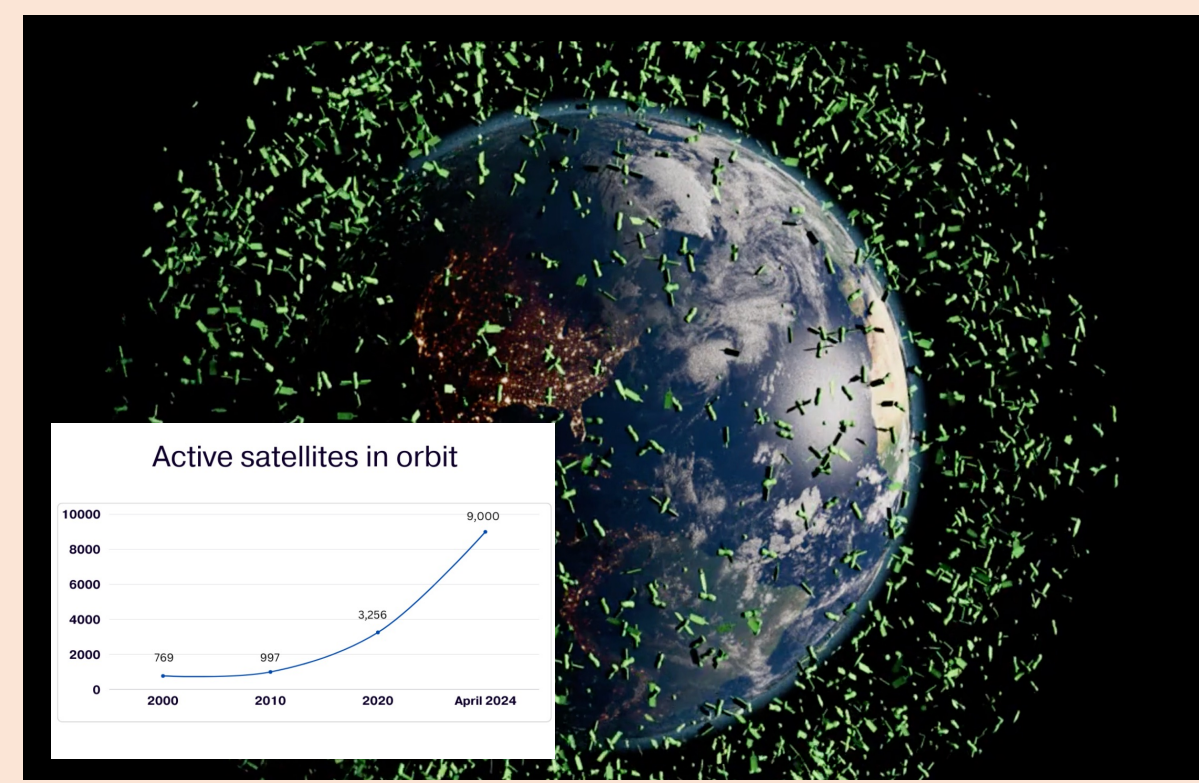


Satellites are closer than you think: A near field MIMO approach for Ground stations

Motivation



Satellites and Orbital Debris in Low Earth Orbit
References: www.gov.uk/government/news/the-four-gigabit-constellations, LEOLABS Visualization

