

UC San Diego
JACOBS SCHOOL OF ENGINEERING
Electrical and Computer Engineering

WCSNG
Wireless Communications
Sensing and Networking

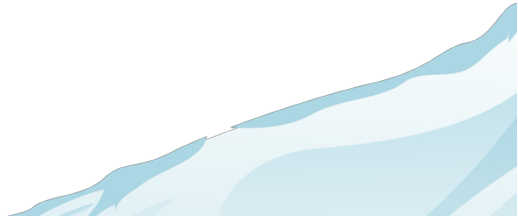
Scaling Satellite Connectivity:

Building Adaptive, Efficient and Deployable systems

Prof. Dinesh Bharadia, Associate Professor, USCD
Director of WCSNG UCSD (wcsng.ucsd.edu)
Students: Rohith Reddy Venman (Primary), Ish Kumar Jain,
William Hunter (see Acknowledgment slides)

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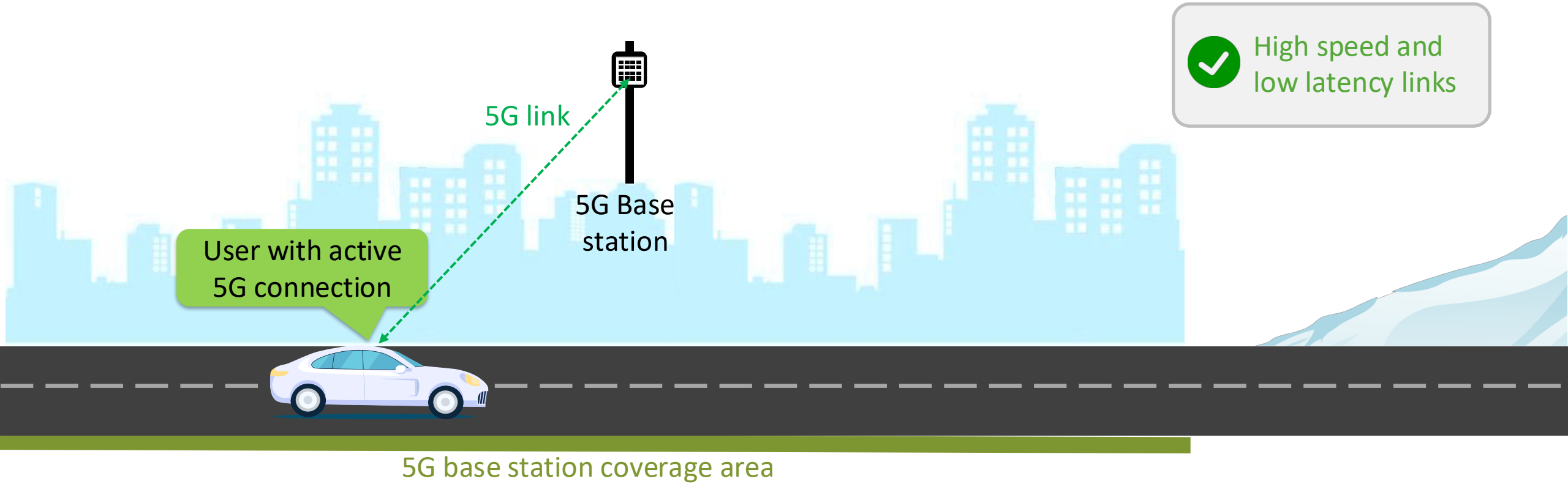
Terrestrial networks (5G)



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Terrestrial networks (5G)

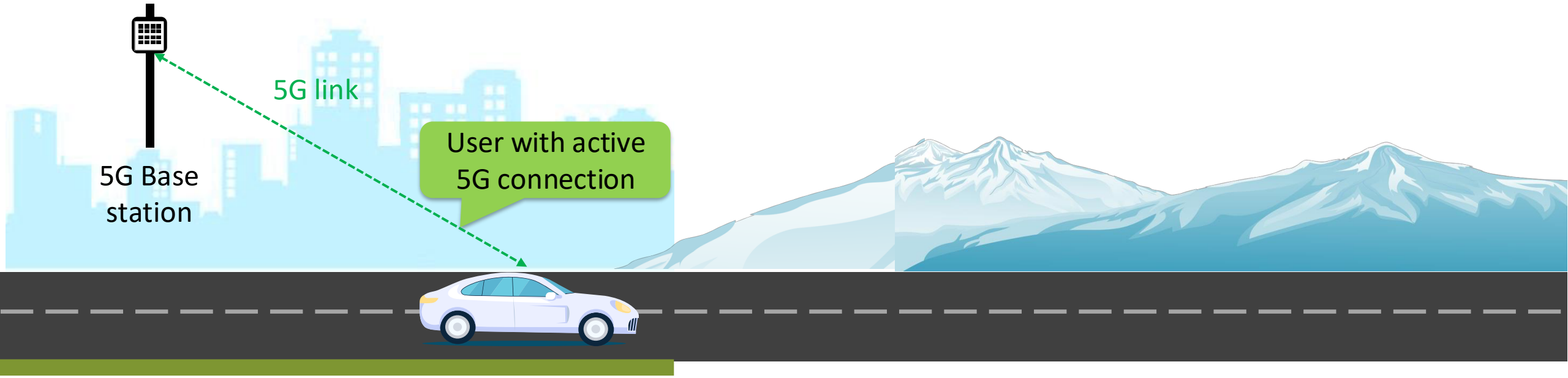
- Terrestrial networks such 5G offers a **high speed** and **low latency link** to vast number of users.



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Terrestrial networks: *Coverage is limited*

High speed and low latency links



5G base station coverage area

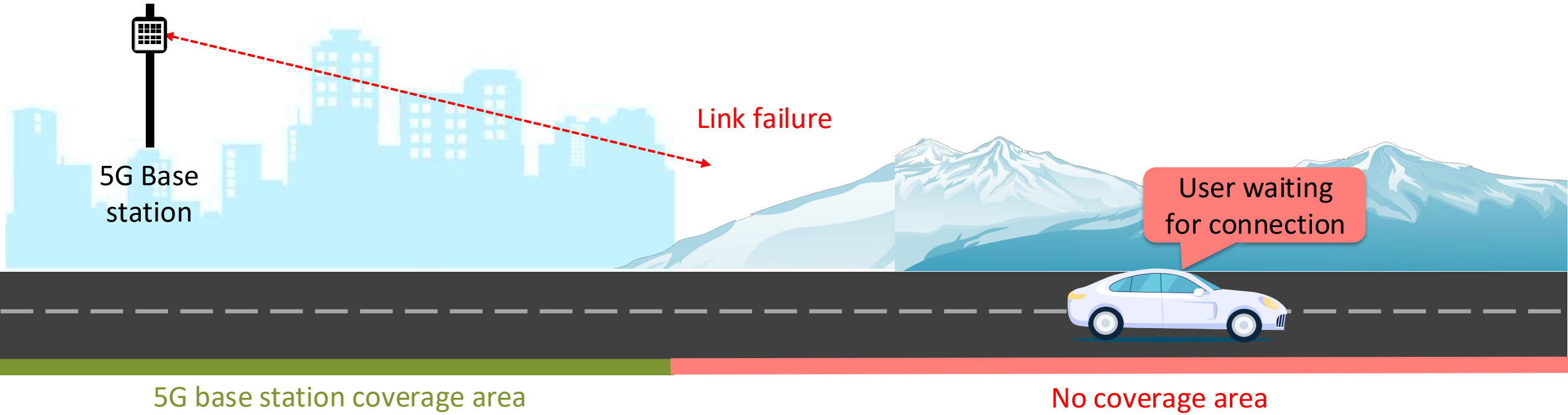
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Terrestrial networks: *Coverage is limited*

Terrestrial networks' coverage is limited to few km

High speed and low latency links

Limited coverage



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Satellite direct-to-device connectivity

- With latest advancements in smartphones and LEO satellites, terrestrial devices can now directly connect to satellites

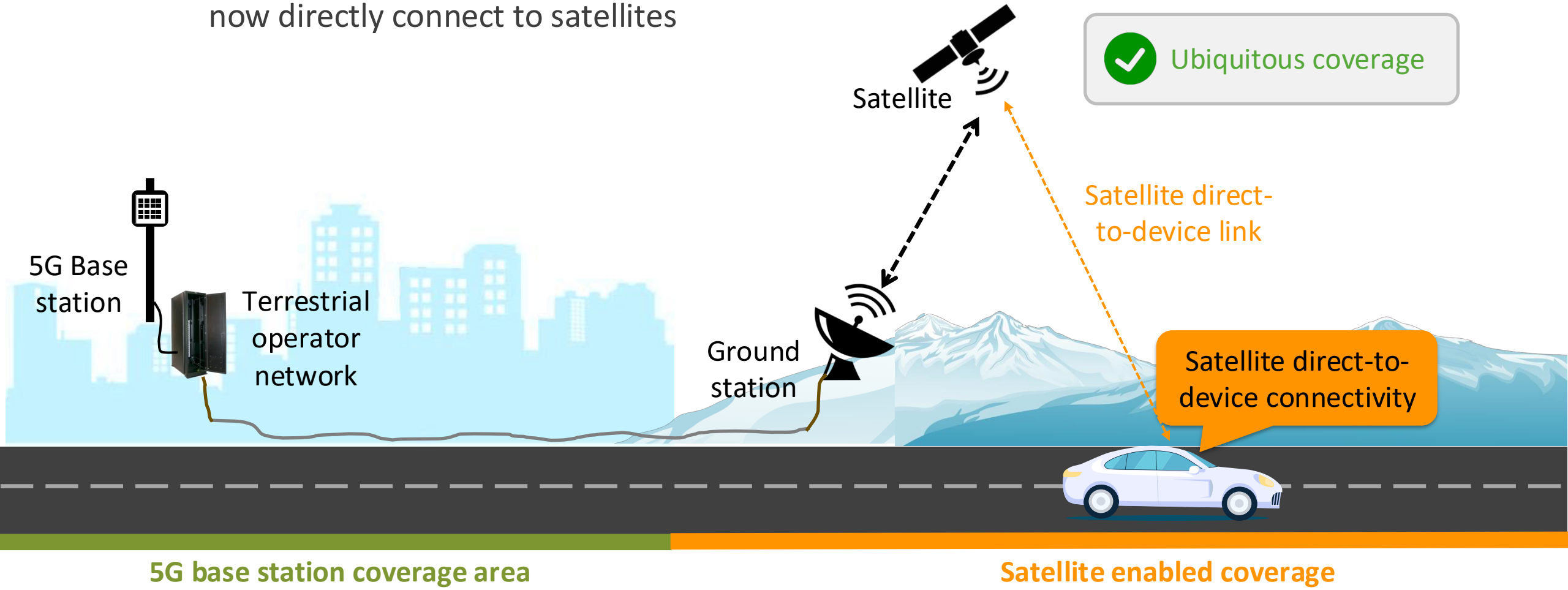


Ref: *starlink.com/business/direct-to-cell*

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Satellite direct-to-device connectivity

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Current trends in Direct-to-Device Connectivity



Ref: https://www.groundcontrol.com/blog/what-direct-to-device-d2d-iot-means/

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Motivation: Satellite IoT applications



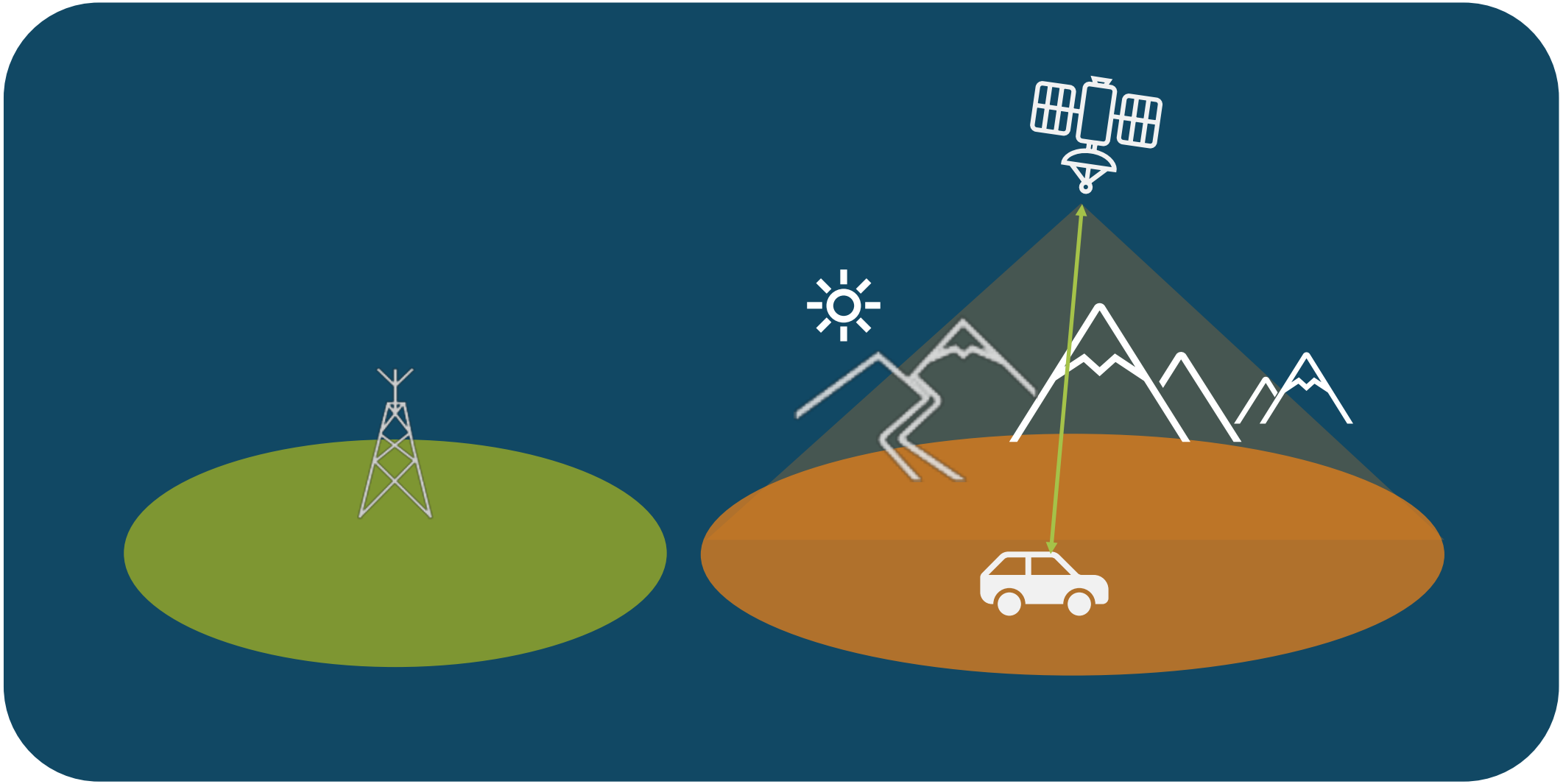
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Motivation: Satellite Direct-to-Device Connectivity



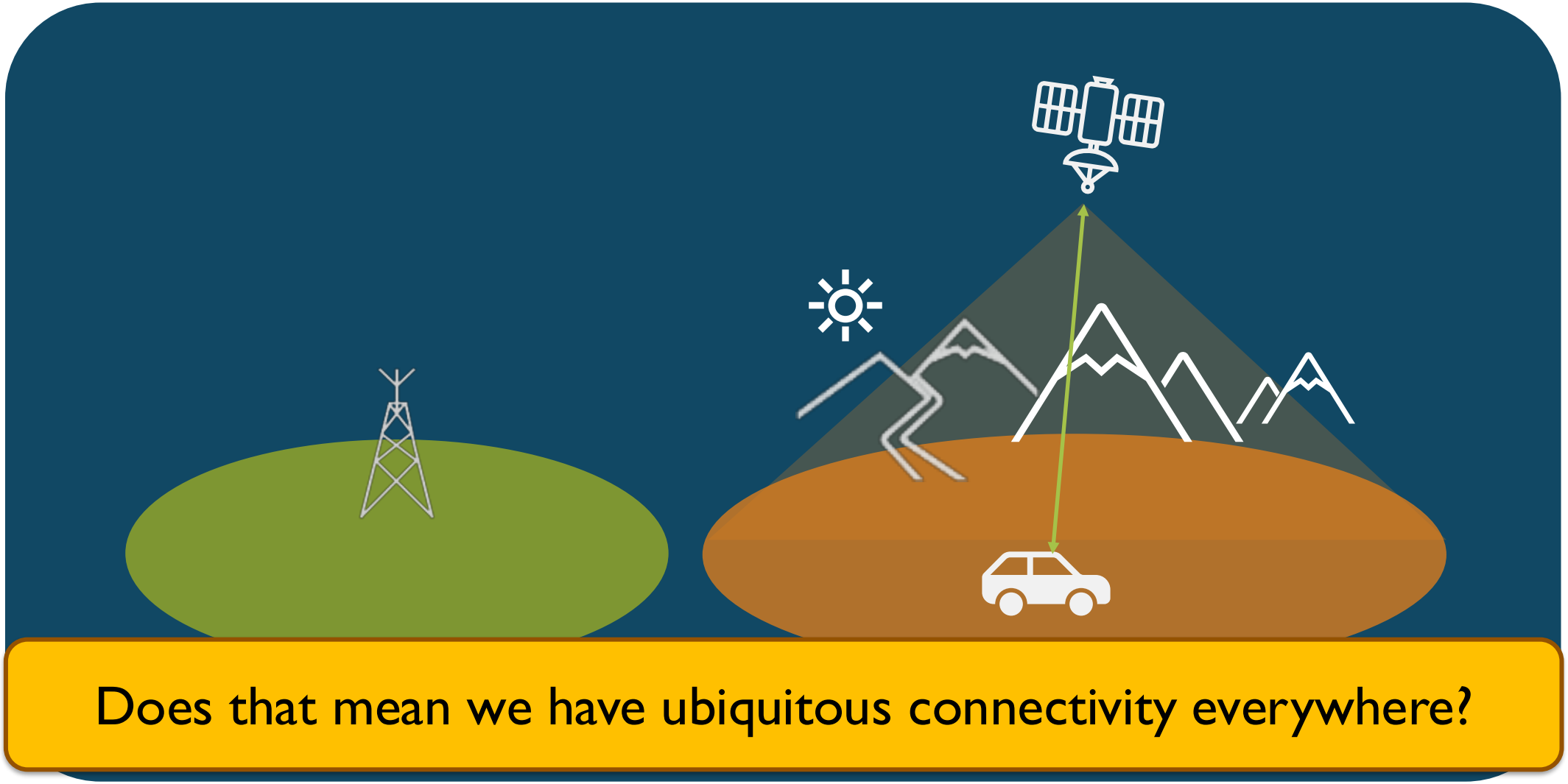
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Motivation: Satellite Direct-to-Device Connectivity



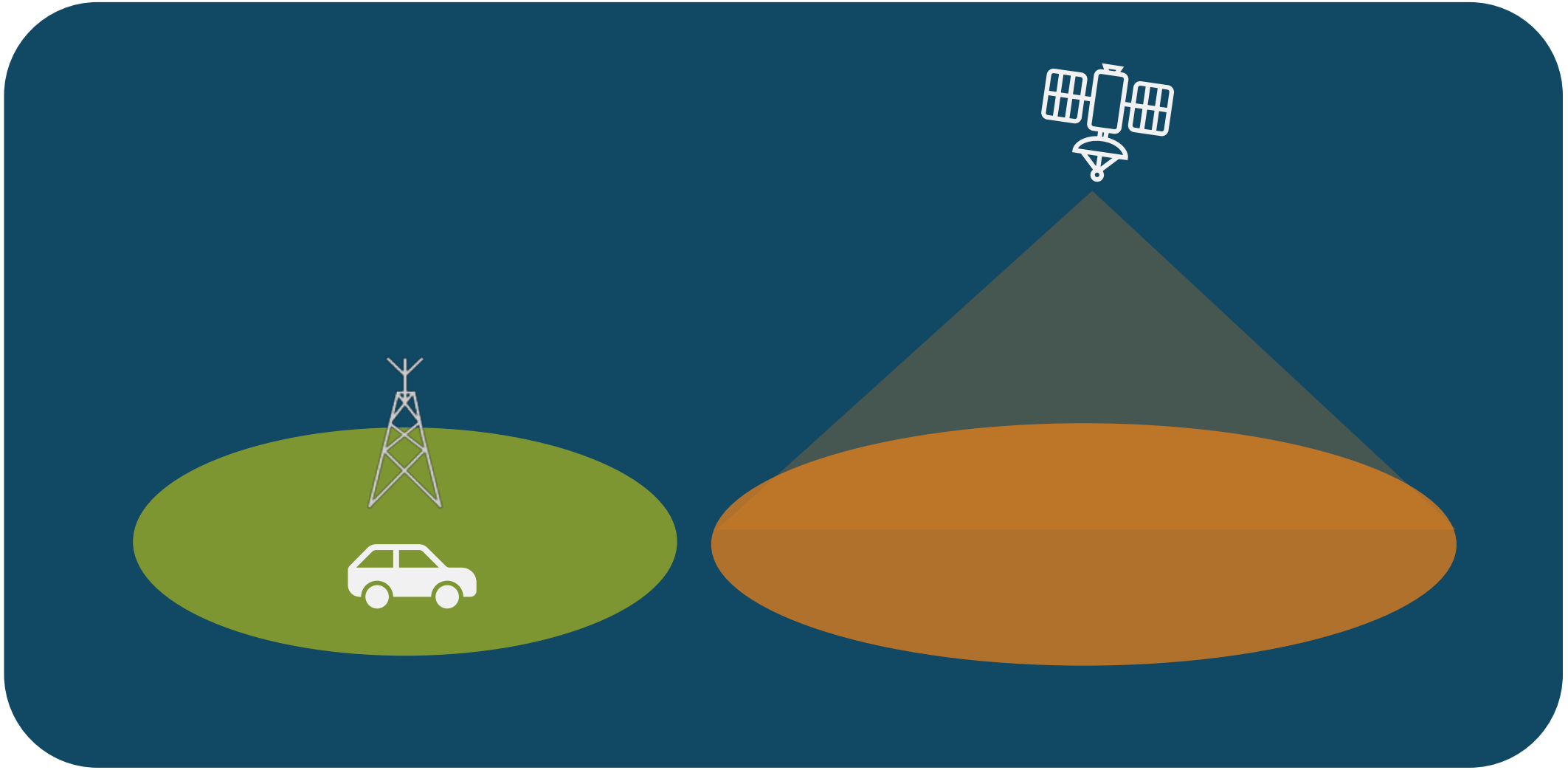
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Motivation: Satellite Direct-to-Device Connectivity



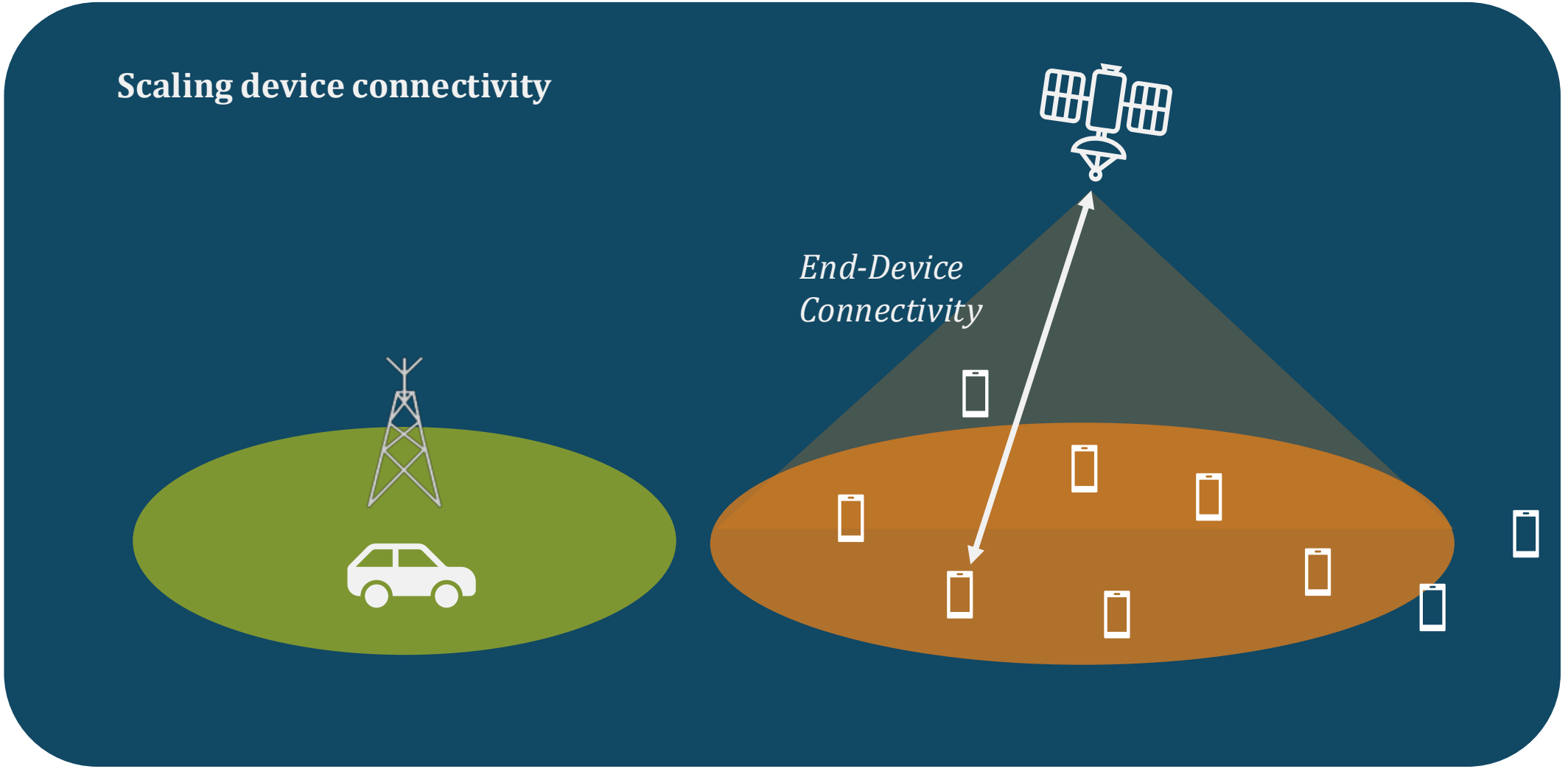
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Challenges: From feasibility to Scale



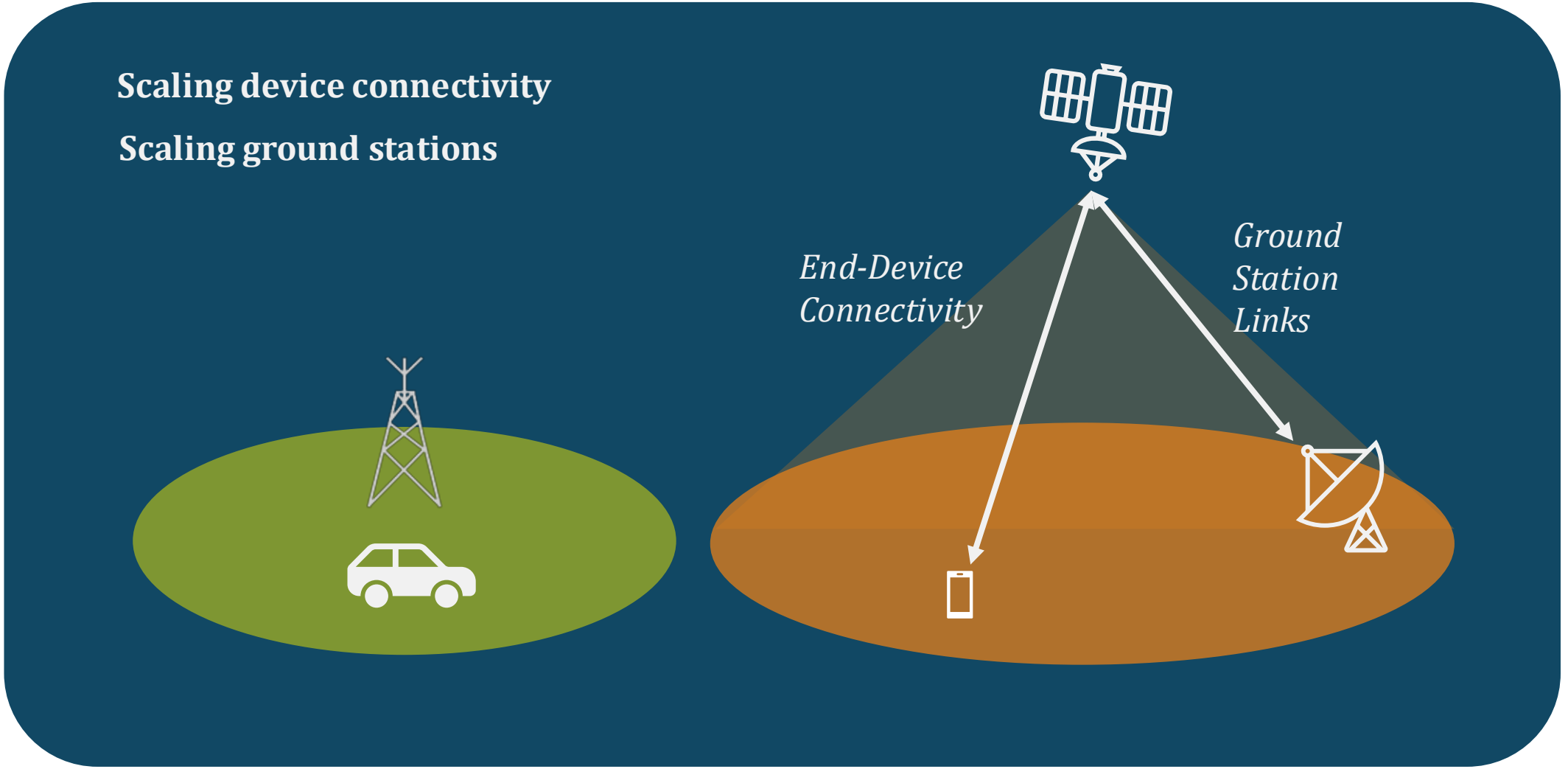
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Challenges: From feasibility to Scale



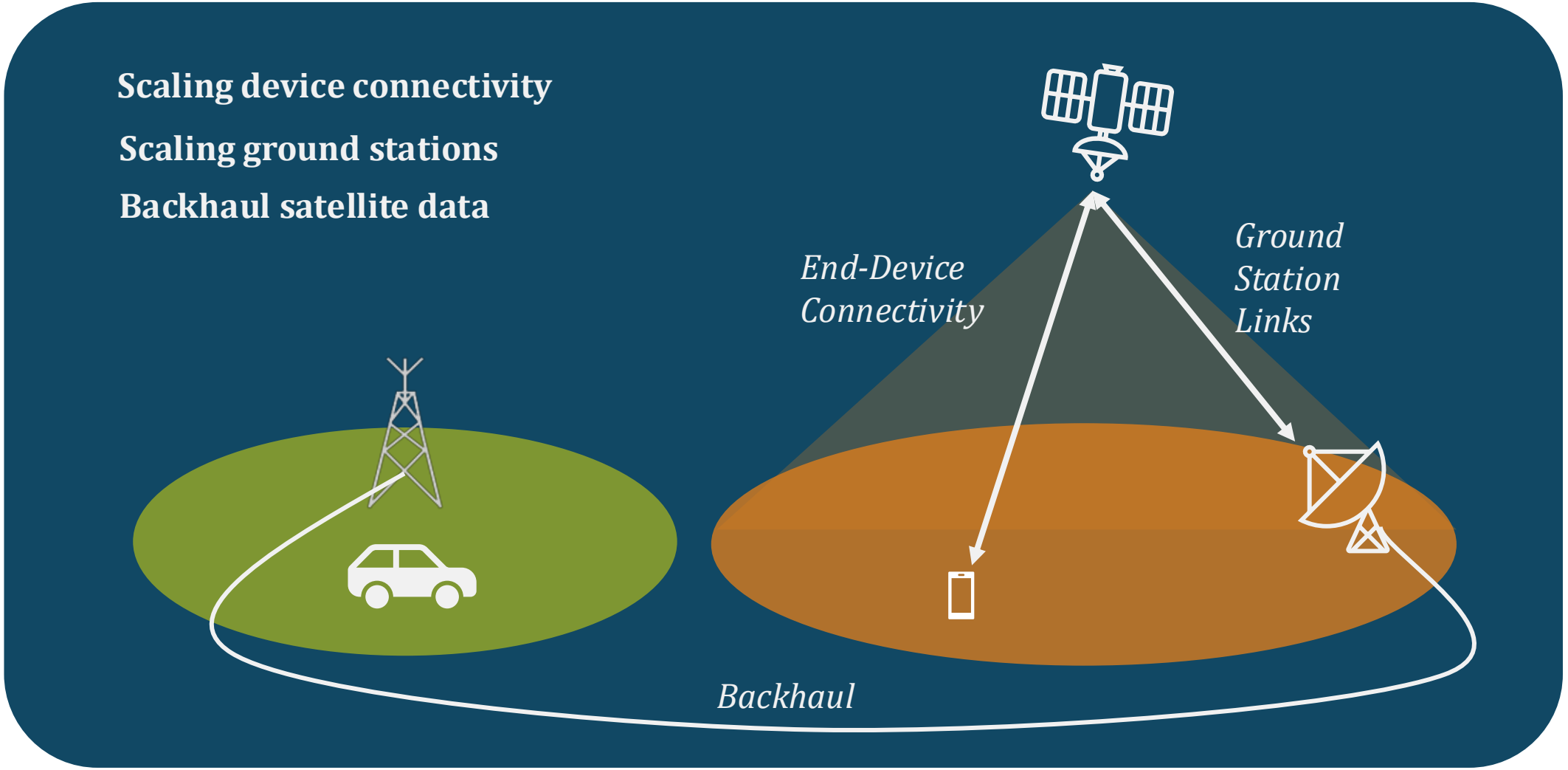
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Challenges: From feasibility to Scale



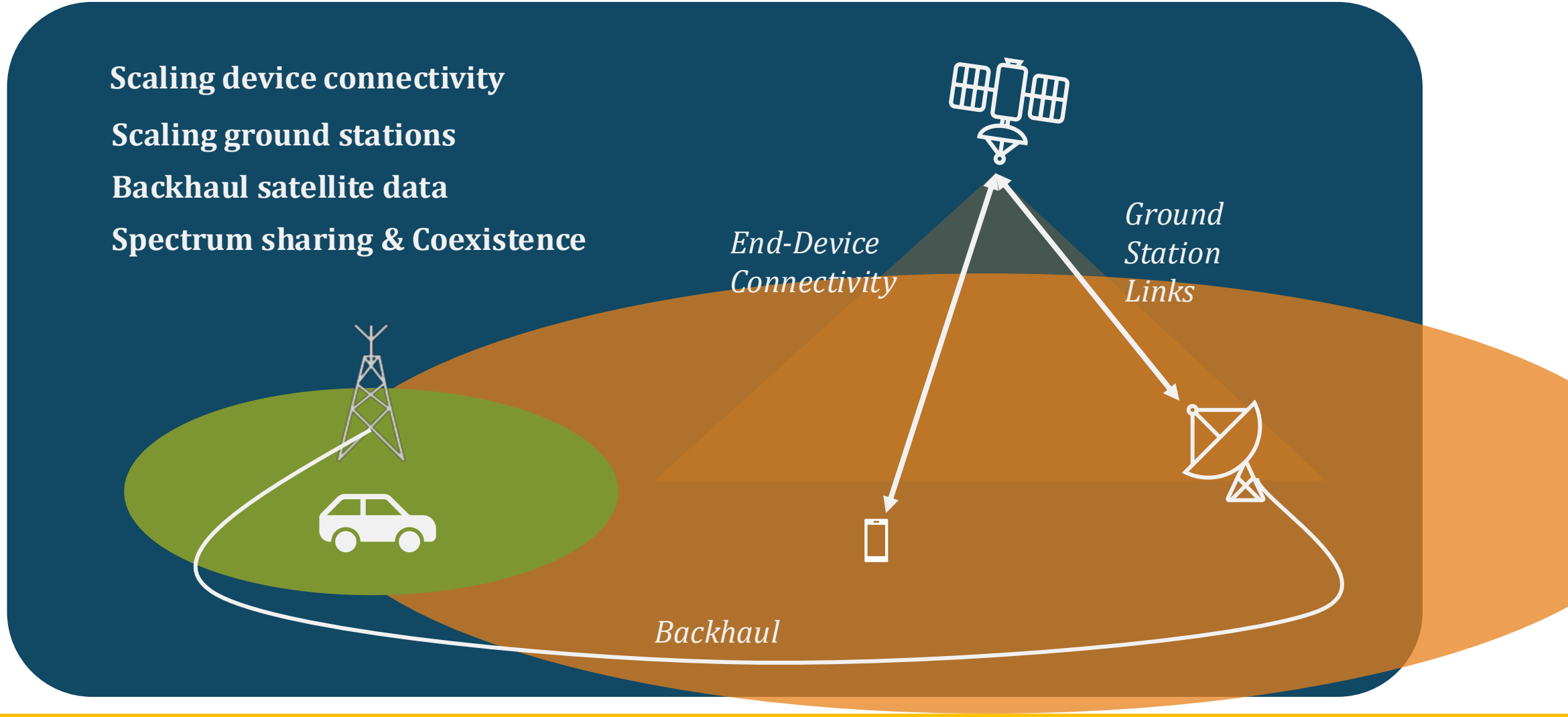
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Challenges: From feasibility to Scale



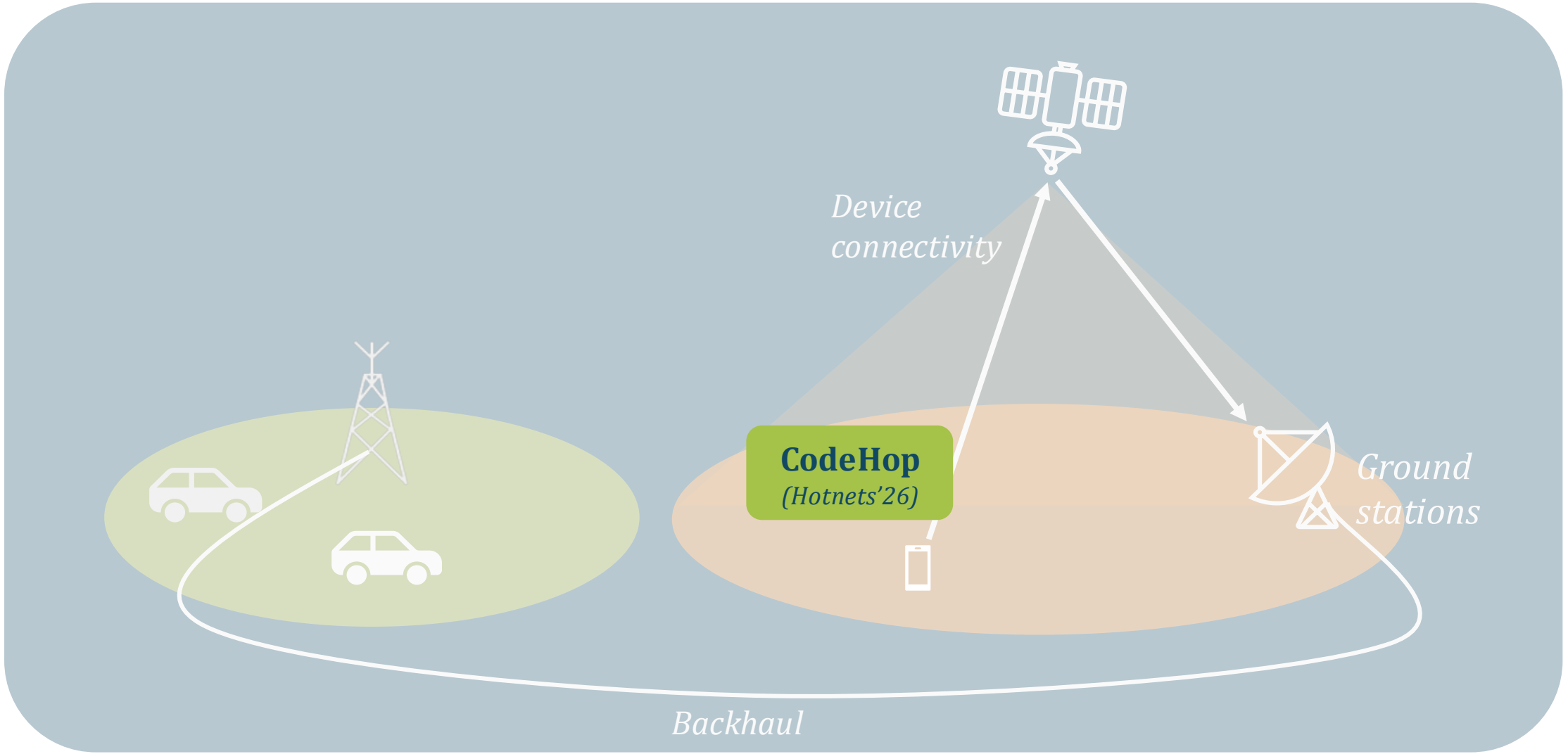
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Challenges: From feasibility to Scale



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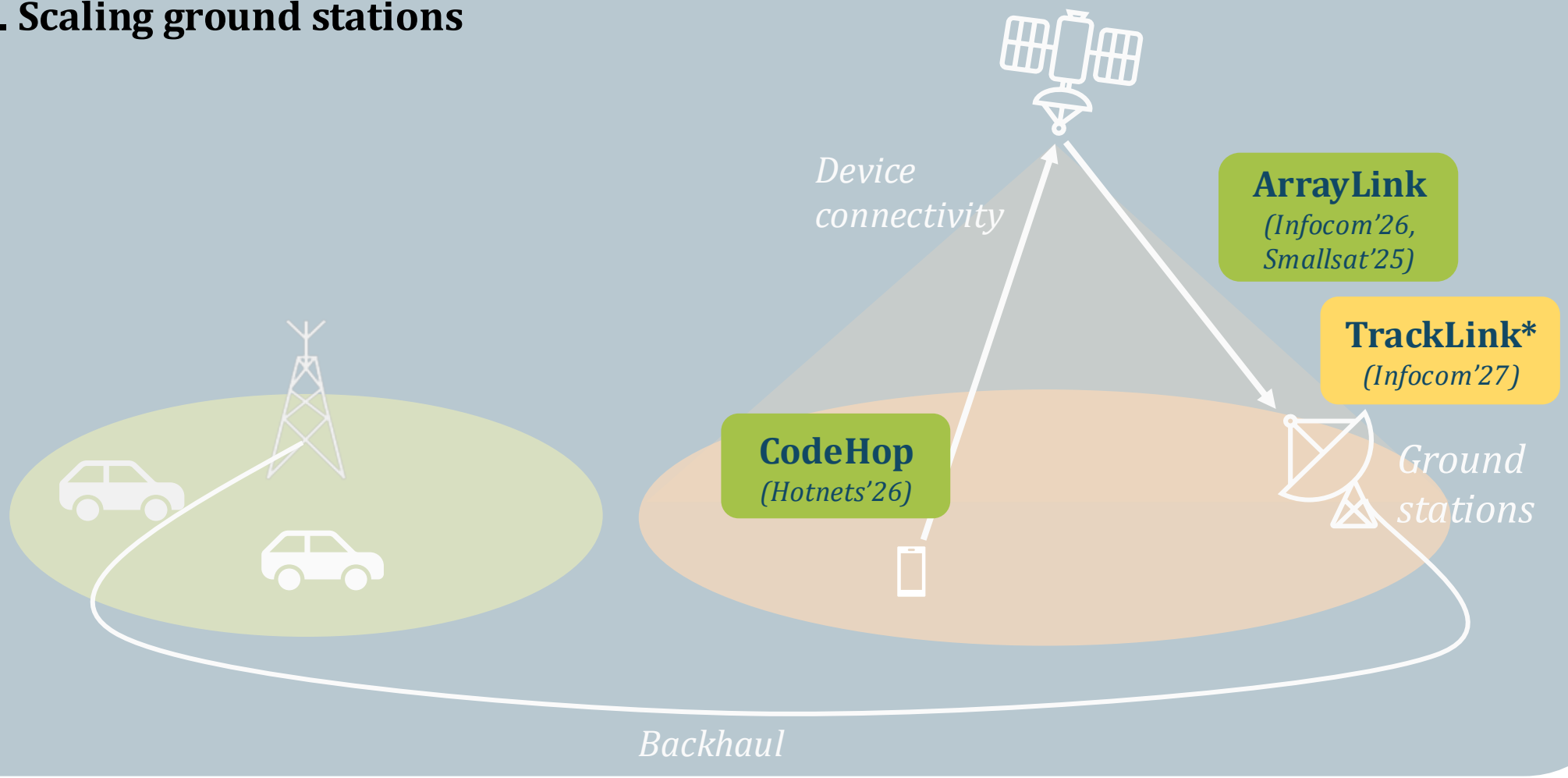
WCSNG: Our work builds systems to address these challenges



