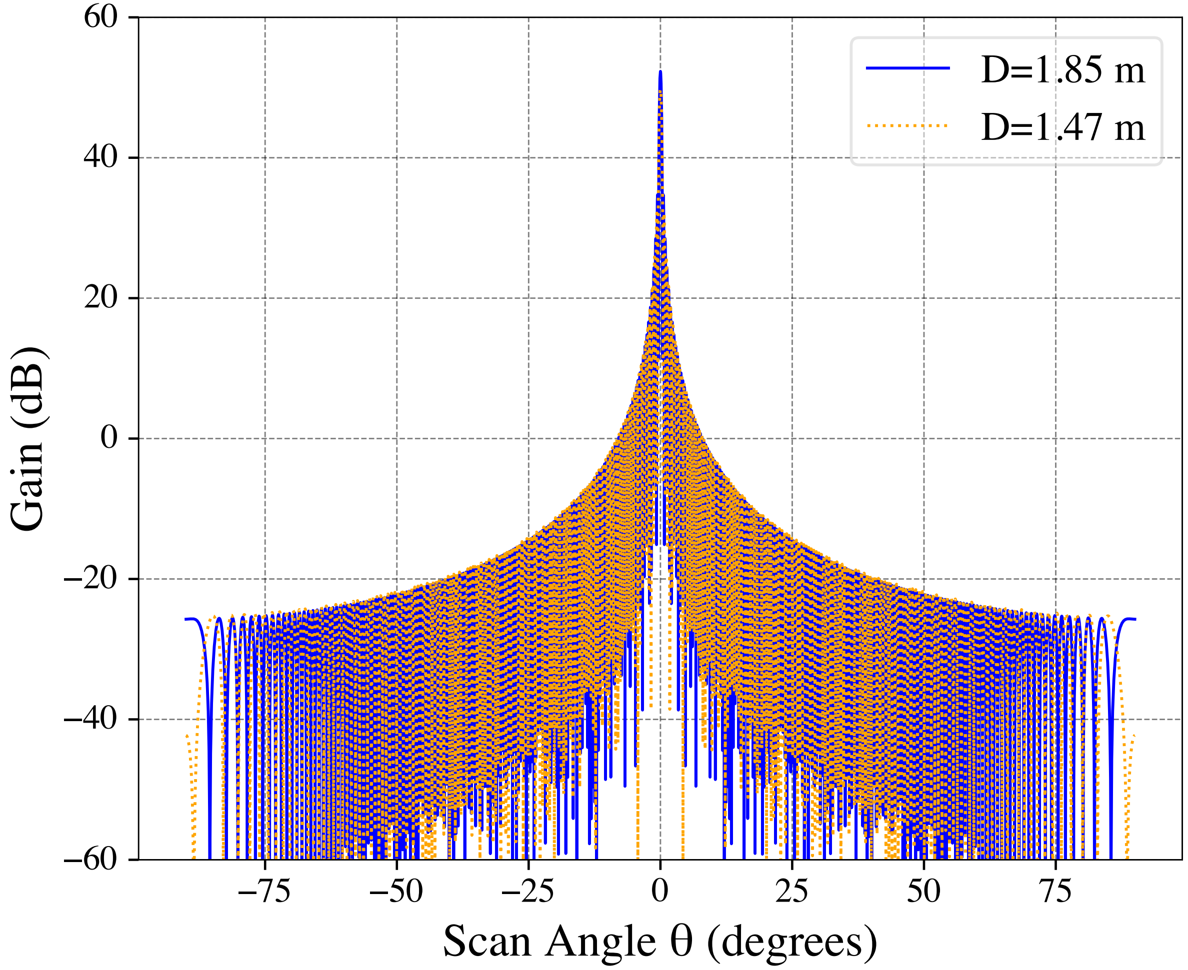


The MIMO feasible region for a given distance (r) can be tuned by adjusting d_{tx}, d_{rx}, and λ.

Evaluations

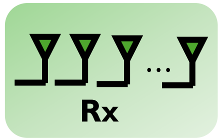
- **Dish-Class gain:** Achieve gain comparable to parabolic dishes.
- **Multi-Stream Feasibility:** Demonstrate in Line-of-Sight (LoS) scenarios.
- **Throughput Comparison:** Parabolic dish vs. *ArrayLink*.