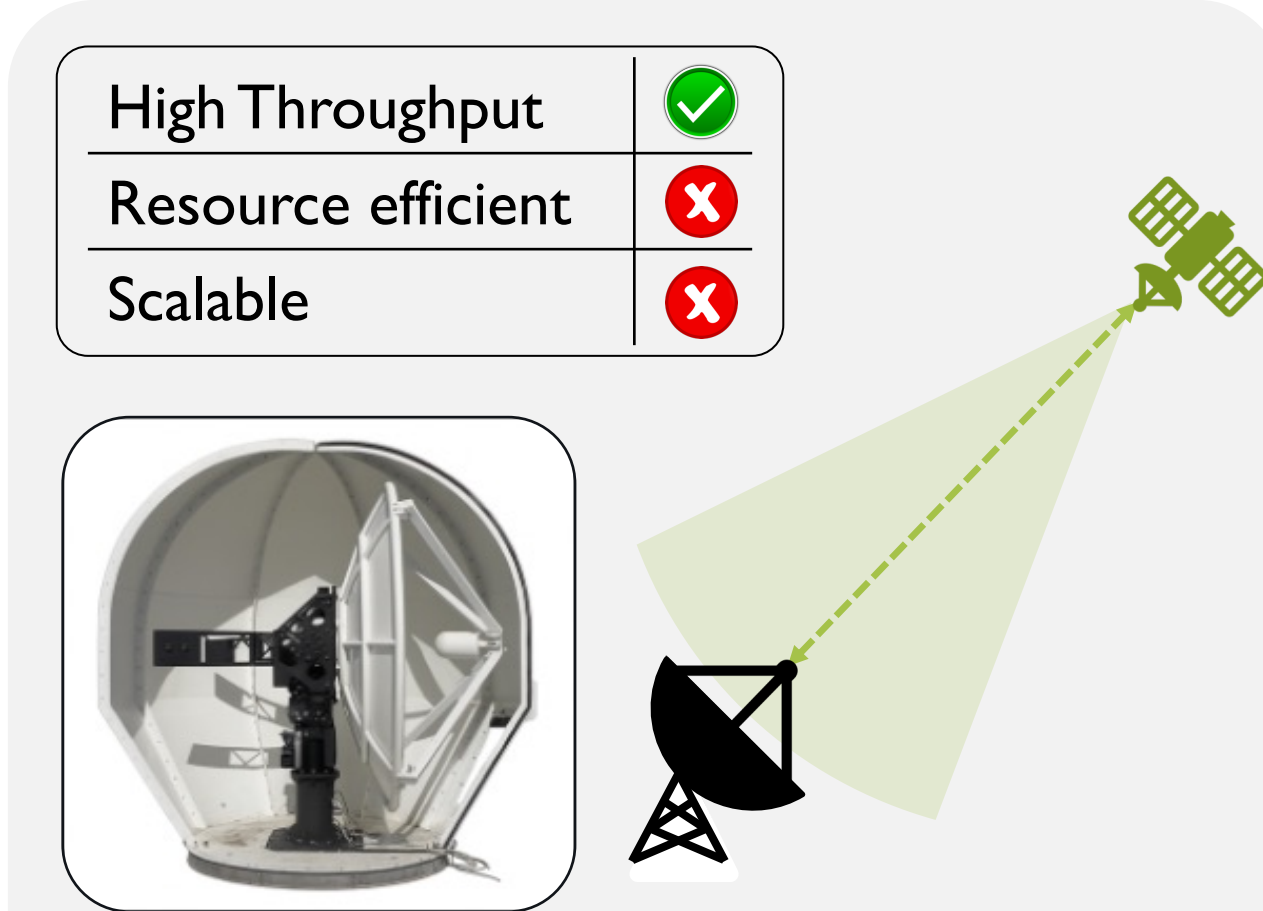


Current deployment of Ground Stations

The number of active satellites is growing at an unprecedented rate...

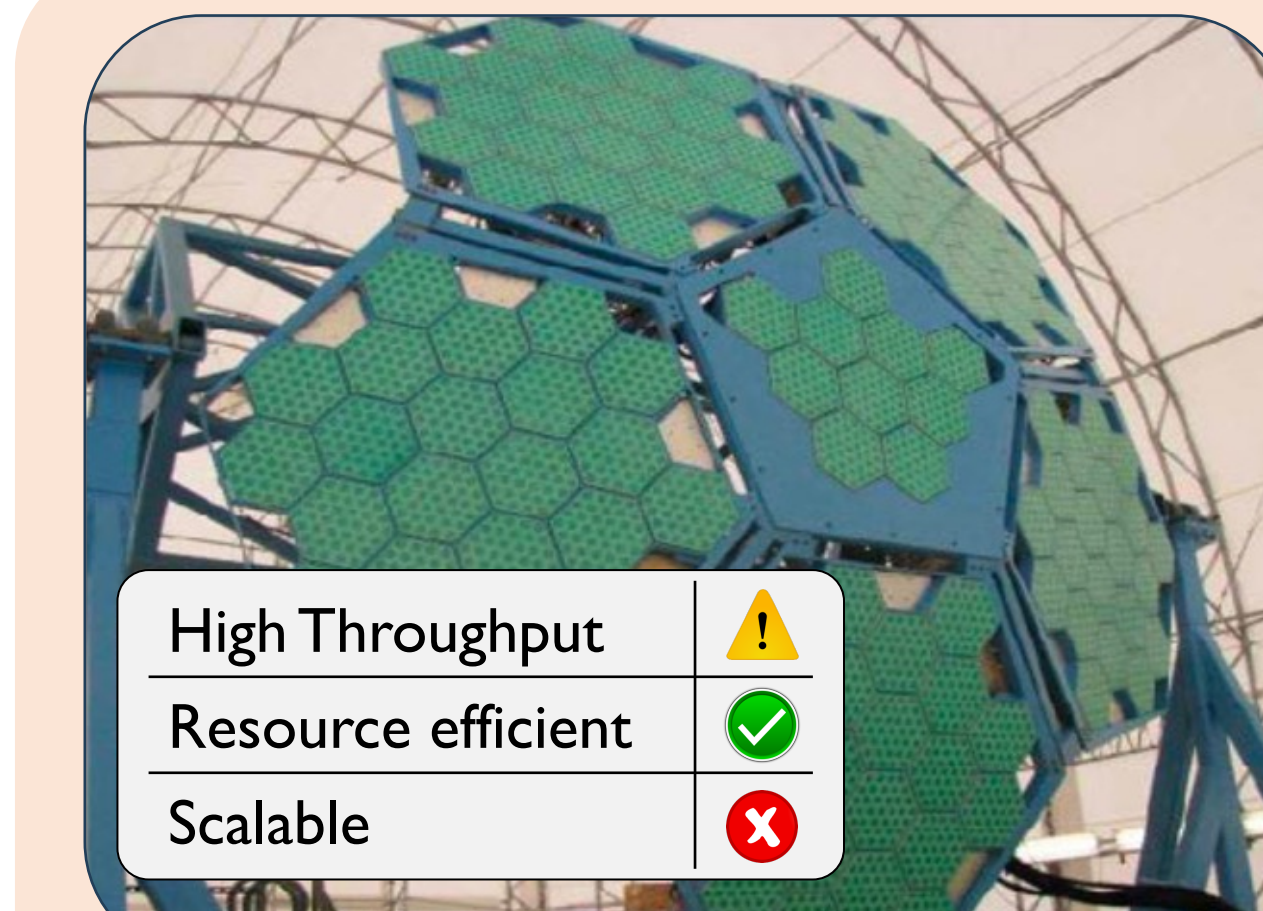
However, Ground stations are not scaling at the pace of satellite constellations