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*under review/submission

WCSNG: Our work builds systems to address these challenges

1. Scaling ground stations

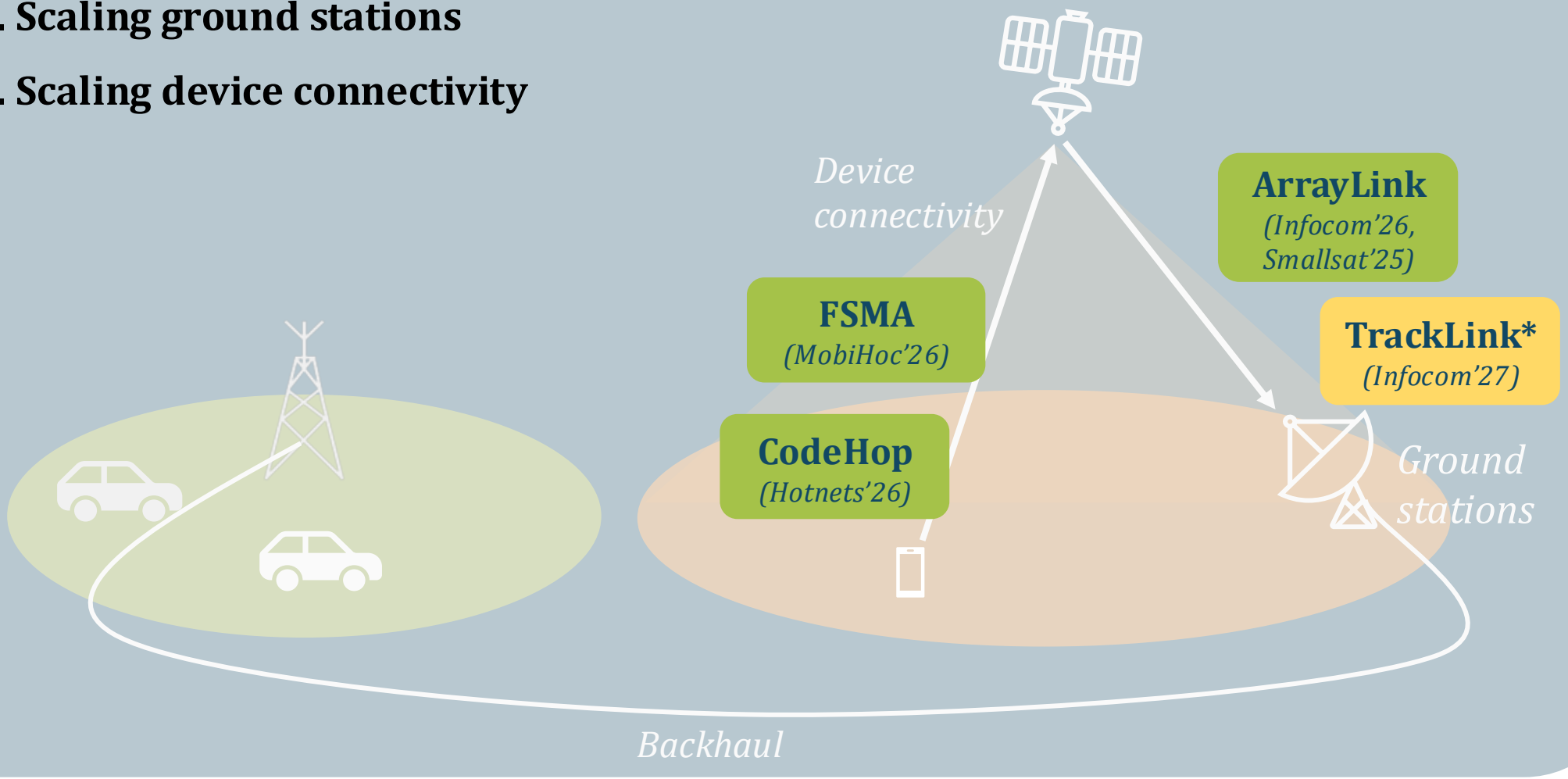


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WCSNG: Our work builds systems to address these challenges

1. Scaling ground stations

2. Scaling device connectivity



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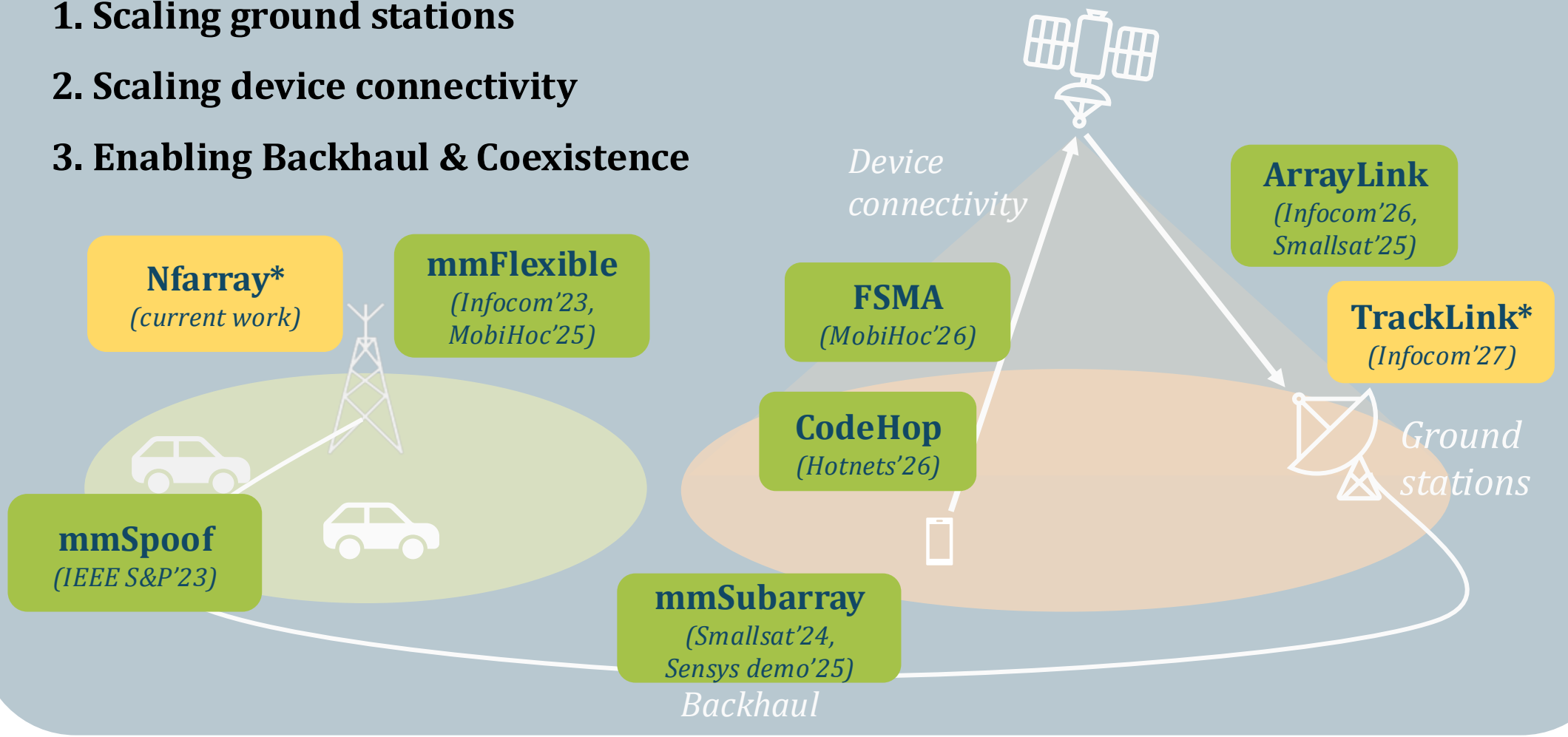
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WCSNG: Our work builds systems to address these challenges

1. Scaling ground stations

2. Scaling device connectivity

3. Enabling Backhaul & Coexistence

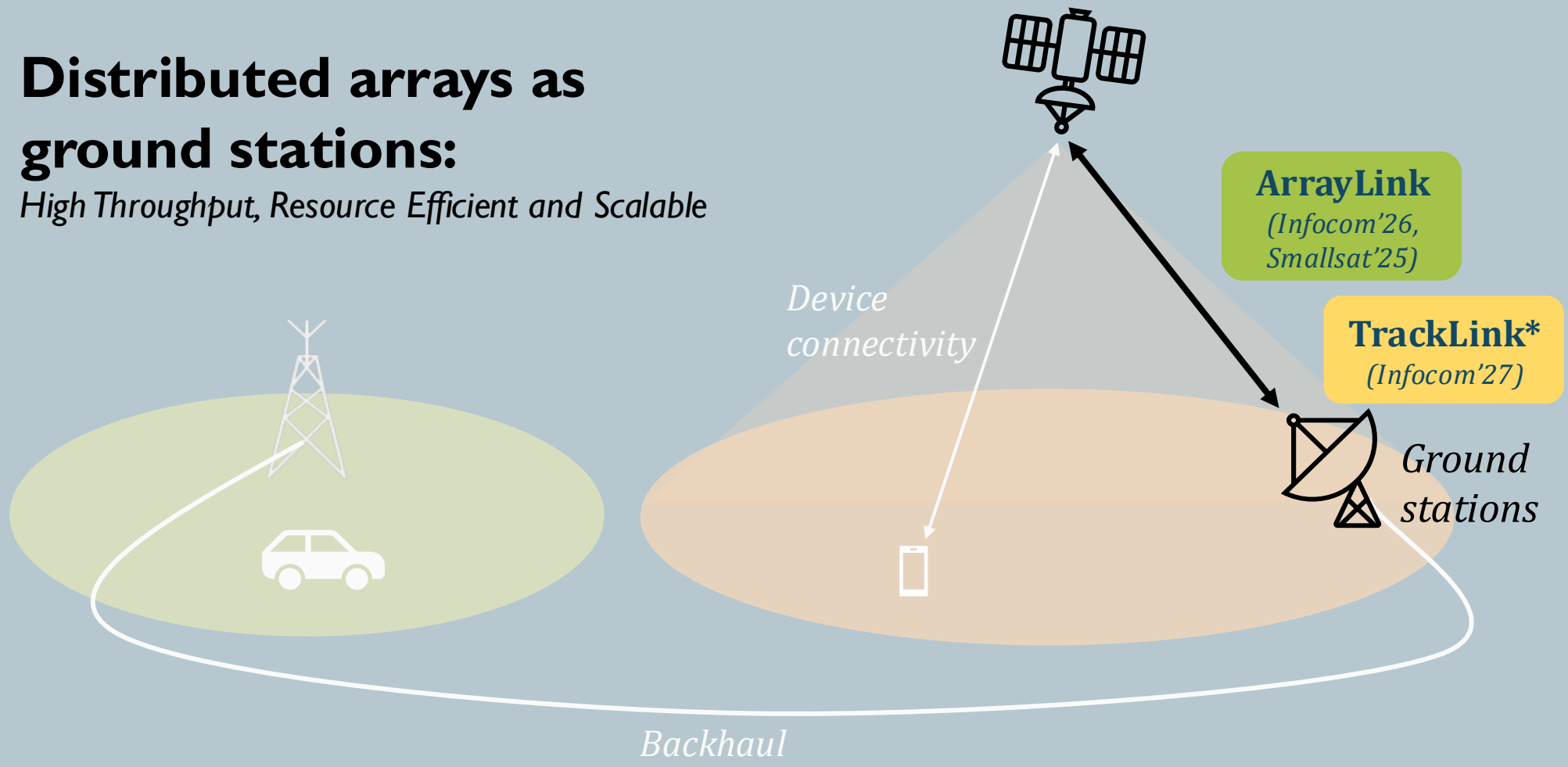


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Part1: Scaling ground stations

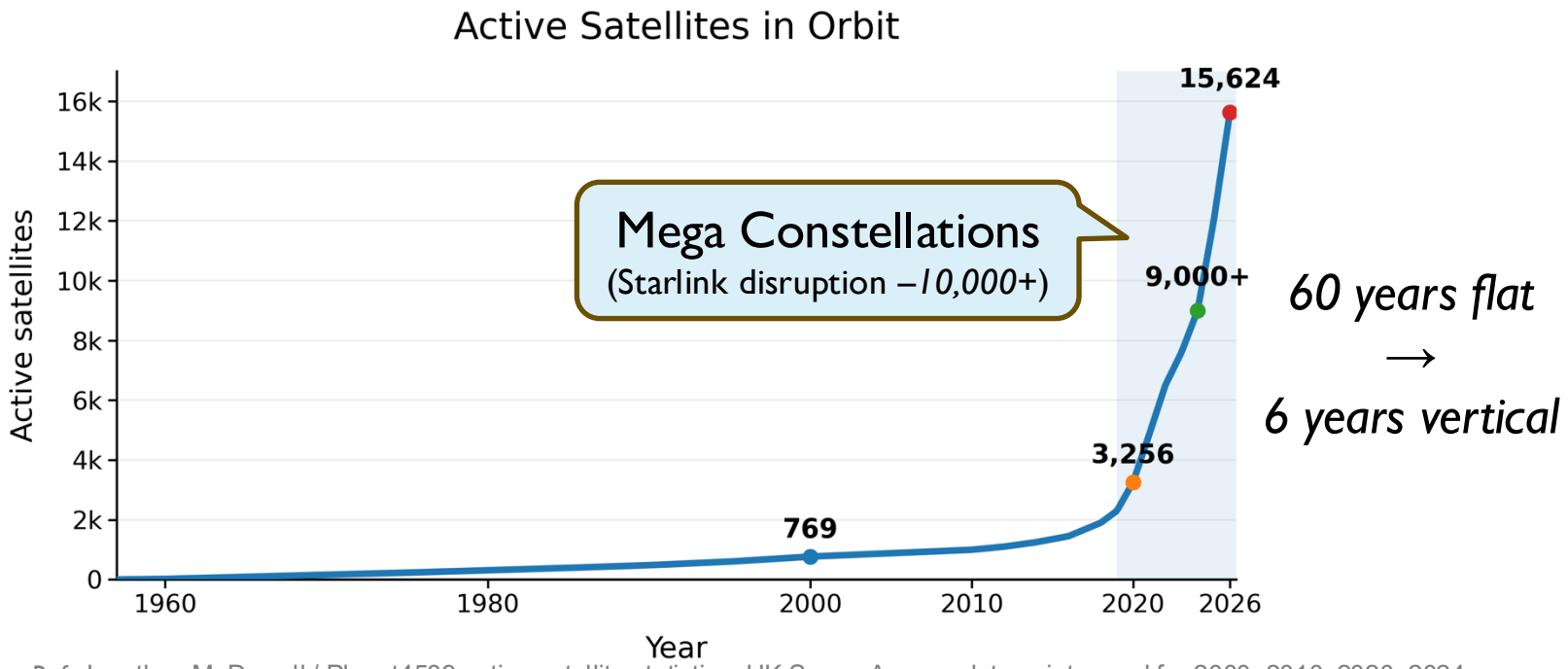
Distributed arrays as ground stations:

High Throughput, Resource Efficient and Scalable



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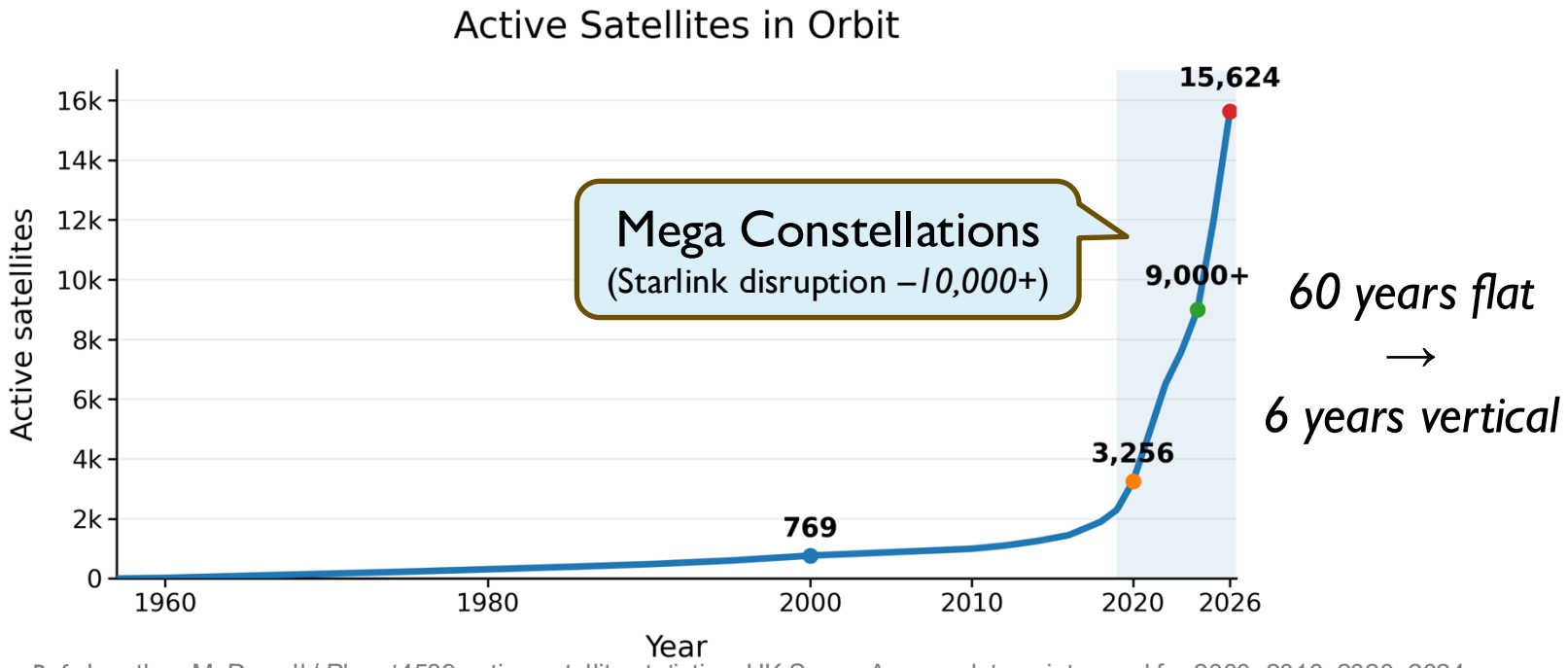
A New Era of Massive Satellite Constellations



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

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A New Era of Massive Satellite Constellations



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

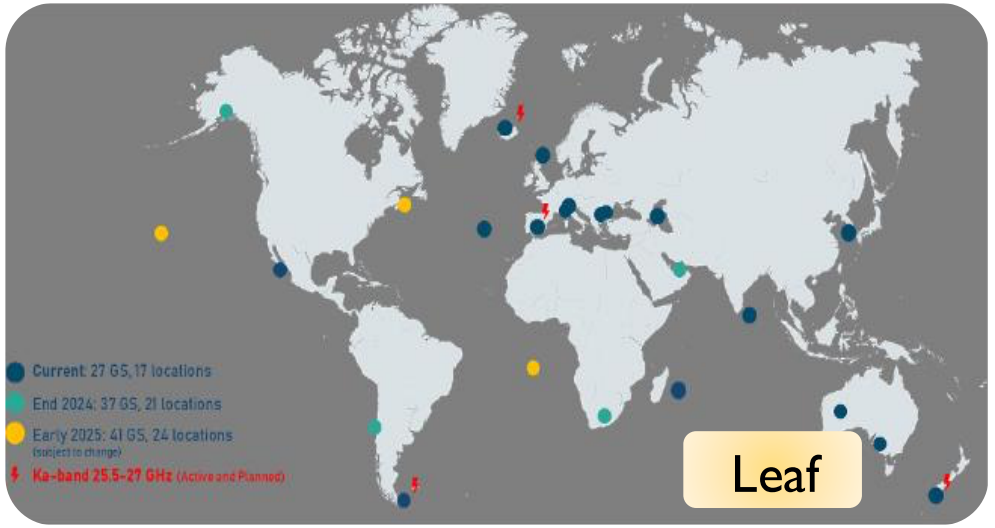
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The Current Landscape of Satellite Ground Stations









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The Current Landscape of Satellite Ground Stations





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





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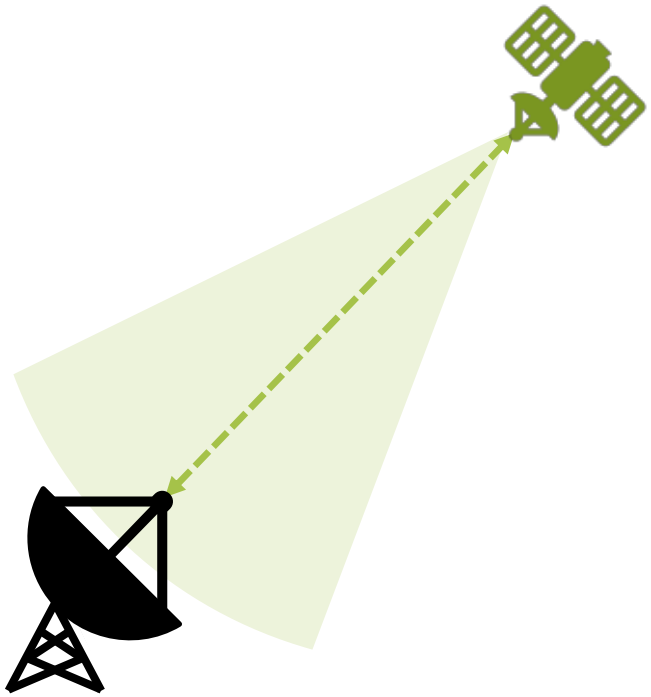
Requirements for Ground Stations

- **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	?

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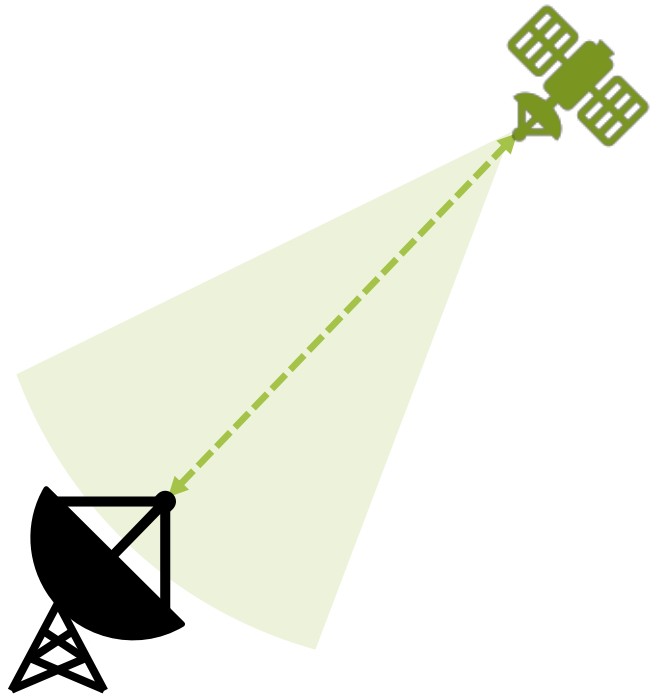
Current solution: Parabolic dishes are not sustainable



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Current solution: Parabolic dishes are not sustainable

- **High-gain Links** ✓
  - Ex: 1.85m Ka-band dish → ~52.6 dBi

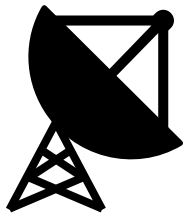


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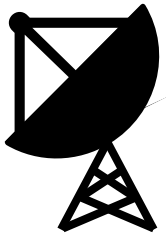
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Current solution: Parabolic dishes are not sustainable

Dwell or handover time overhead





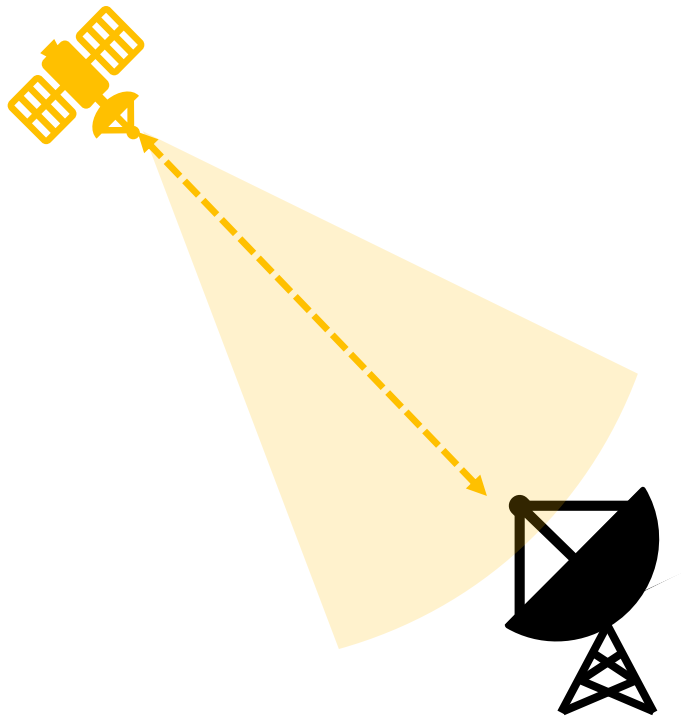


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- **Resource Inefficient ✗**
  - ***Time:*** Mechanical steering 2–5°/s
    → a few seconds to minutes of idle time per handover (depends on dish size)
  - ***Spectrum:*** One satellite at a time
    → no multiplexing, unused bandwidth is wasted

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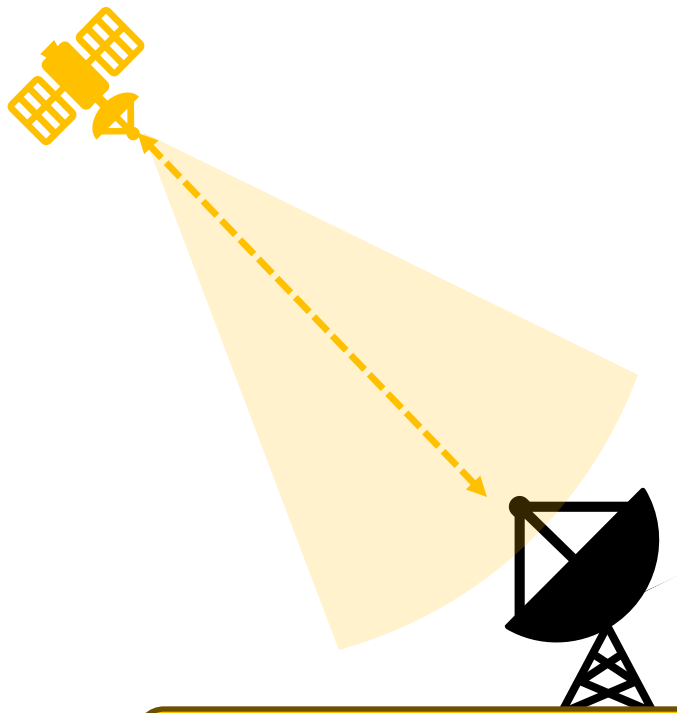


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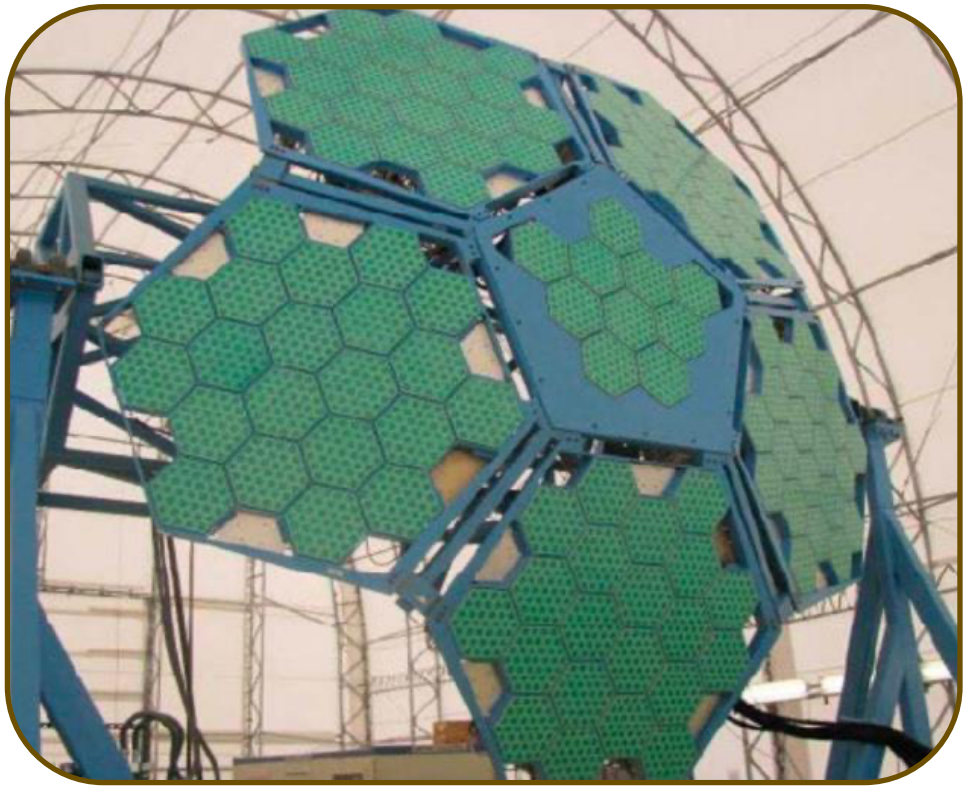


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- **Poor Scalability** ✗
  - Huge CAPEX & OPEX per site (dish, motor, land, fiber backhaul, maintenance)

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

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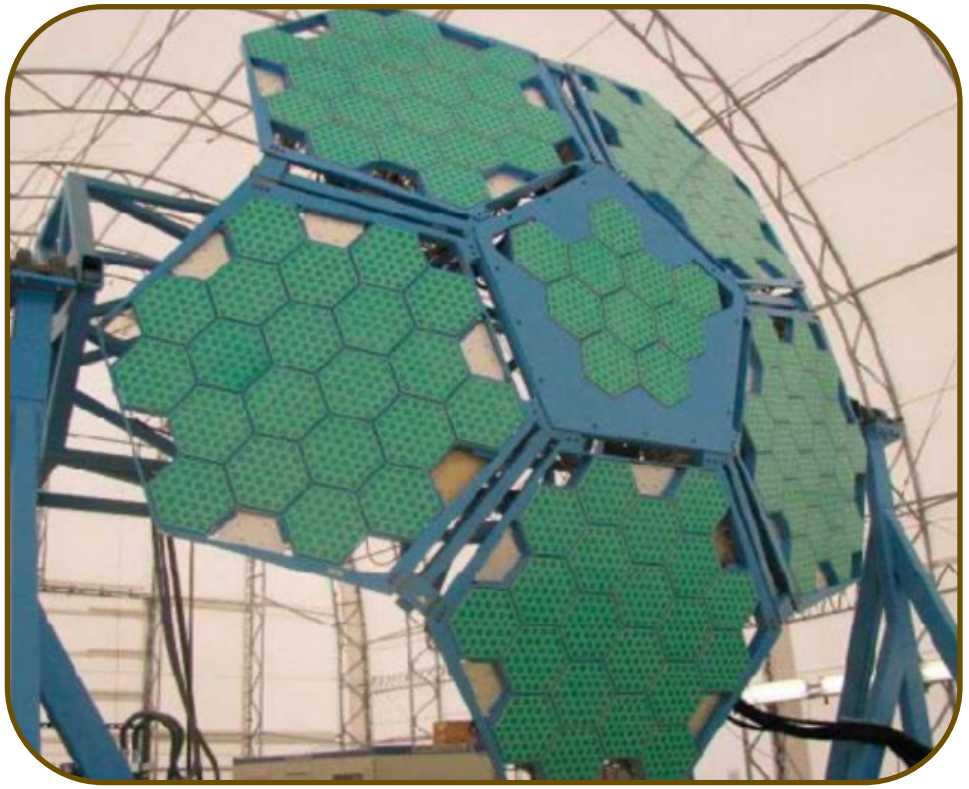
Alternative approach: Large (monolithic) phased arrays



References:
- *"He, Guolong, et al. "A review of multibeam phased array antennas as LEO satellite constellation ground station." IEEE Access 9 (2021): 147142-147154."*
- *"Henderson, Monte, Mark Bruce Davis, and Martin Huisjen. "GDPAA advanced technology demonstration overview and results." 2010 IEEE International Symposium on Phased Array Systems and Technology. IEEE, 2010.*

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Alternative approach: Large (monolithic) phased arrays

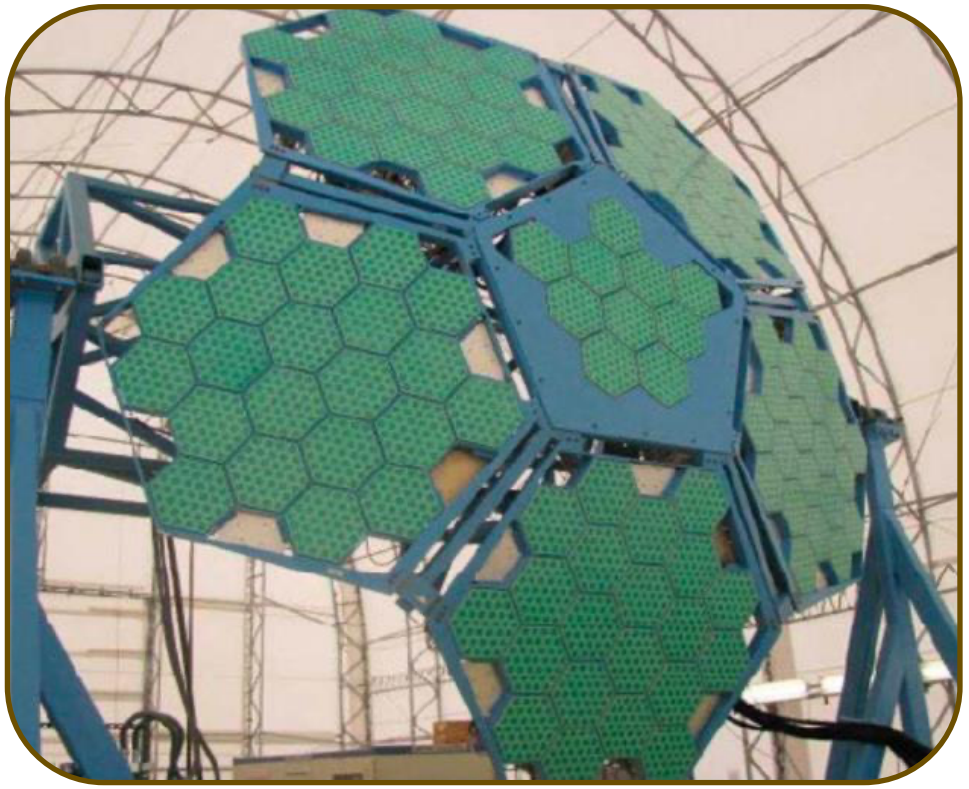


- **Resource efficient ✓:**
  - ***Time :*** Electronic steering (no moving parts)
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  - ***Frequency:*** Multi-satellite support
    → efficient spectrum usage

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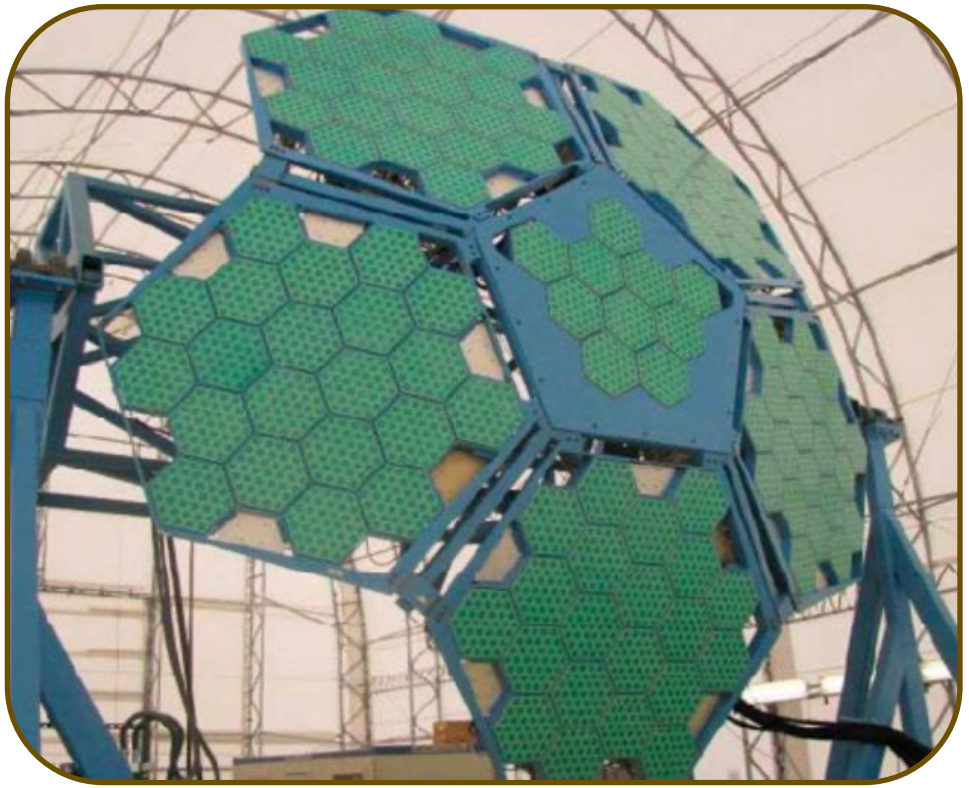


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  - ***Frequency:*** Multi-satellite support → efficient spectrum usage
- **High throughput ⚠:**
  - Possible, but matching 1.85 m (~52.6 dBi) needs > 50k elements
- **Not scalable ✗:**
  - High power draw, thermal issues, costly manufacturing → impractical to deploy in the field.

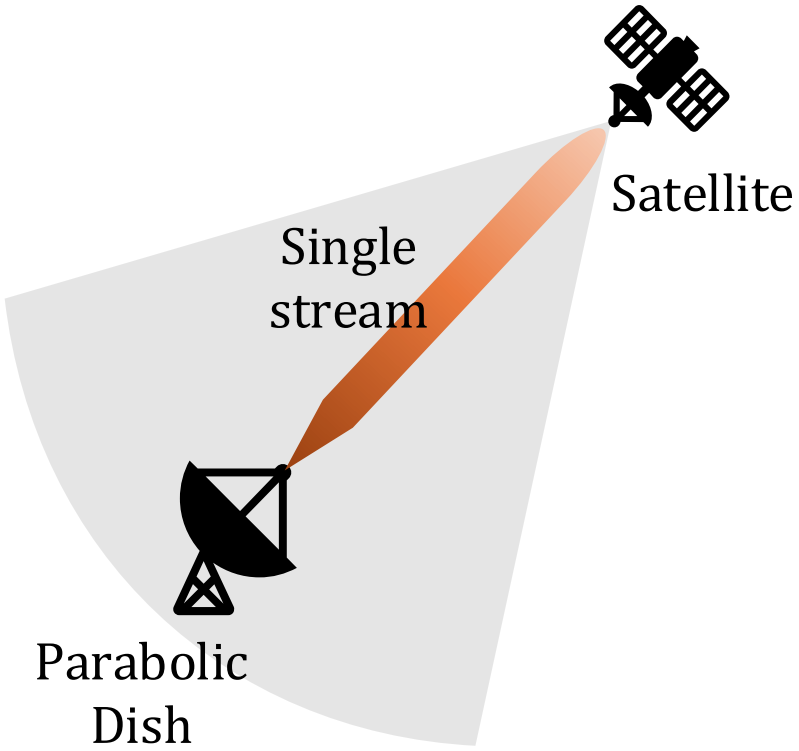
Large phased arrays **address efficiency and throughput**, but gain limits, complexity, and cost make them impractical and **not scalable**.

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Our Approach: Distributed phased arrays *(ArrayLink)*

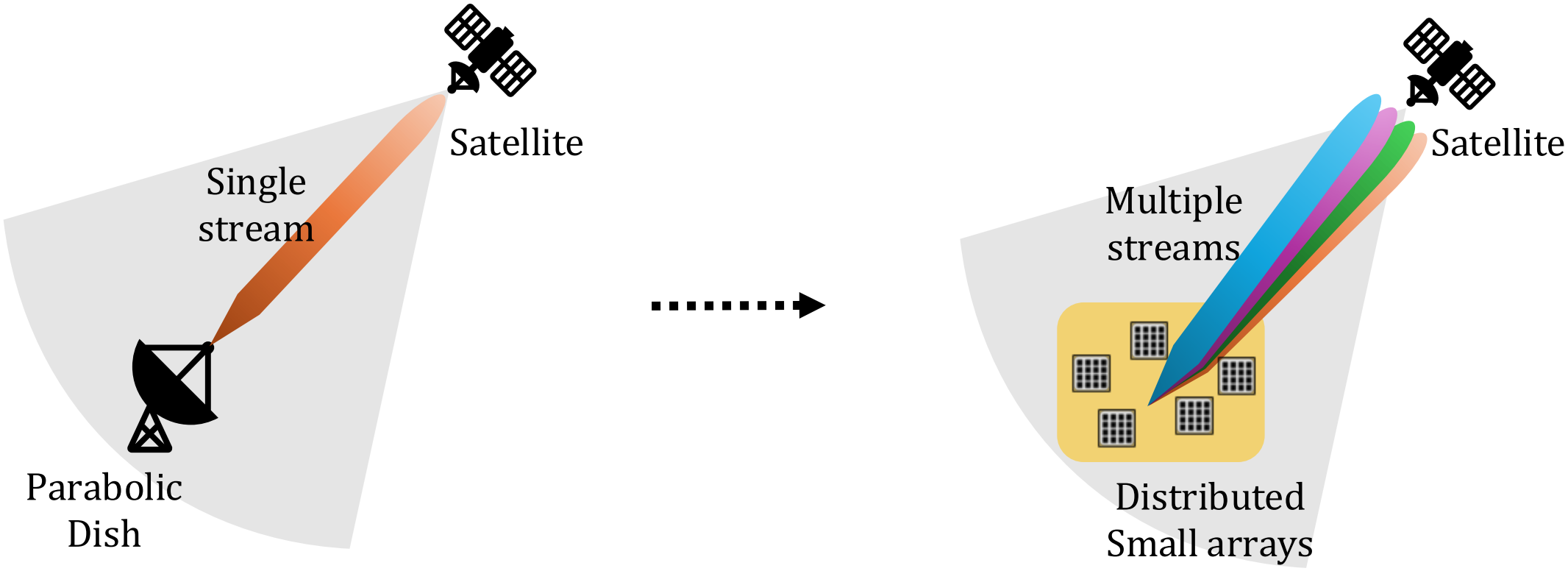
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Our Approach: Distributed phased arrays *(ArrayLink)*



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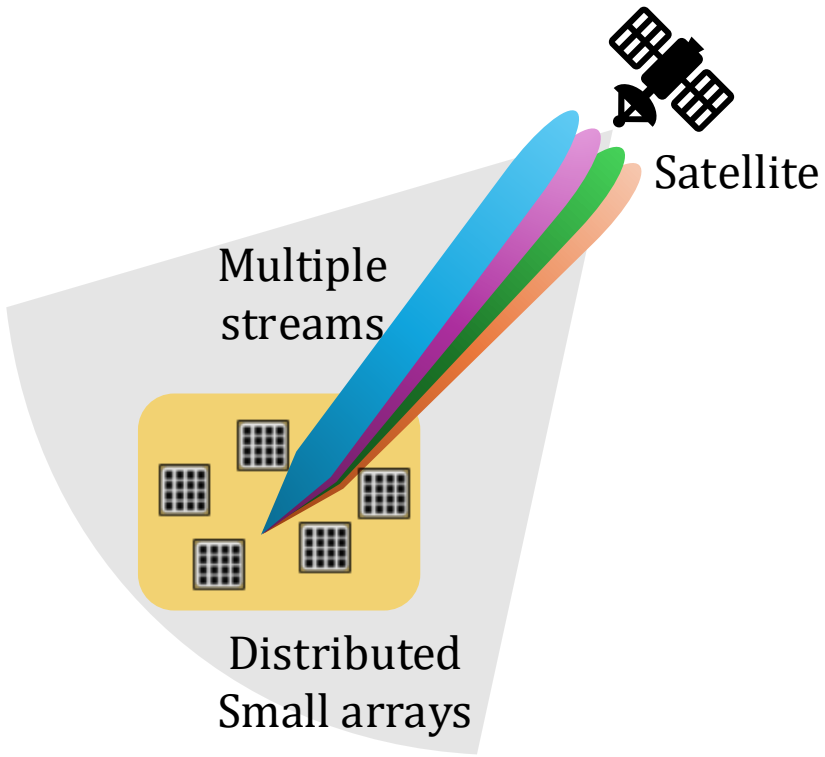
Our Approach: Distributed phased arrays *(ArrayLink)*



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

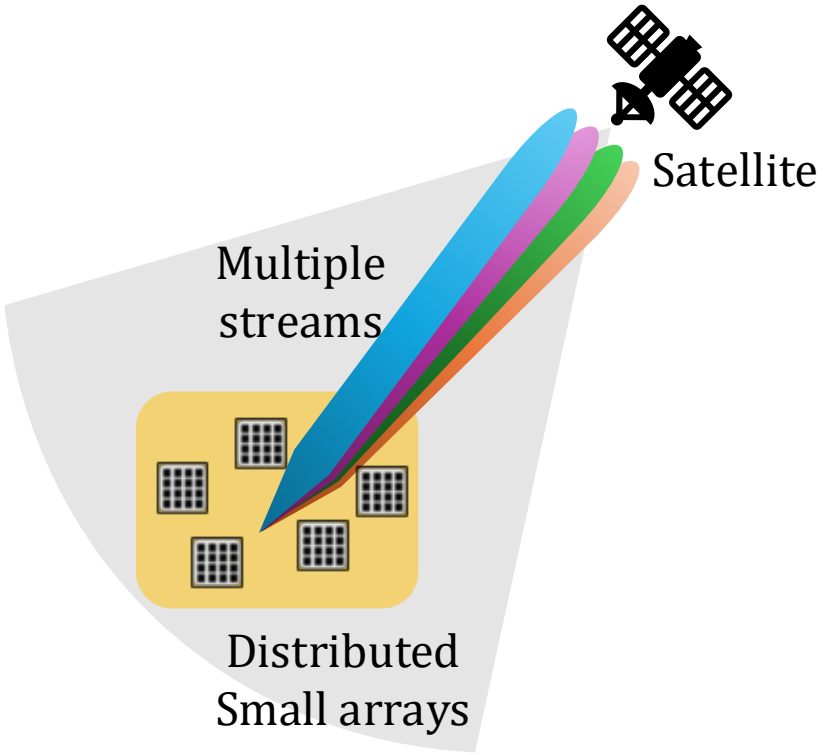
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ArrayLink: Scalable Architecture with Higher Throughput



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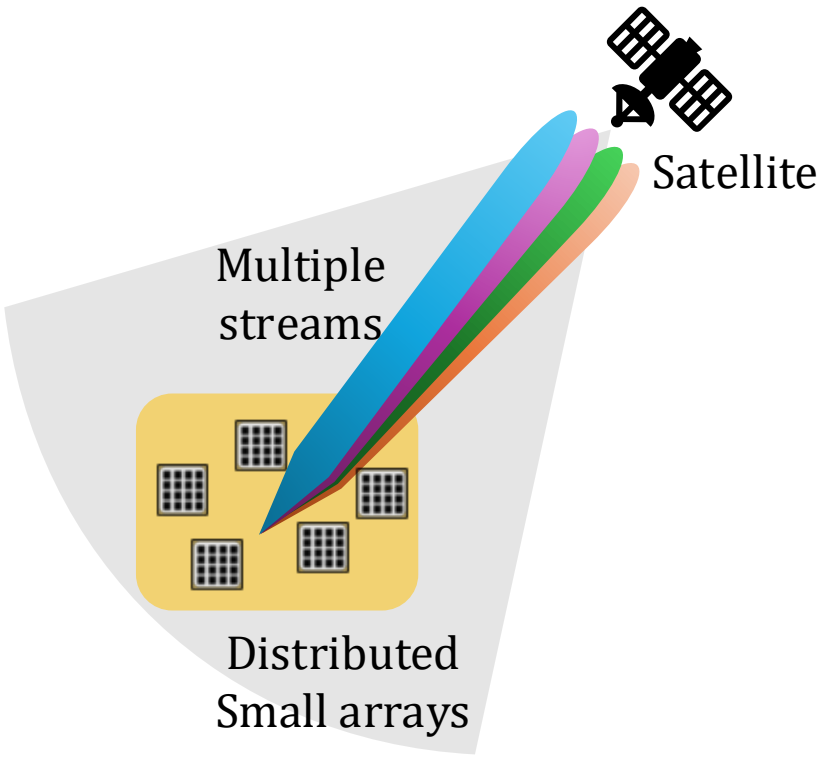
ArrayLink: Scalable Architecture with Higher Throughput



- **Scalable Design ✓**
  - Trade a small amount of gain to significantly reduce the number of phased-array panels.
  - Practical and cost-efficient **with a few panels**

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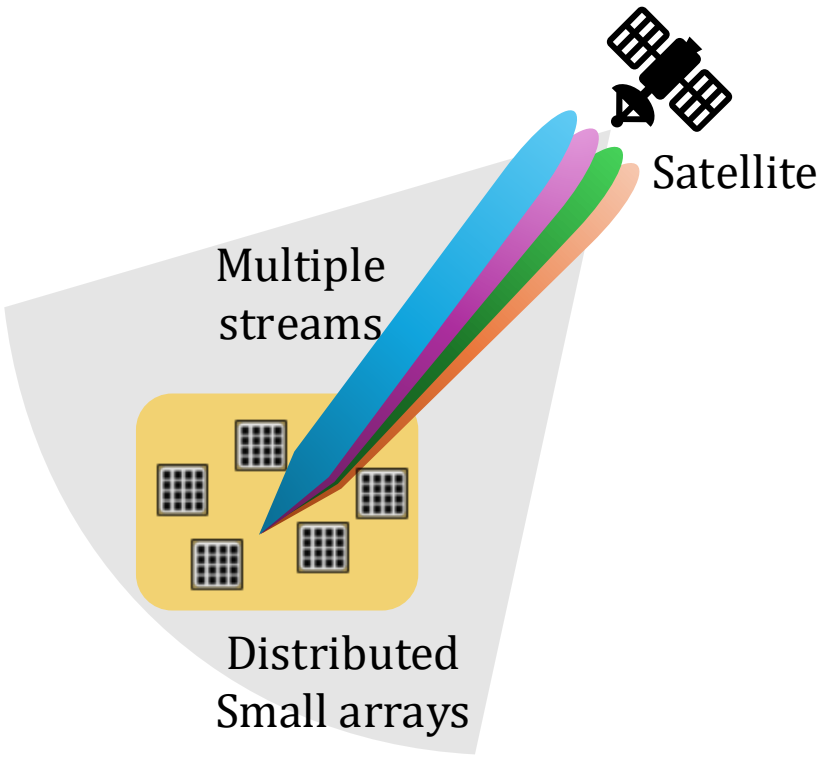
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  - Near field effect with **distributed panels**
  - Enable multiple simultaneous streams in line-of-sight channels with near field to match or exceed single high-gain link capacity.