Evaluation: Beamforming gain with parabolic dishes

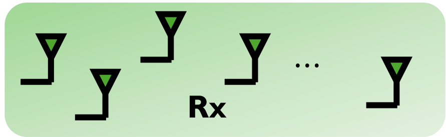


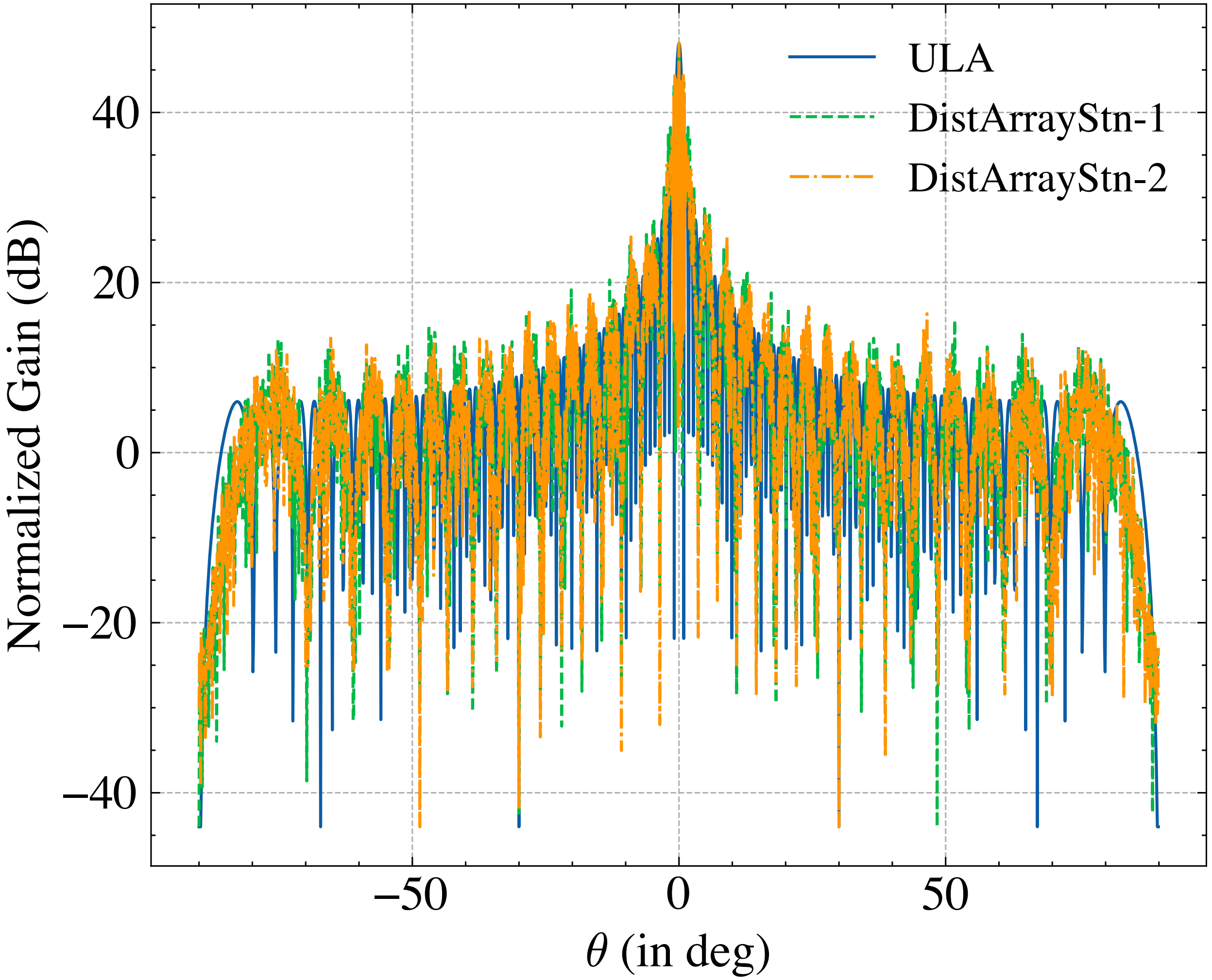
Evaluation: Beamforming gain comparing ULA with *DistArrayStn*