Current Solutions: Parabolic Dishes and Large Monolithic Arrays



Parabolic Dishes
Fig Ref: www.satelliteday.com/connectivity/2017/10/18/orbit-provide-satellite-tracking-ground-stations-endorsal/

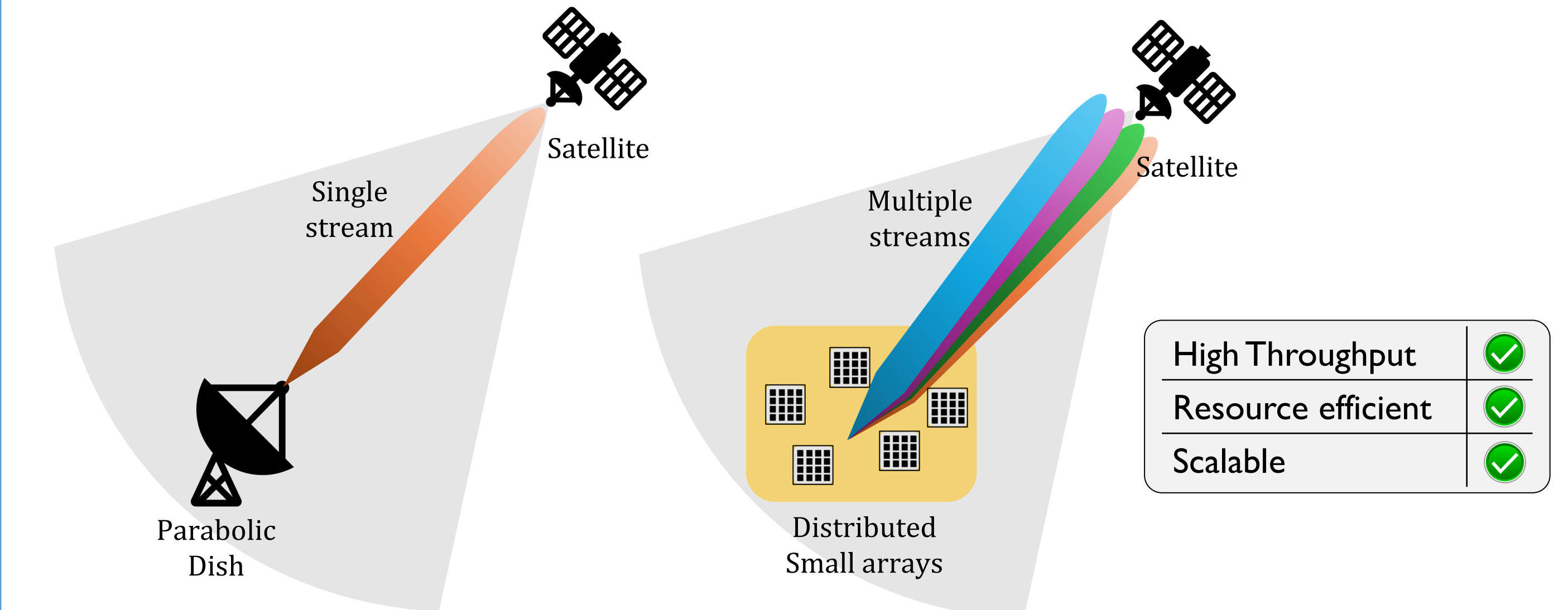
Parabolic dishes achieve high throughput but fail on resource efficiency and scalability



Large Monolithic Phased Array
Fig Ref: Henderson et al., "Advanced Technology Demonstration," IEEE Phased Array Systems & Technology, 2010. GPOAA

Large Monolithic arrays are resource efficient, but are limited by gain, complexity, and cost

Transforming Ground Stations from Dishes to Distributed arrays



ArrayLink: A distributed phased arrays approach that delivers high-throughput, efficient, and scalable multi-stream feeder links

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

The Problem

- Achieving high gain is critical (e.g., SpaceX 1.85 m dish \rightarrow 52.6 dBi)
- Matching this with phased arrays is expensive \rightarrow requires \sim 50,000 elements



Example: SpaceX ground station dishes (ka band):