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ArrayLink: Scalable Architecture with Higher Throughput



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  - Practical and cost-efficient **with a few 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

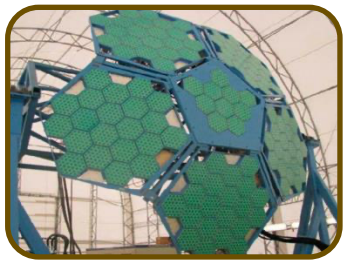
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ArrayLink: Satisfies all three requirements

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.

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ArrayLink address two challenges

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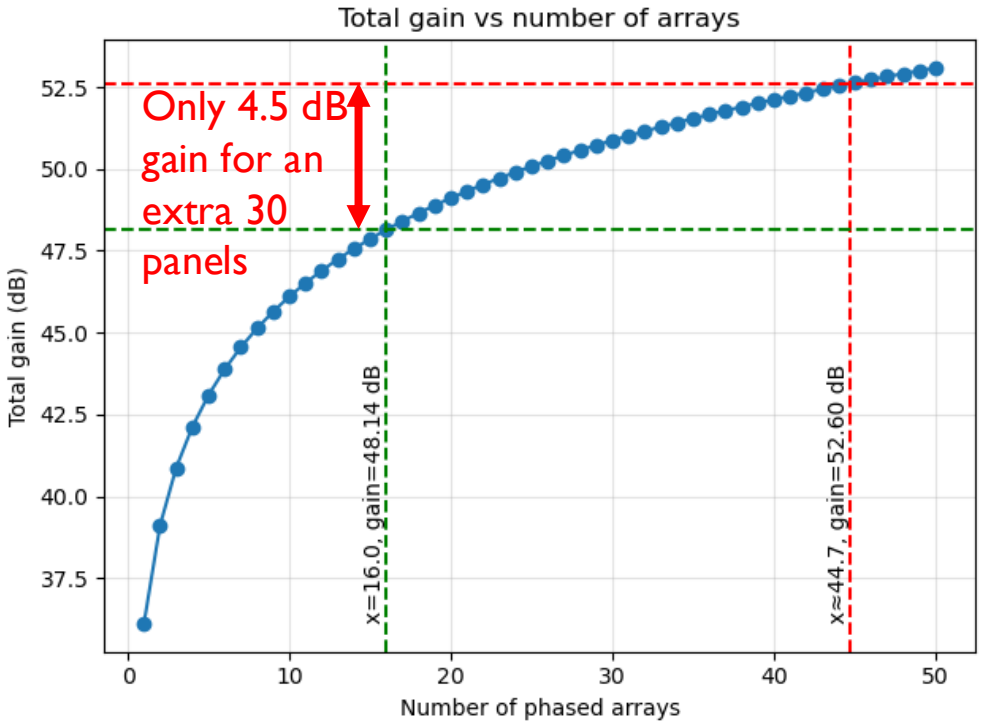
ArrayLink address two challenges

1. Enabling Dish-Class Gain

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ArrayLink address two challenges

1. Enabling Dish-Class Gain



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



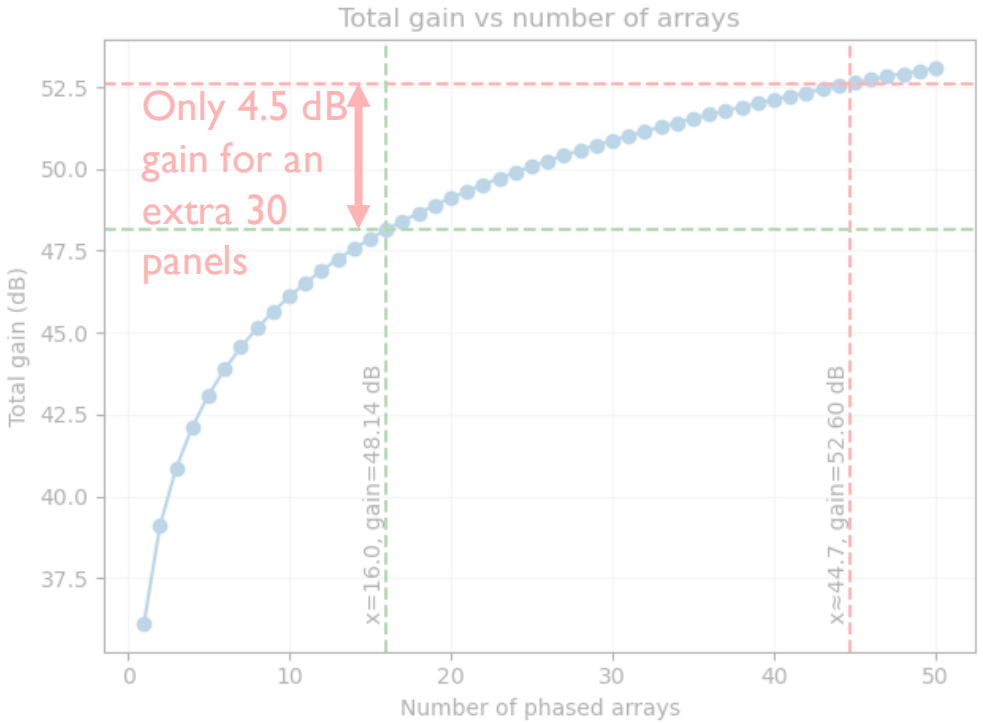
Kuiper user panels < $500

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ArrayLink address two challenges

1. Enabling Dish-Class Gain

2. Enabling Multiple streams



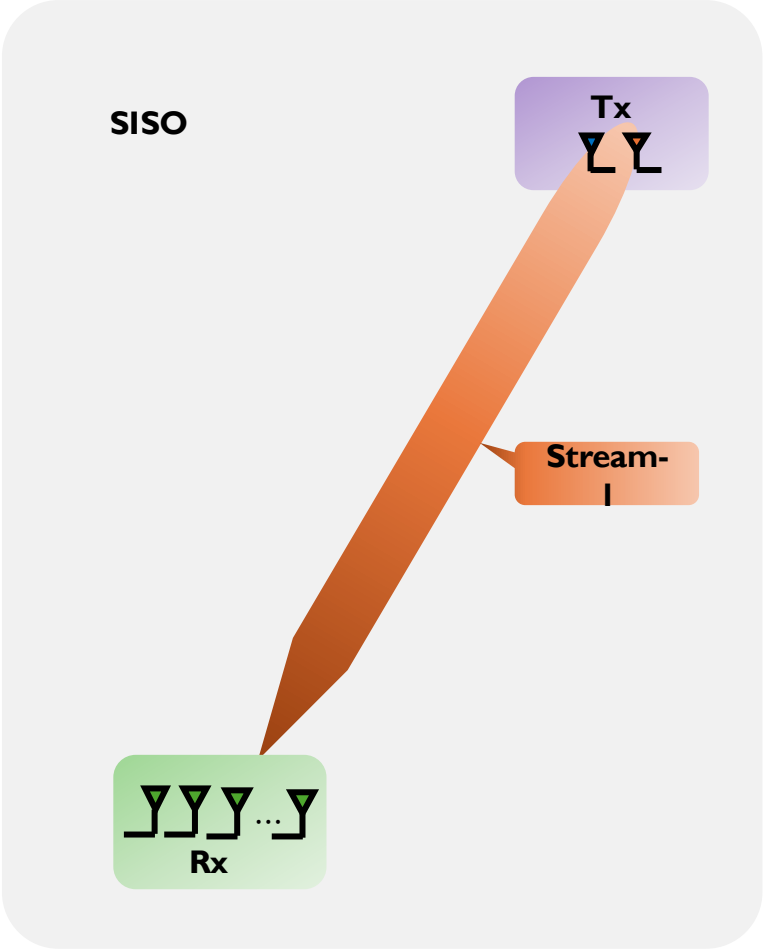
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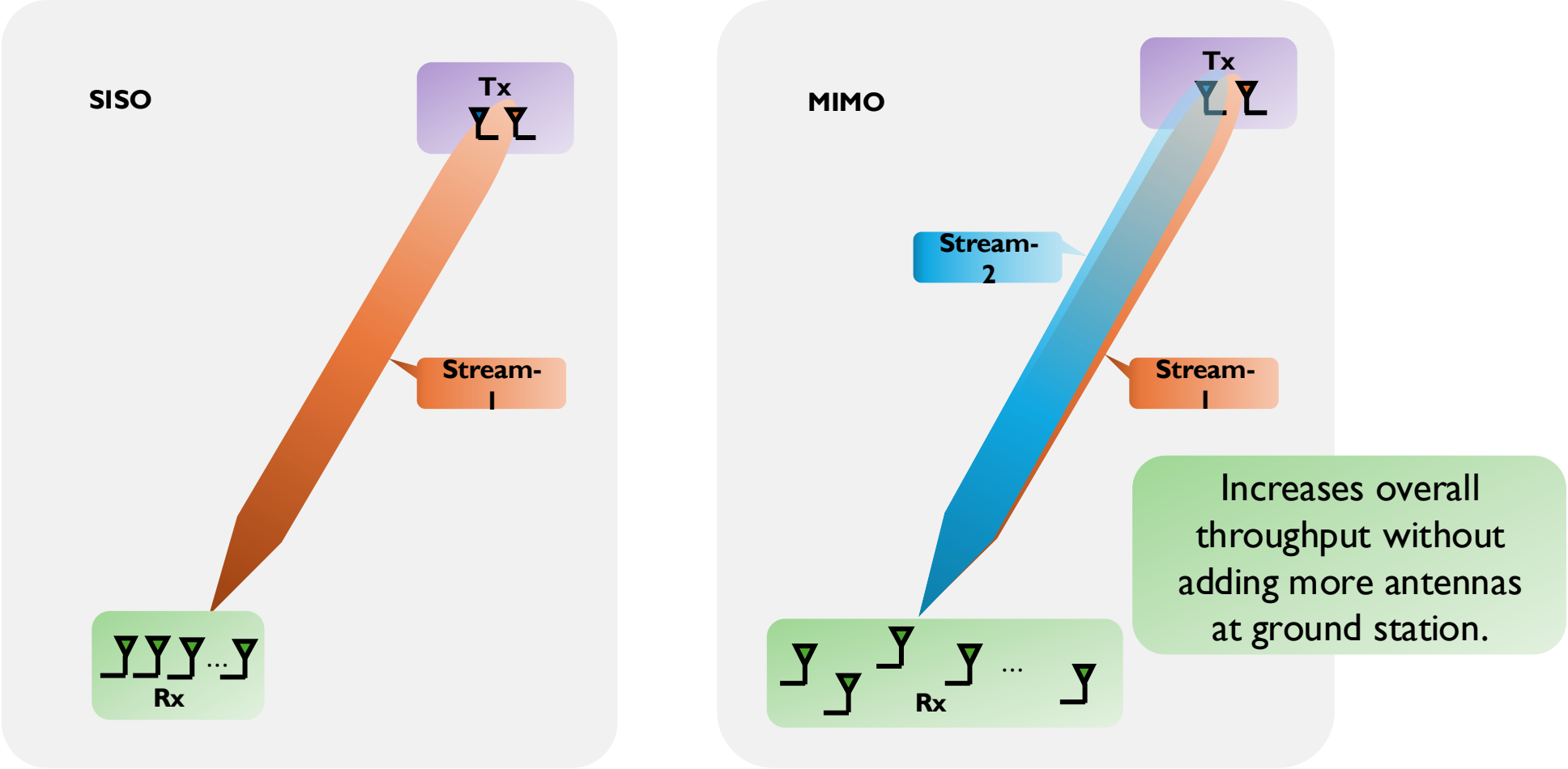
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Challenge: Enabling multiple streams to boost throughput



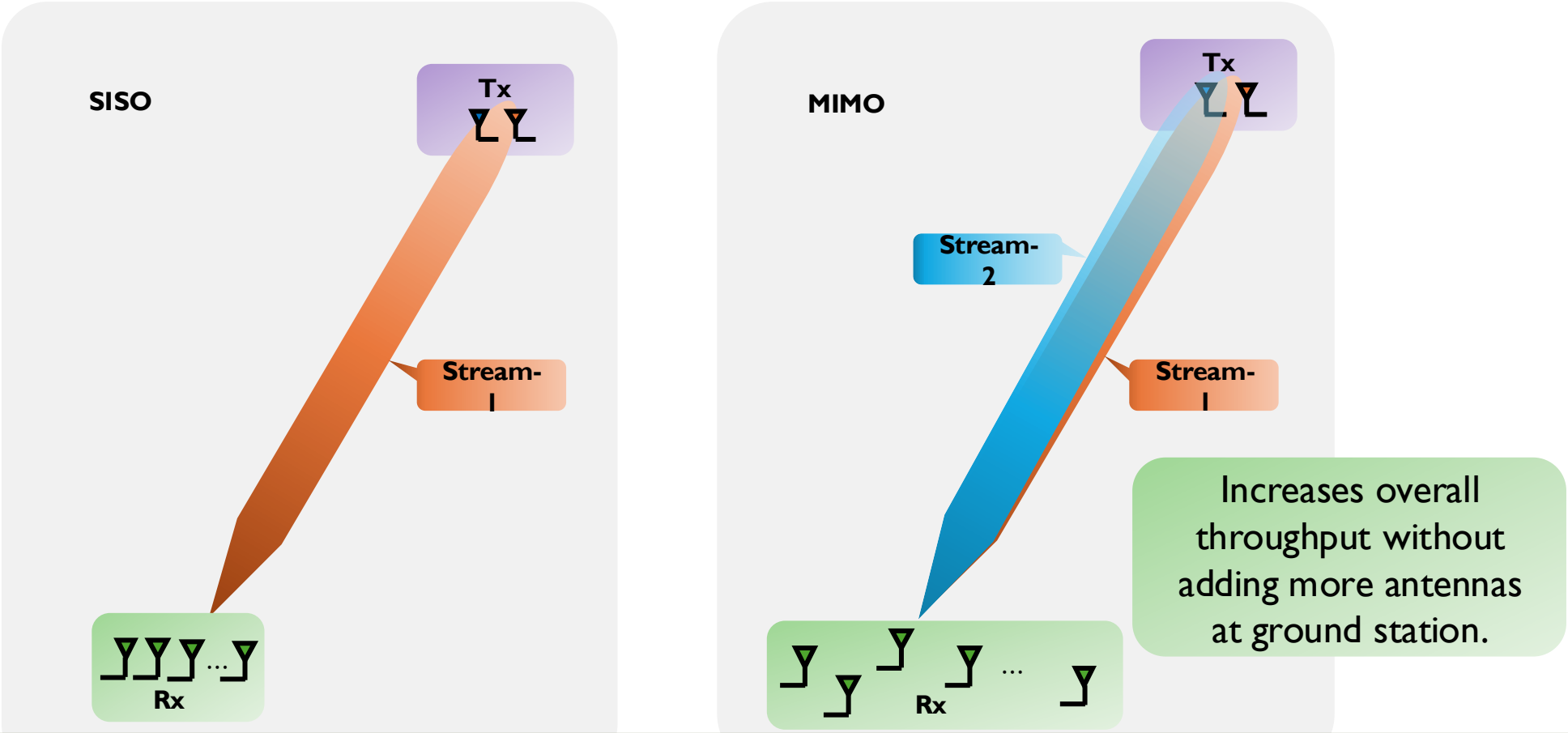
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Challenge: Enabling multiple streams to boost throughput



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Challenge: Enabling multiple streams to boost throughput



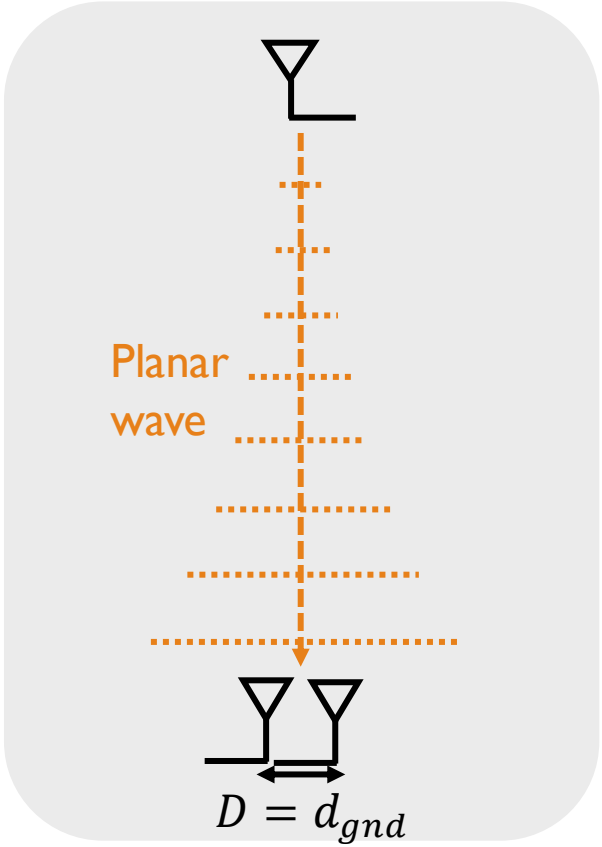
How to do we enable multiple streams in a line-of-sight scenario?

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

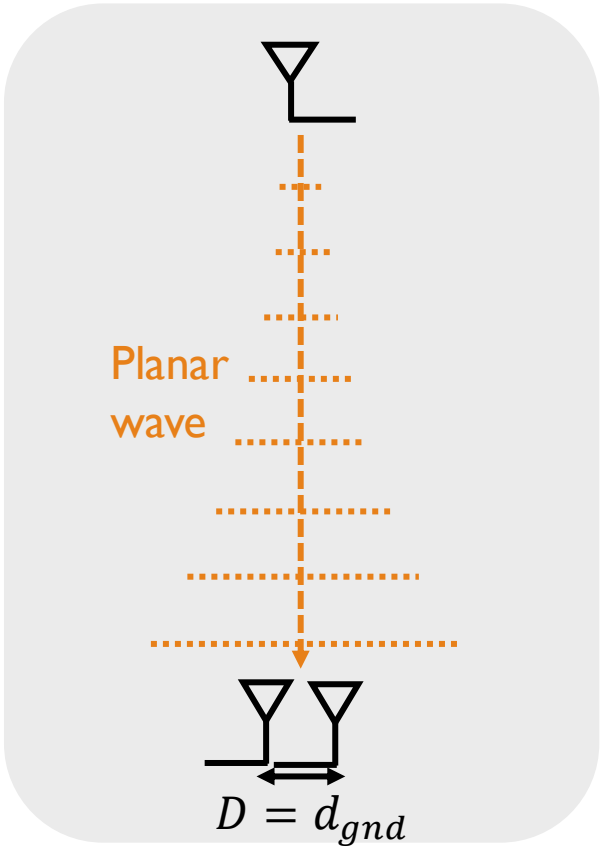
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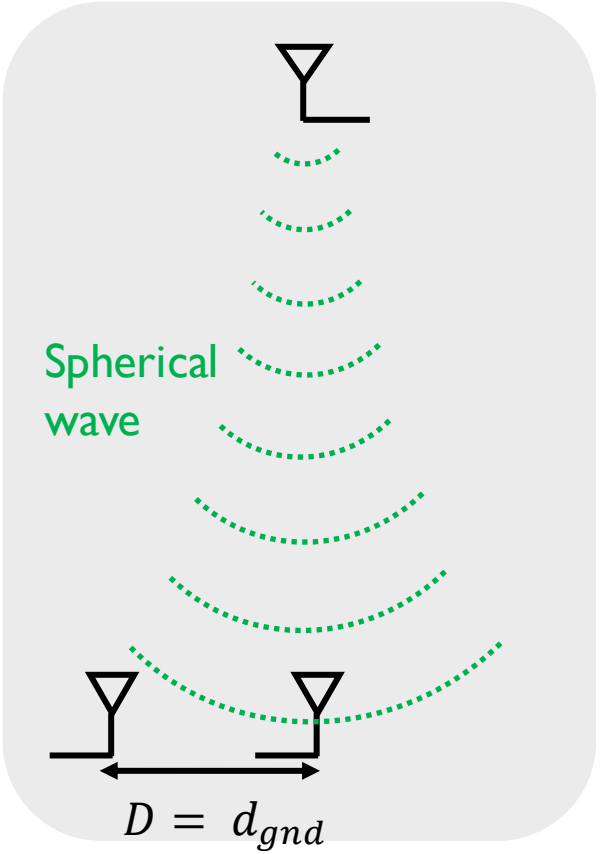
Key Insight – Increasing antenna spacing at ground station brings Satellites from Far-Field to Near-Field



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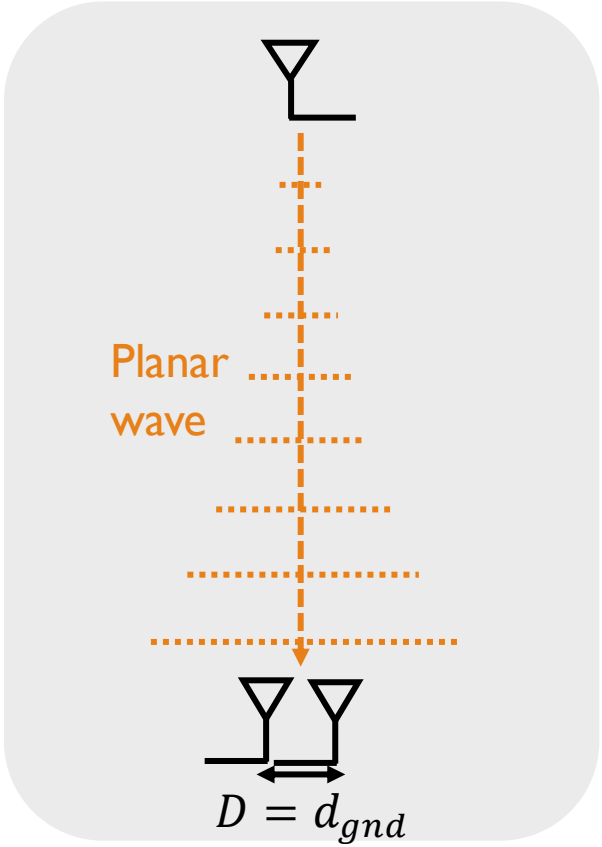
Key Insight – Increasing antenna spacing at ground station brings Satellites from Far-Field to Near-Field

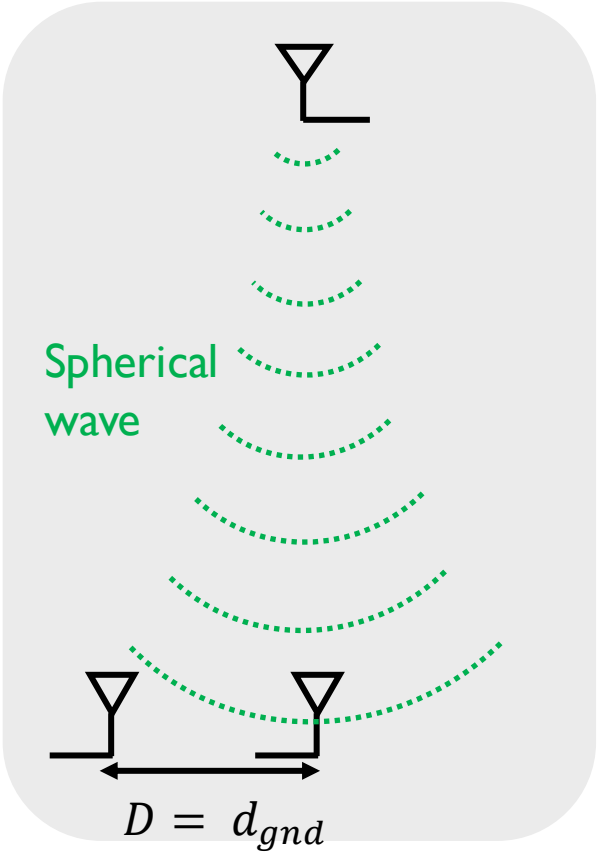




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Key Insight – Increasing antenna spacing at ground station brings Satellites from Far-Field to Near-Field



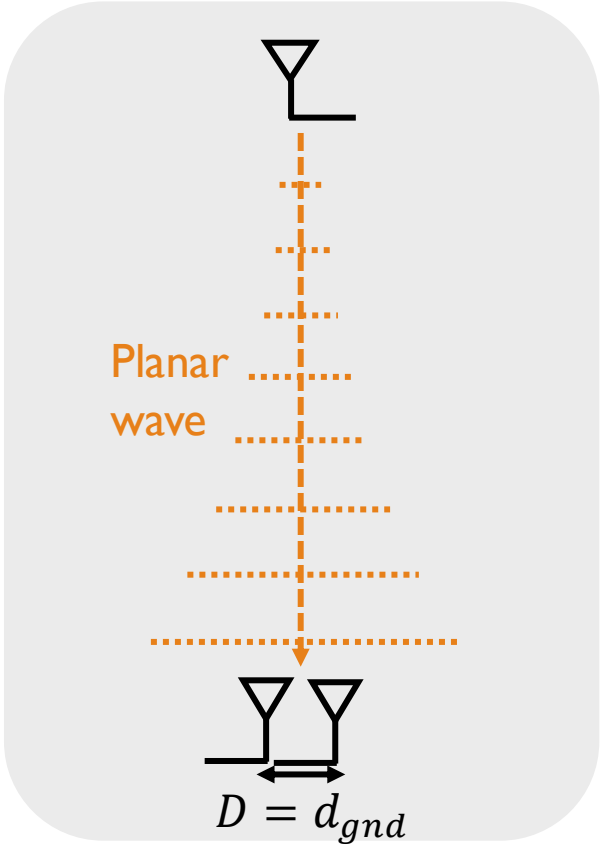


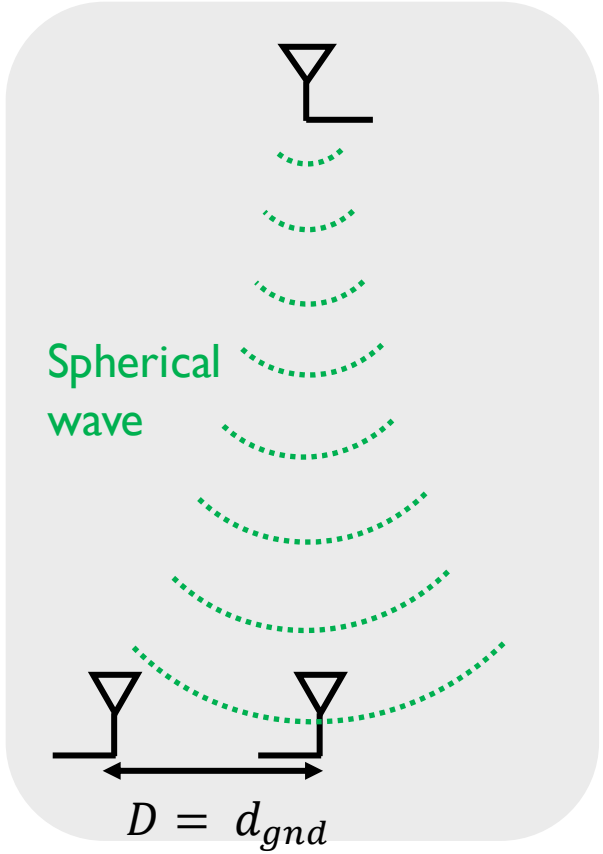
Fraunhofer distances at 28 GHz (Ka band, $\lambda \approx 0.01m$):

$$D = 0.1\ m \quad \left| \quad \frac{2D^2}{\lambda} \approx 2\ m \right.$$

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



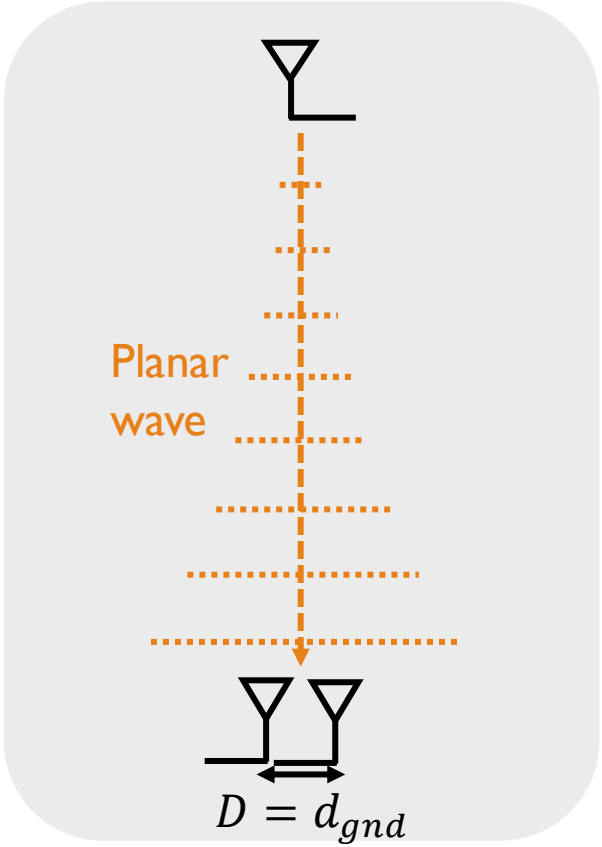


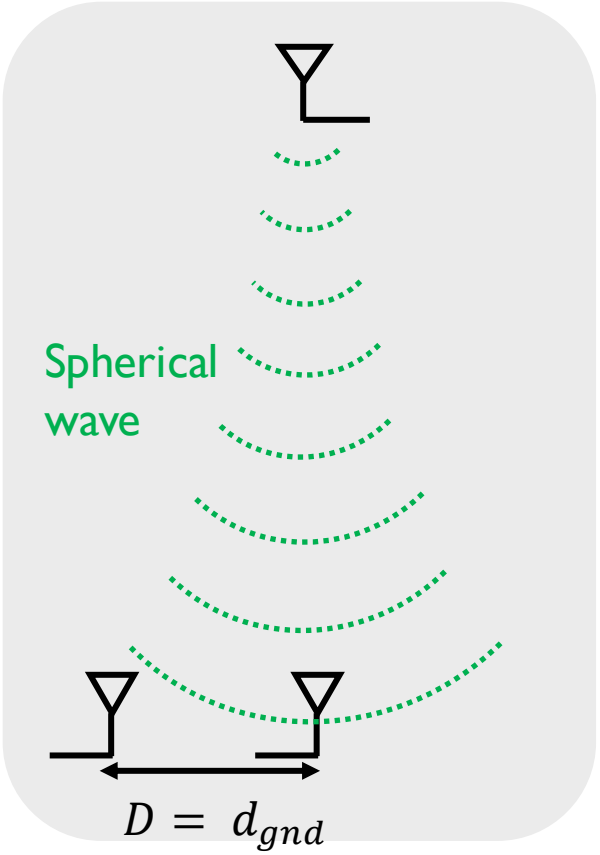
Fraunhofer distances at 28 GHz (Ka band, $\lambda \approx 0.01m$):

$D = 0.1\ m$	$\frac{2D^2}{\lambda} \approx 2\ m$
$D = 1\ m$	$\frac{2D^2}{\lambda} \approx 200\ m$

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



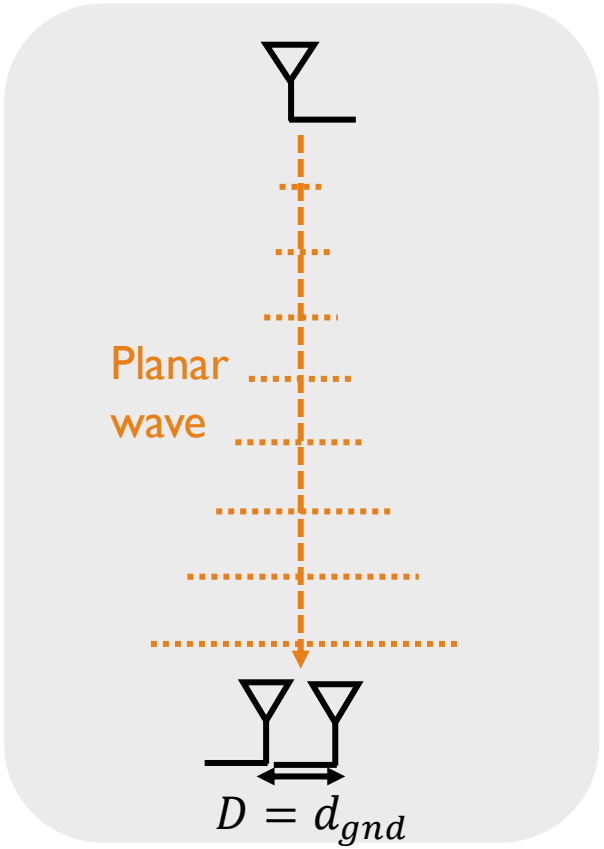


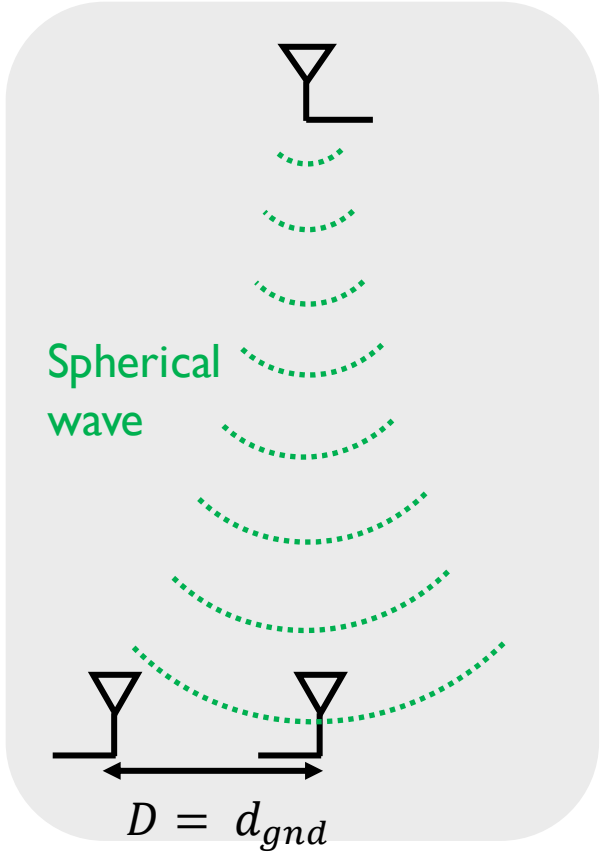
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$D = 10\ m$	$\frac{2D^2}{\lambda} \approx 20\ km$

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



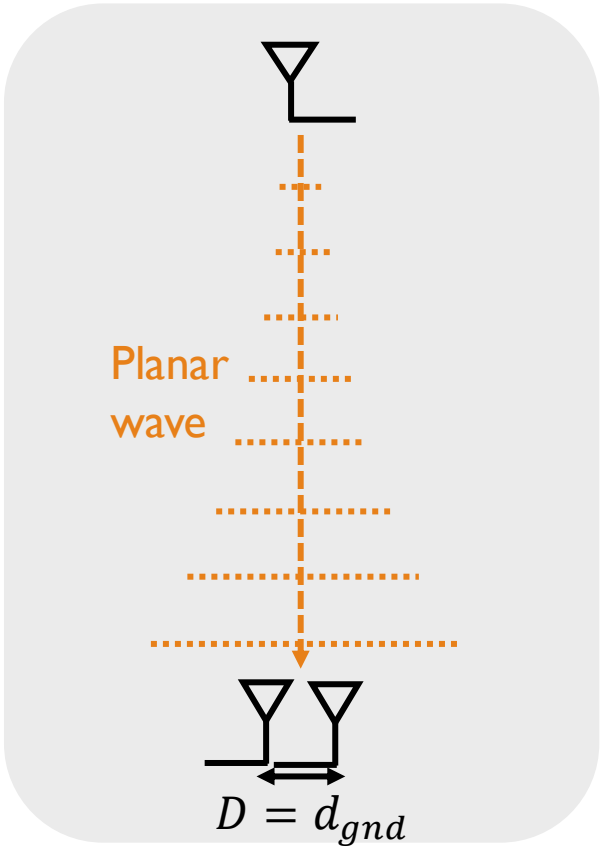


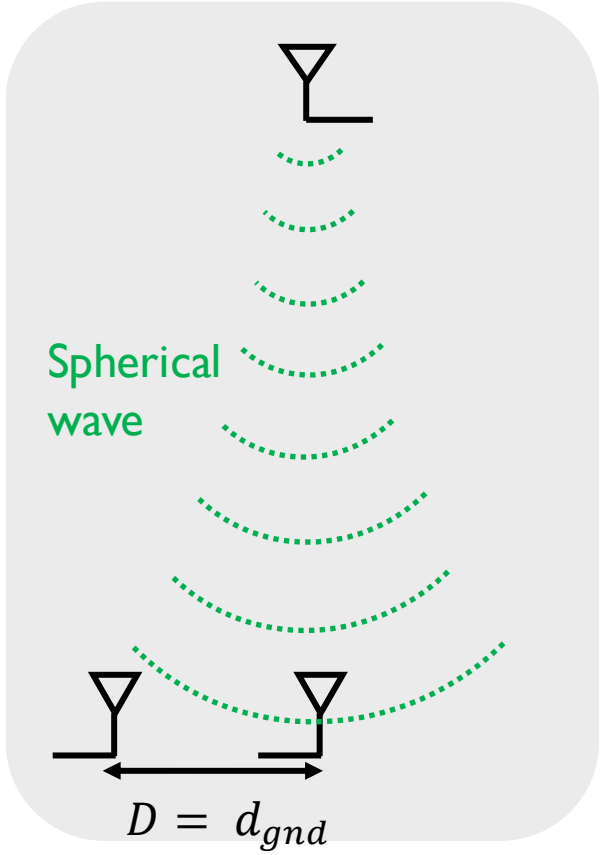
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Key Insight – Increasing antenna spacing at ground station brings Satellites from Far-Field to Near-Field





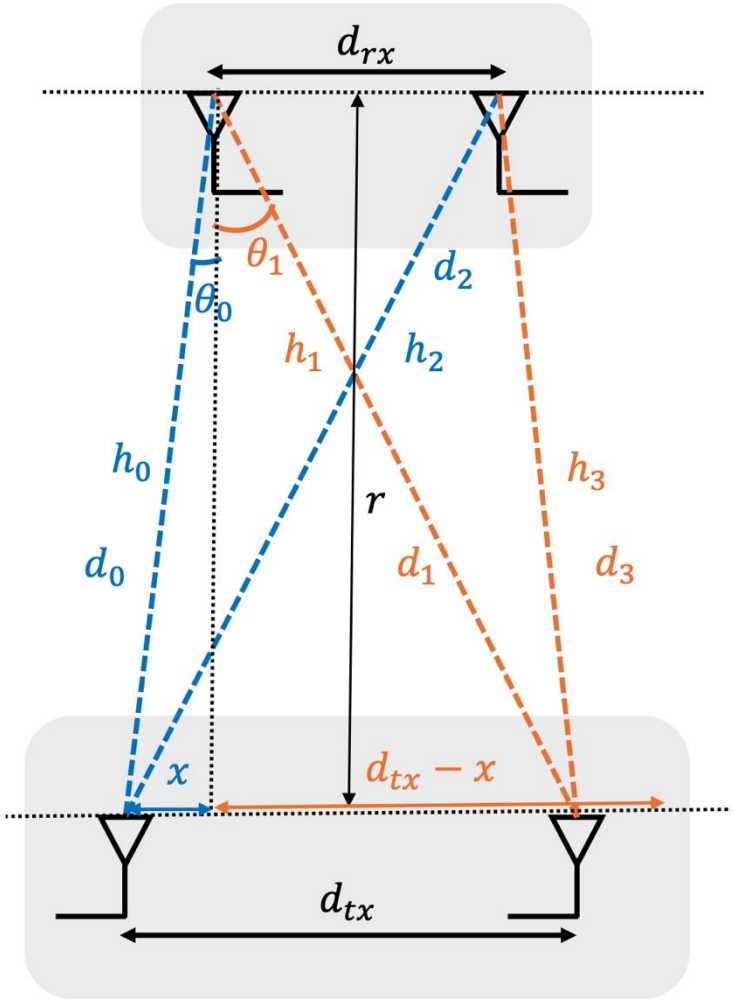
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$D = 1000\ m$	$\frac{2D^2}{\lambda} \approx 200000\ km$

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

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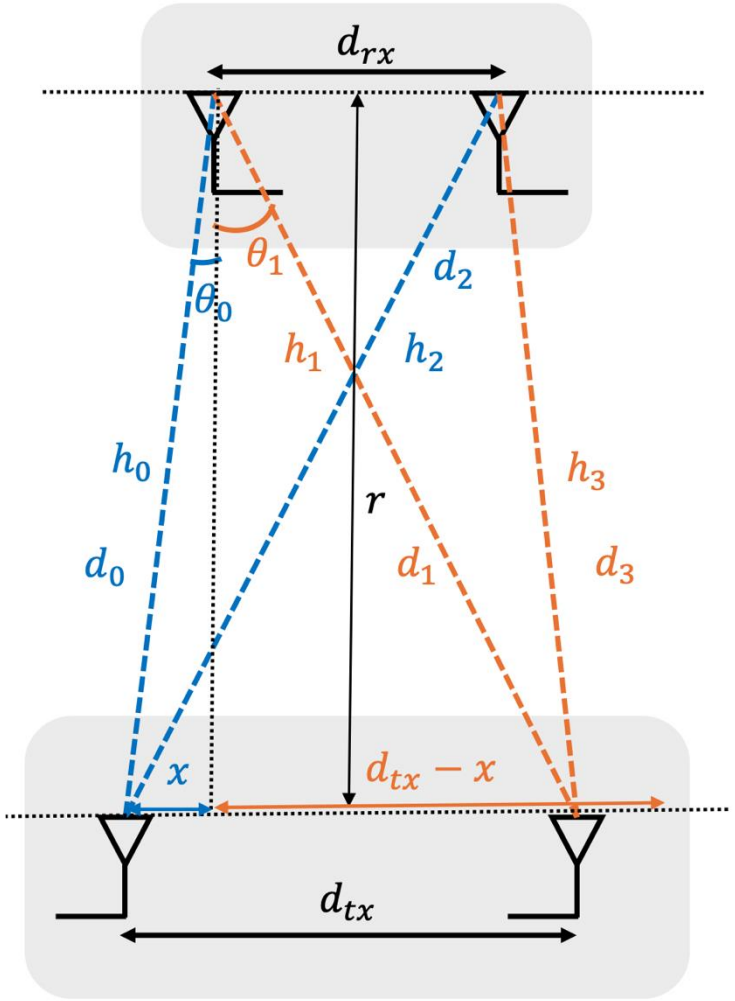
Key Insight - Singular values dependency on Phase Spread



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

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Key Insight - Singular values dependency on Phase Spread



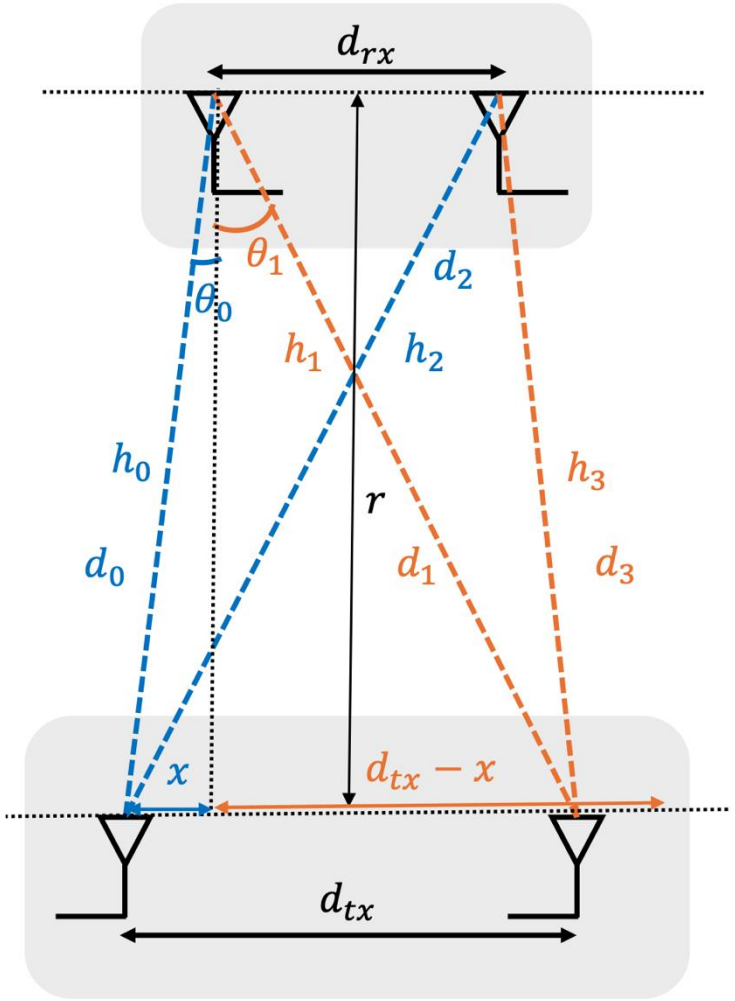
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- When $\beta_i \approx \beta$, The singular values σ_1 and σ_2 depend only on the phase spread Δ:

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

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Key Insight - Singular values dependency on Phase Spread



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- Phase spread Δ is defined as

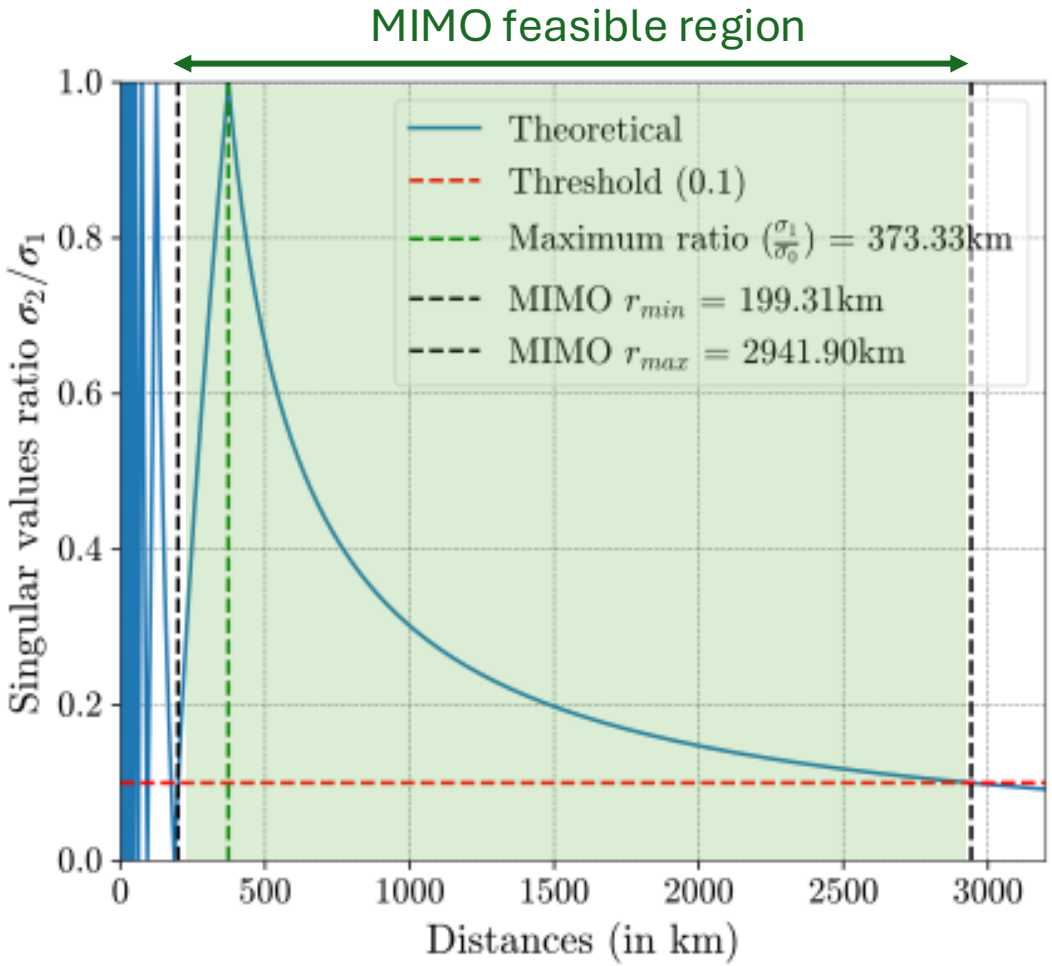
$$\Delta = \frac{2\pi}{\lambda} d_{tx}[(-(d_0 - d_1) + (d_2 - d_3)].$$

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

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

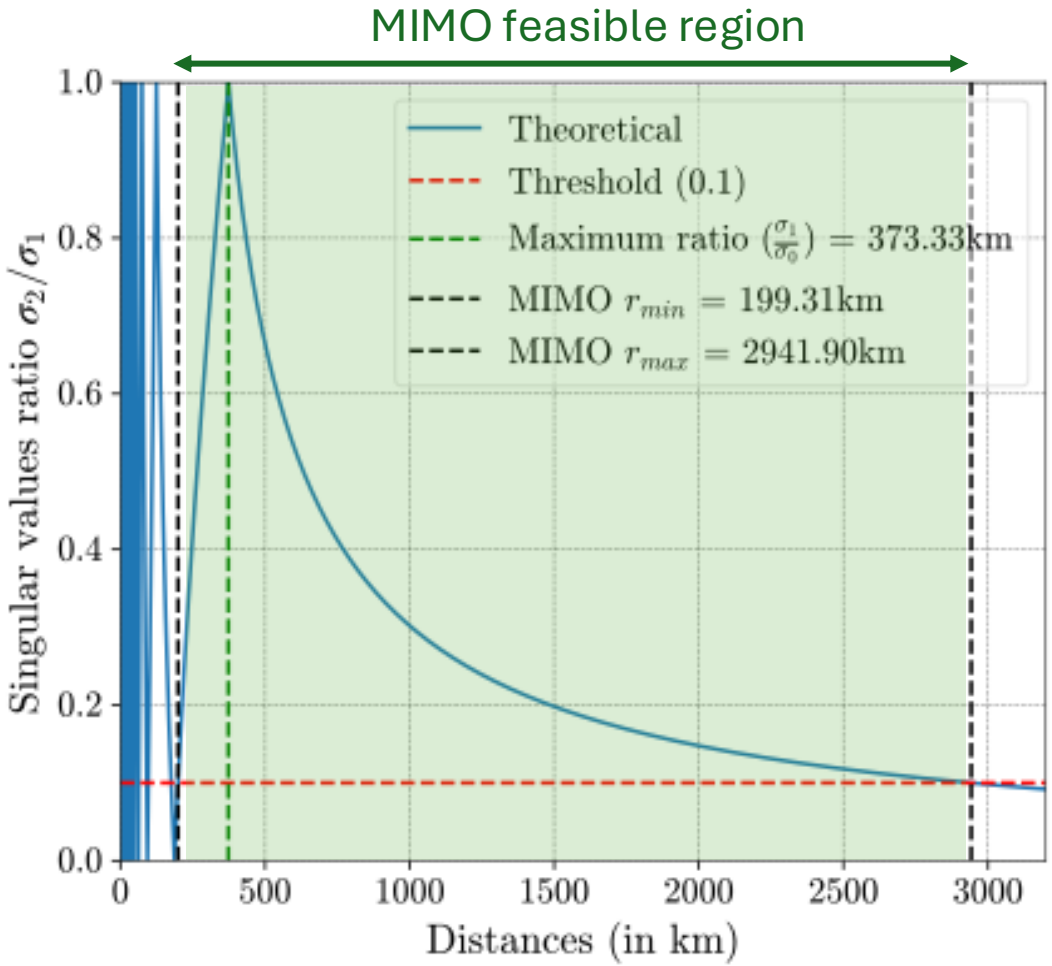
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MIMO bounds for stable min and max region



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MIMO bounds for stable min and max region



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

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

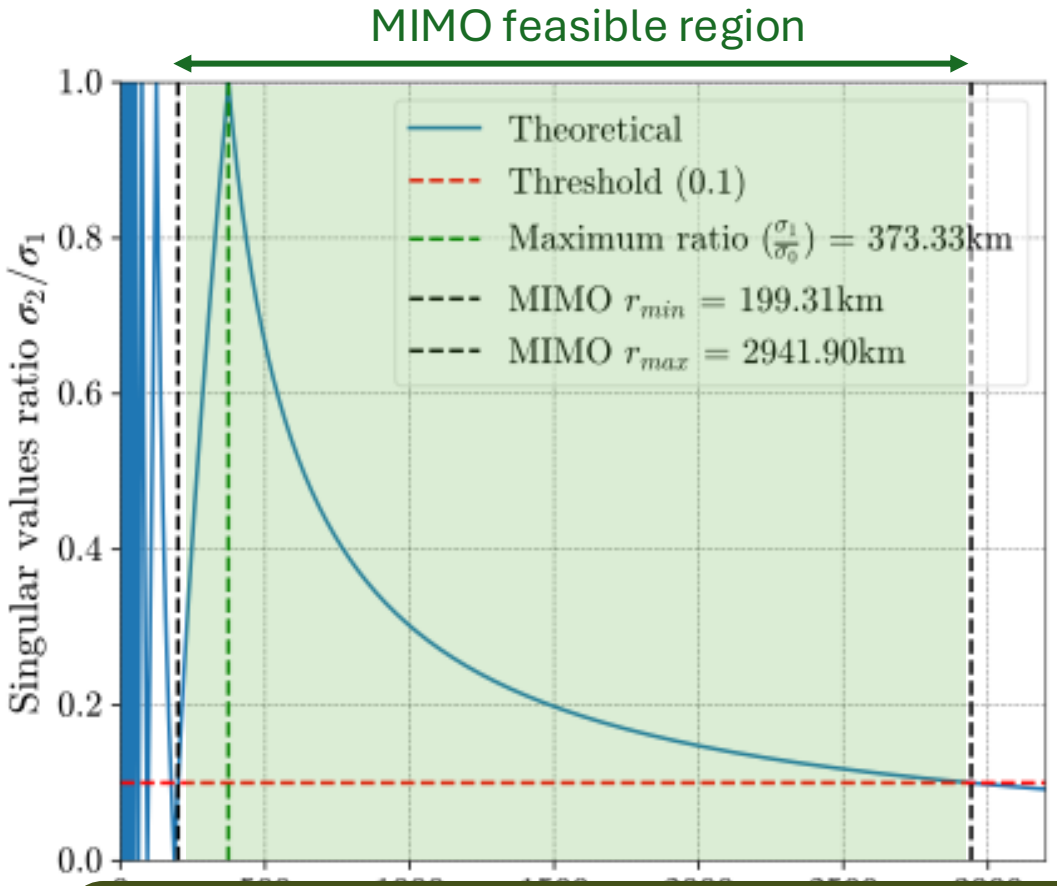
Given, threshold $\tau = min\frac{\sigma_2}{\sigma_1}$ to enable MIMO

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

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

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MIMO bounds for stable min and max region



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

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

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

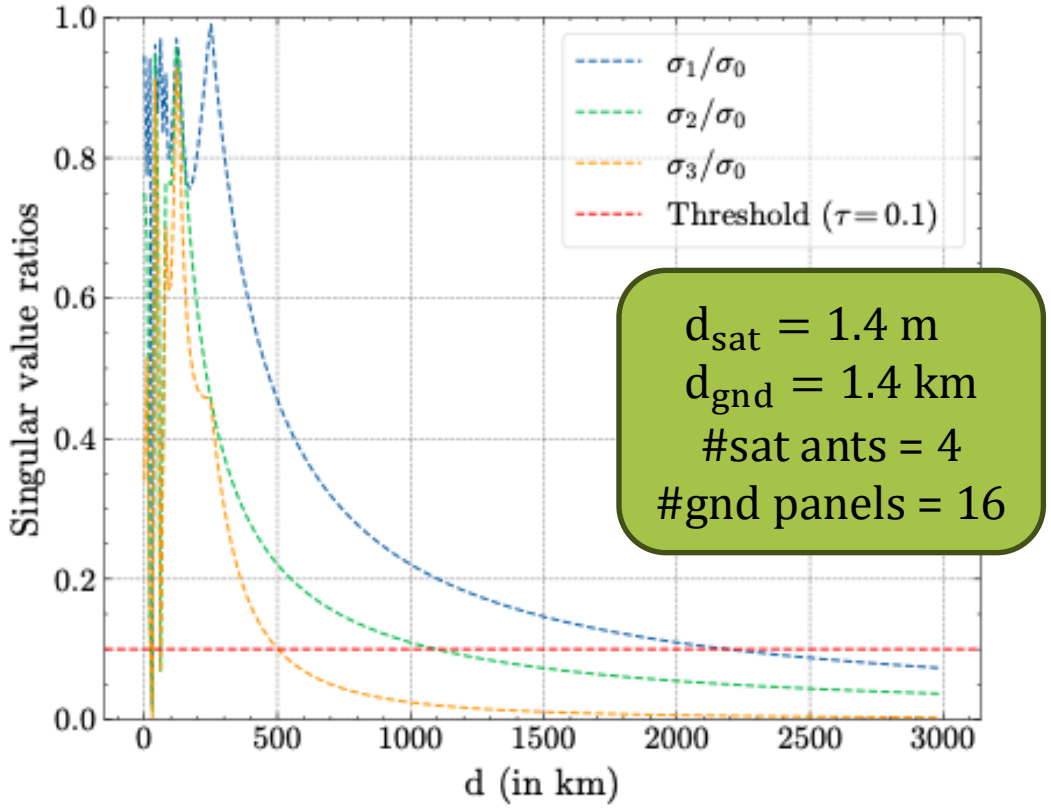
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Experimental Demo

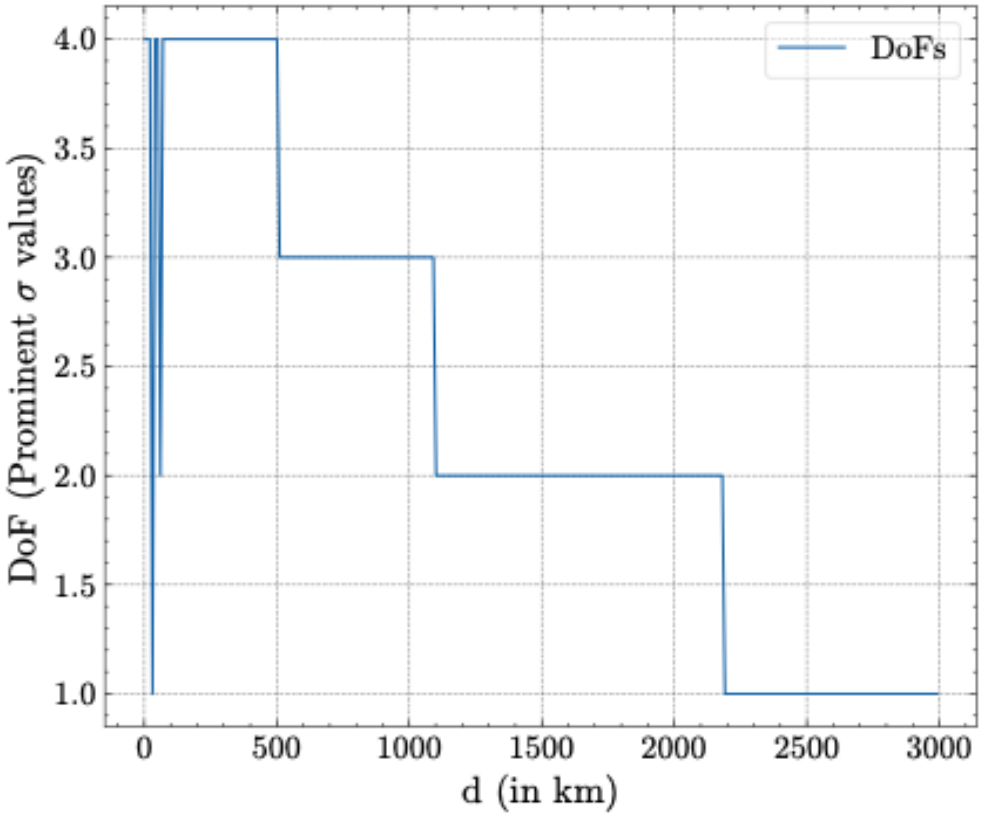
Showing feasibility with commercial hardware on a small-scale setup

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Evaluations: Multiple streams for satellite-scale distances



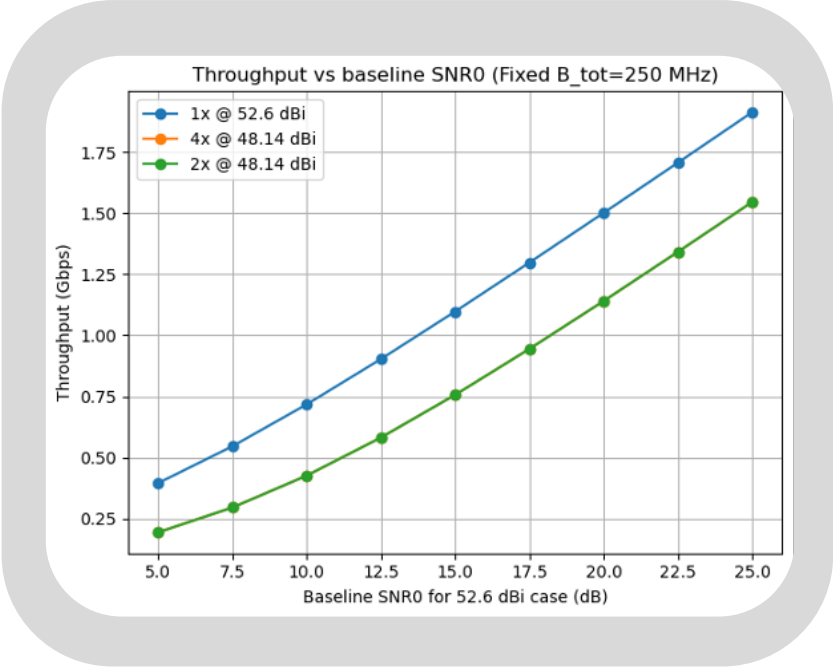
$d_{sat} = 1.4$ m
$d_{gnd} = 1.4$ km
#sat ants = 4
#gnd panels = 16



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

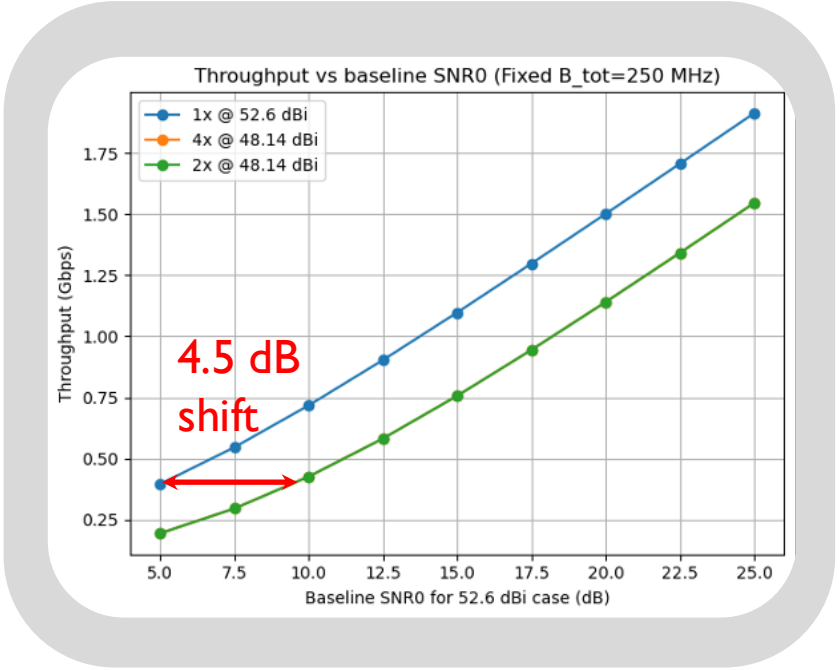
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Total throughput comparing parabolic dish vs *ArrayLink*



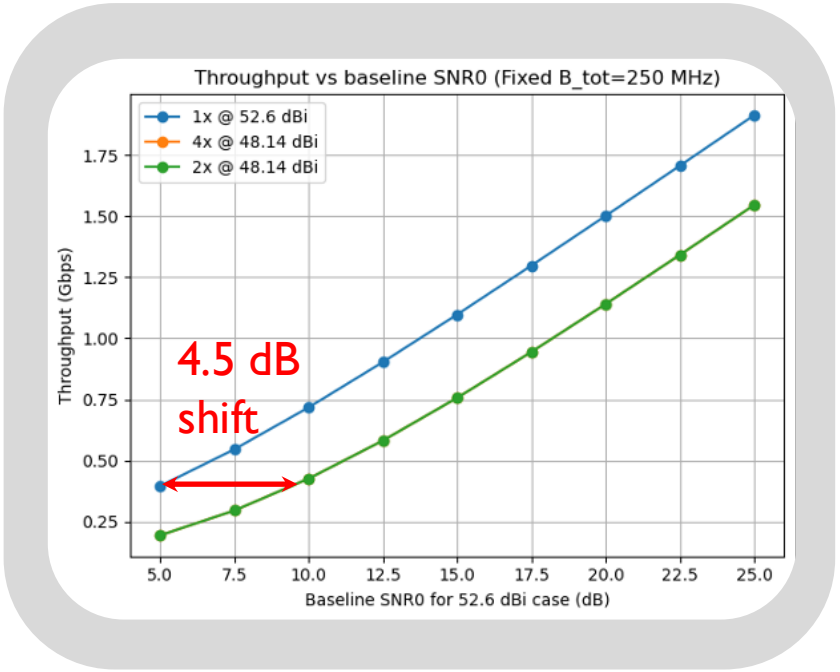
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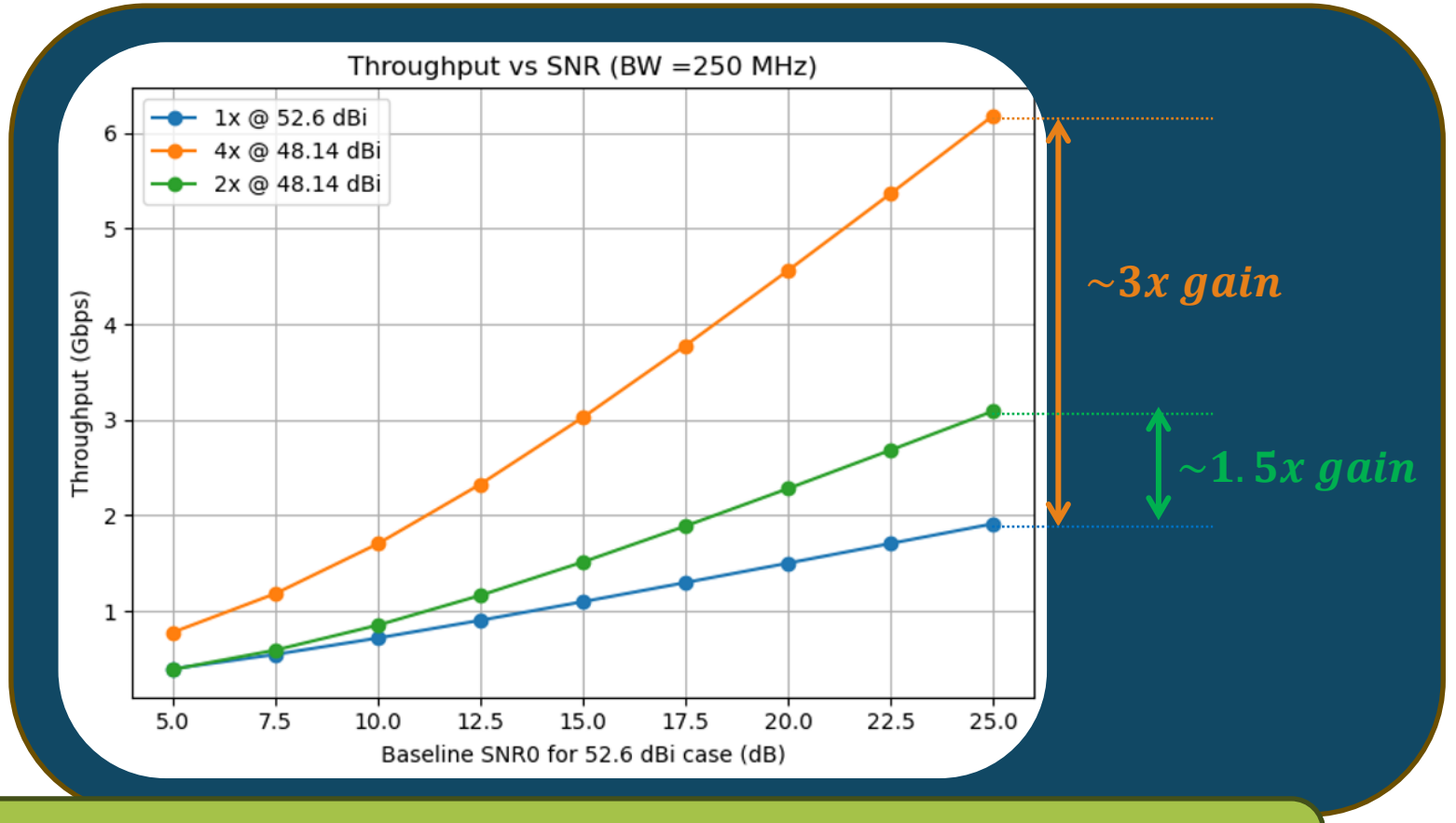
Total throughput comparing parabolic dish vs *ArrayLink*



© WCSNG Lab

Total throughput comparing parabolic dish vs *ArrayLink*





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

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To make ***ArrayLink*** practical we need to solve two challenges

© WCSNG Lab

To make ***ArrayLink*** practical we need to solve two challenges

I

SPATIAL CHALLENGE

Suppress grating lobes

across a kilometer-scale sparse aperture

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To make ***ArrayLink*** practical we need to solve two challenges

1

SPATIAL CHALLENGE

Suppress grating lobes

across a kilometer-scale sparse aperture

2

TEMPORAL CHALLENGE

Track fast-moving satellites

with ultra-narrow beams and sub-ms updates

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Challenge I: Addressing grating lobes due to Sparse Array

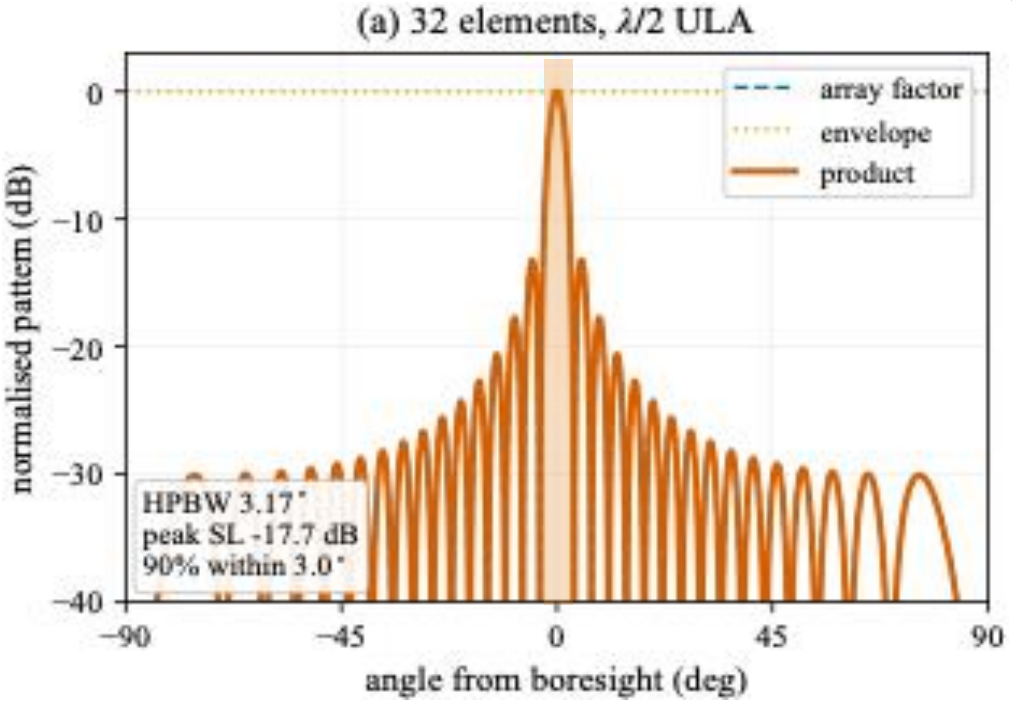
A simplified example 32 antennas ULA – No grating lobes

- 32 antennas uniformly separated by $10\frac{\lambda}{2}$ spacing



$$B(\theta) = E(\theta)\frac{1}{N}\sum_{N} e^{j2\pi\frac{d}{\lambda}sin\theta}$$

B(θ) = element pattern (envelope) × array factor



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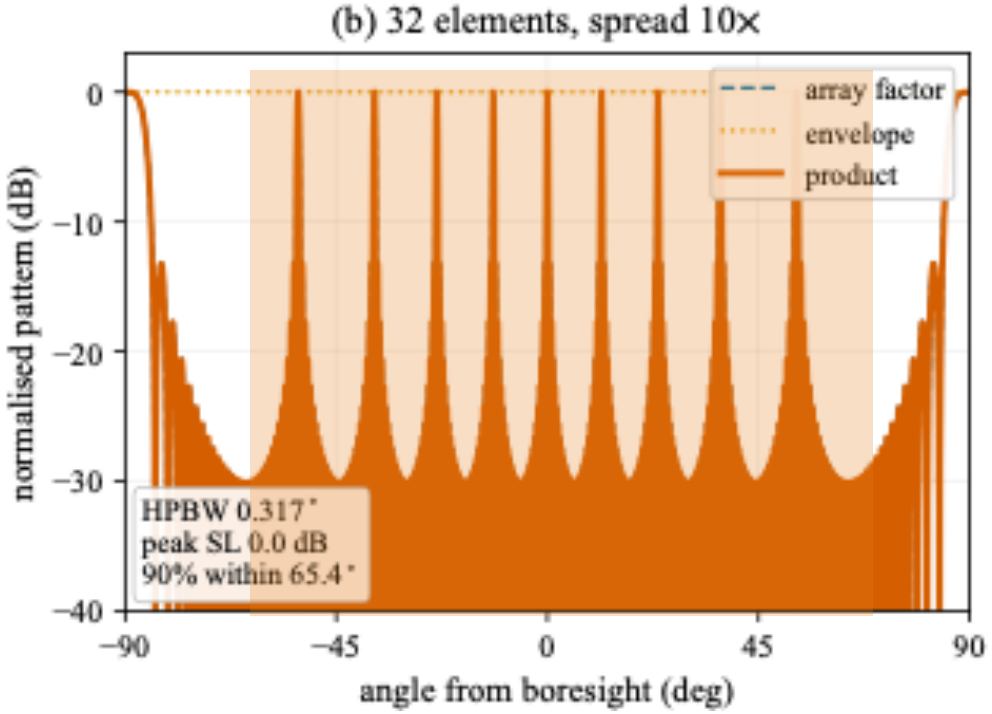
Challenge 1: Grating lobes cause off-axis interference

32 antennas sparsely distributed – grating lobes

- 32 antennas uniformly separated by $10\frac{\lambda}{2}$ spacing



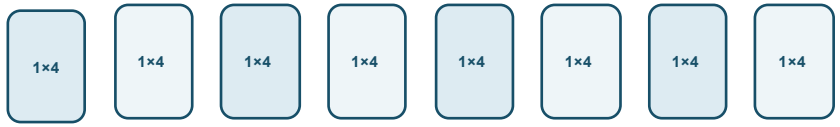
Why it matters: Off-axis radiation creates interference.



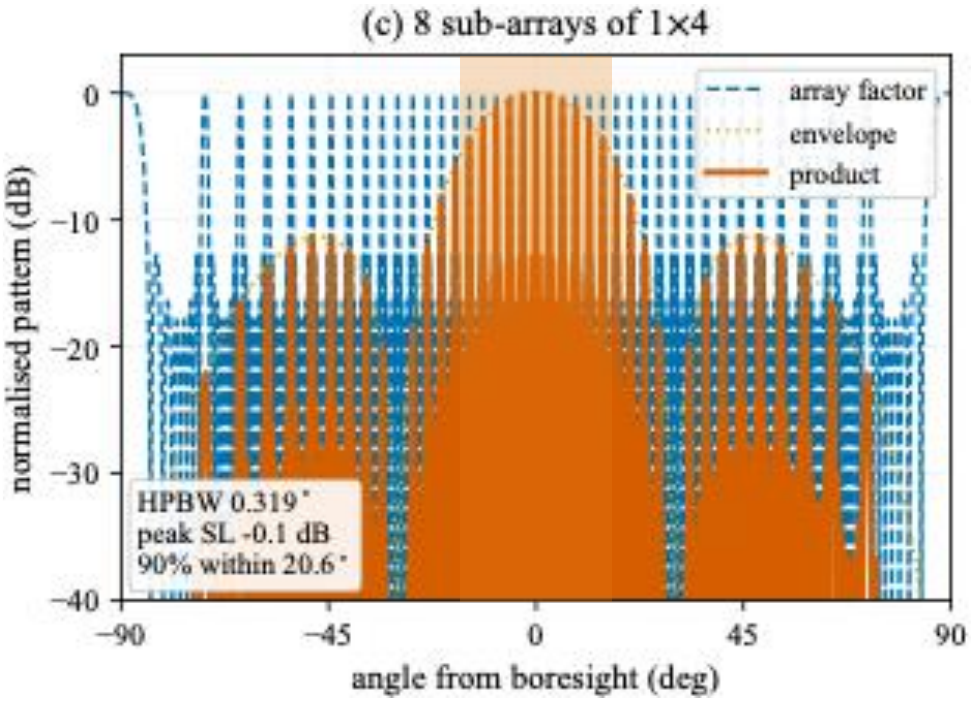
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Solution: Distributed sub-arrays suppress grating lobes

8 subarrays (1 × 4 elements)
distributed across the sparse aperture



Subarray envelope limits the visible grating lobe region.

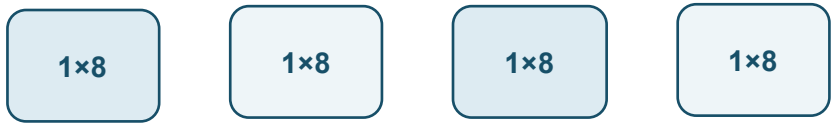


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Solution: Larger sub-arrays further narrow the radiated envelope

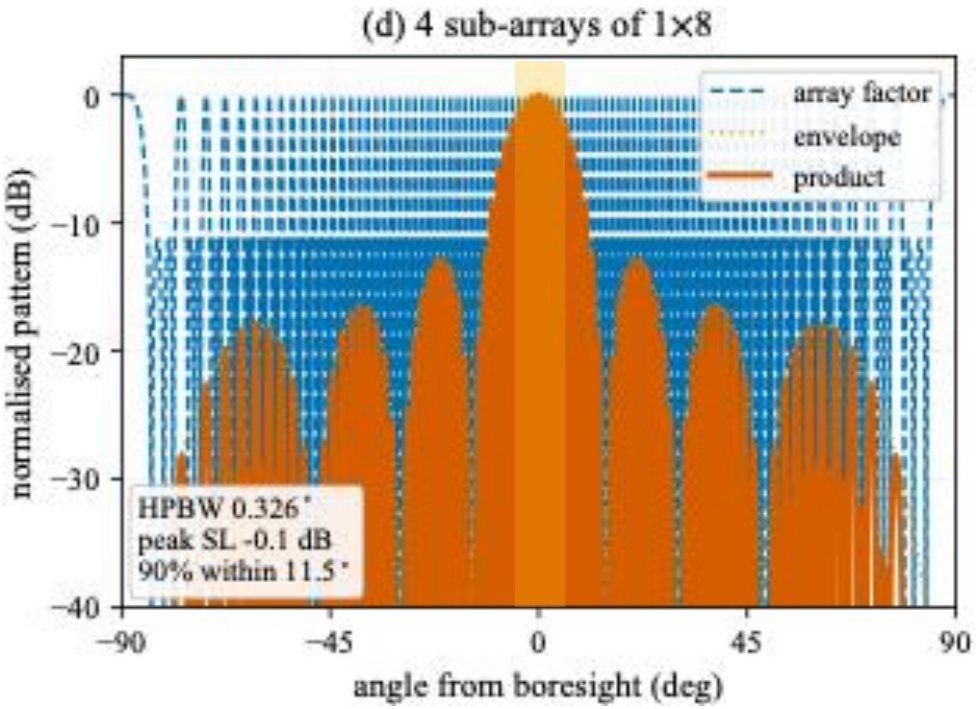
4 distributed sub-arrays × 8 elements

distributed across the sparse aperture



Result: 90% of radiated power is concentrated within $\pm$ 11.5° of boresight.

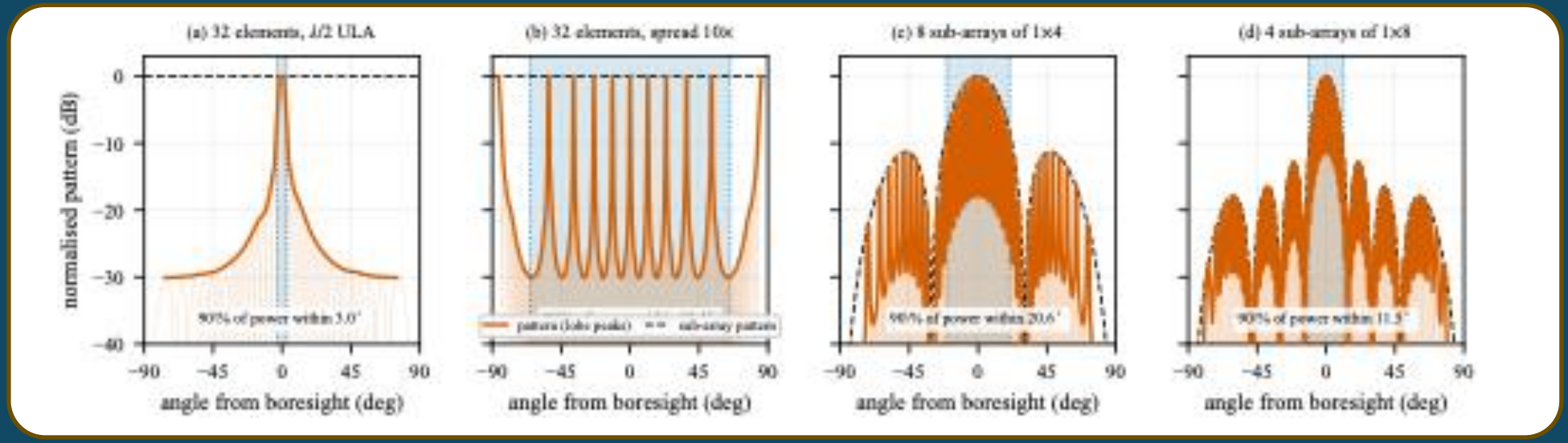
Larger sub-arrays focus power near boresight, reducing off-axis interference.



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Distributed sub-arrays turn grating lobes into a controllable trade-off

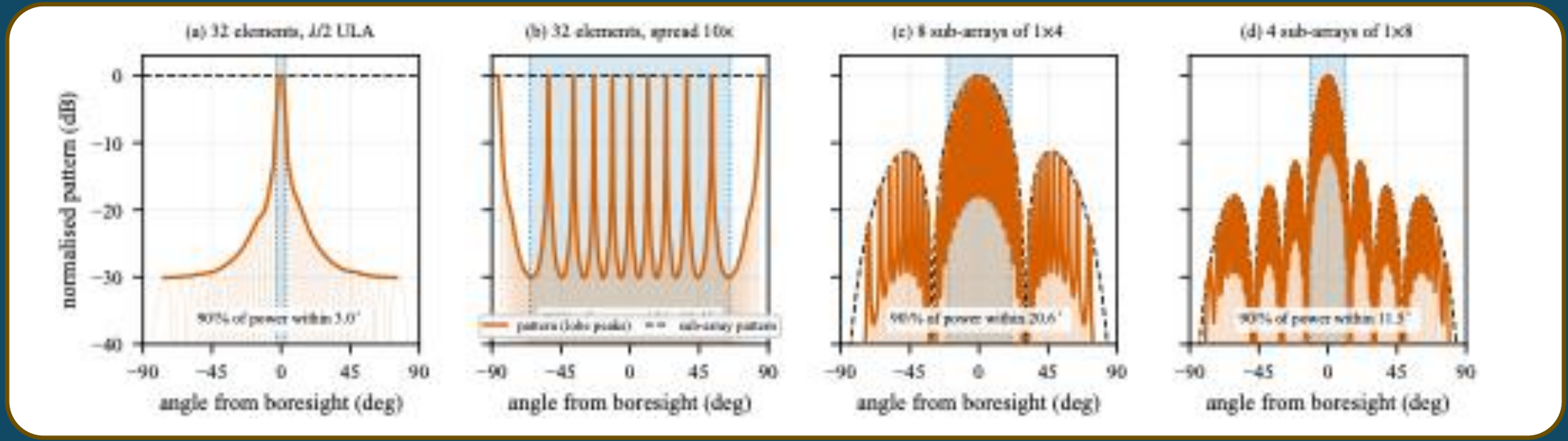
- Baseline → Sparse-element grating lobes → Eight 1×4 sub-arrays → Four 1×8 sub-arrays



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Distributed sub-arrays turn grating lobes into a controllable trade-off

- Baseline → Sparse-element grating lobes → Eight 1×4 sub-arrays → Four 1×8 sub-arrays

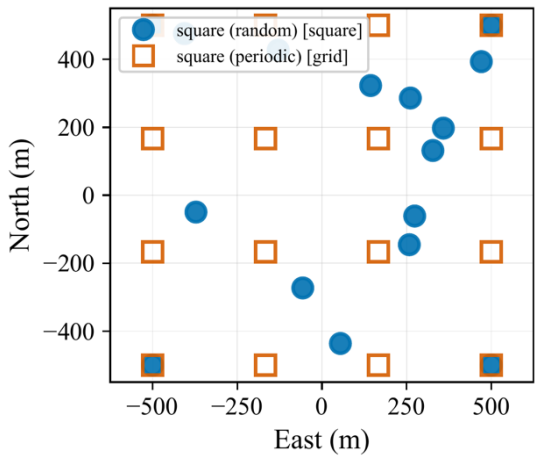


Trade-off: Larger sub-arrays create a narrower, higher-directivity radiation envelope, while fewer distributed sub-arrays produce more prominent grating lobes.

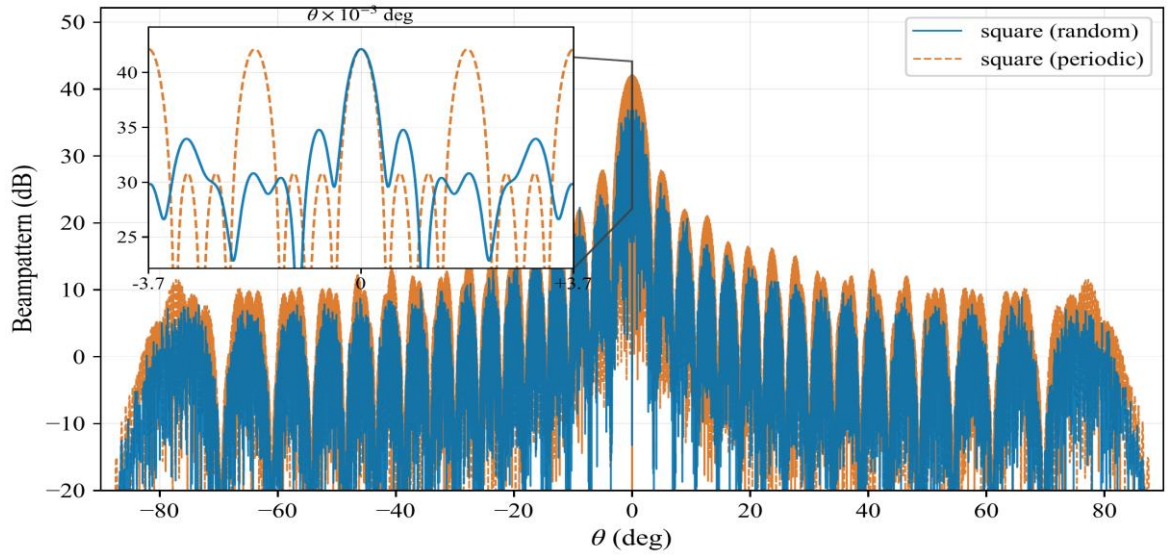
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Satellite case: Random placement suppresses nearby grating lobes

- **Setup:** 16 distributed 32×32 planar arrays → uniform grid vs. random positions
- **Observation:** Random placement reduces nearby grating-lobe energy, while main-beam HPBW remains similar



Array placement



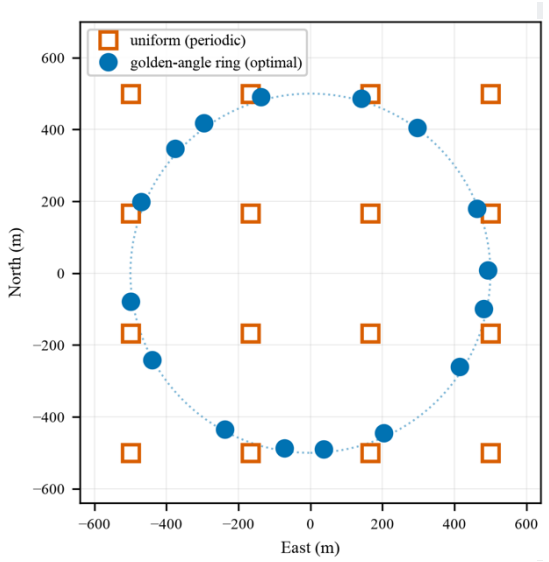
Beam Pattern

Distributed arrays reduce the grating lobes challenge into pointing requirement.

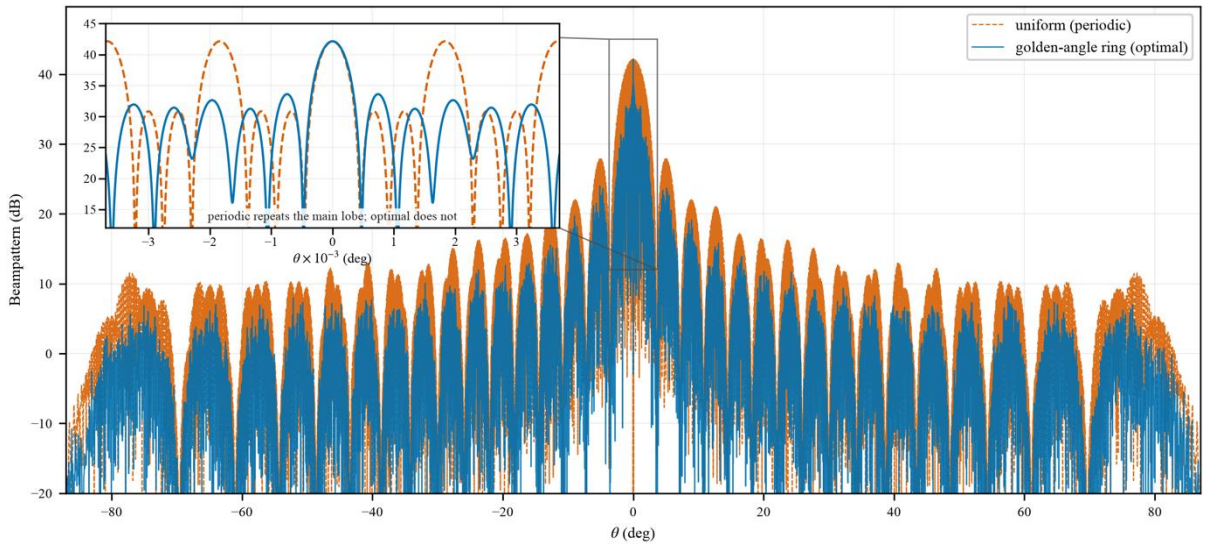
© WCSNG Lab

Satellite case: Aperiodic placement removes nearby grating lobes **by design**

- **Setup:** 16 distributed 32×32 planar arrays over a 1 km site → uniform grid vs golden-angle
- **Observation:** The uniform grid repeats the main lobe at full height every $\lambda/d = 1.8\times10^{-3}$°; the golden-angle ring holds every sidelobe ≥3.8 dB down, at identical gain (42.1 dB) and HPBW



Array placement



Beam Pattern

Distributed arrays reduce the grating lobes challenge into pointing requirement.