- Large (monolithic) array – ULA case



- Distributed arrays approach – *ArrayLink*

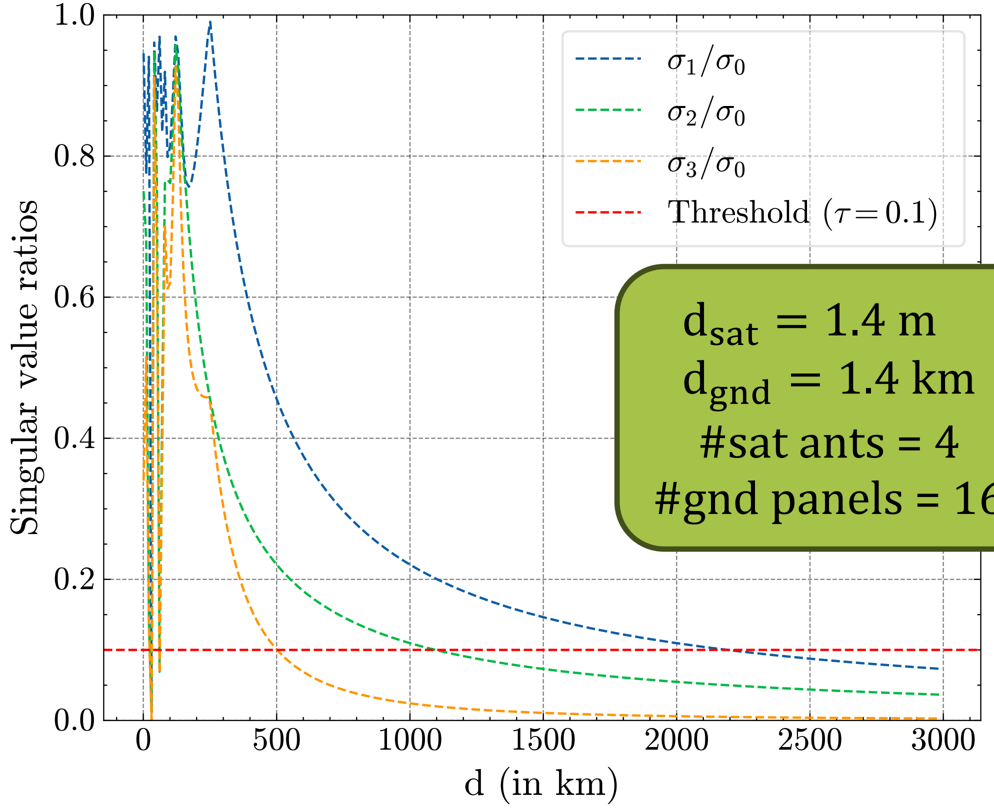




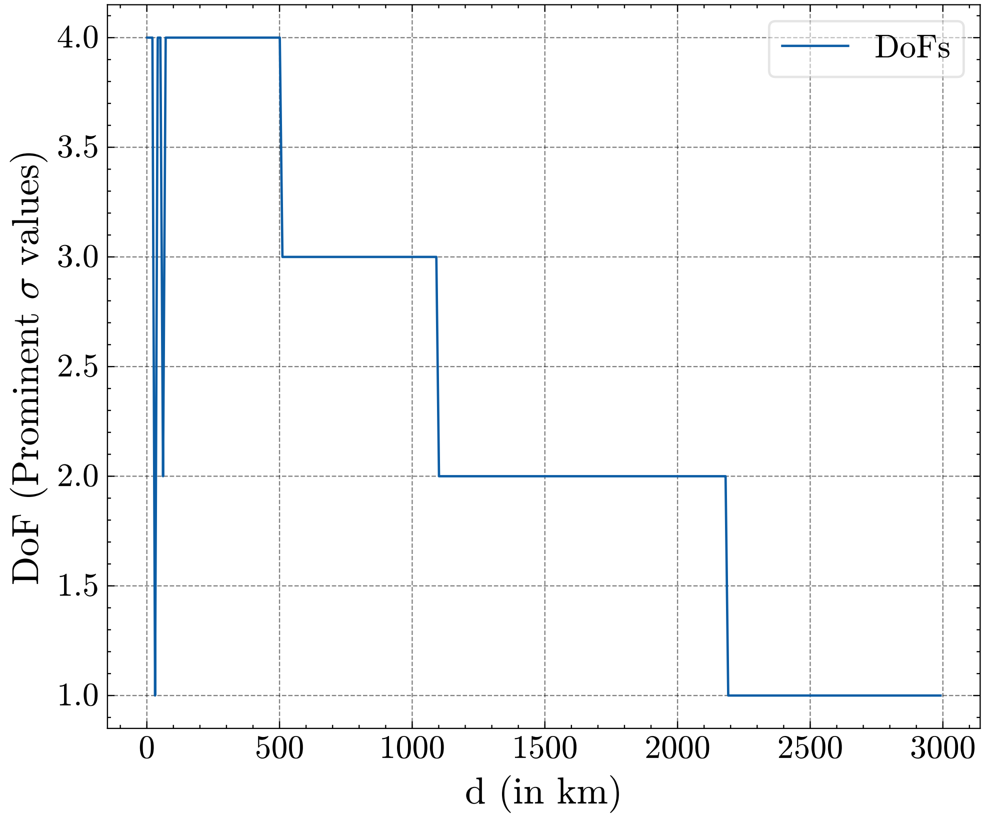
Experimental Demo

Showing feasibility with commercial hardware on a small-scale setup

Evaluations: Multiple streams for satellite-scale distances

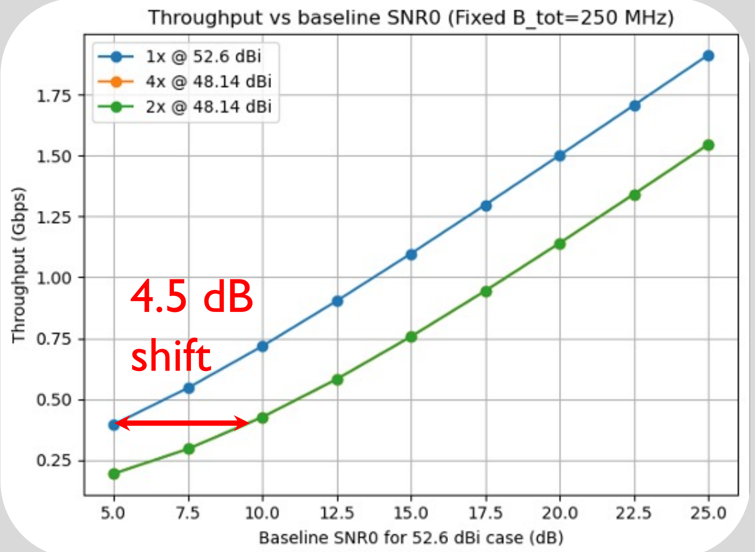


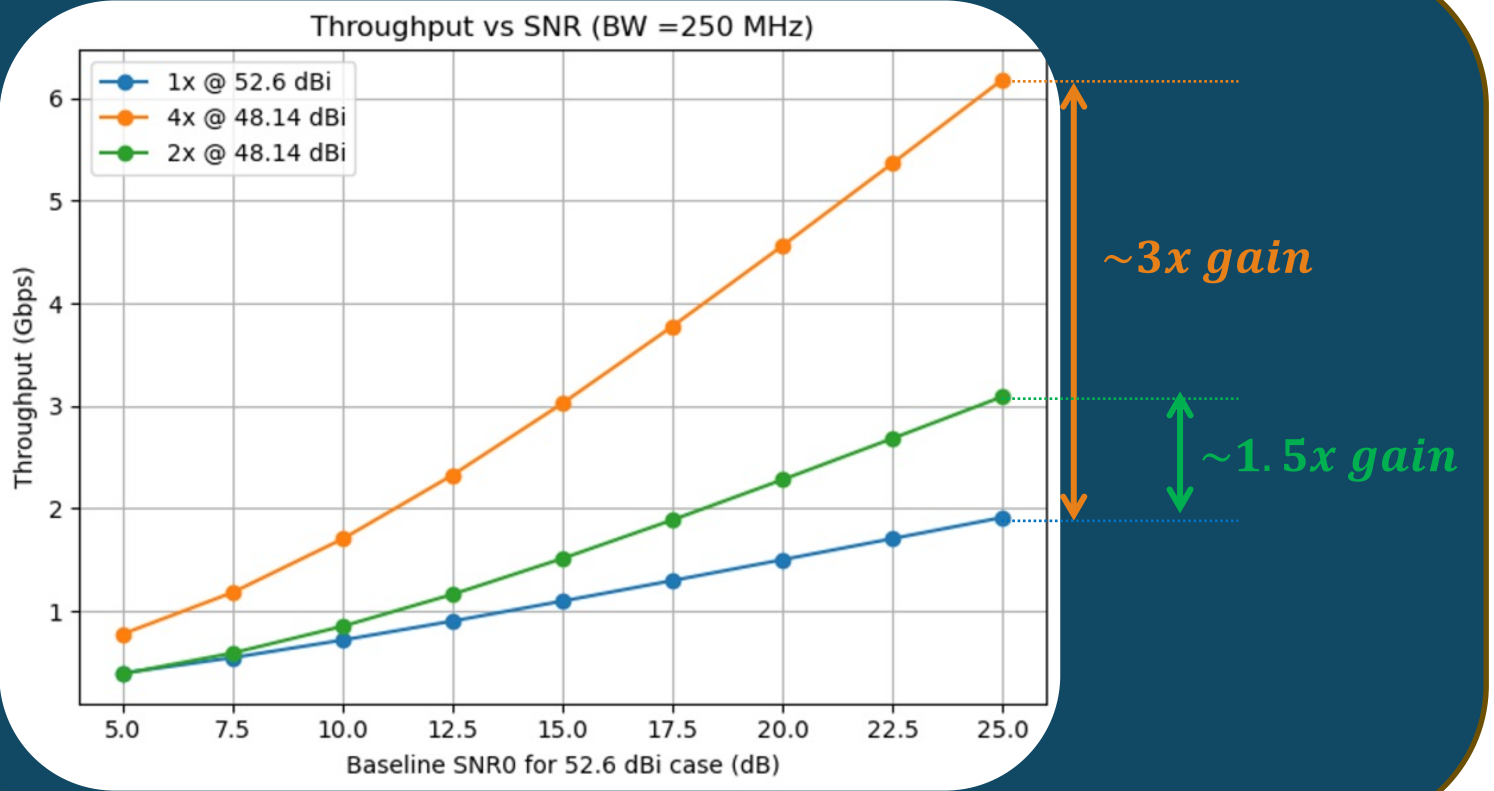
d_{sat} = 1.4 m
d_{gnd} = 1.4 km