- 1.85m \rightarrow 52.6 dBi
- 1.47m \rightarrow 49.5 dBi

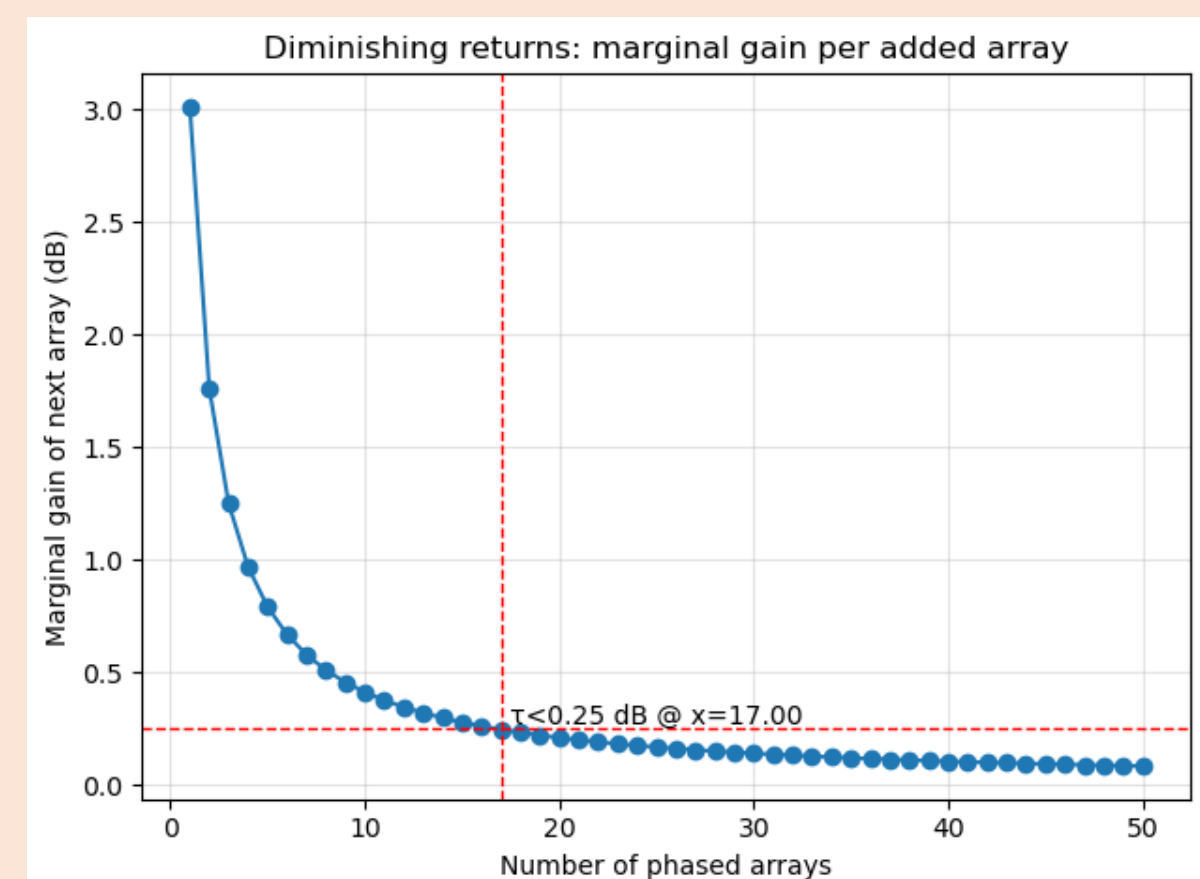
Distributed arrays approach

- Use commercially available phased-array terminals (e.g., 1024 elements \rightarrow 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

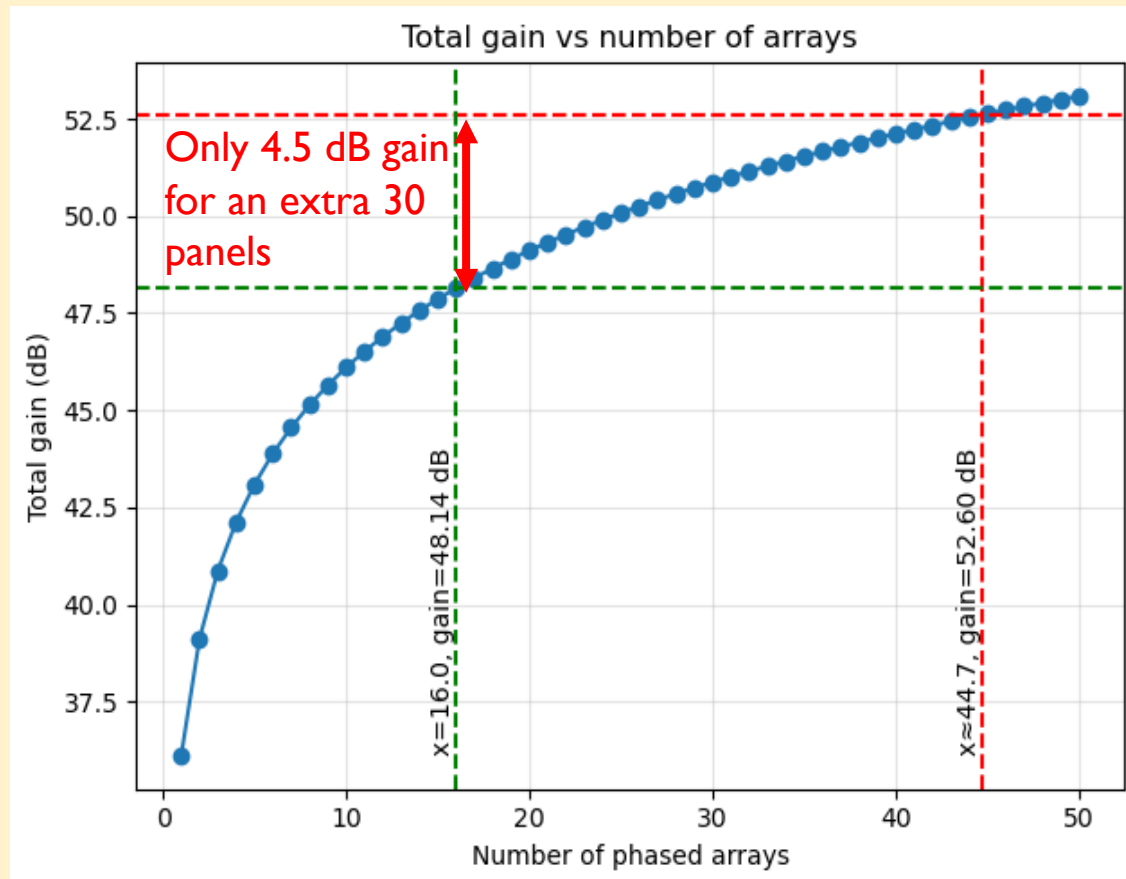


Kuiper/LEO user terminal panels < \$500 (ka band)