© WCSNG Lab

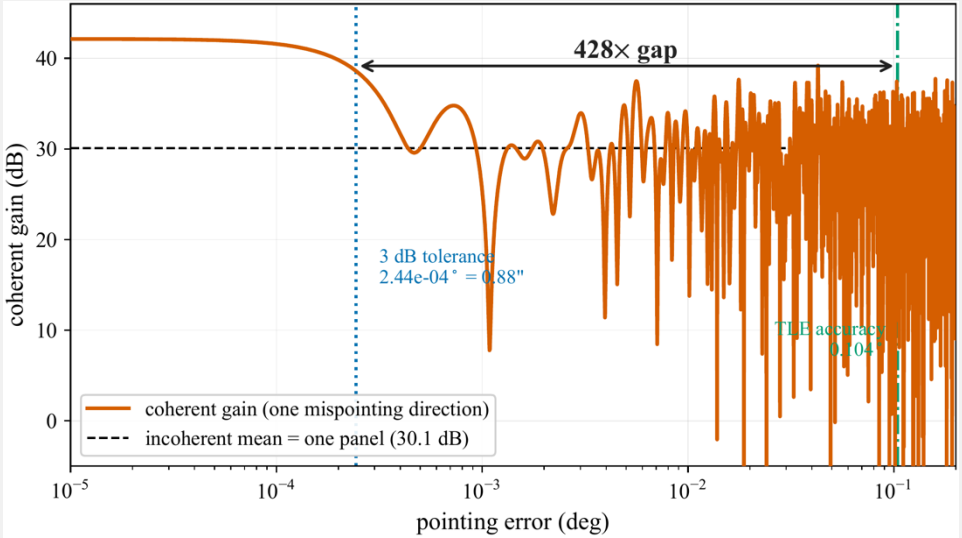
Challenge 2: Tracking fast moving satellites

© WCSNG Lab

Challenge 2: Tracking fast moving satellites

Pointing accuracy:

- Small errors rapidly reduce coherent gain
- 3dB tolerance ≈ 2.4×10^{-4} deg

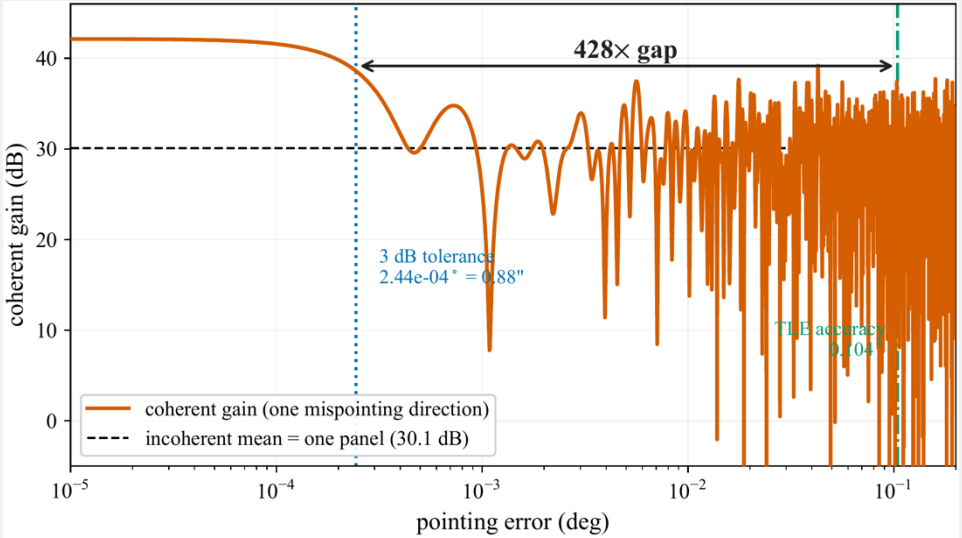


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Challenge 2: Tracking fast moving satellites

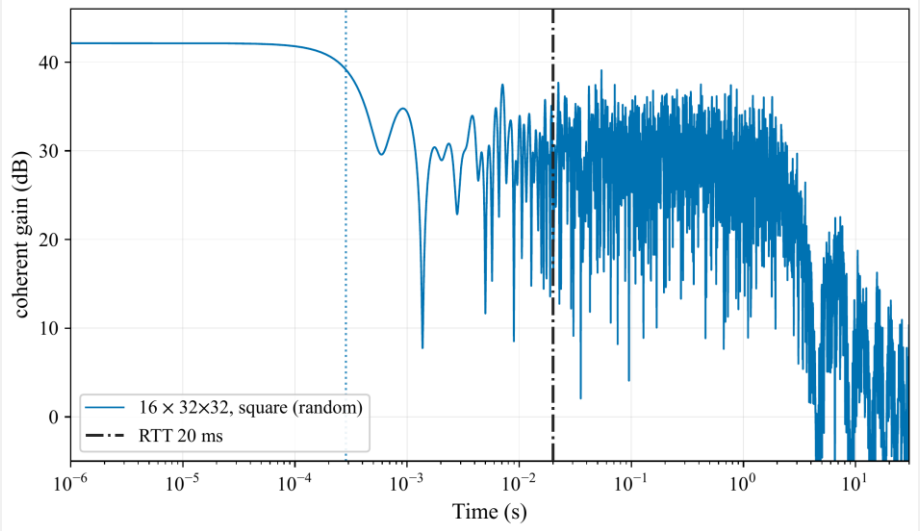
Pointing accuracy:

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Update latency:

- Fast motion makes pointing estimates stale
- Updates must remain below coherence time (< 1ms)

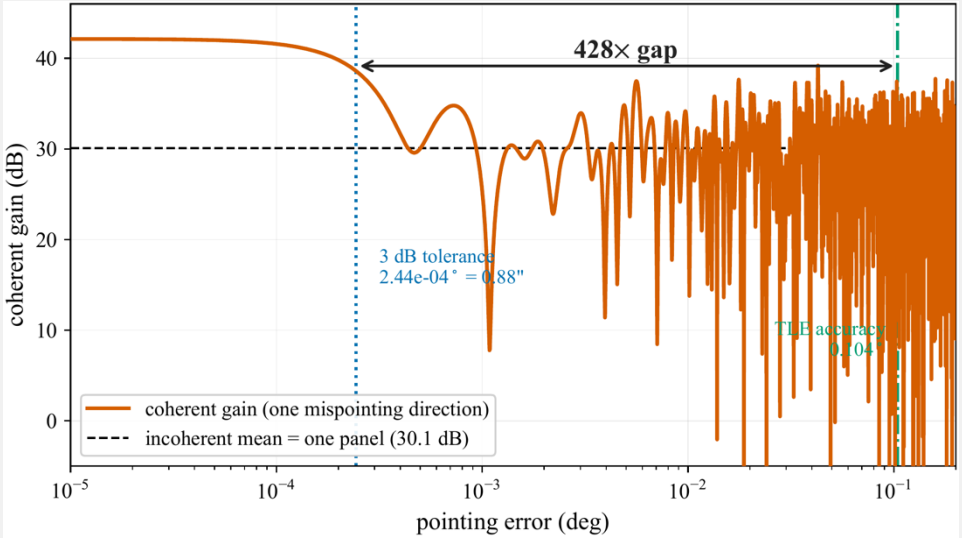


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Challenge 2: Tracking fast moving satellites

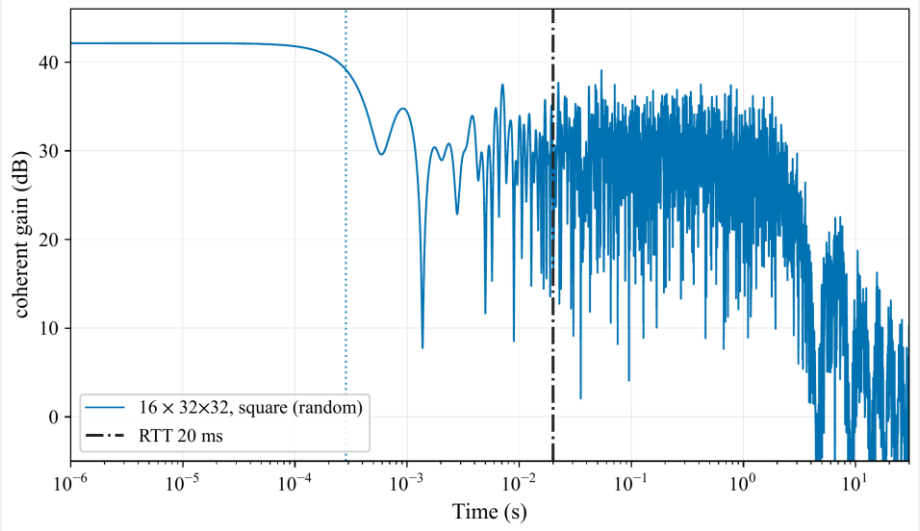
Pointing accuracy:

- Small errors rapidly reduce coherent gain
- 3dB tolerance $\approx 2.4 \times 10^{-4}$ deg



Update latency:

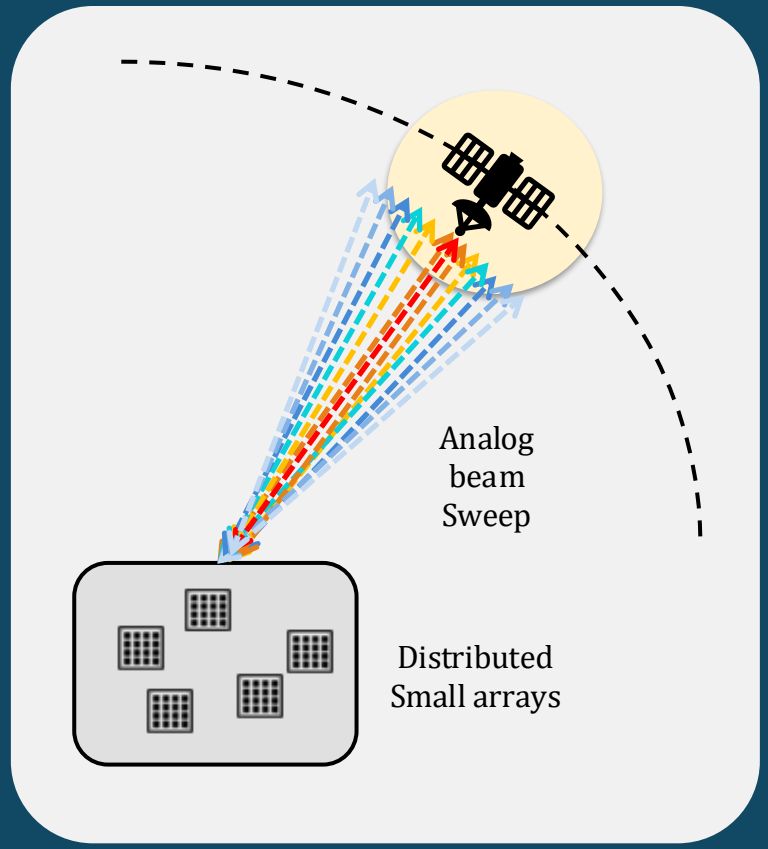
- Fast motion makes pointing estimates stale
- Updates must remain below coherence time (< 1ms)



Requirements: To enable coherent gain, we need pointing tolerance ($\approx 2.4 \times 10^{-4}$ deg) and low-latency tracking (< 1 ms).

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Naive solution: Exhaustive beam search

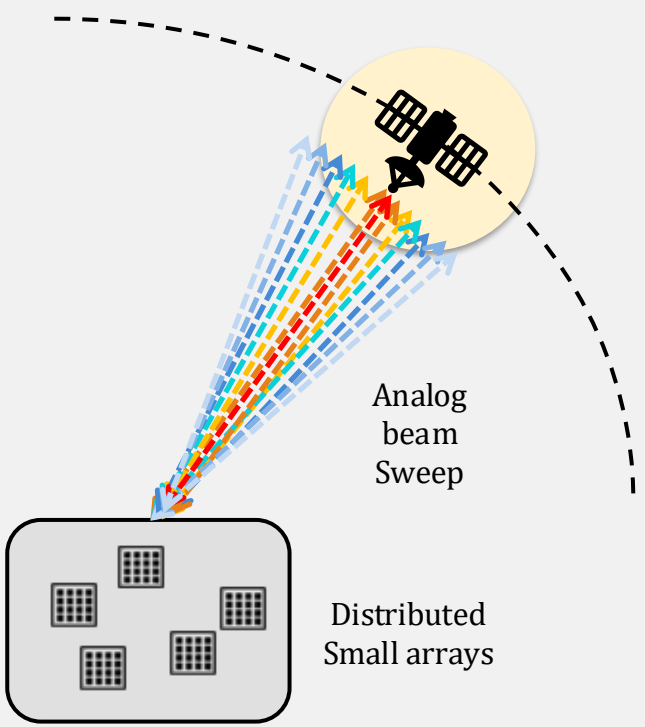


1	Angular step	$\delta\theta = 2.4 \times 10^{-4}$ (deg)
2	Sweep in known TLE (0.1°)	$N \geq 0.1°/\delta\theta \approx 428$ beams
3	Time per pointing	1 ms/N ≤ 2.4 microseconds

A narrow uncertainty window leaves only 2.4 us per pointing

© WCSNG Lab

Naive solution: Exhaustive beam search



1	Angular step	$\delta\theta = 2.4 \times 10^{-4}$ (deg)
2	Sweep in known TLE (0.1°)	$N \geq 0.1°/\delta\theta \approx 428$ beams
3	Time per pointing	$1\ ms/N \leq 2.4$ microseconds

A narrow uncertainty window leaves only 2.4 us per pointing

Analog exhaustive beam search cannot provide required pointing tolerance ($\approx 2.4 \times 10^{-4}$ deg) within the coherence time ($< 1ms$).

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TrackLink (our approach): Coarse pointing + fast digital phase tracking

TWO-TIMESCALE TRACKING

Shift precision from slow analog steering to fast digital phase correction.

1 **Coarse analog pointing**

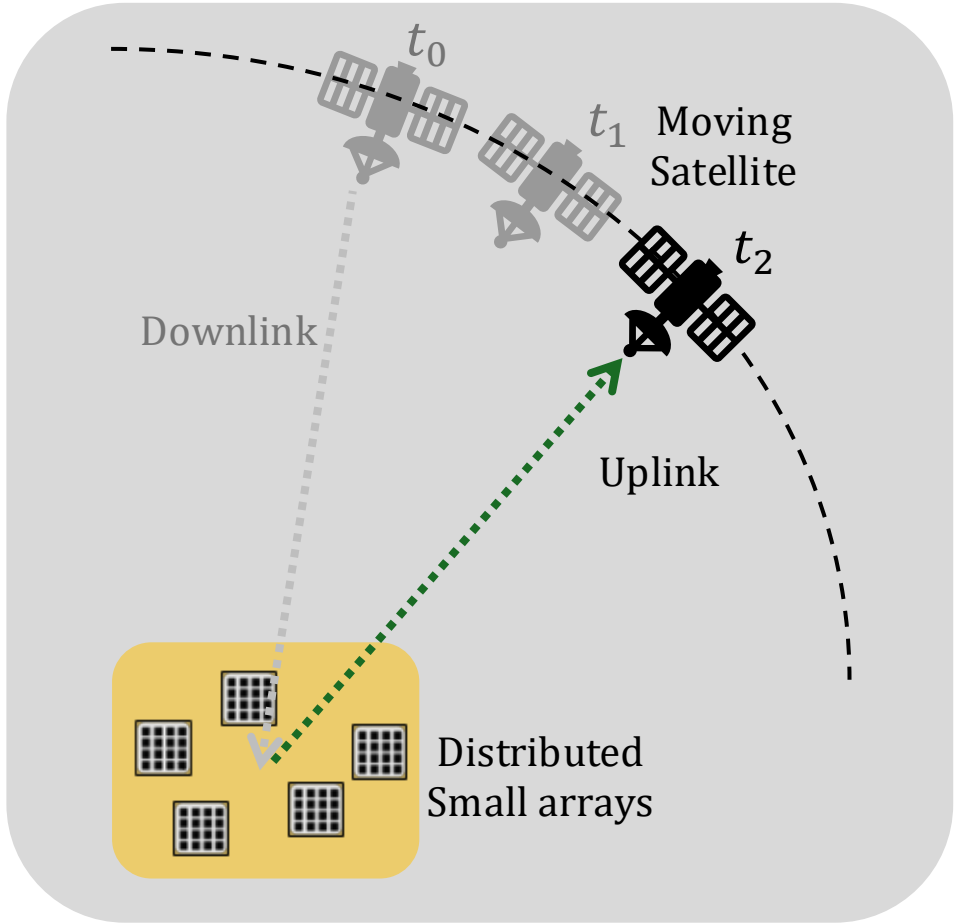
TLE/ephemeris keeps each subarray inside a broad beam

2 **Track phase, not the full channel**

Geometry drives the fast change; residual channel effects evolve slowly.

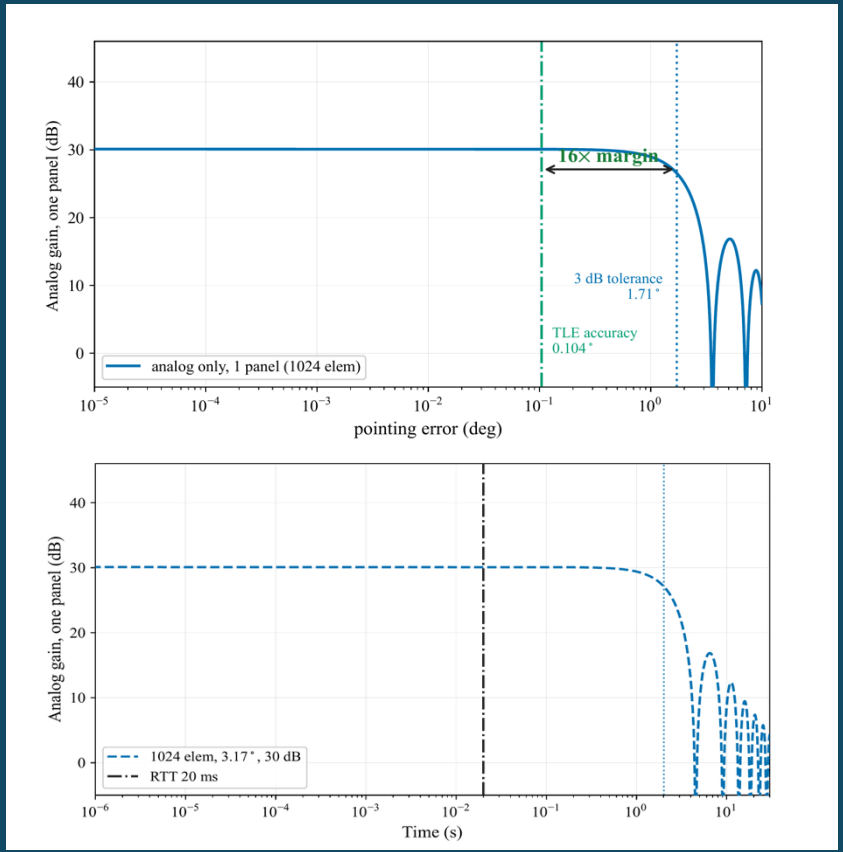
3 **Predict phase at transmit time**

CFFR uses measured wrapped pilot phases, array geometry, and coarse TLE and predicts phase at satellite reception time.



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Step1: Coarse analog pointing with TLE ephemeris angle



WHY COARSE POINTING IS ENOUGH

16 cm
32×32 subarray aperture

1.71°
per-panel 3 dB tolerance

≈0.1°
typical TLE pointing error

≈16×
pointing margin

Analog pointing can update on a slow timescale; digital phase alignment supplies the precision.

The analog beam only needs to keep the satellite inside each broad subarray beam.

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Step2: Separate fast geometry from slow residual effects

$$h(t) = h_{geo}(t) \odot h_{res}(t)$$

FAST-VARYING

Geometric component $h_{geo}(t)$

Driven by satellite motion

Estimate continuously from geometry and phase

SLOW-VARYING

Residual component $h_{res}(t)$

Captures quasi-static channel effects

Measure and refresh at a lower rate

© WCSNG Lab

Step2: Separate fast geometry from slow residual effects

$$h(t) = h_geo(t) \odot h_res(t)$$

FAST-VARYING

Geometric component h_geo(t)

Driven by satellite motion

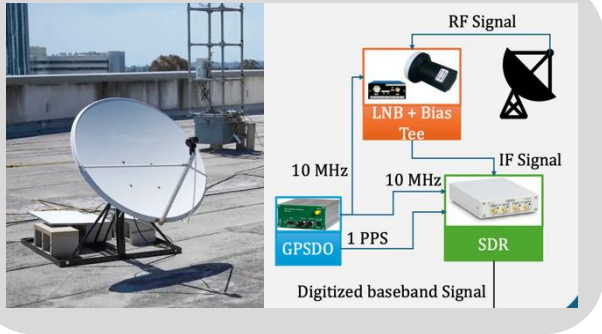
Estimate continuously from geometry and phase

SLOW-VARYING

Residual component h_res(t)

Captures quasi-static channel effects

Measure and refresh at a lower rate



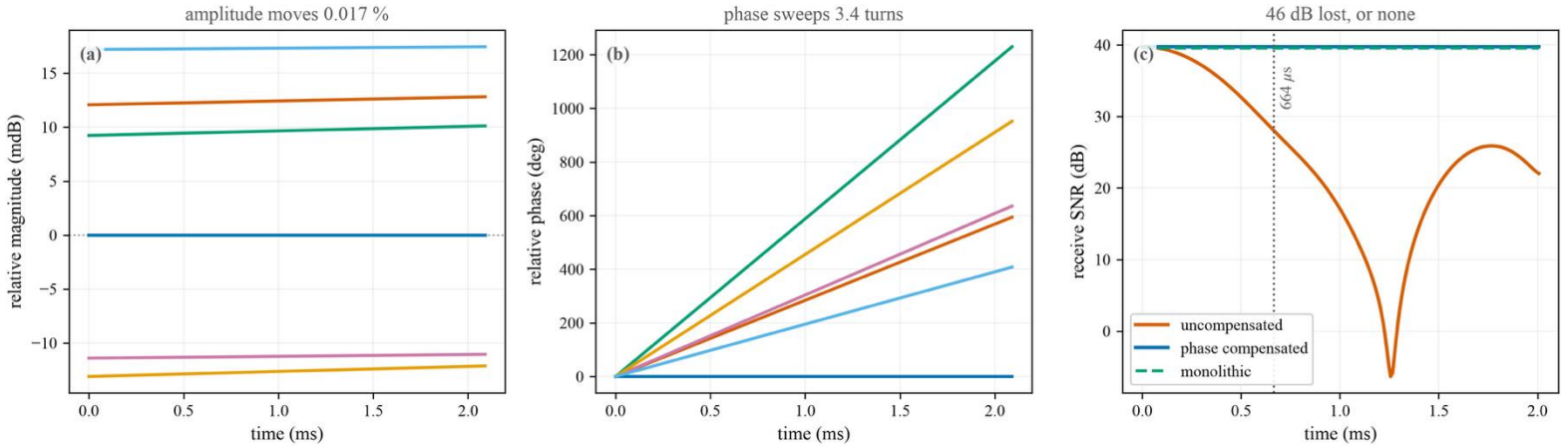
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In a geometry driven channel – “Phase is all we need”

© WCSNG Lab

In a geometry driven channel – “Phase is all we need”

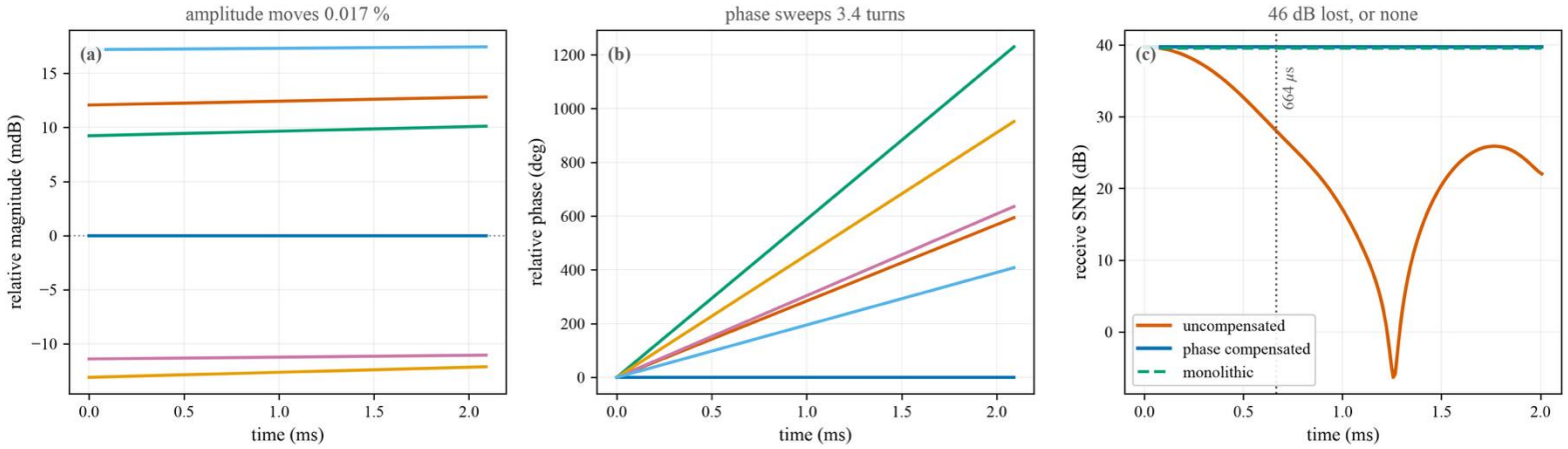
2 ms



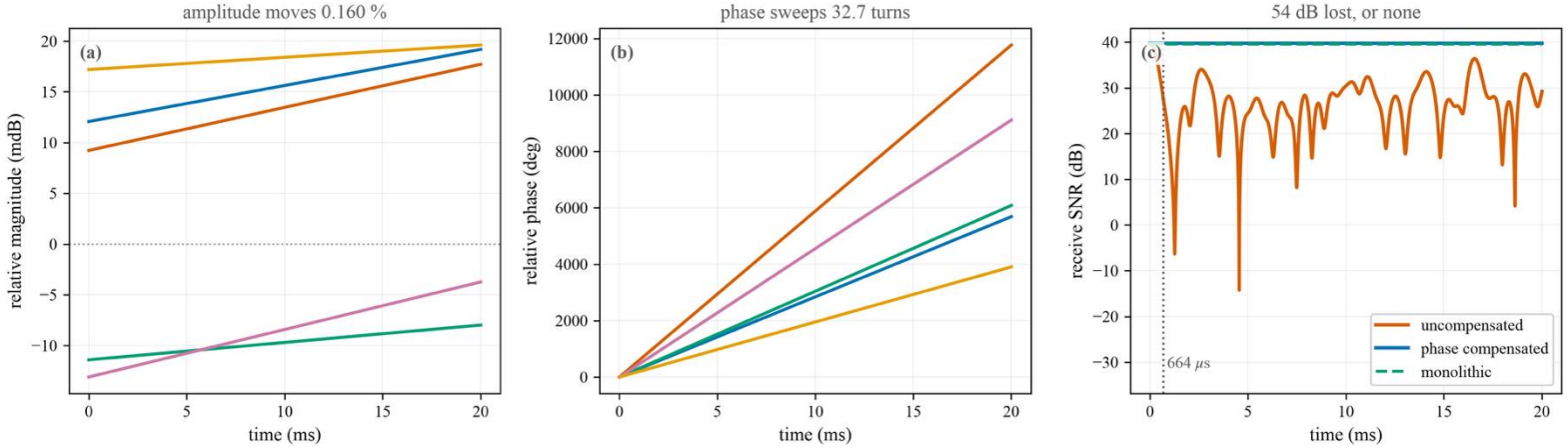
© WCSNG Lab

In a geometry driven channel – “Phase is all we need”

2 ms



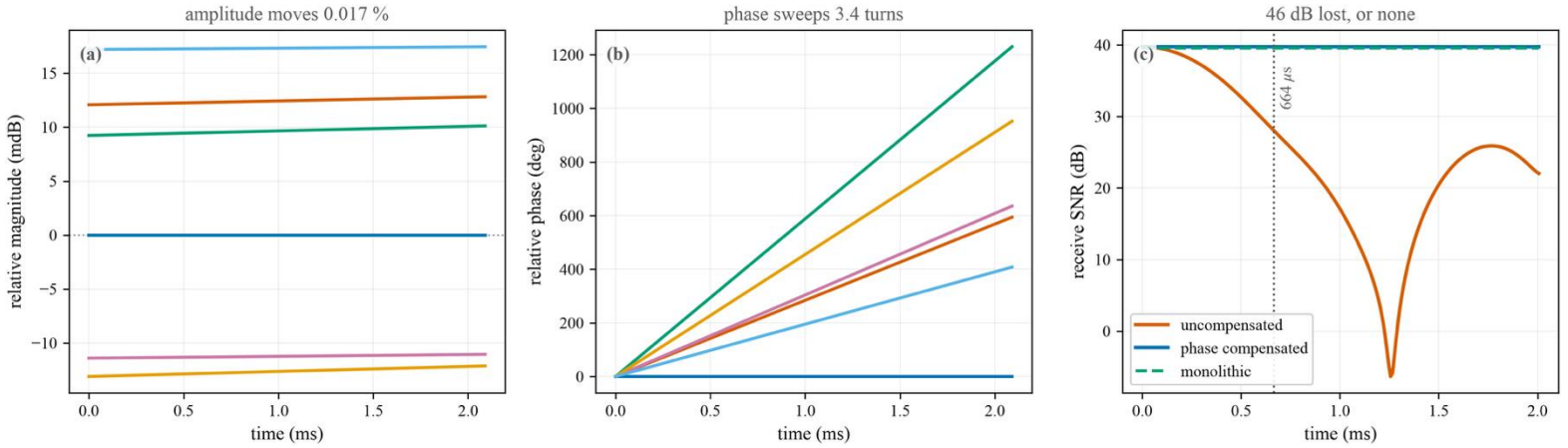
20 ms



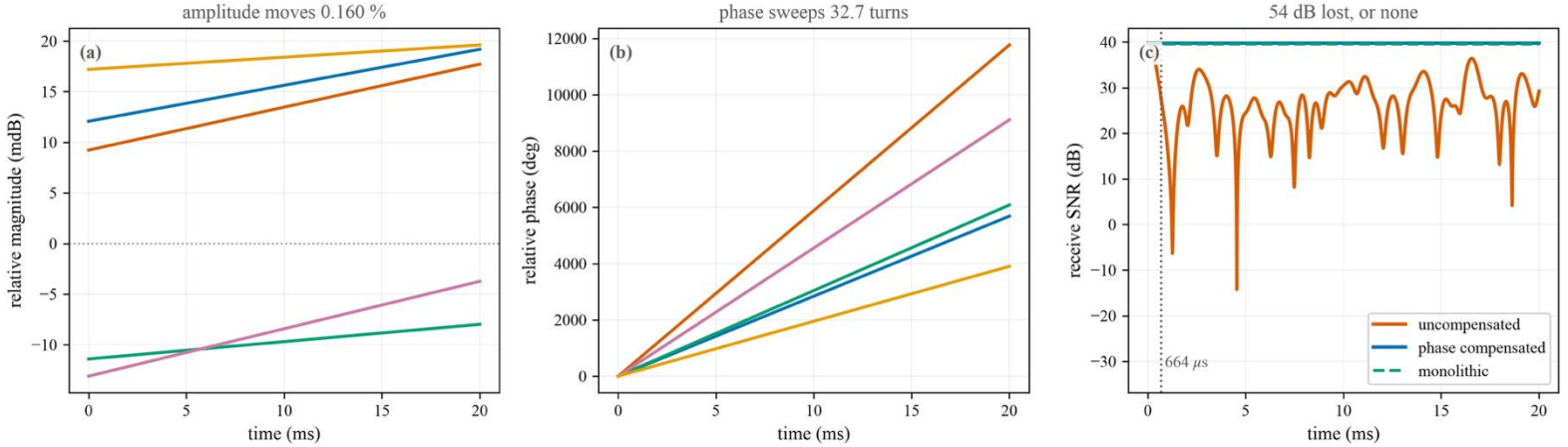
© WCSNG Lab

In a geometry driven channel – “Phase is all we need”

2 ms



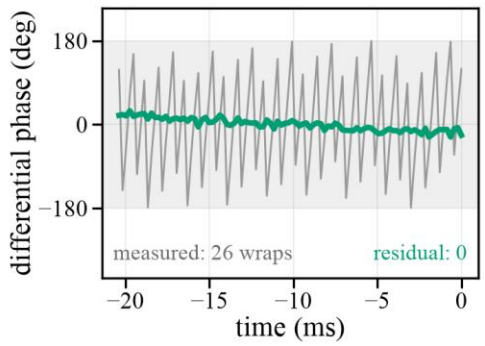
20 ms

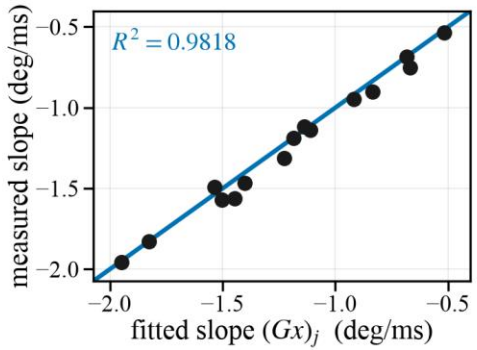


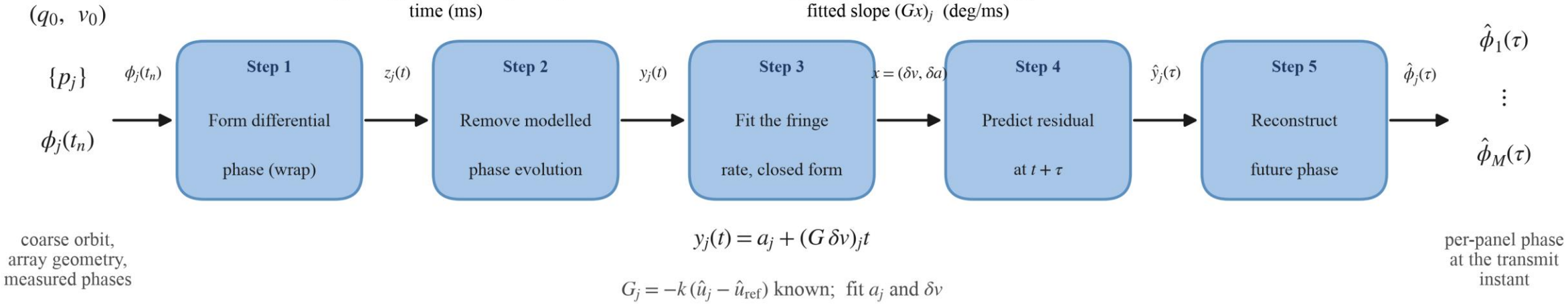
Track phase continuously and refresh the residual channel slowly.

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Step3: CFFR predicts future phase by fitting residual fringe rate





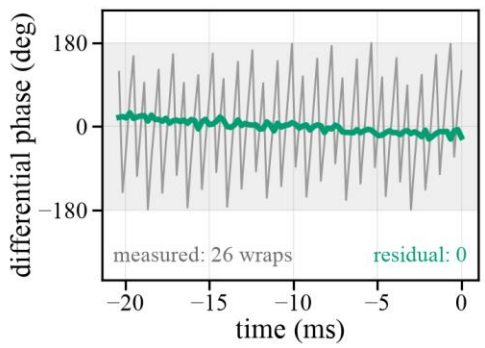


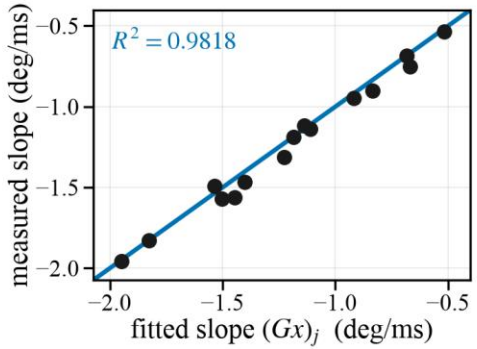
$$y_j(t) = a_j + (G\,\delta v)_j t$$

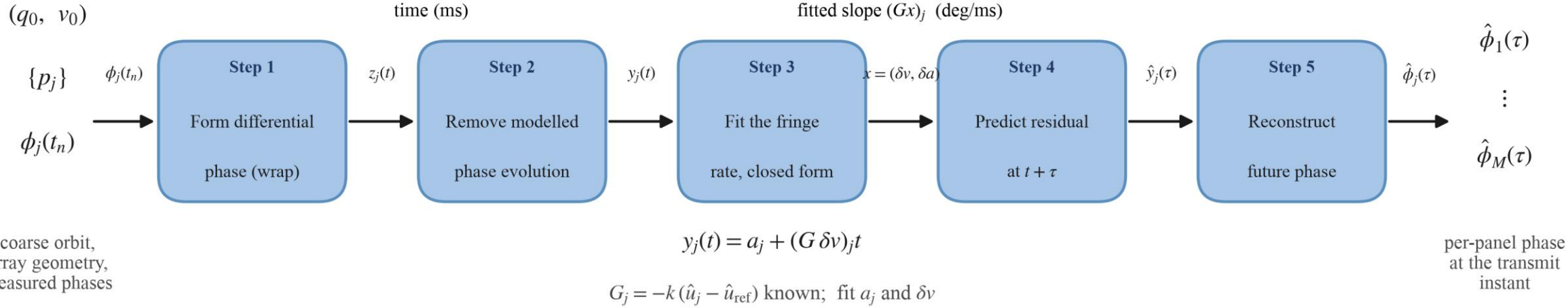
$G_j = -k\,(\hat{u}_j - \hat{u}_{\text{ref}})$ known; fit a_j and δv

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Step3: CFFR predicts future phase by fitting residual fringe rate







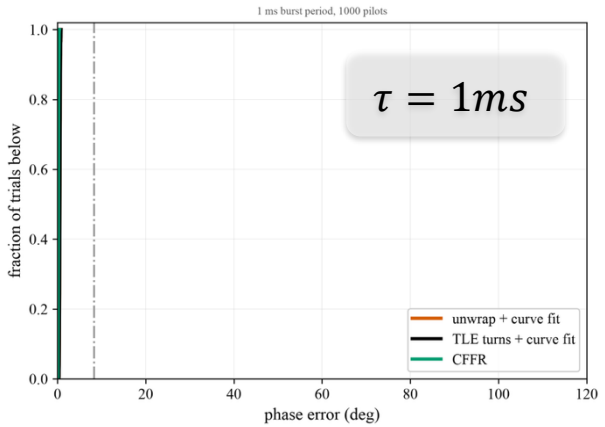
Model geometry, fit residual fringe rate, and extrapolate phase to transmission.

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CFFR maintains near-perfect gain across 1–100 ms turnaround

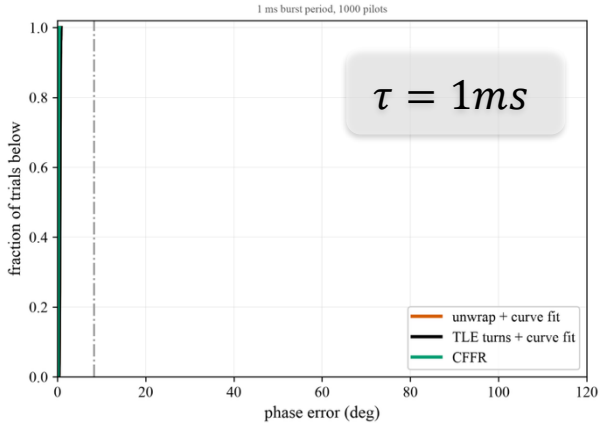
© WCSNG Lab

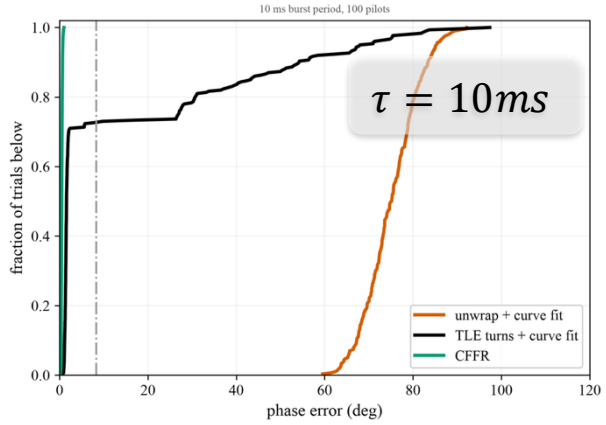
CFFR maintains near-perfect gain across 1–100 ms turnaround



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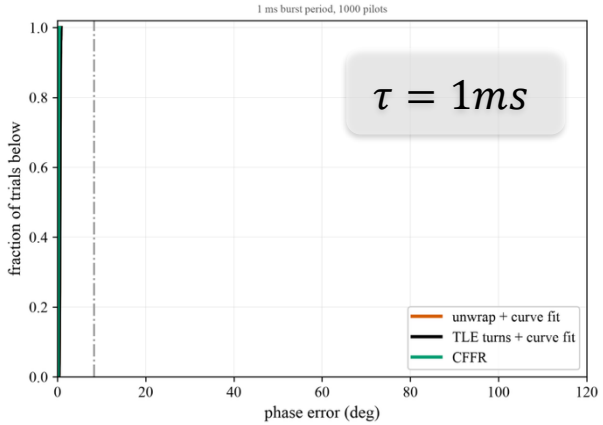
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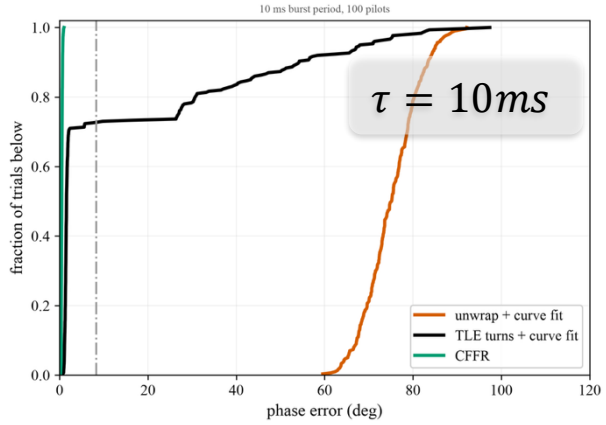


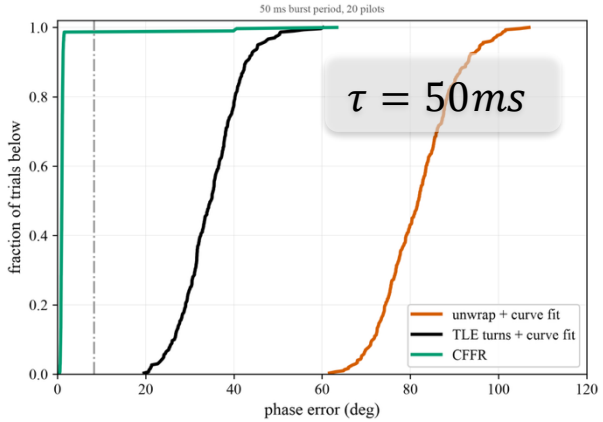


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CFFR maintains near-perfect gain across 1–100 ms turnaround

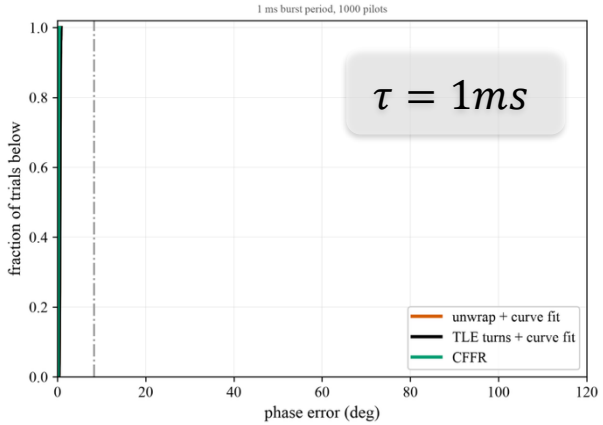


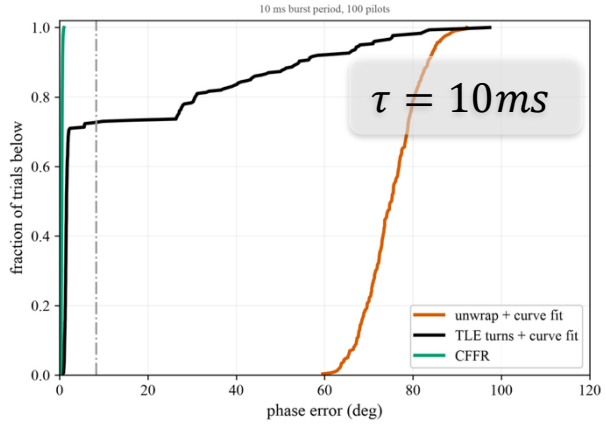


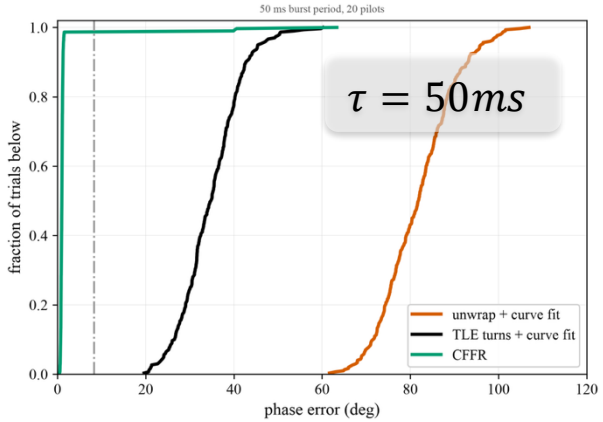


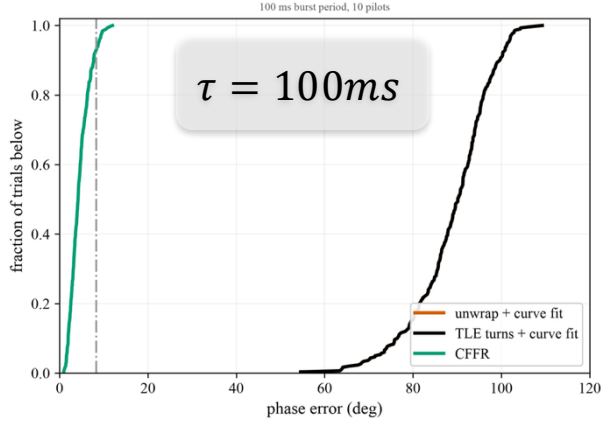
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CFFR maintains near-perfect gain across 1–100 ms turnaround