#sat ants = 4
#gnd panels = 16



16-panel *ArrayLink* architecture delivers 4 streams at 500 km, sustaining 2 streams beyond 2000 km

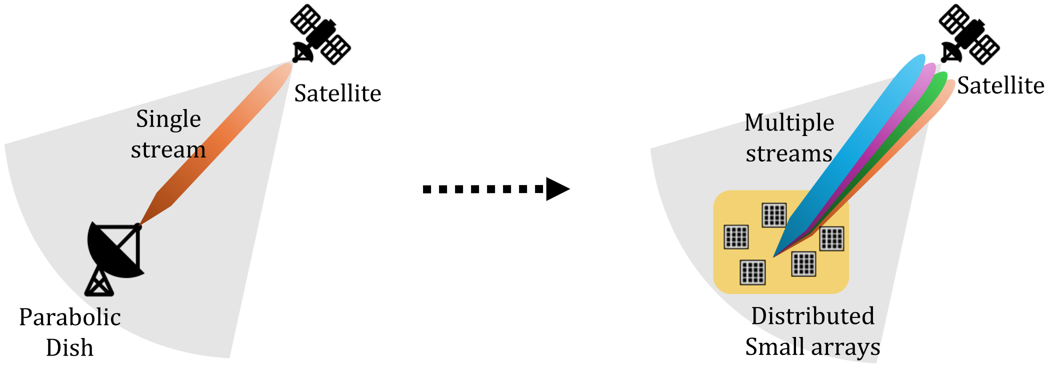
Total throughput comparing parabolic dish vs *ArrayLink*





ArrayLink boosts throughput — up to 3x with 4 streams and 1.5x with 2 streams.

ArrayLink Summary



- **Near-field is not a short-range phenomenon → it is a design choice:** By controlling aperture and carrier frequency, we can bring satellites into the near-field.
- **Line-of-sight MIMO is practical and tunable:** Distributed arrays create channel diversity even in pure LoS environments.
- ***ArrayLink* jointly delivers scalability and throughput:** Commodity phased-array panels replace monolithic ground stations with modular, deployable architectures.

Full paper is available at link: wcsng.ucsd.edu/arraylink/

Questions?