ArrayLink's gain and off-the-shelf panels (phased arrays) requirement trade-off



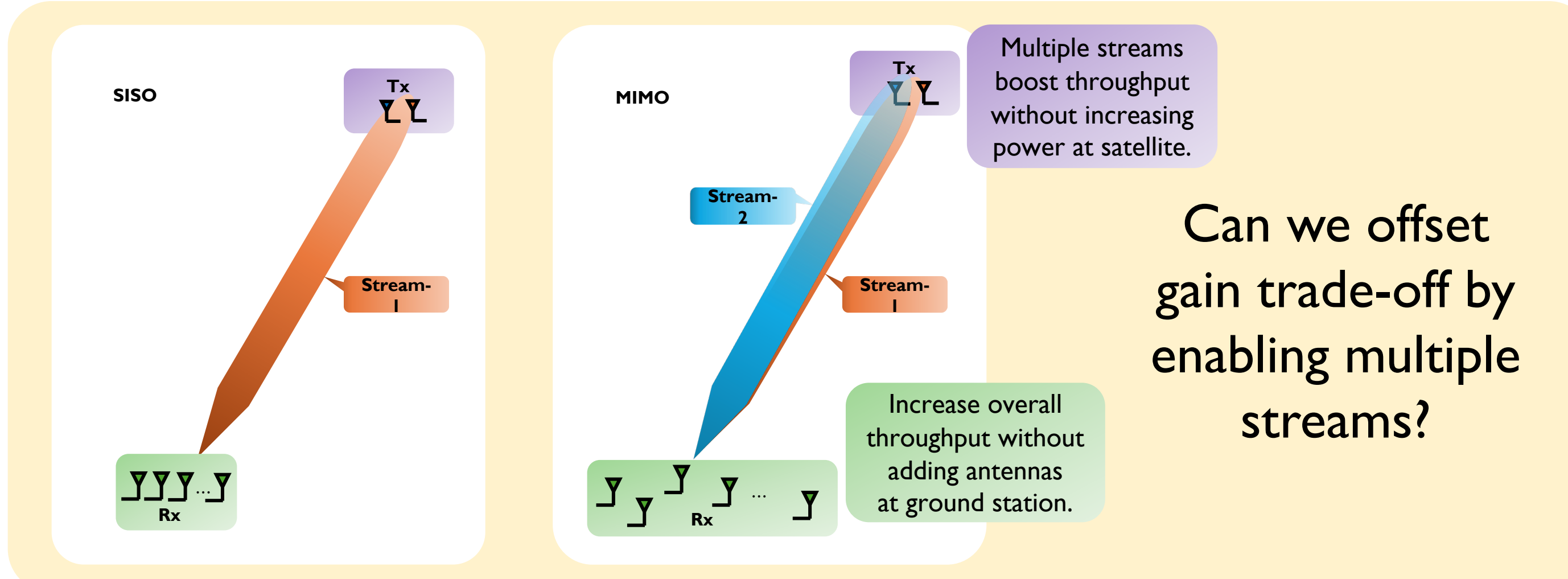
Total gain as a function of the number of phased arrays