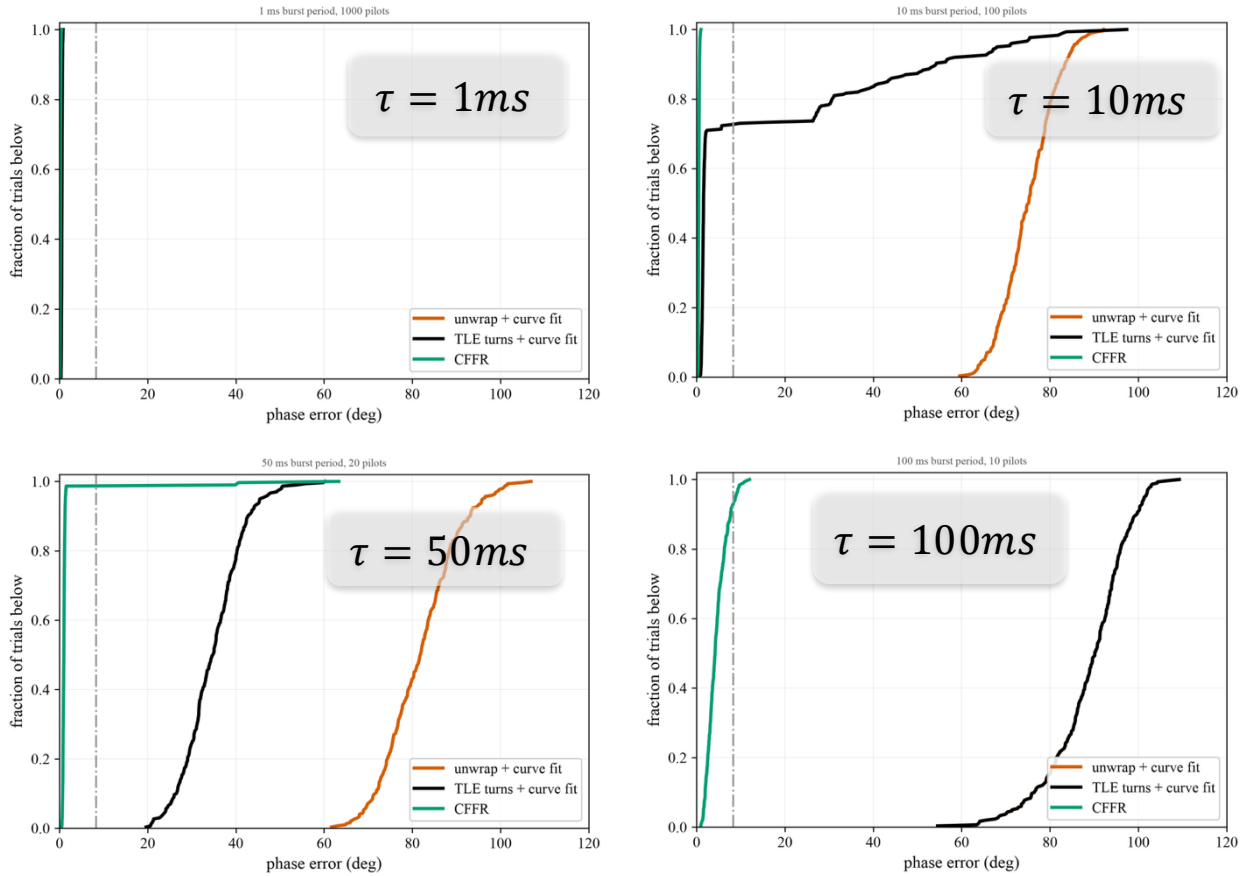


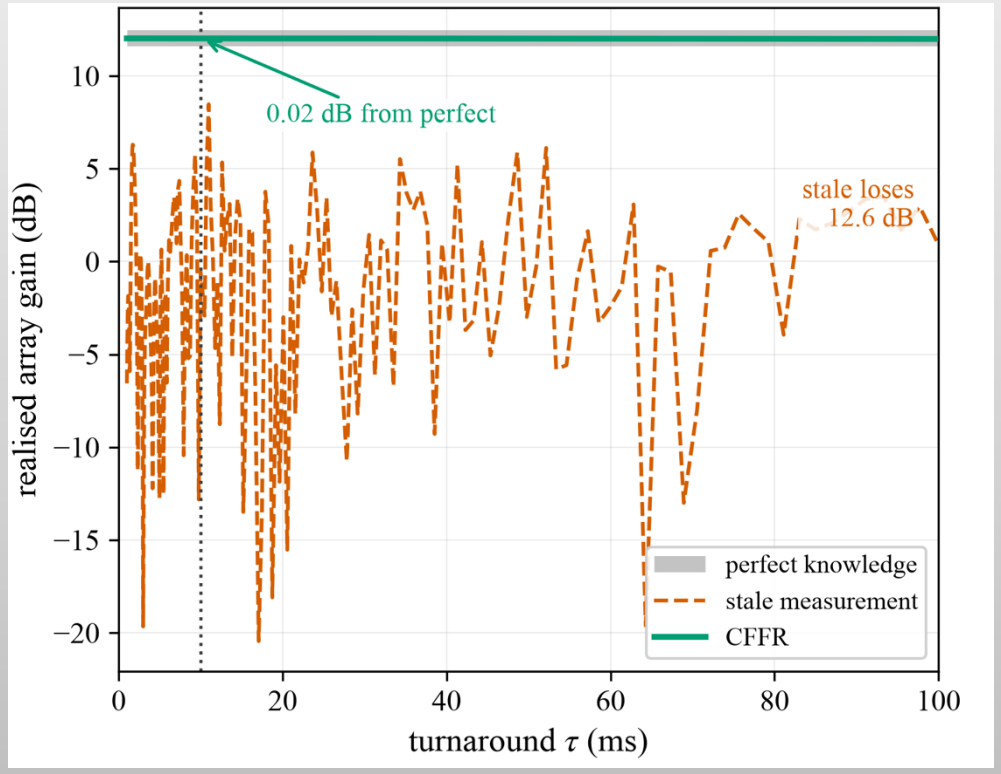




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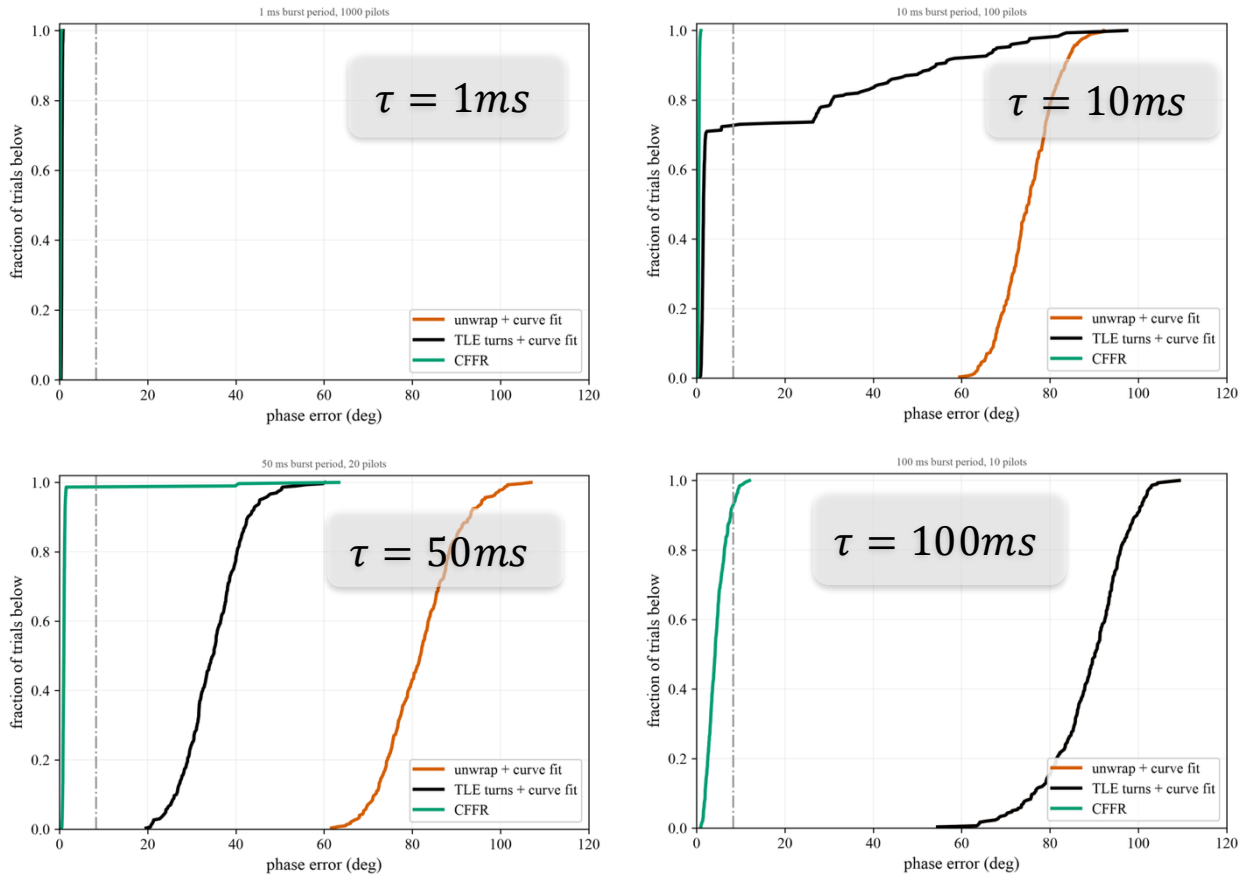
CFFR maintains near-perfect gain across 1–100 ms turnaround

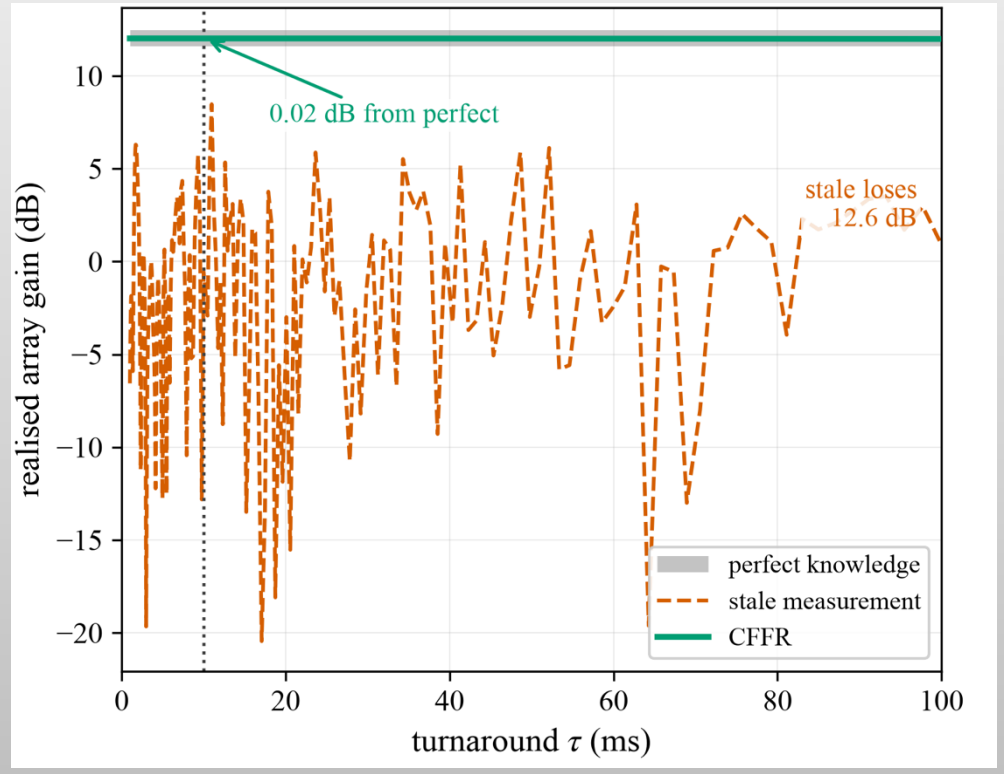




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CFFR maintains near-perfect gain across 1–100 ms turnaround

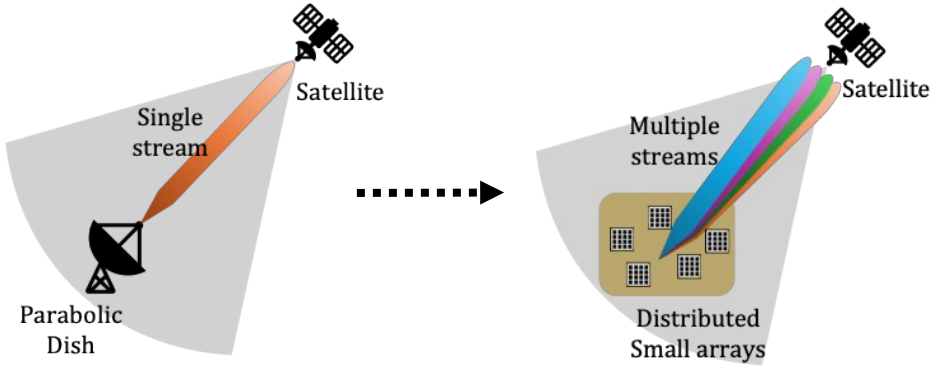




CFFR is 0.02 dB from perfect; stale channel estimates lose 12.6 dB.

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Summary: ArrayLink creates capacity, TrackLink preserves it

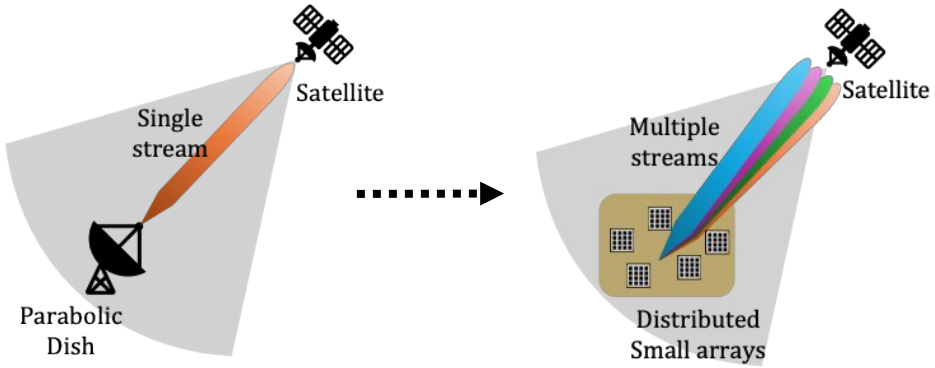


Full more details refer:
wcsng.ucsd.edu/arraylink/

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Summary: ArrayLink creates capacity, TrackLink preserves it

- ArrayLink creates dish-class gain with 16 commodity phased-array panels.
- A kilometer-scale aperture creates tunable LoS spatial streams aperiodic distributed sub arrays placement suppresses grating lobes.
- TrackLink preserves coherent gain and usable streams as fast-moving LEO satellites traverse the focus.



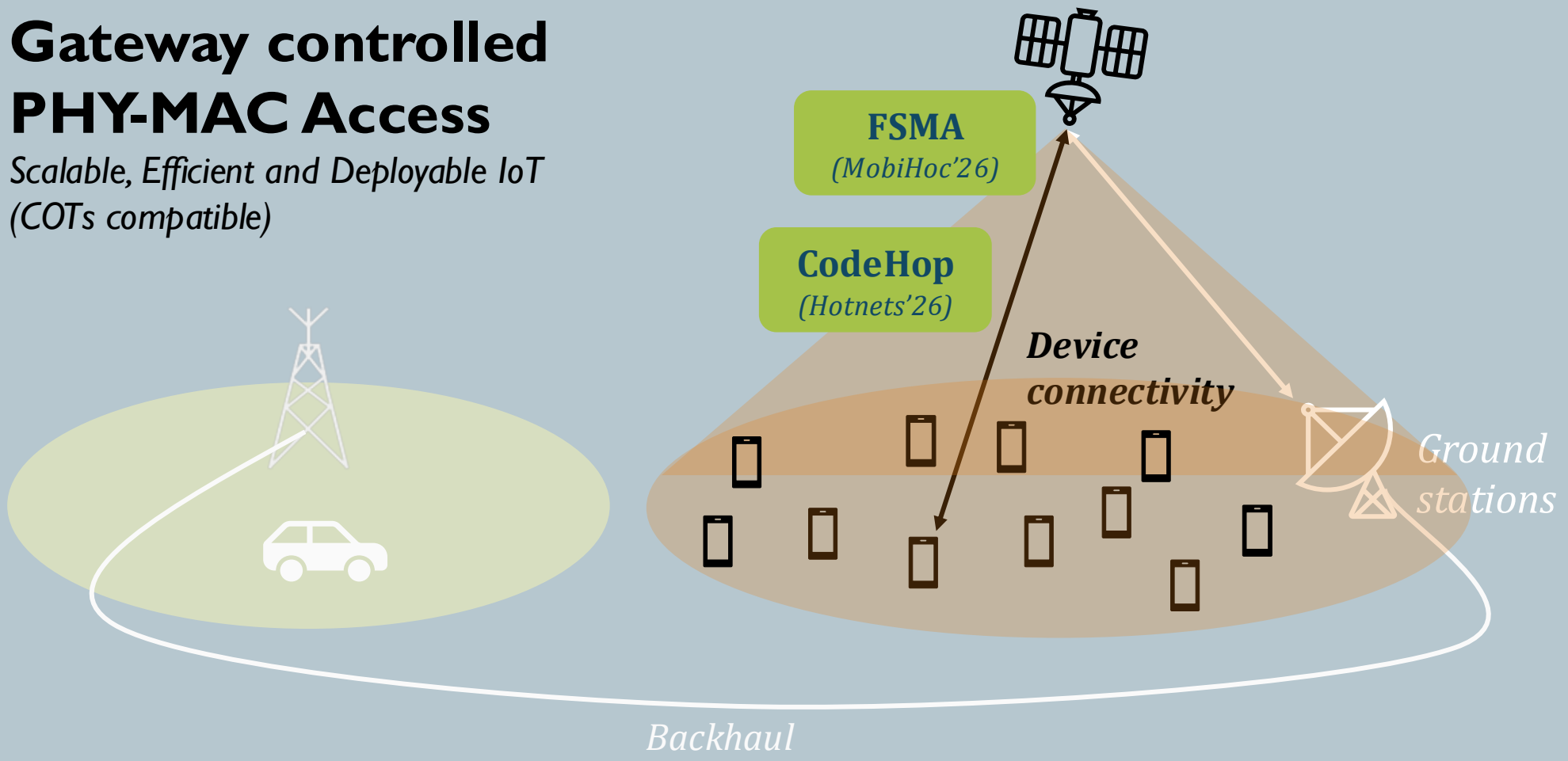
Full more details refer:
wcsng.ucsd.edu/arraylink/

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Part2: Scaling device connectivity

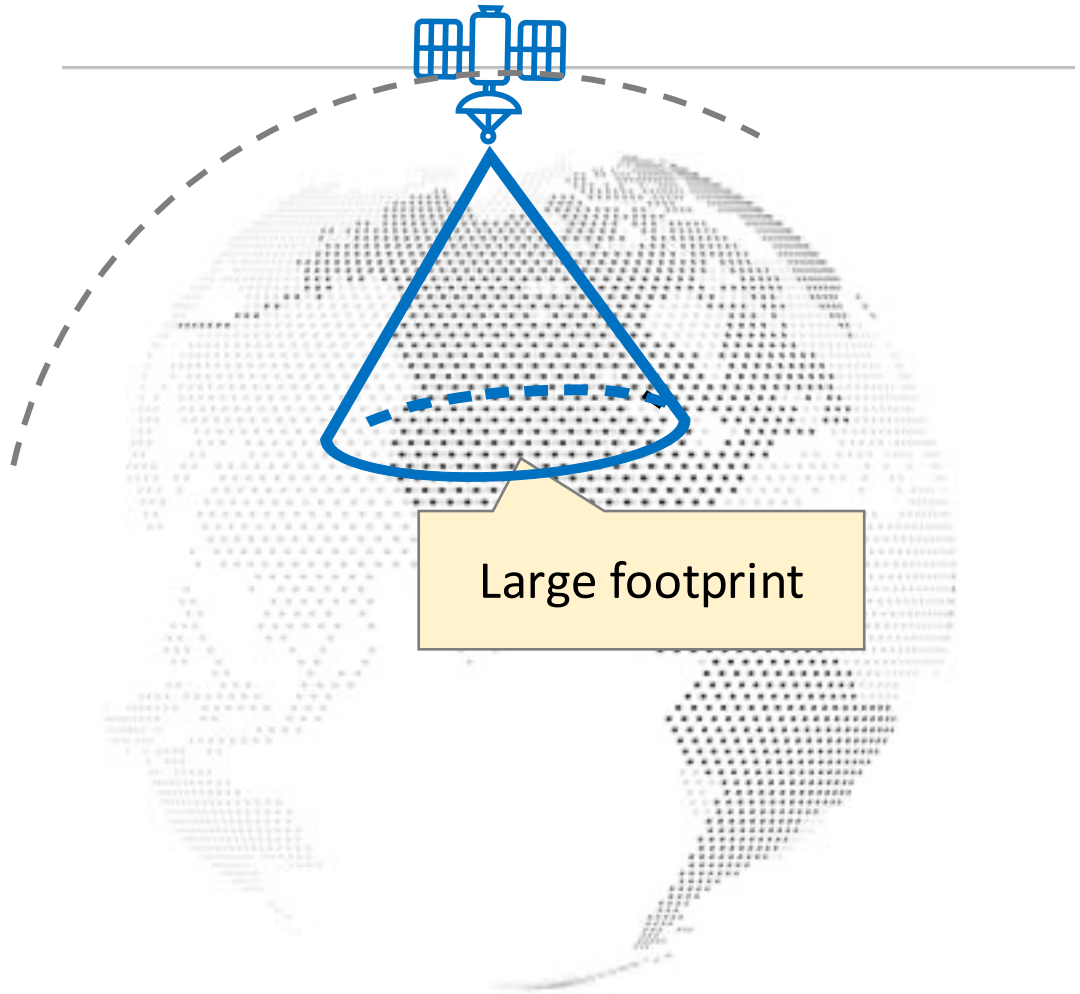
Gateway controlled PHY-MAC Access

Scalable, Efficient and Deployable IoT (COTs compatible)



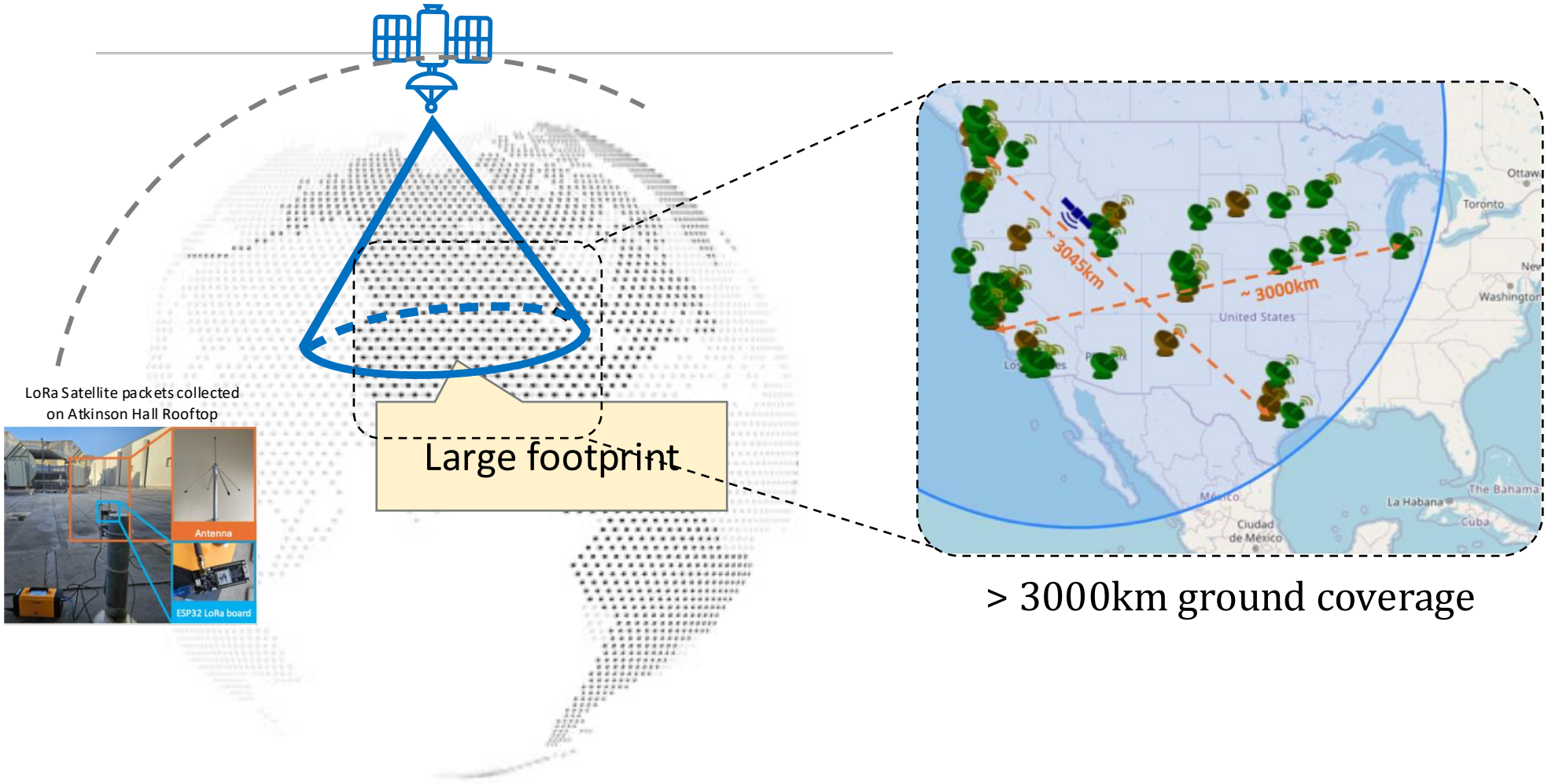
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*under review/submission

Challenges with satellite gateways: *Large footprint*



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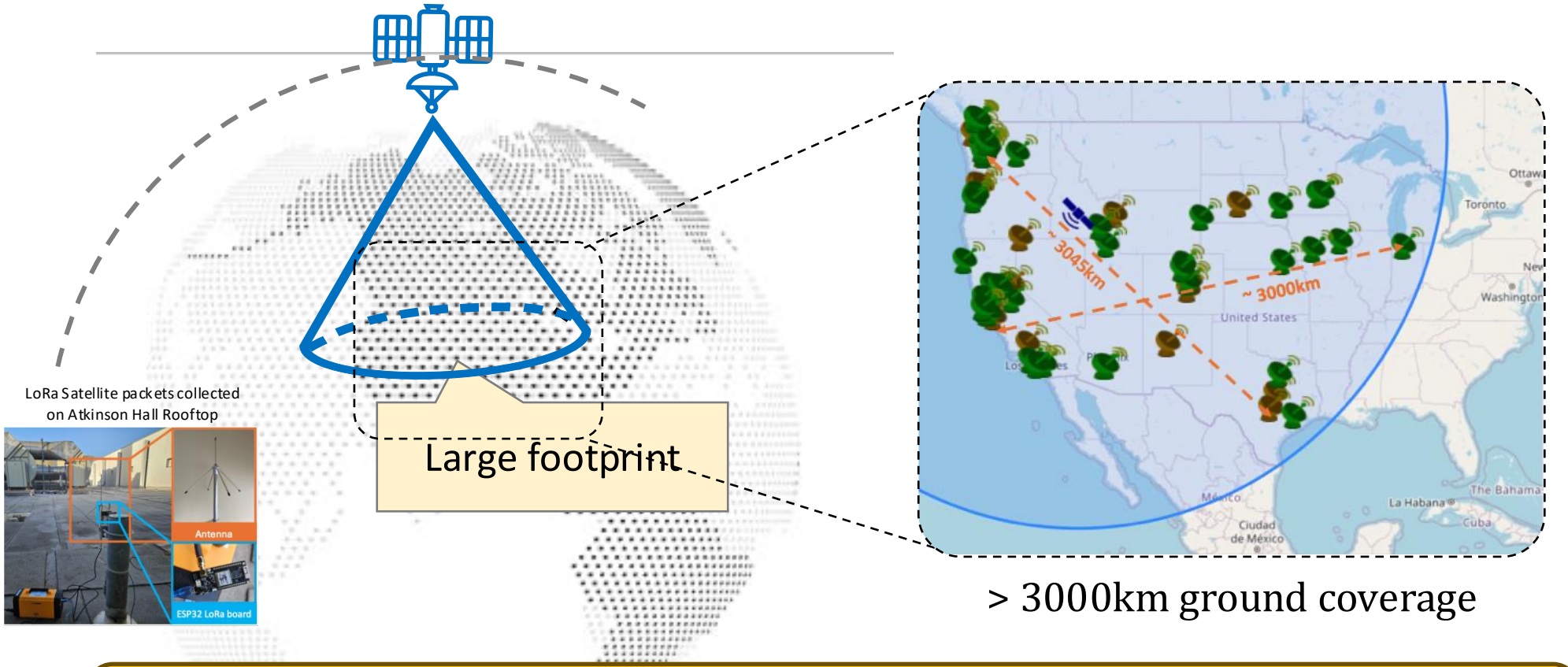
Challenges with satellite gateways: *Large footprint*



> 3000km ground coverage

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Challenges with satellite gateways: *Large footprint*

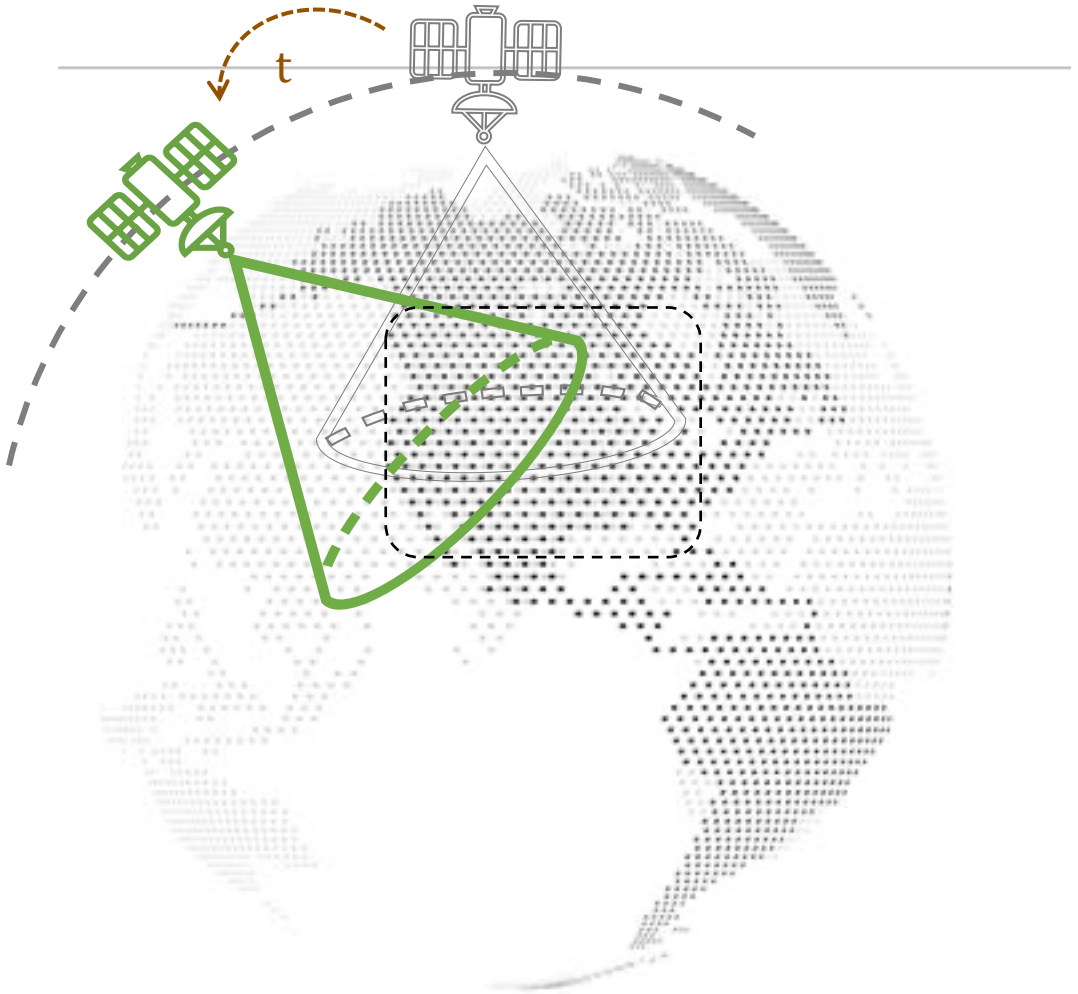


> 3000km ground coverage

Large footprint → huge number of active devices
(contends for the same channel leading to collisions, packet loss)

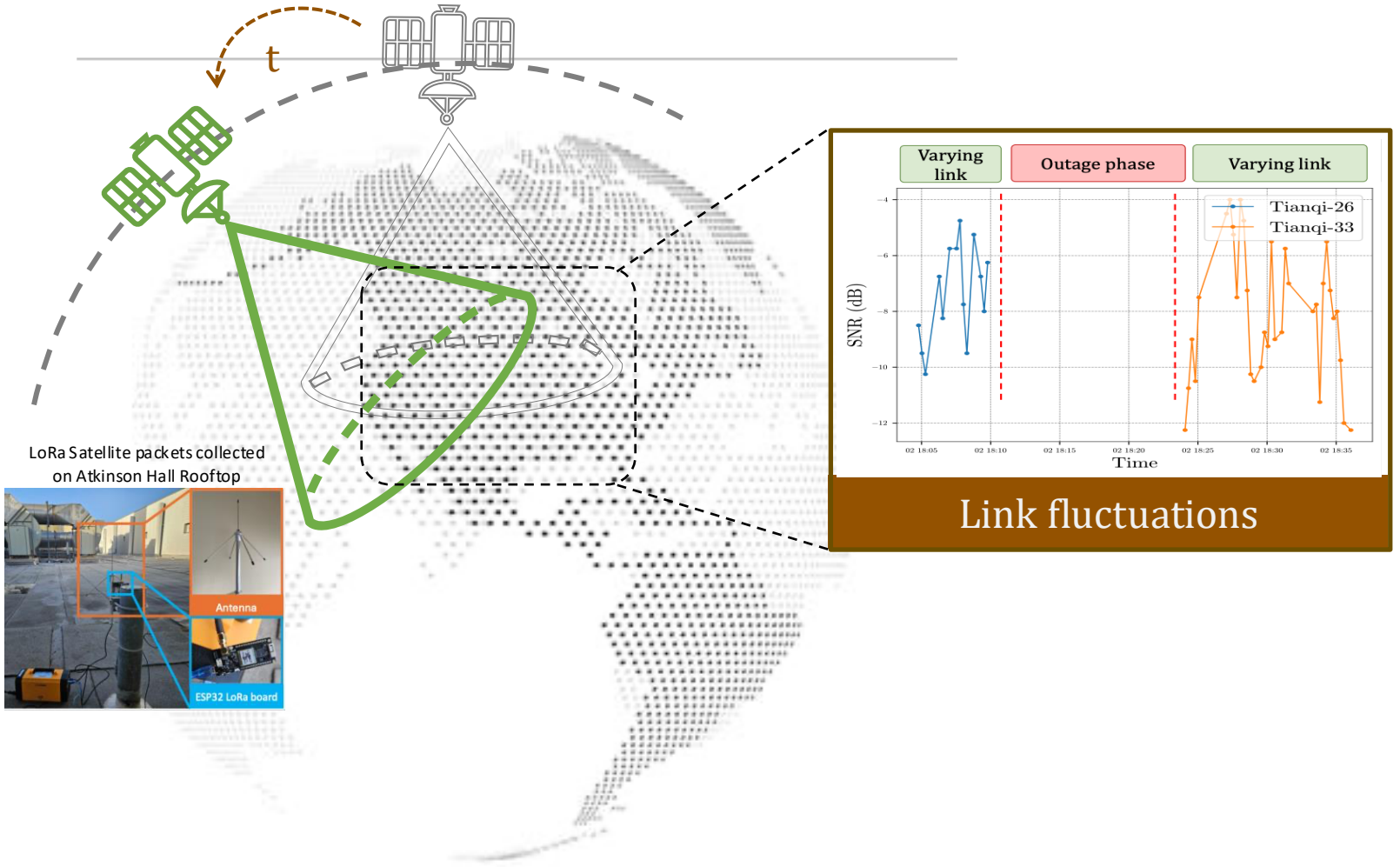
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Challenges with satellite gateways: *Moving gateways*



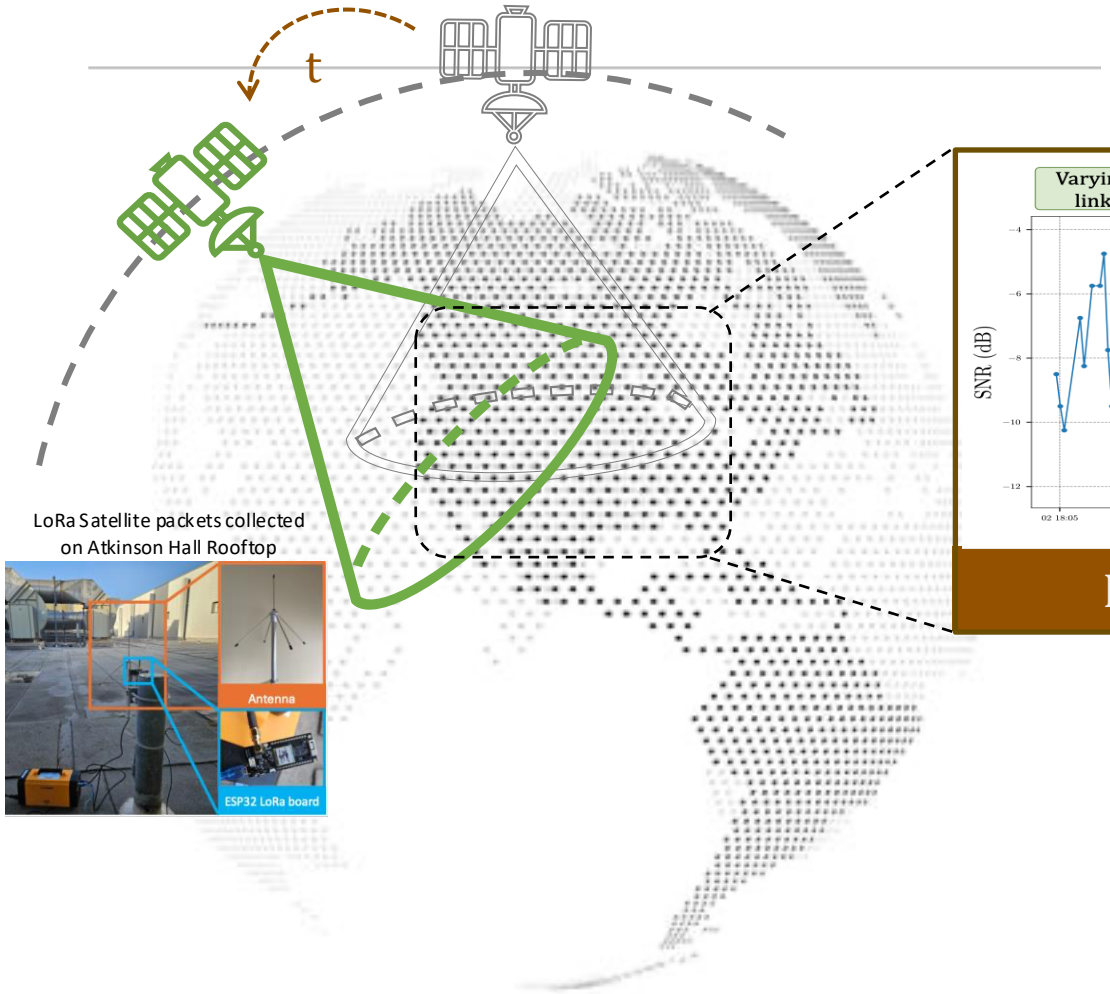
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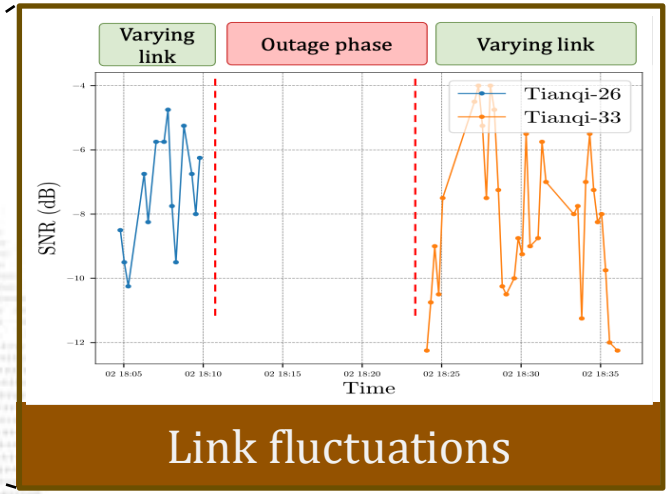
Challenges with satellite gateways: *Moving gateways*



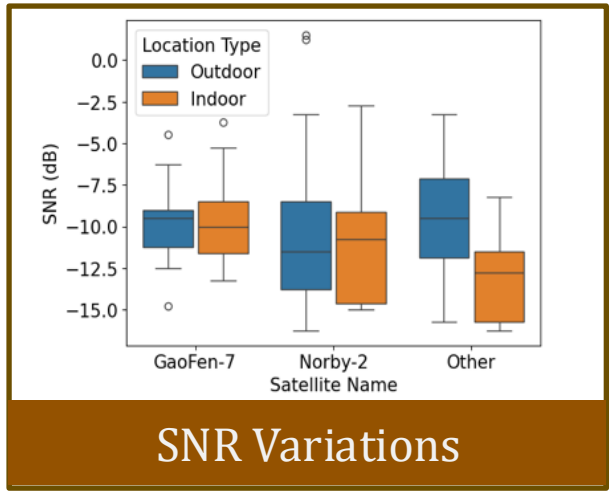
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Challenges with satellite gateways: *Moving gateways*





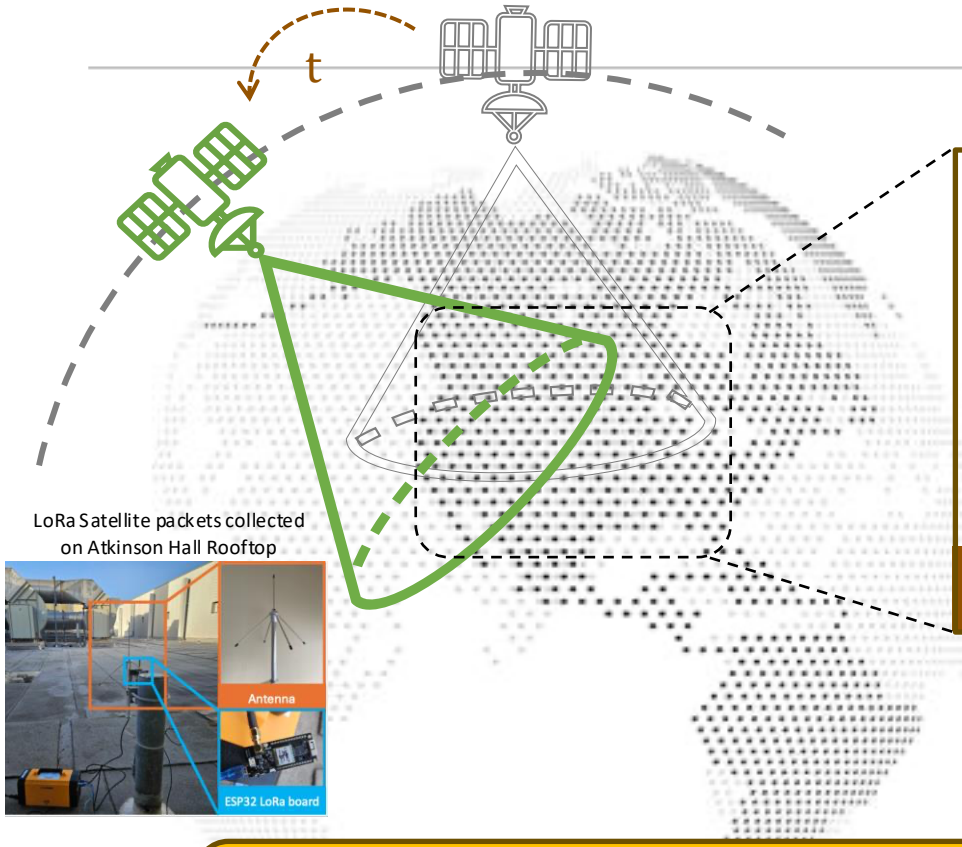
Link fluctuations

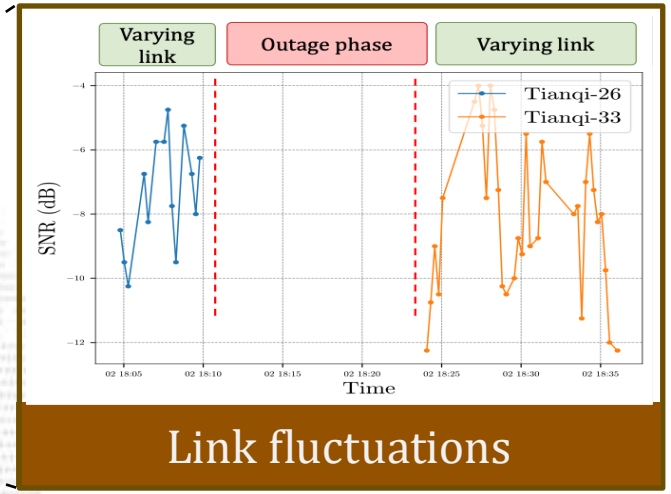


SNR Variations

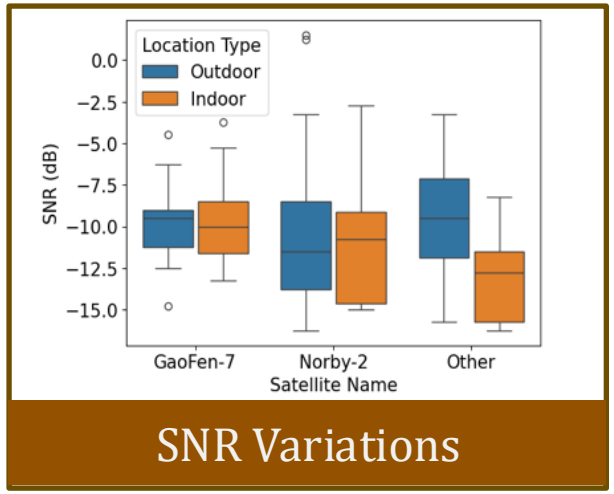
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Challenges with satellite gateways: *Moving gateways*