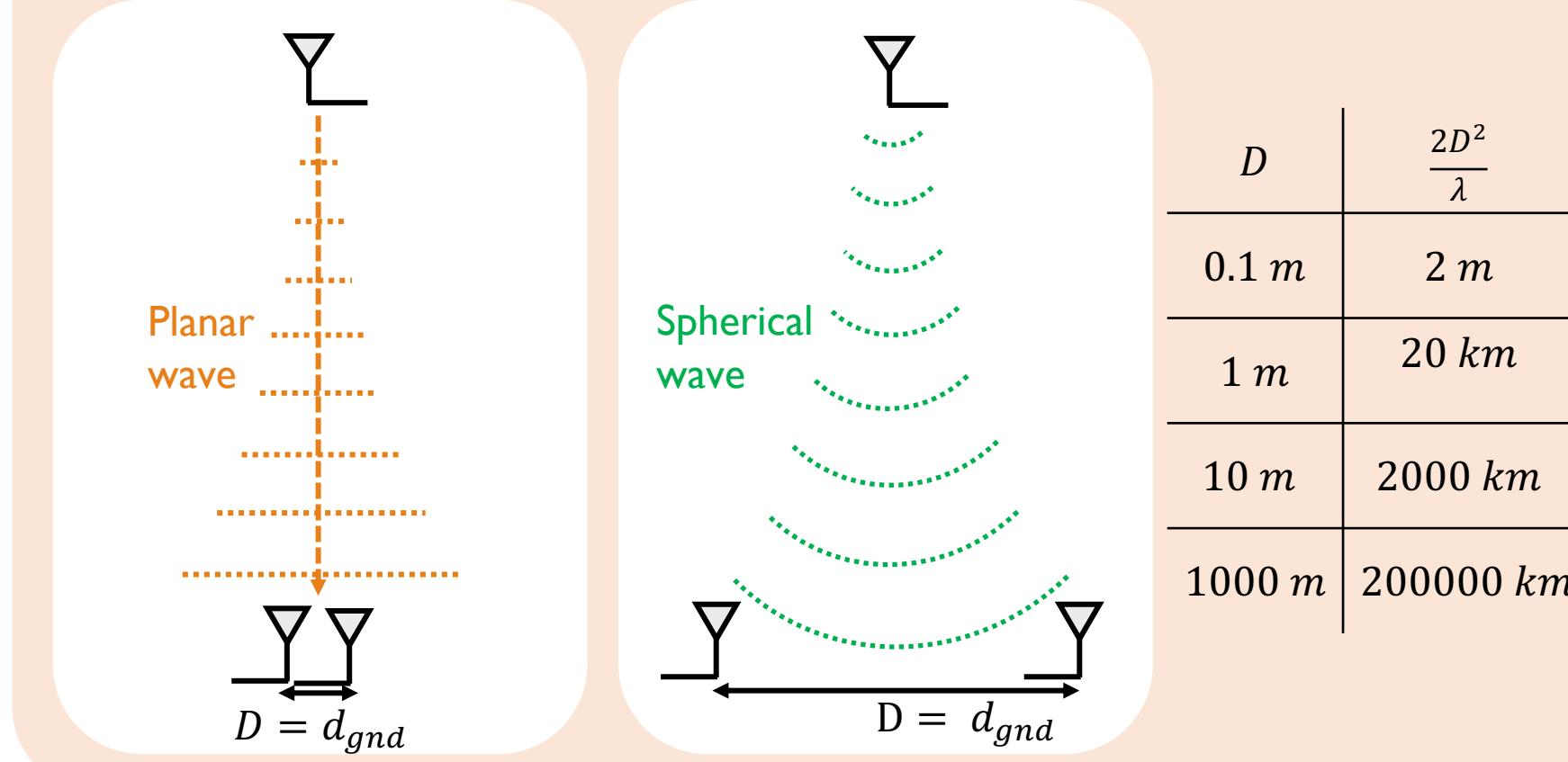
Marginal gain contributed by each additional array

ArrayLink trades 4.5 dB of array gain to reduce the system from 45 panels to just 16, enabling practical hardware deployment.

ArrayLink Challenge-2: Enabling multiple streams in LoS Links



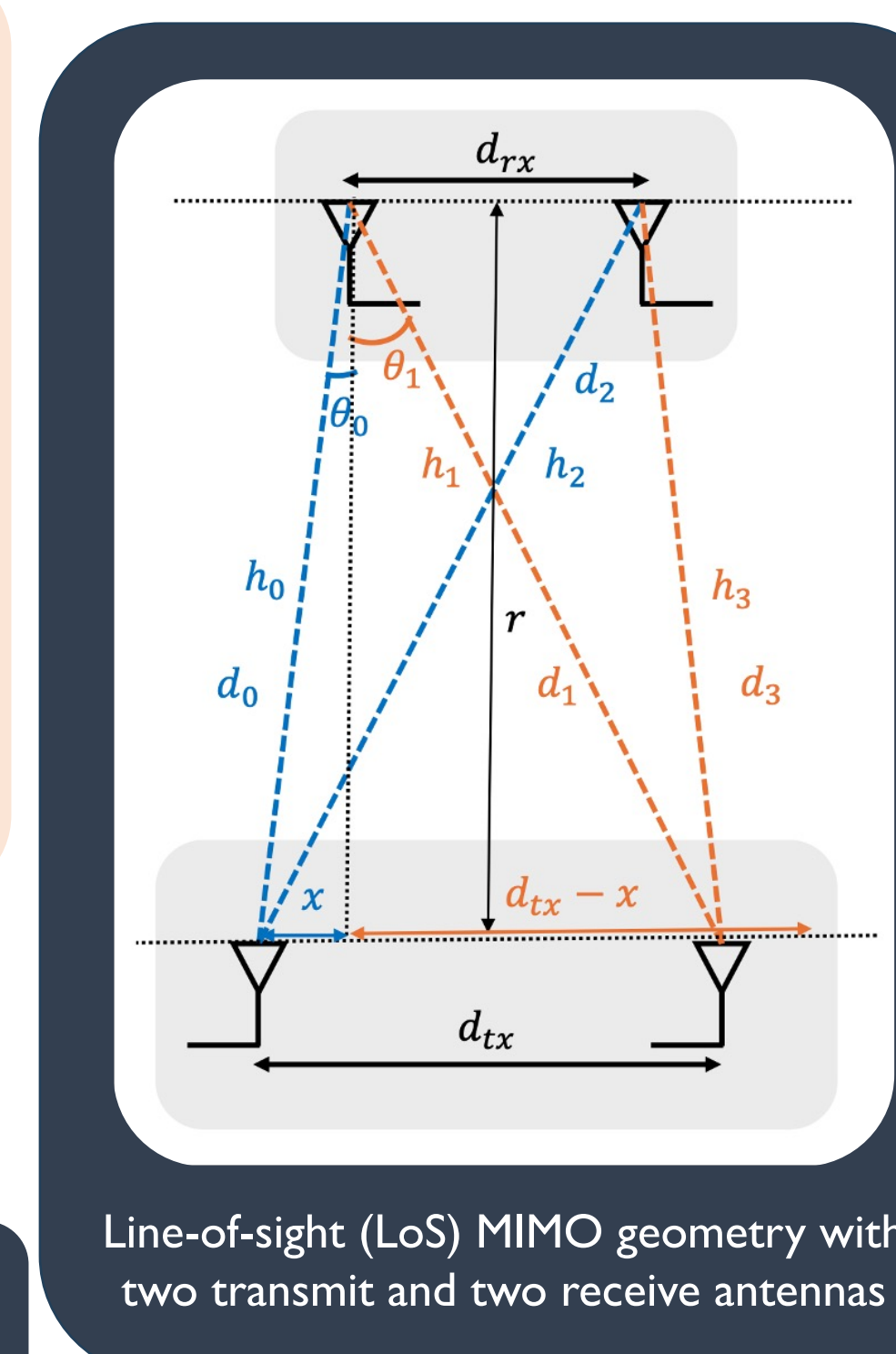
Increasing antenna spacing at ground station brings Satellites from Far-Field to Near-Field



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

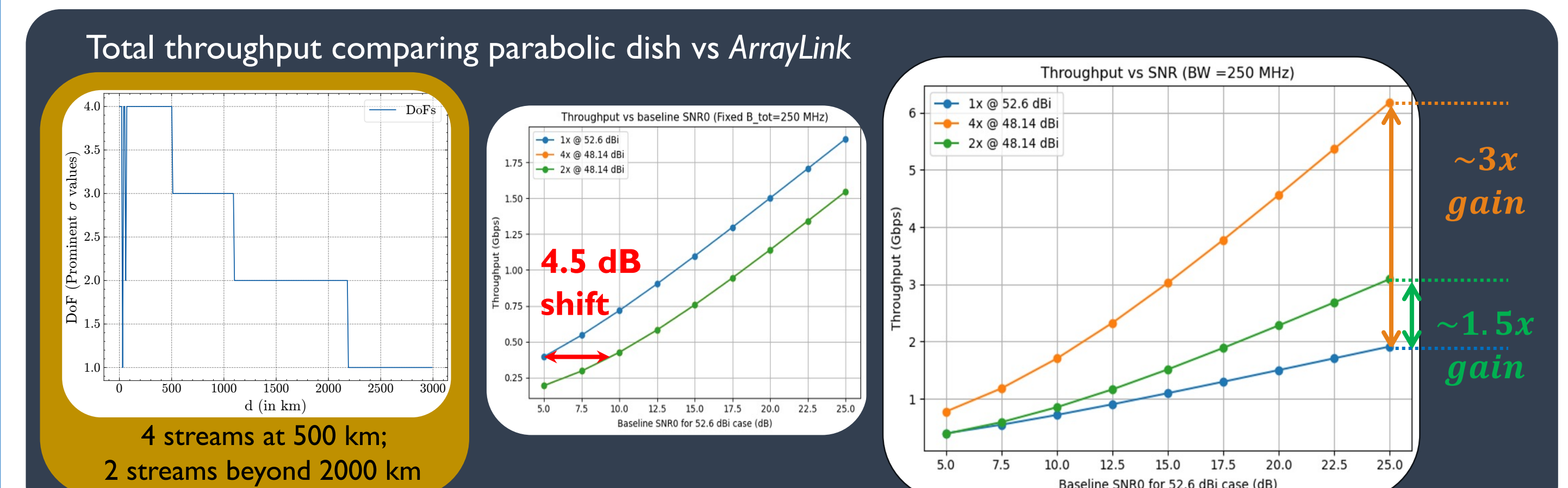
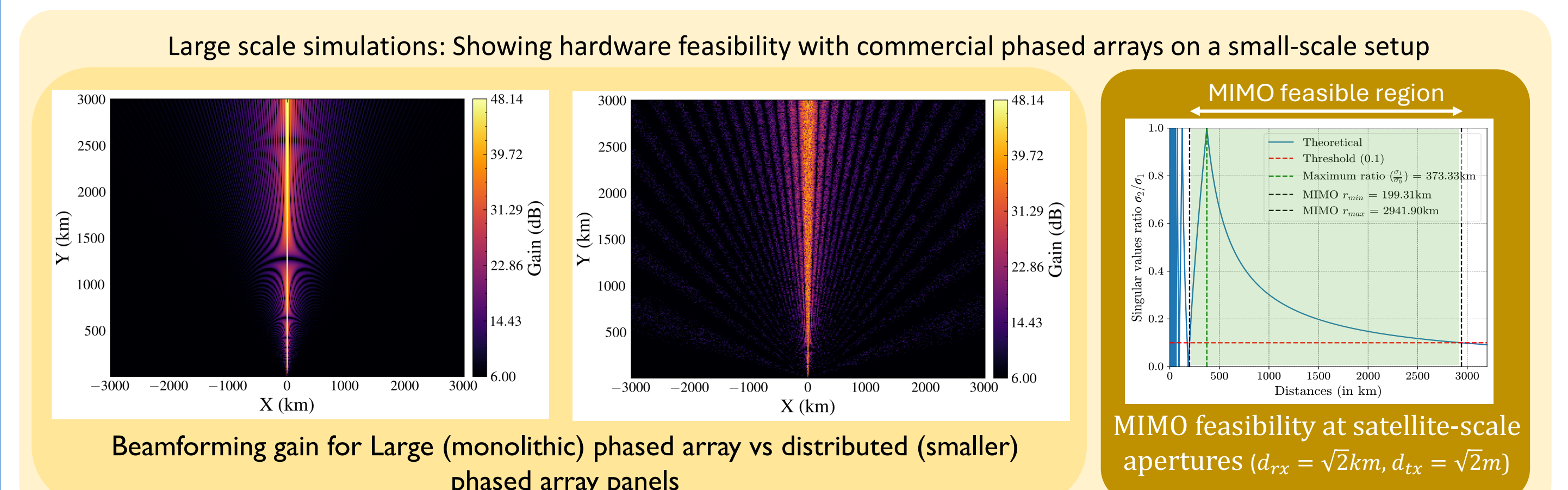
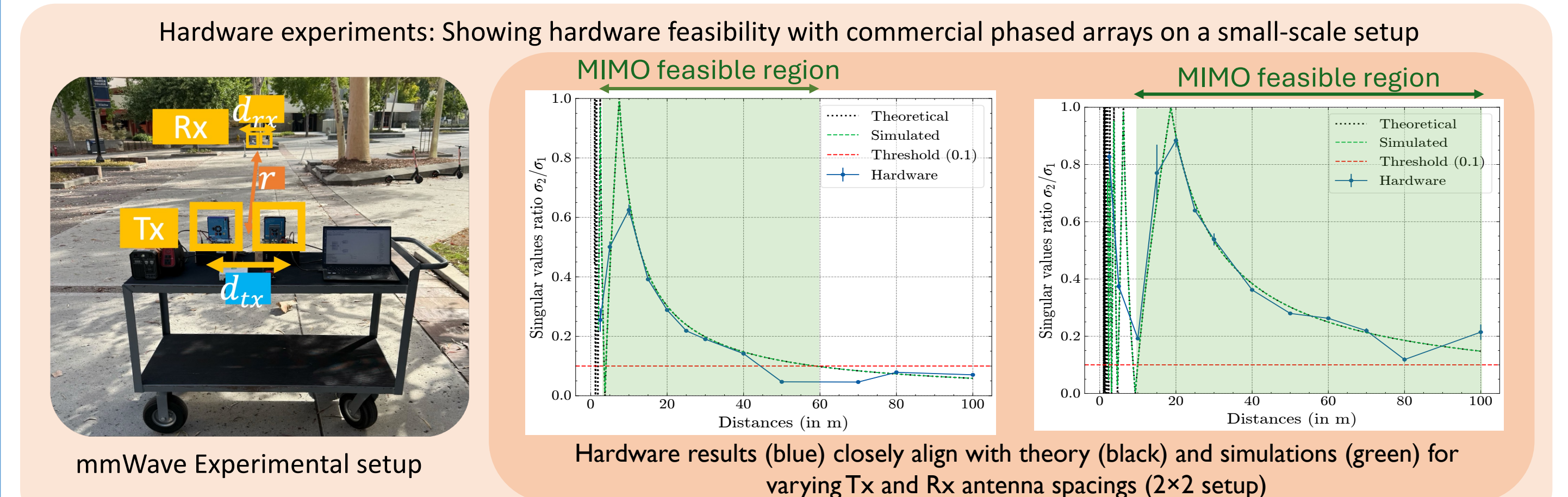
$$\sigma_{1,2} = \sqrt{2 \pm 2 \left| \cos\left(\frac{\Delta}{2}\right) \right|}, \Delta = \frac{2\pi}{\lambda} \left(\frac{d_{tx} d_{rx}}{r} \right)$$