Link fluctuations



SNR Variations

Moving gateway → Dynamic and fluctuating links
(unreliable links leading to packet loss)

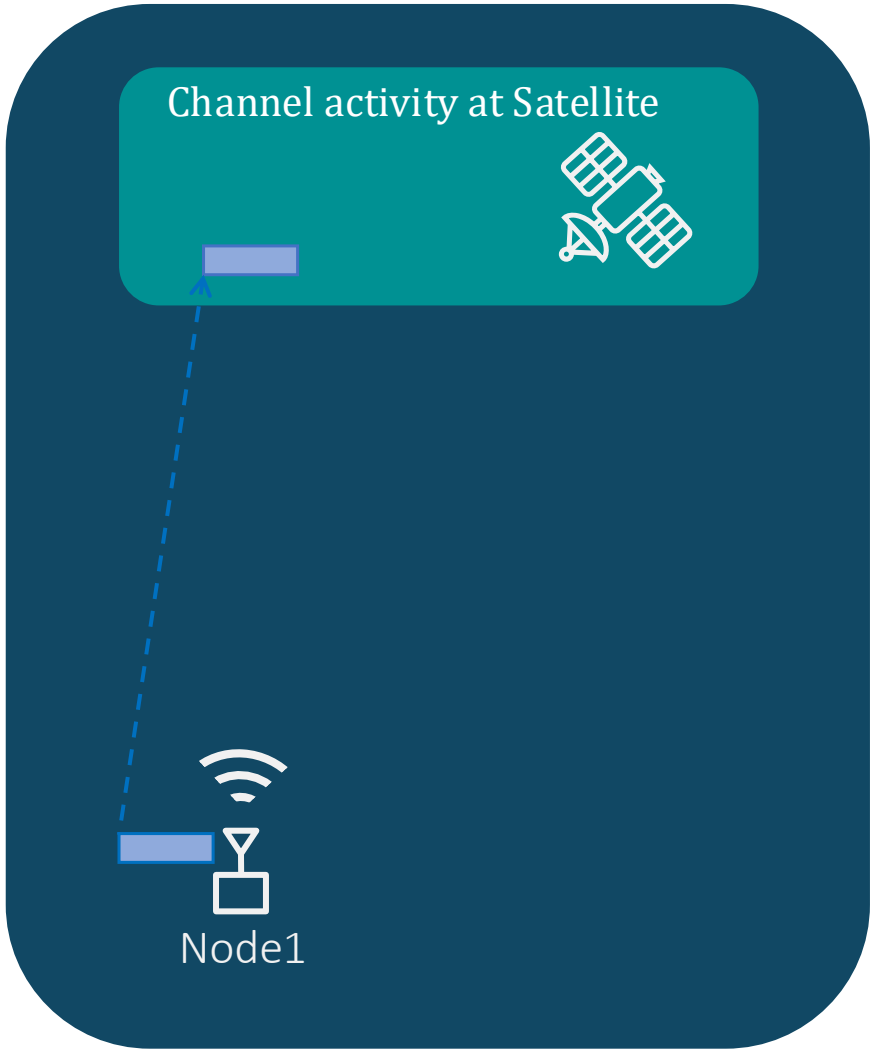
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Existing solutions: ALOHA



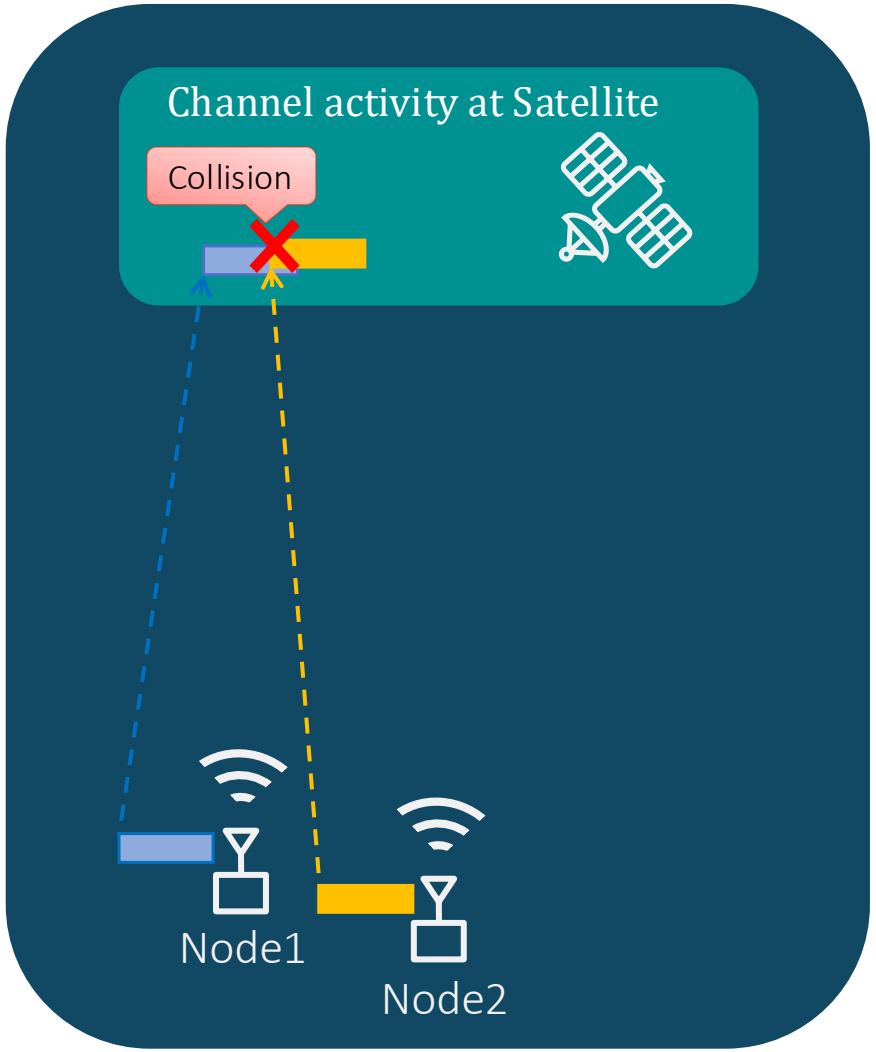
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Existing solutions: ALOHA



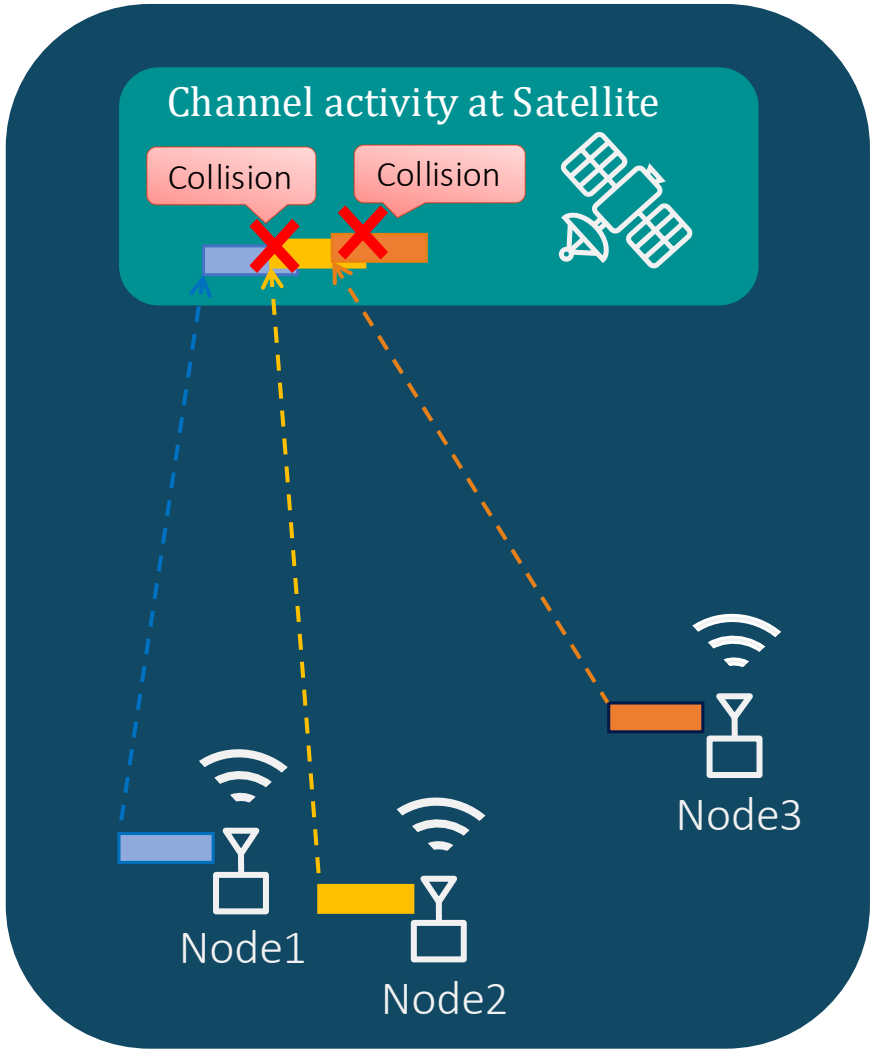
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Existing solutions: ALOHA



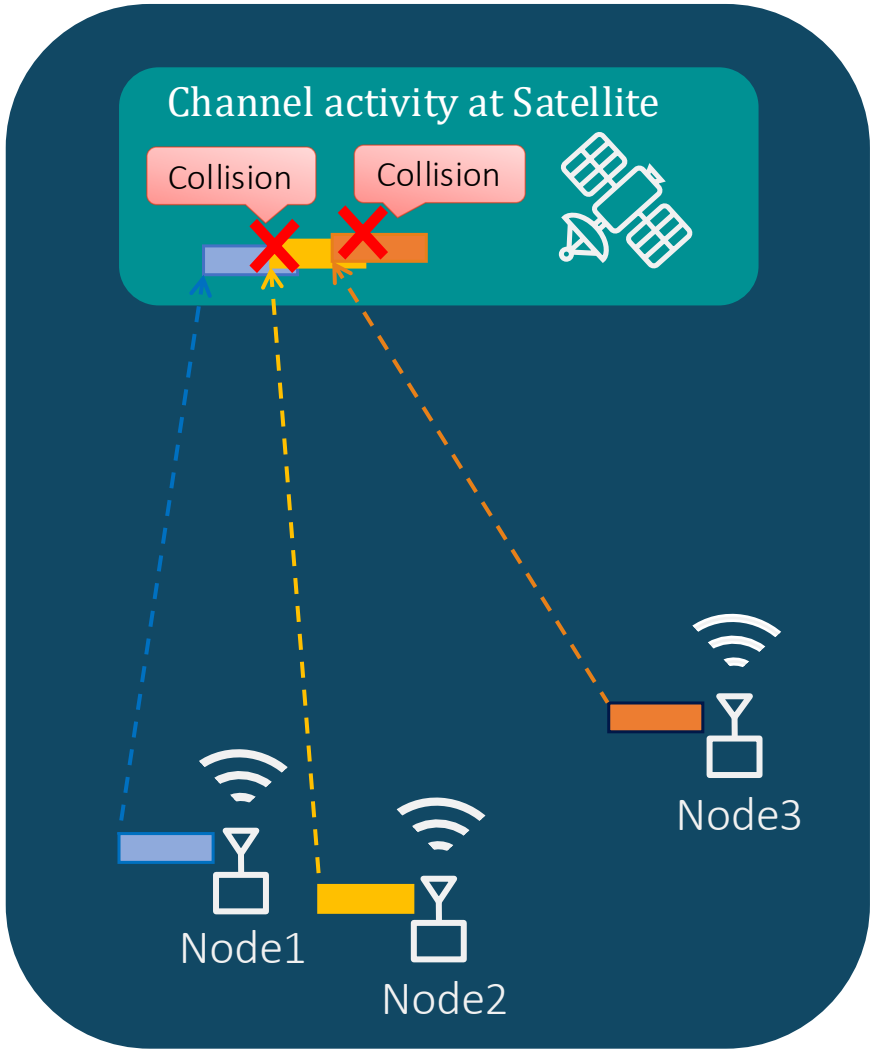
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Existing solutions: ALOHA



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Existing solutions: ALOHA



Collisions mitigation	✗
Link-aware access	✗
Energy efficient (nodes)	✗
Energy efficient (gateway)	✓
Off-the-shelf hardware	✓

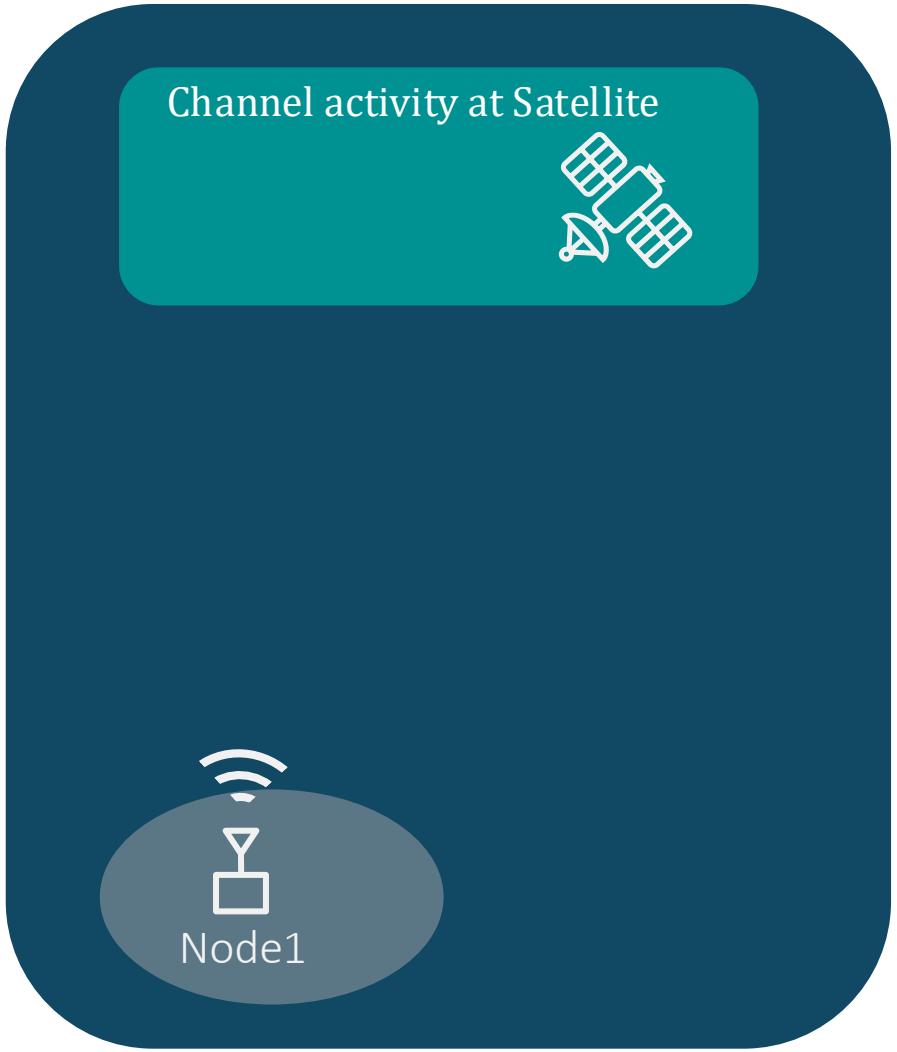
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Existing solutions: Carrier-sense Multiple Access (CSMA)



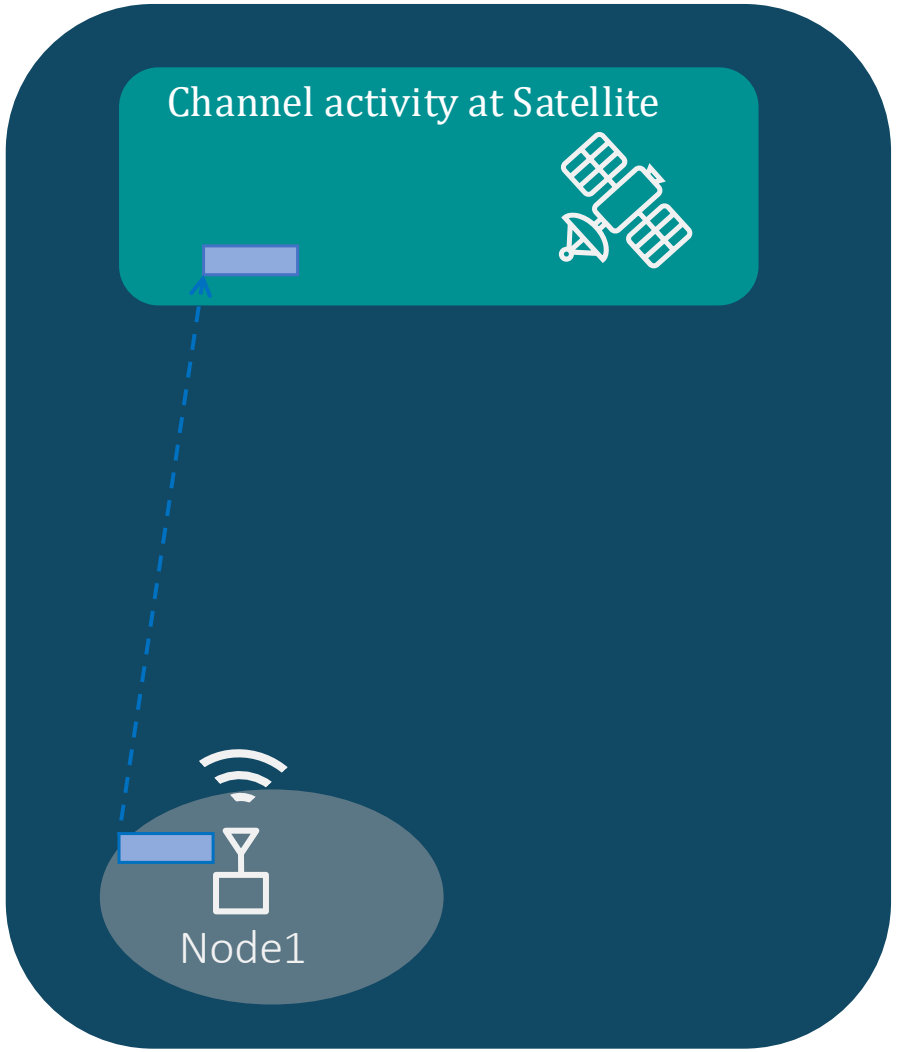
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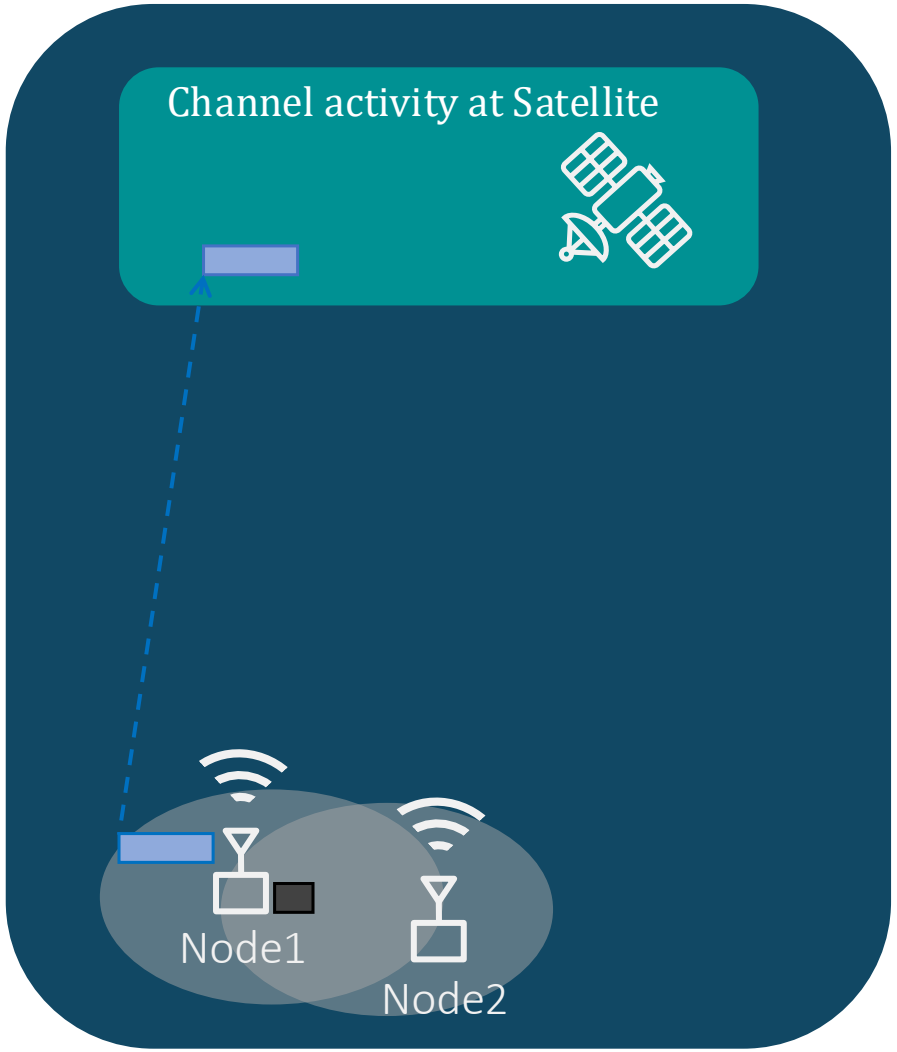
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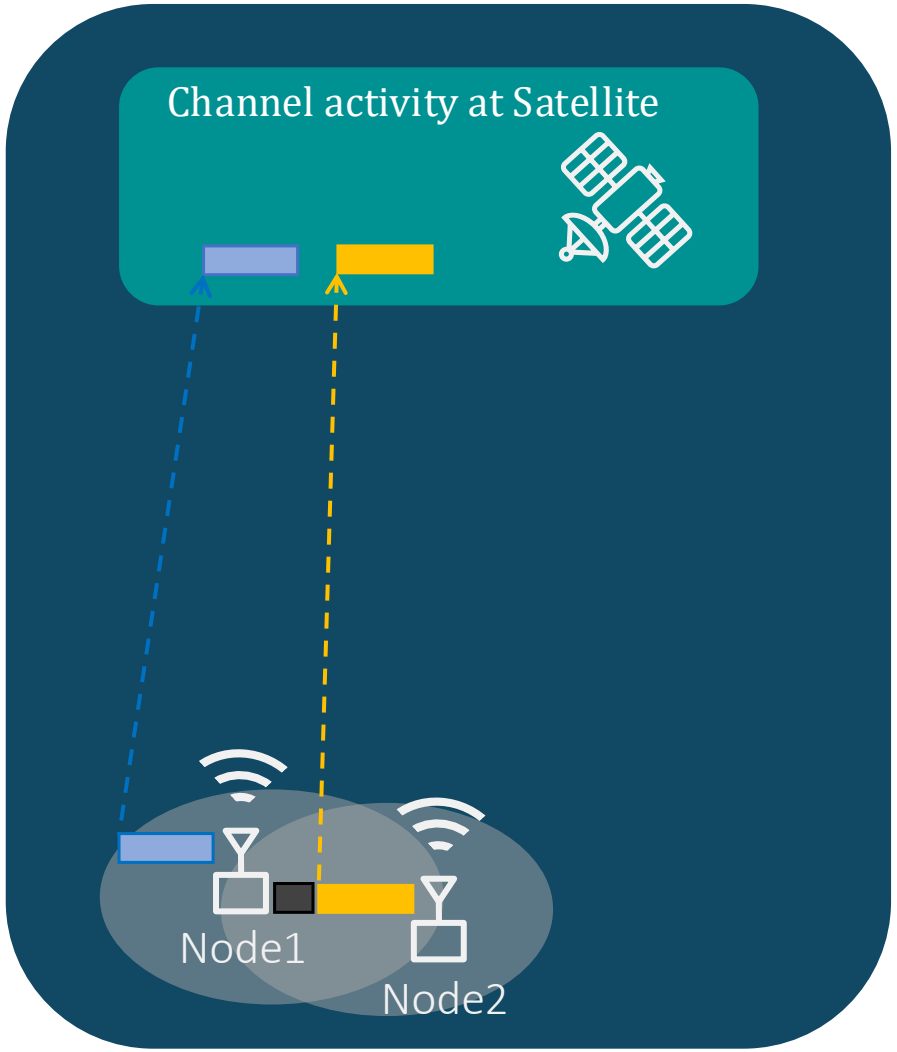
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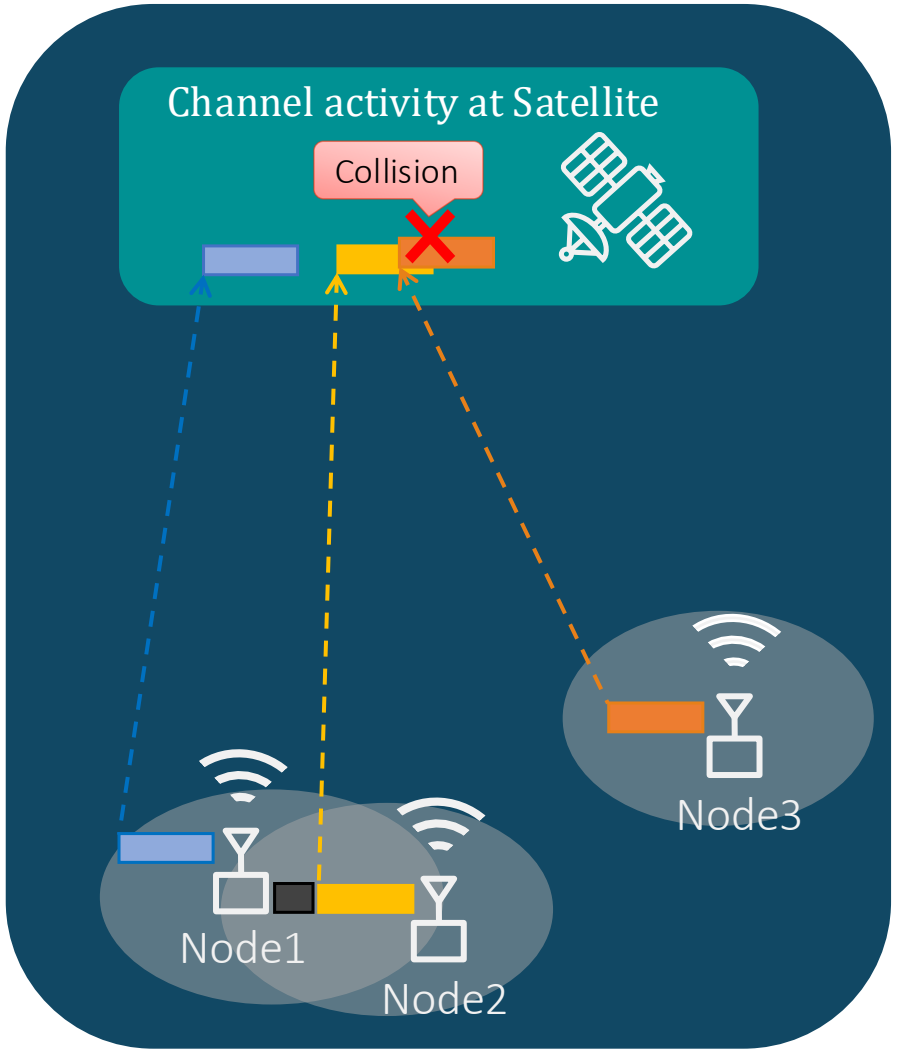
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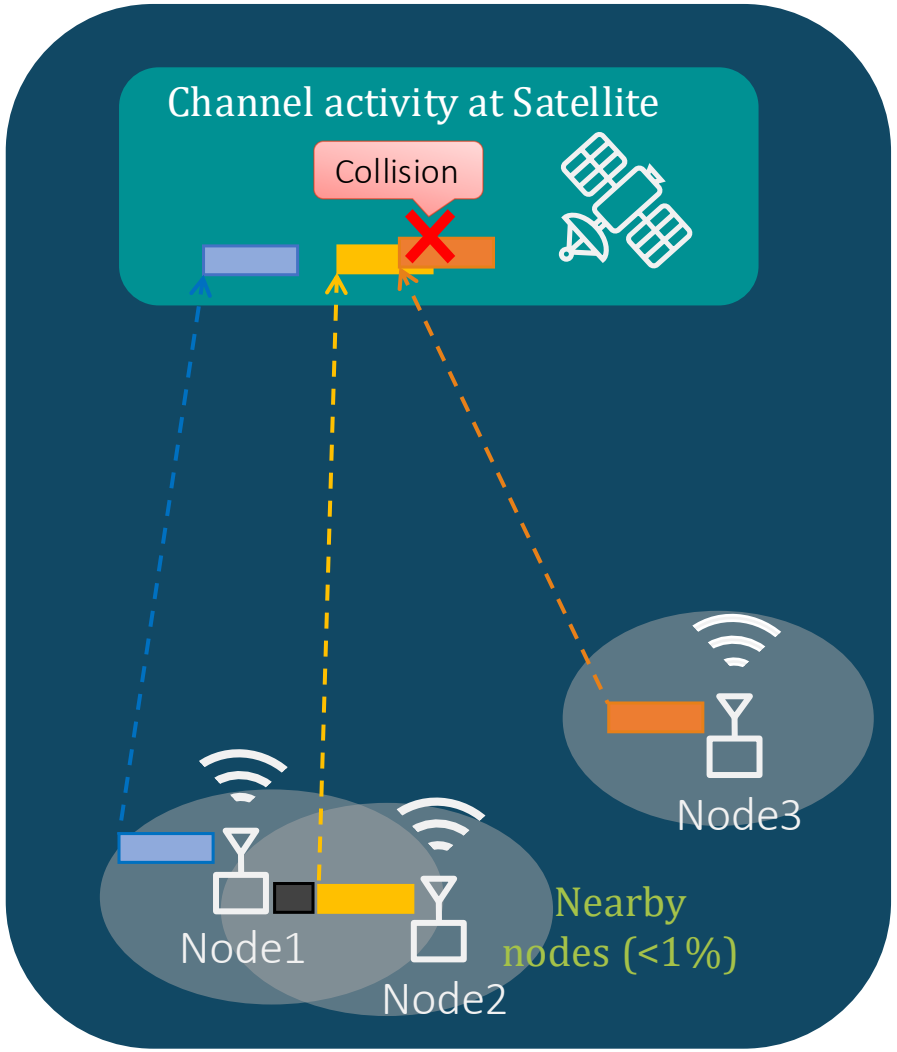
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Existing solutions: Carrier-sense Multiple Access (CSMA)



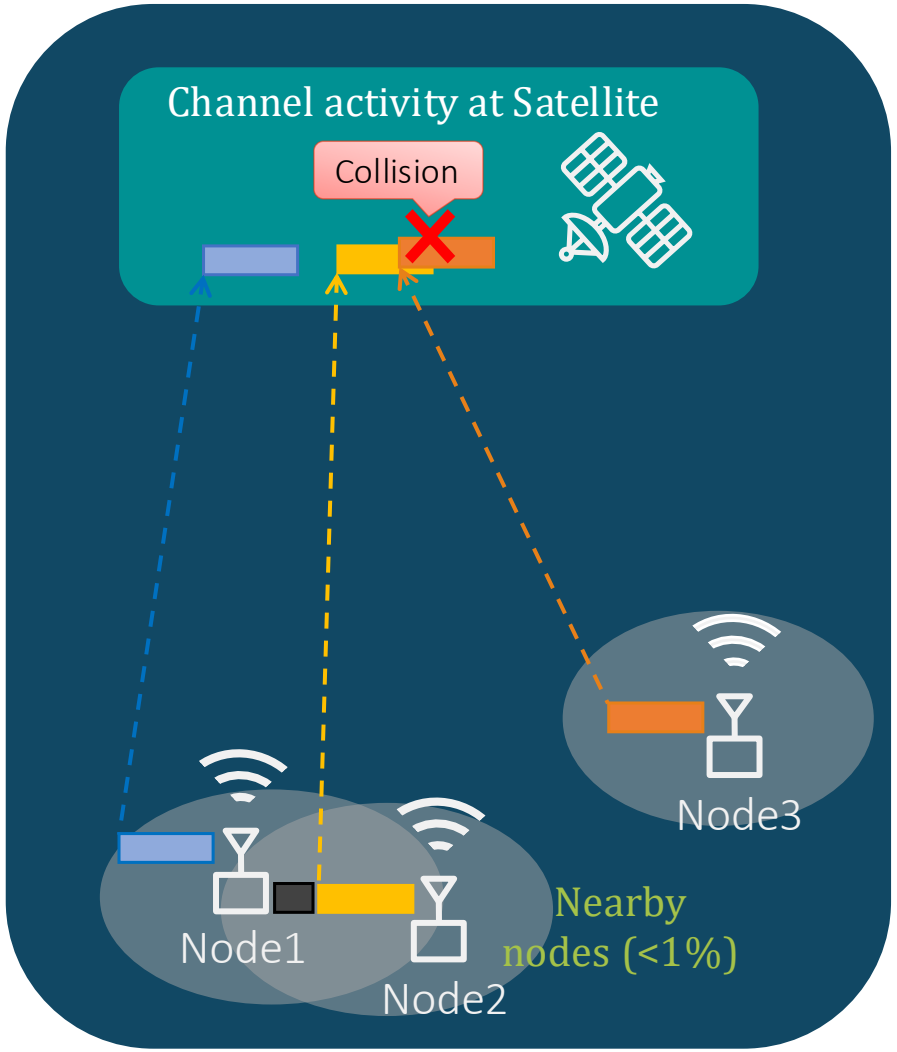
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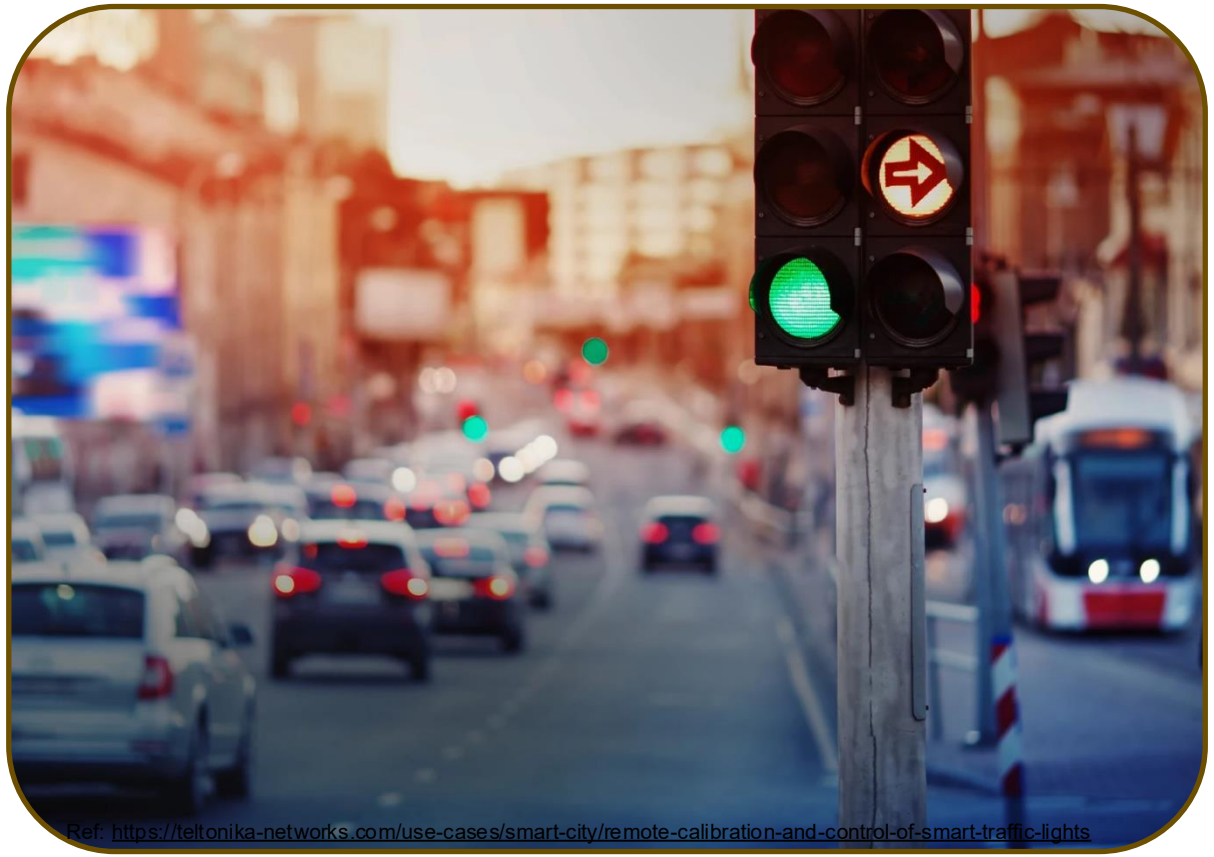
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Collisions mitigation	✗
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Energy efficient (gateway)	✓
Off-the-shelf hardware	✓

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Our approach: Free Signal Multiple Access (FSMA)



Ref: https://teltonika-networks.com/use-cases/smart-city/remote-calibration-and-control-of-smart-traffic-lights

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Our approach: Free Signal Multiple Access (FSMA)



FSMA: Sends free signal → nodes transmit
Stops free signal → nodes backoff

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Our approach: Free Signal Multiple Access (FSMA)

Channel activity at Satellite



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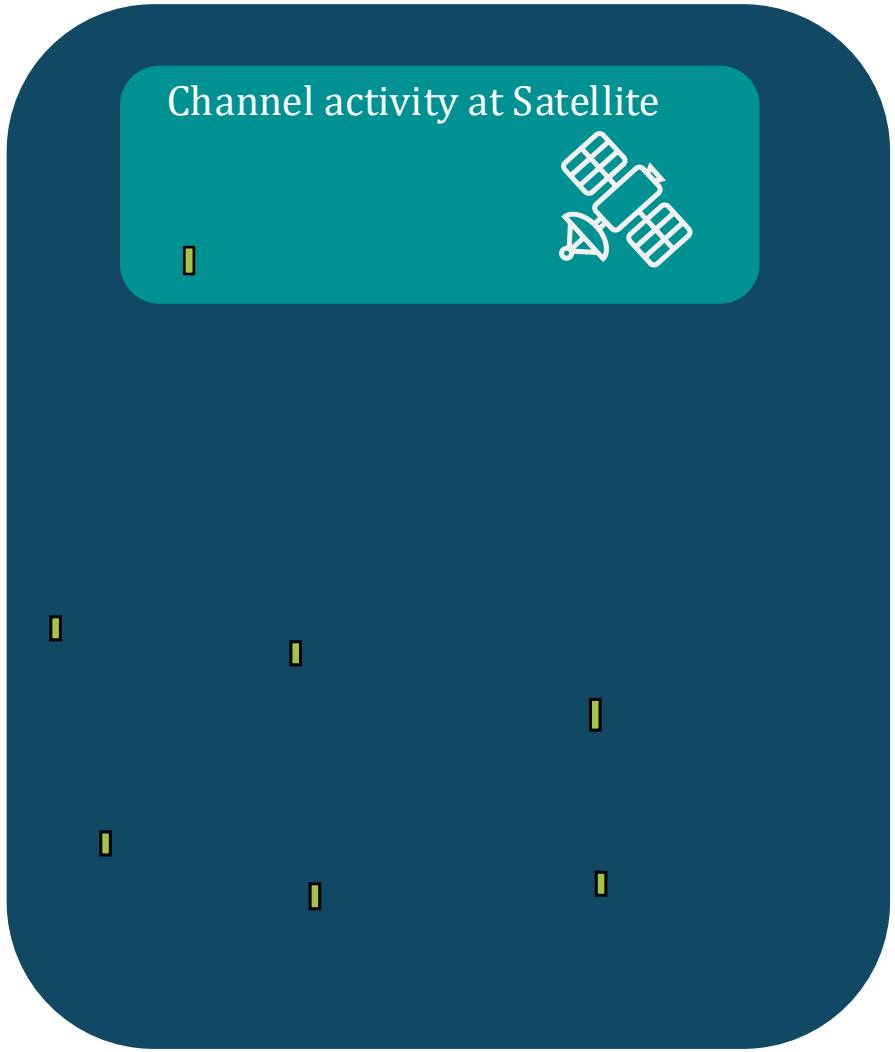
Our approach: Free Signal Multiple Access (FSMA)

Channel activity at Satellite



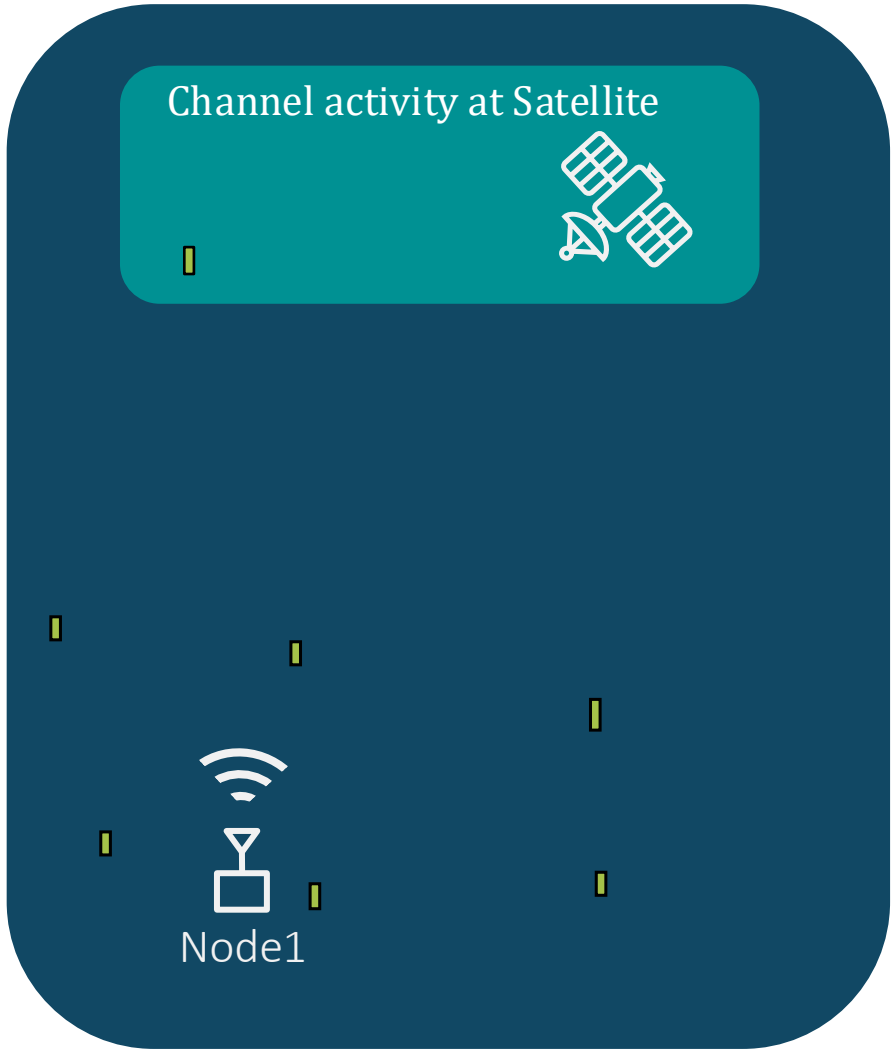
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Our approach: Free Signal Multiple Access (FSMA)