$$r_{min} = \frac{\pi}{2 \tan^{-1}\left(\frac{\Delta}{2}\right)} \frac{d_{tx} d_{rx}}{\lambda}, r_{max} = \frac{\pi}{2 \tan^{-1}(r)} \frac{d_{tx} d_{rx}}{\lambda}$$



ArrayLink enables multi-stream line-of-sight MIMO without multipath, with feasibility governed by distance (r) and antenna spacing at the transmitter and receiver (d_{tx}, d_{rx})

Evaluation: Hardware Experiments and Large-Scale Simulations



ArrayLink boosts throughput by up to 3x with 4 streams and 1.5x with 2 streams, while achieving up to 48 dB per link gain comparable to dish class antennas

Summary and contributions

- ArrayLink:** A scalable ground-station architecture built from commercially available small phased-array panels
- Hardware-Feasible:** Enables practical phased-array ground stations using low-cost, off-the-shelf array panels
 - Near-Field MIMO:** An analytical framework showing how aperture size and geometry enable spatial multiplexing in LoS channels at satellite-scale distances
 - End-to-End Validation:** Demonstrated via 27 GHz mmWave hardware experiments (2.5–100 m) and large-scale satellite-distance simulations, with open-sourced simulator and real-world channel datasets

Future work and Open problems

- Validation with in-orbit satellites:** Validate ArrayLink using operational satellites (e.g., Starlink) to demonstrate multi-stream performance with real satellites in orbit
- Grating Lobe Mitigation and Array Placement:** Identify optimal panel geometries and placements to suppress grating lobes and sampling artifacts while preserving near-field MIMO gains
- High-Precision Satellite Localization:** Develop accurate joint angle and range estimation techniques for distributed arrays, where large apertures yield extremely narrow beams and demand precise localization for coherent combining and beam focusing

Acknowledgements: Thanks to WCSNG lab members for their contribution and valuable feedback, This research was partially supported by the National Science Foundation grants 2232481 and 2211805.



More details on the project webpage wcsng.ucsd.edu/arraylink/