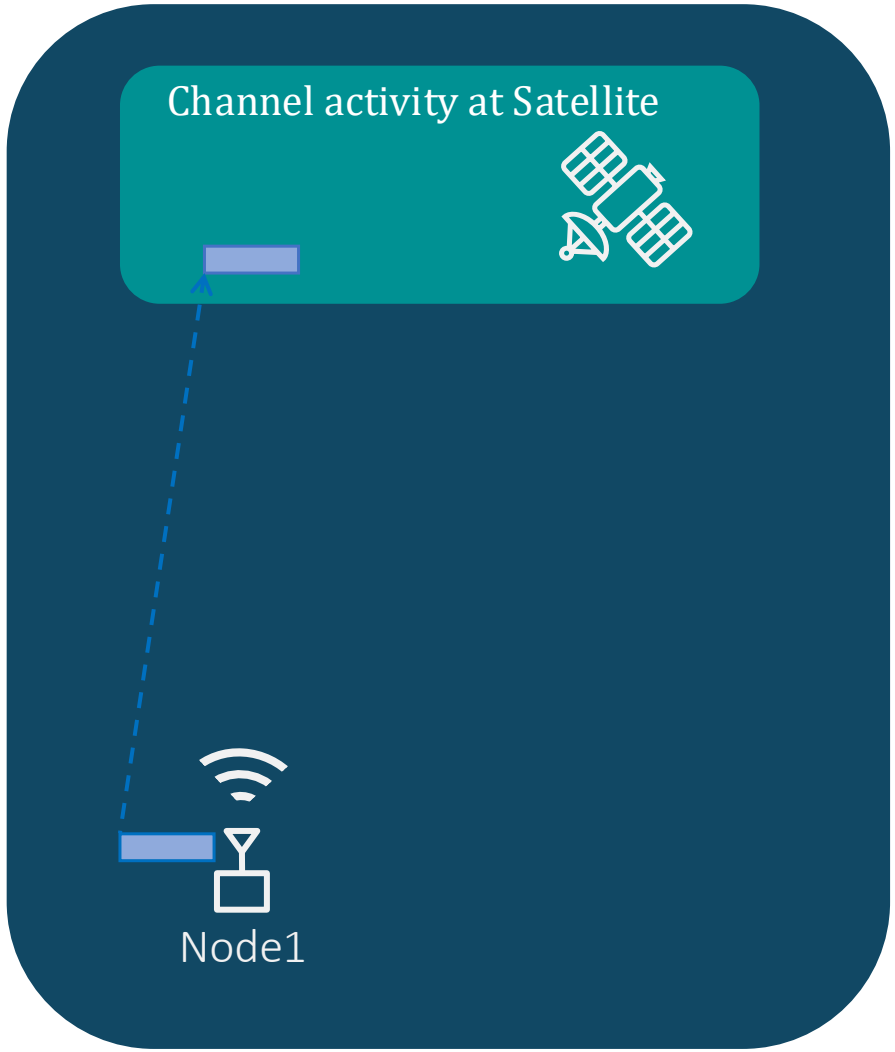
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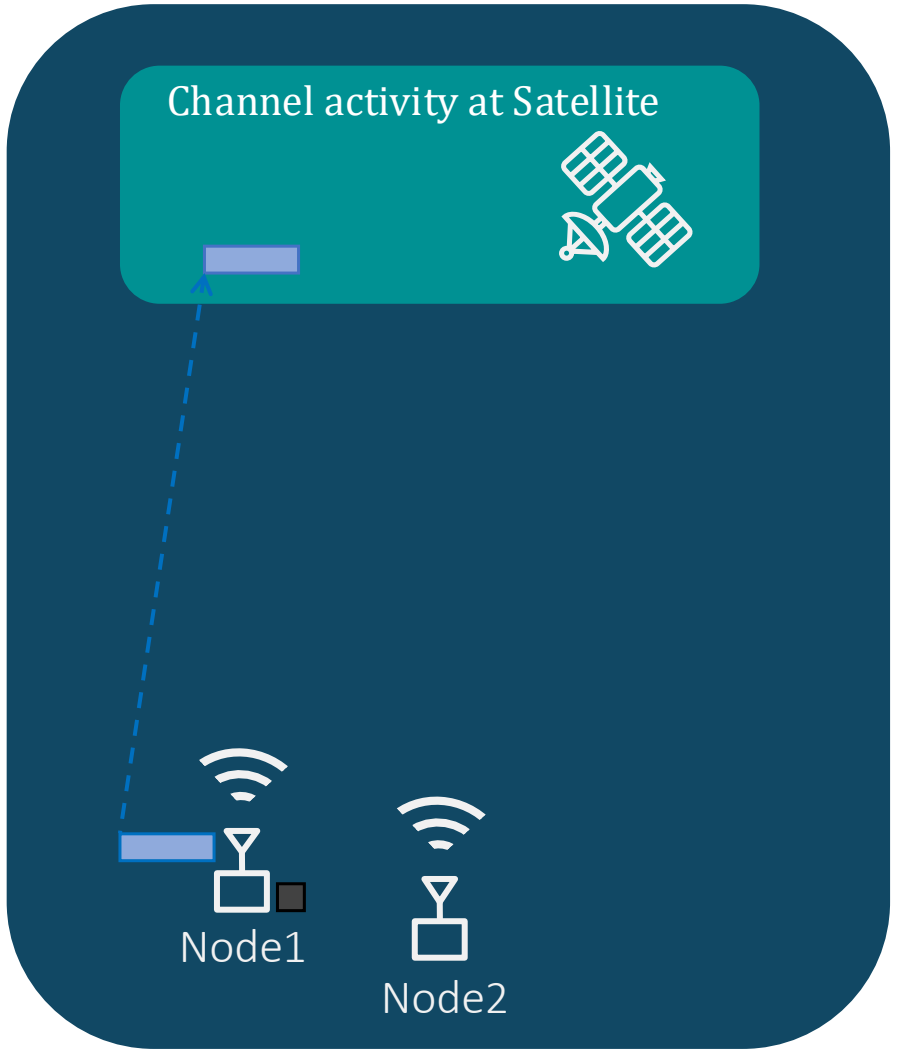
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Our approach: Free Signal Multiple Access (FSMA)



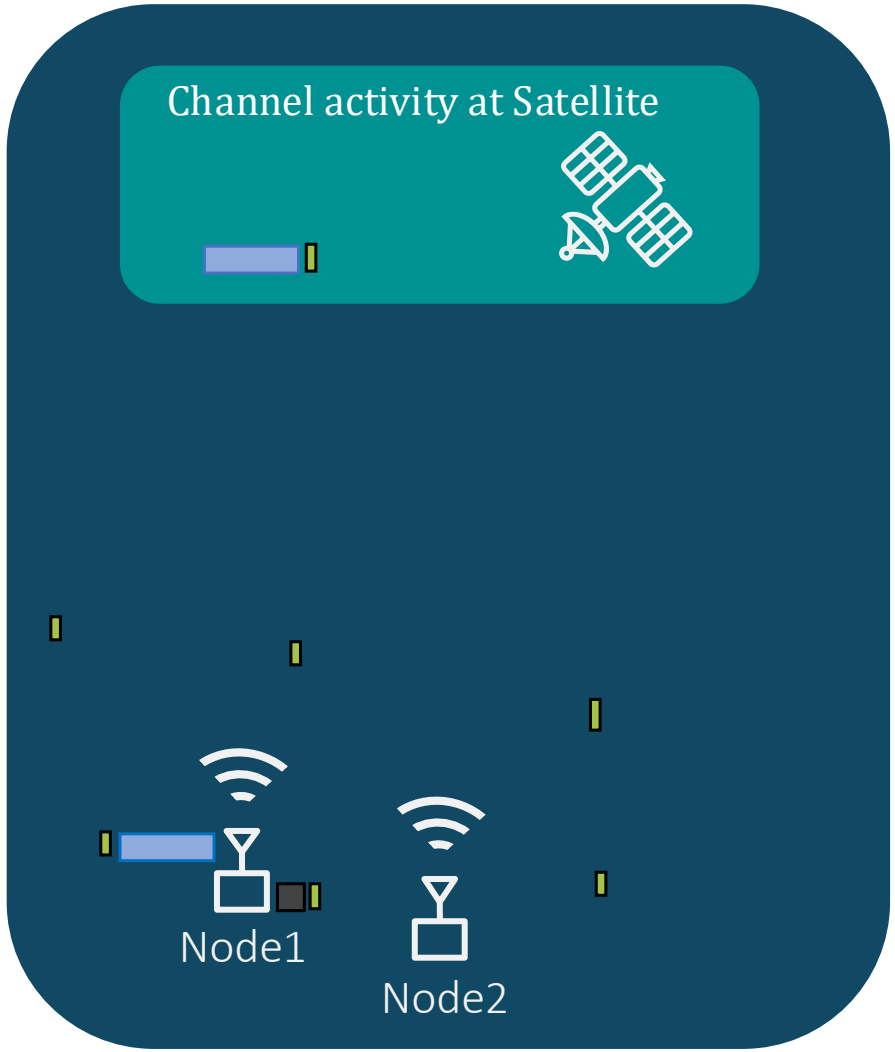
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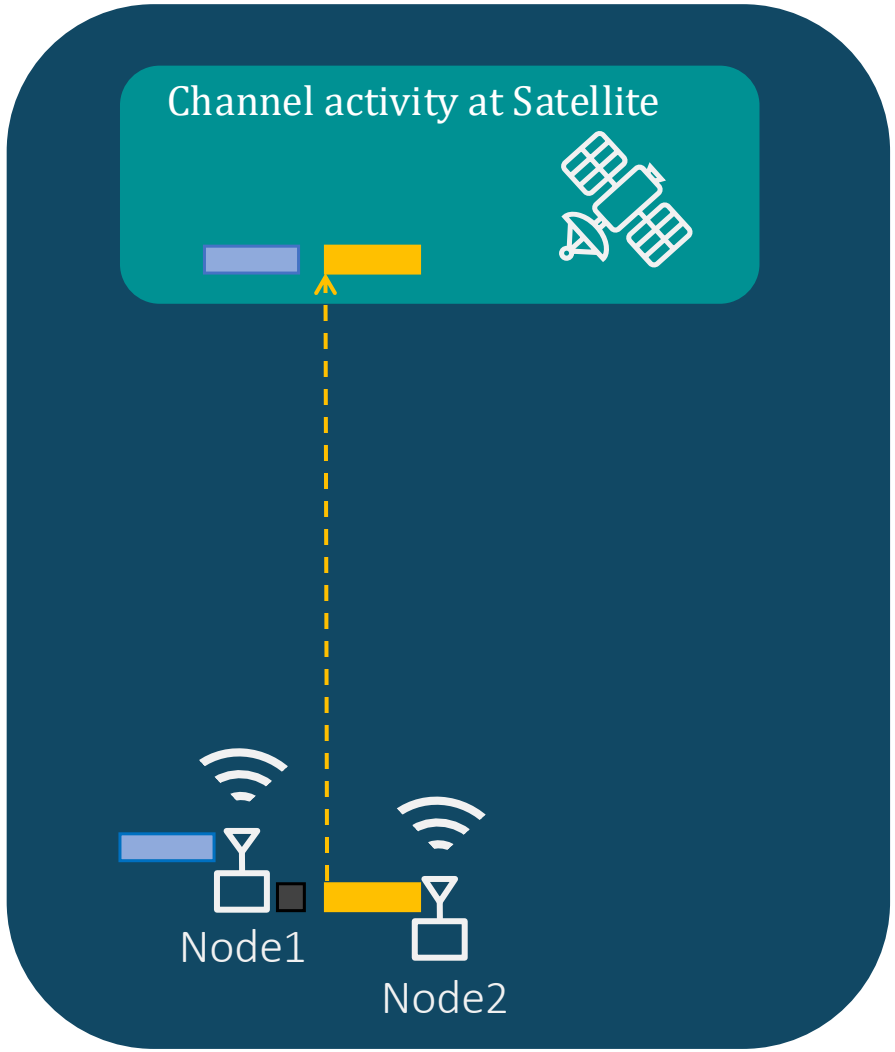
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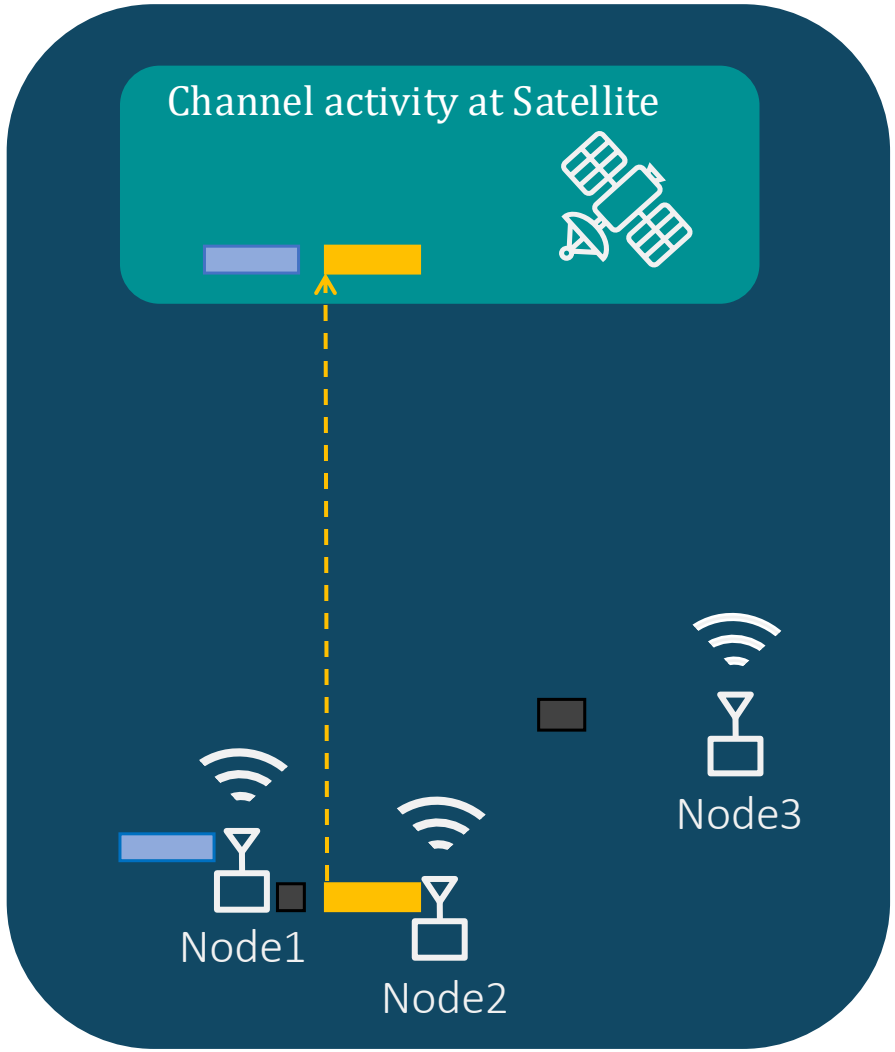
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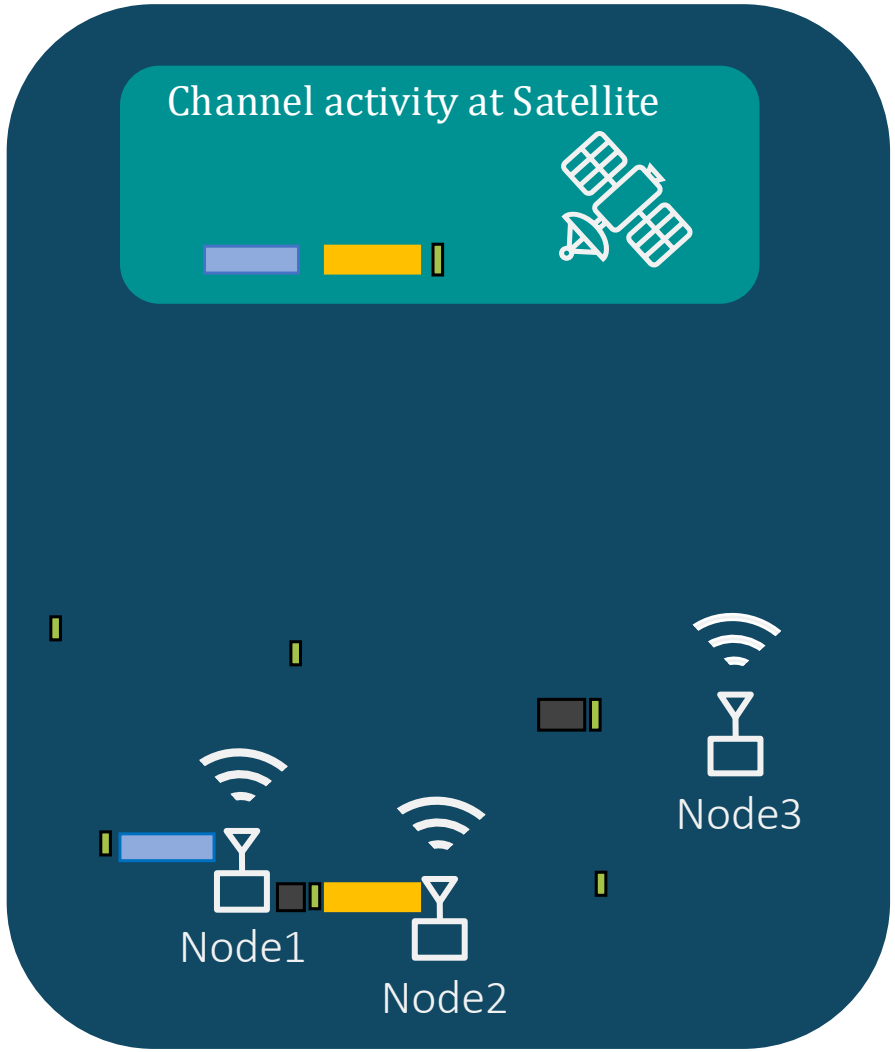
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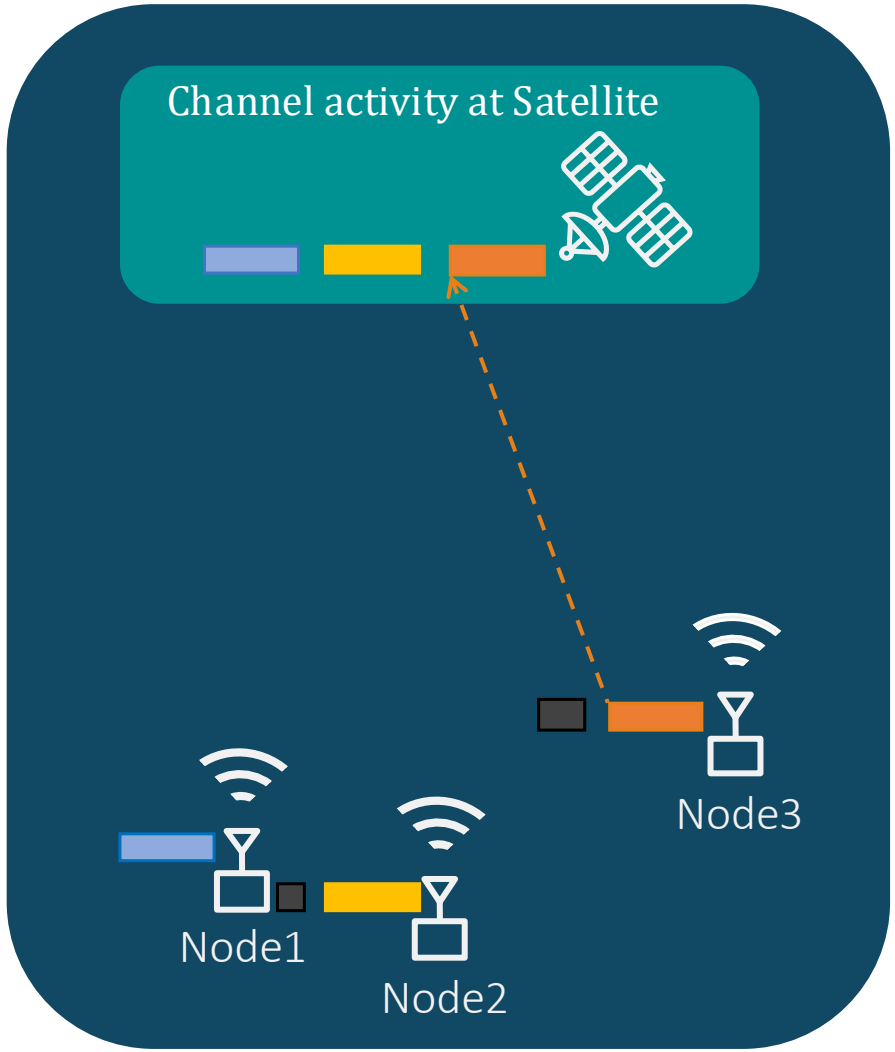
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Our approach: Free Signal Multiple Access (FSMA)



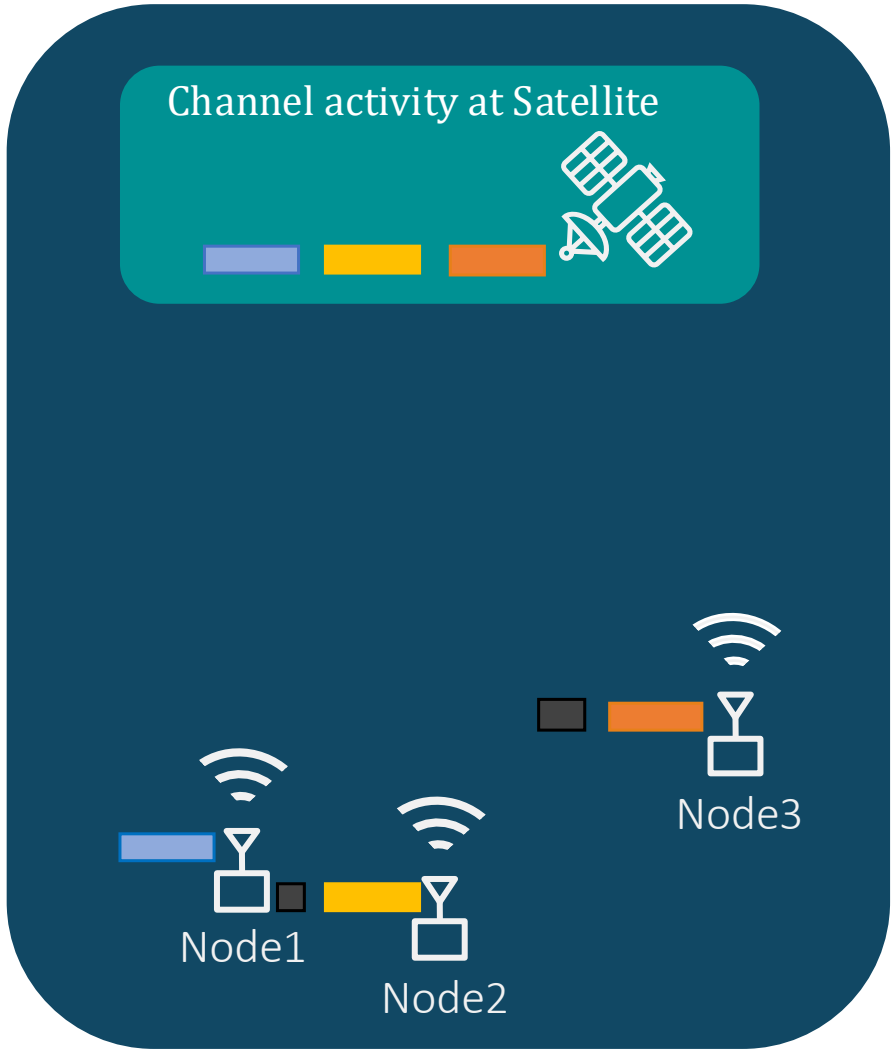
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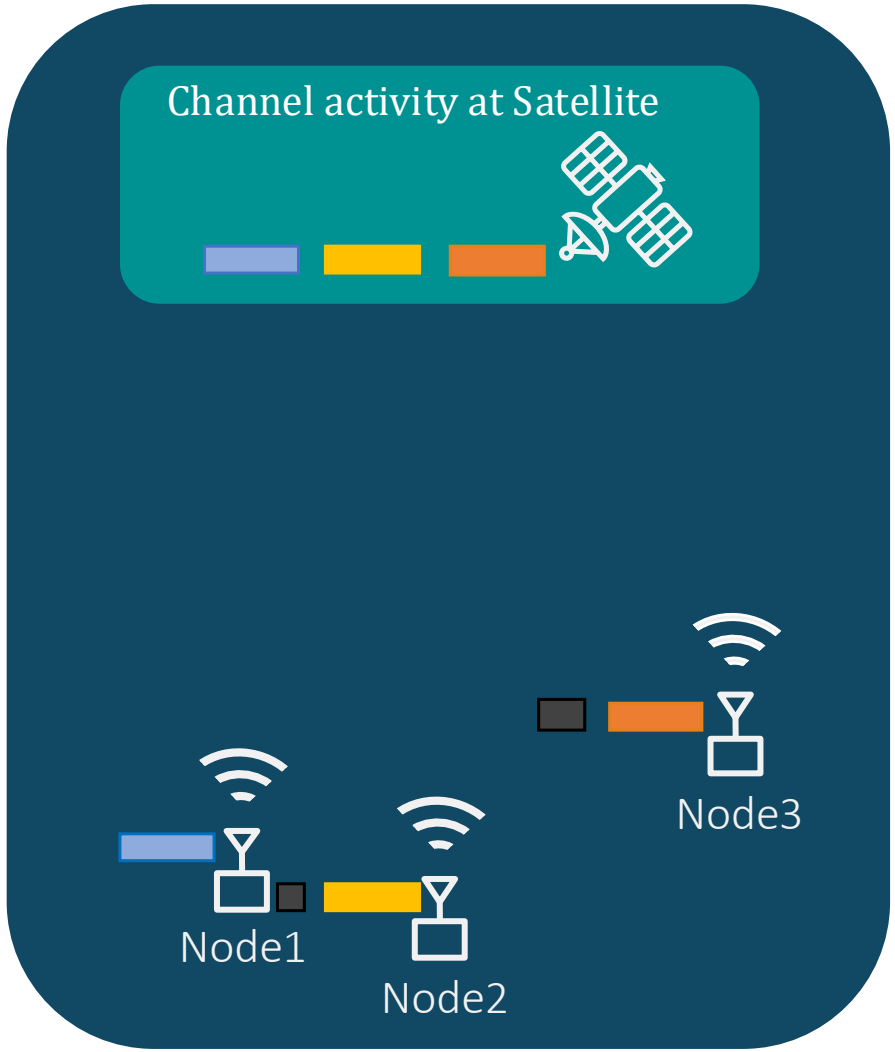
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Our approach: Free Signal Multiple Access (FSMA)



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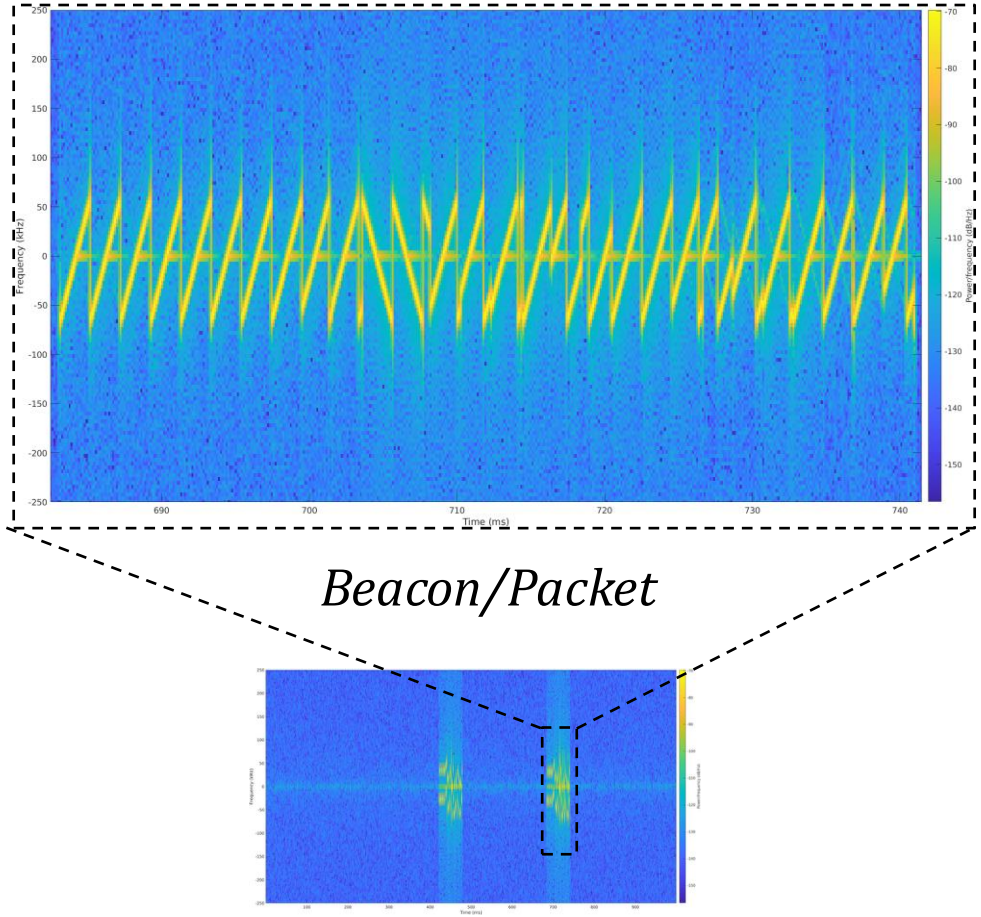


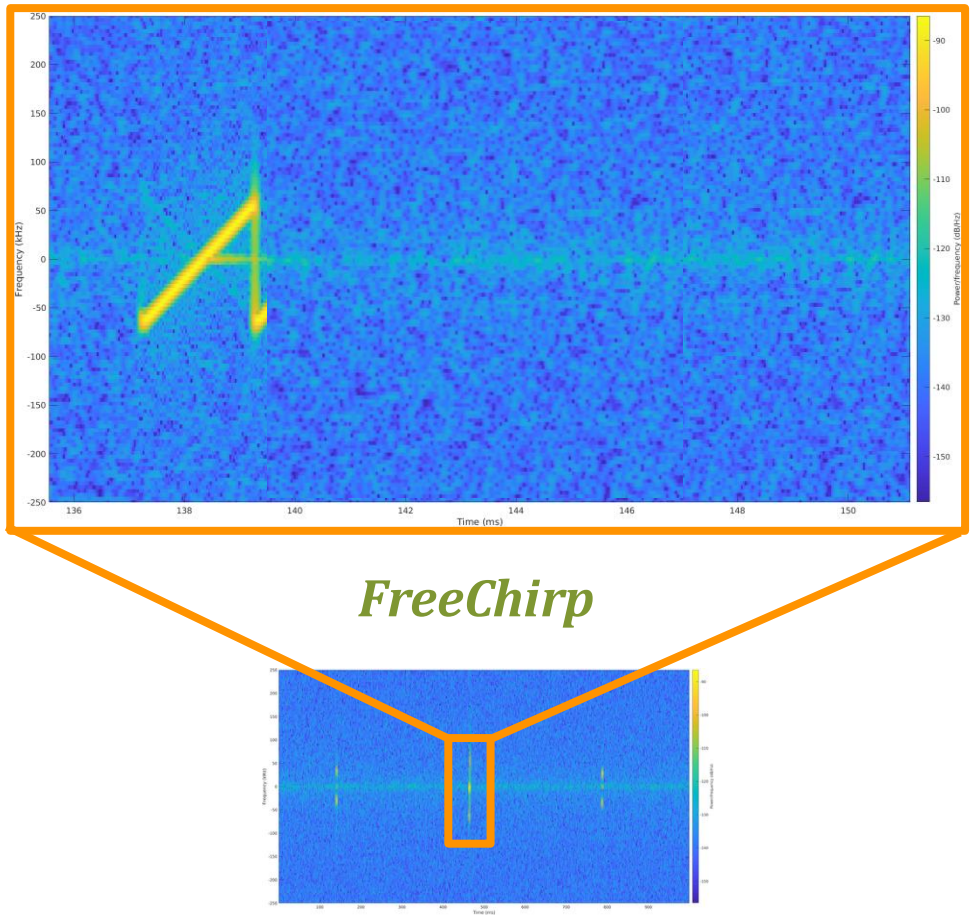
Requirements	Aloha	CSMA	BSMA	FSMA
Collisions mitigation	✗	✗	✓	✓
Link-aware access	✗	✗	✗	✓
Energy efficient (nodes)	✗	✗	✓	✓
Energy efficient (gateway)	✓	✓	✗	✓
Off-the-shelf hardware	✓	✓	✗	✓

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What is a ***FreeChirp***?

Not a beacon, Not a tone, But a single LoRa up-chirp

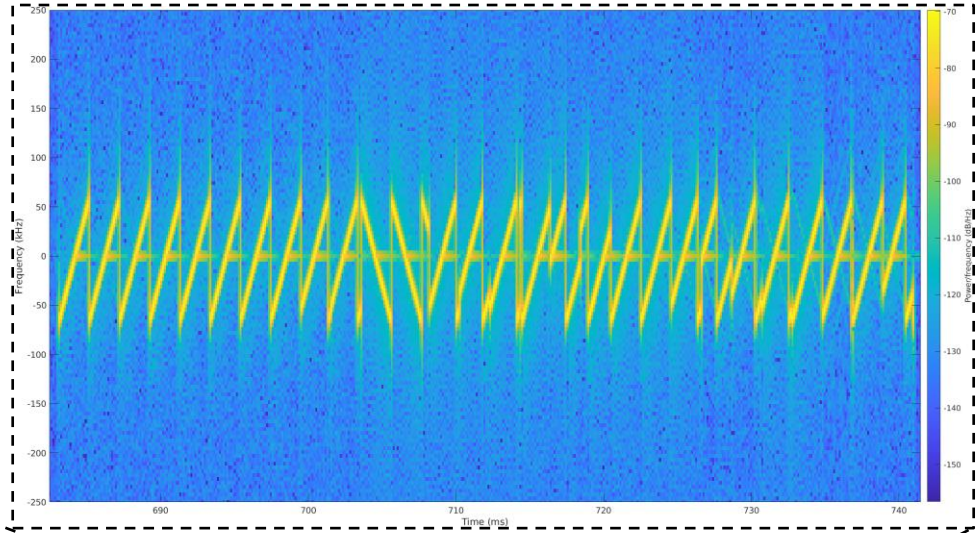




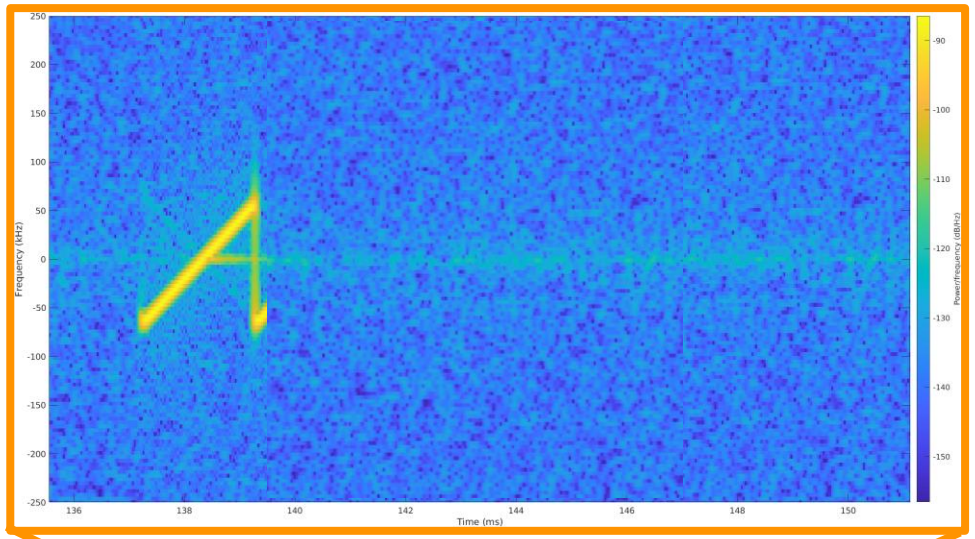
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What is a ***FreeChirp***?

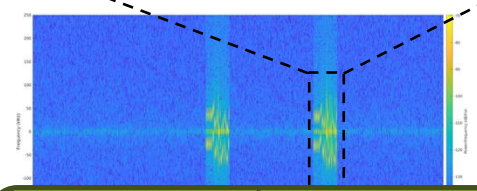
Not a beacon, Not a tone, But a single LoRa up-chirp

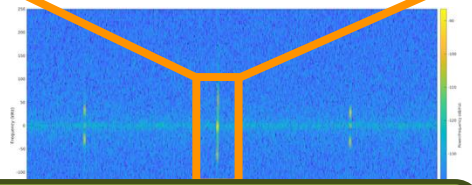


Beacon/Packet



FreeChirp

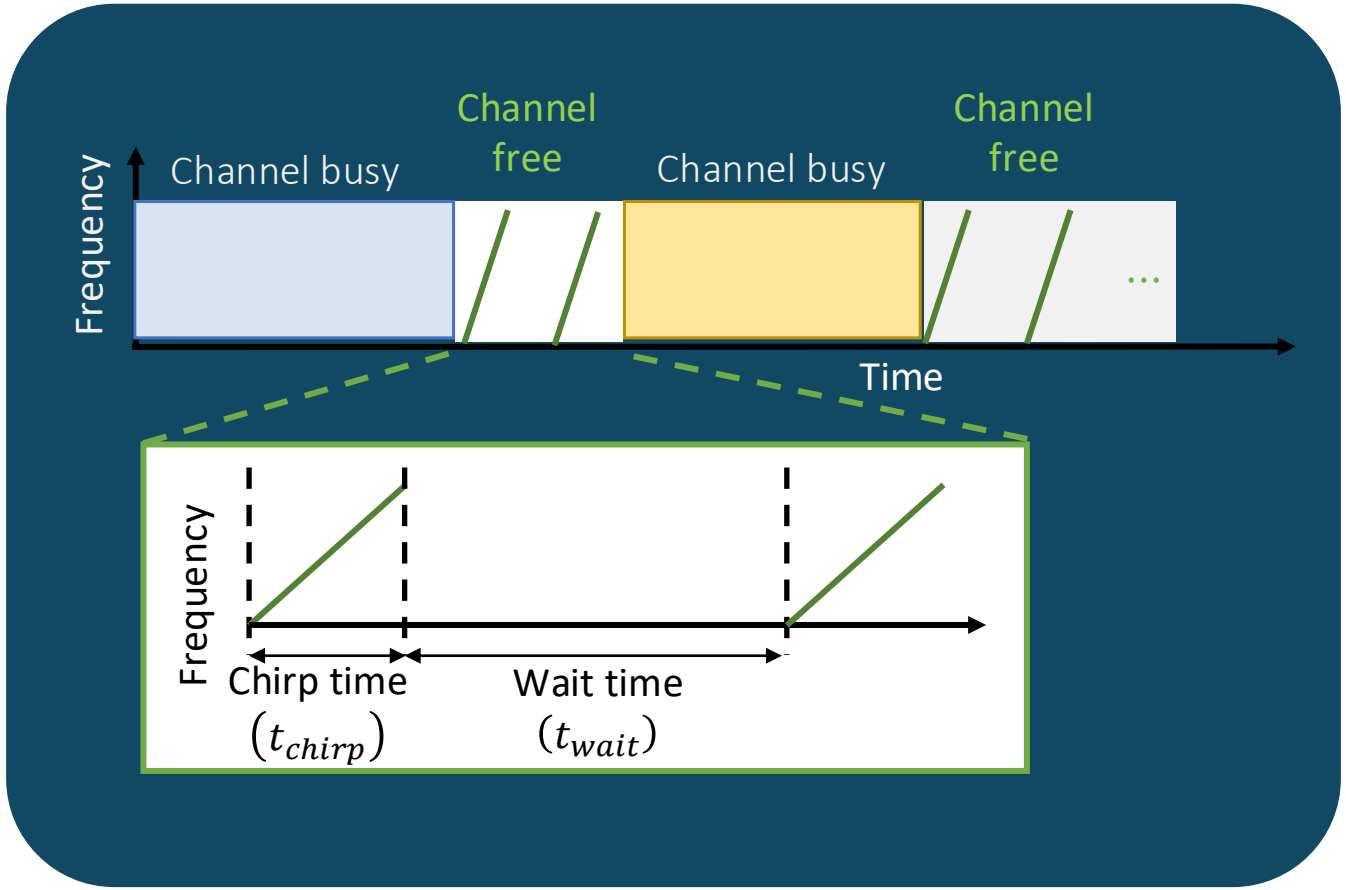




FSMA uses ***FreeChirp*** to coordinate channel access.

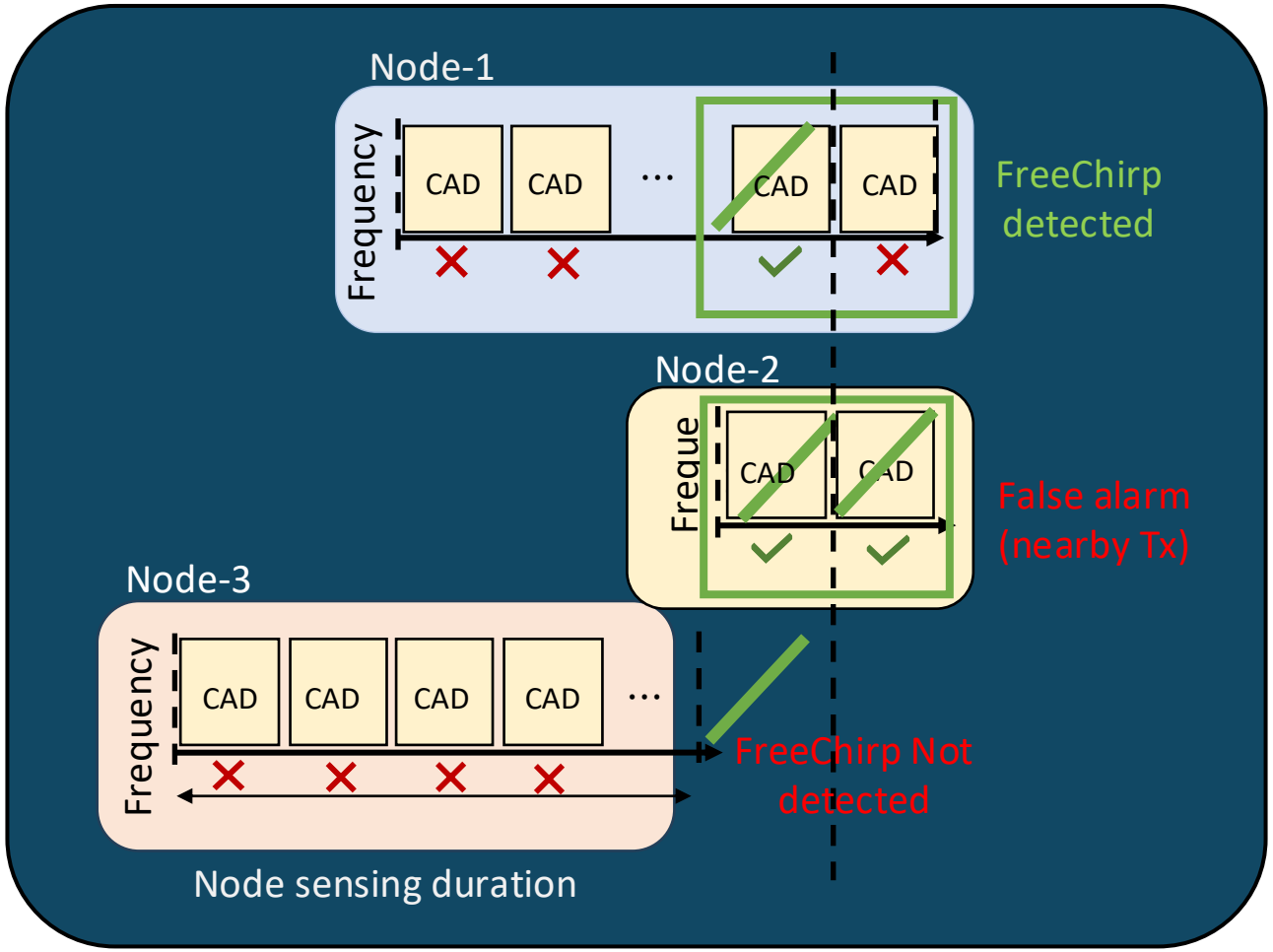
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FreeChirp structure at gateway: Sense and Transmit



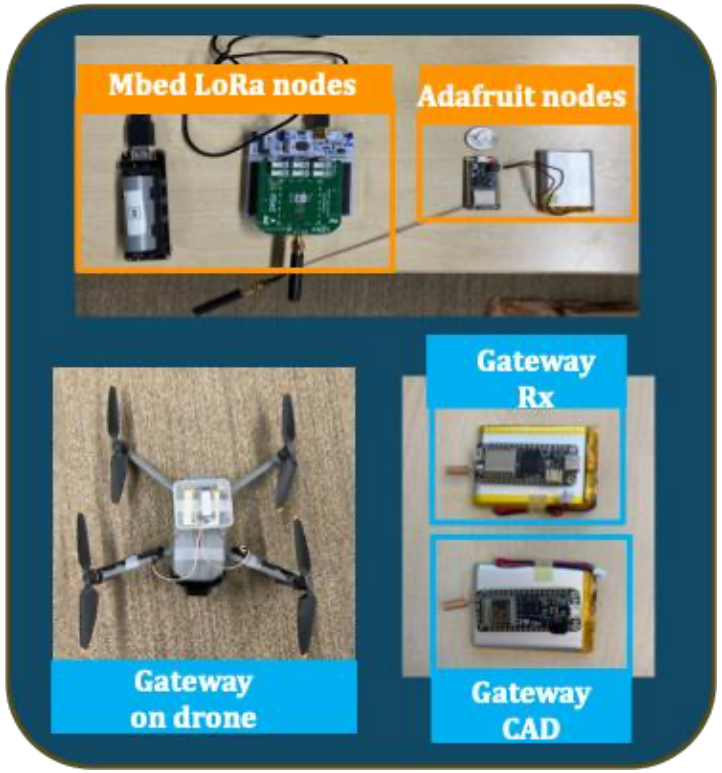
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FreeChirp detection at nodes: Sense and Transmit



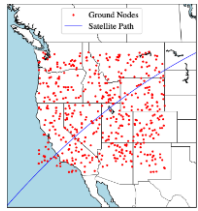
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Evaluations: FSMA performance over baselines approaches



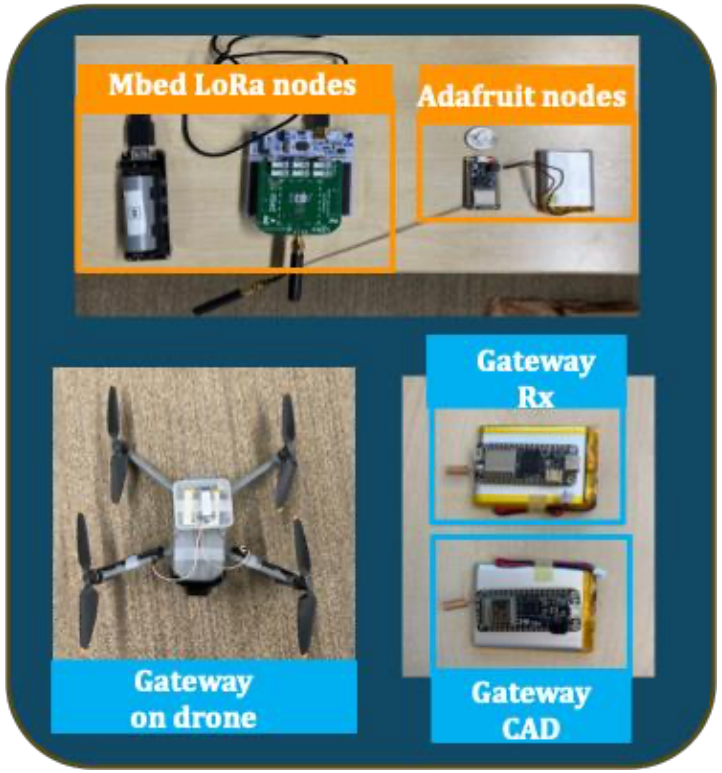
Evaluations

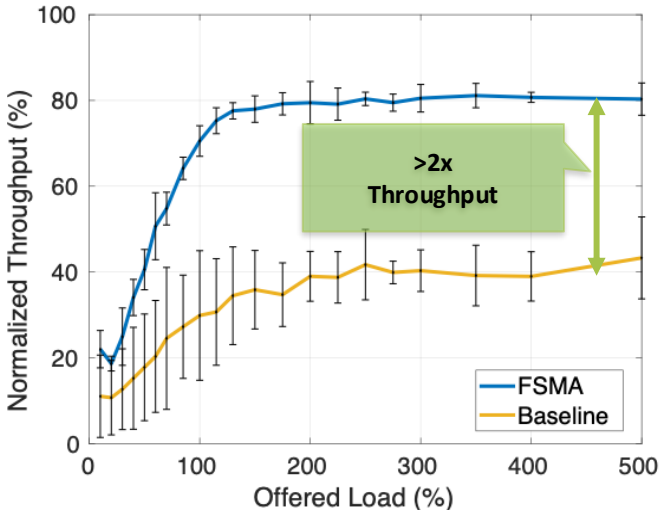
- ***Small-scale hardware experiments:*** static and drone-based moving experiments with 25 COTS LoRa nodes
- ***Large-scale simulations:*** custom satellite IoT simulator modeling satellite orbital mechanics and deploying up to 5000 nodes



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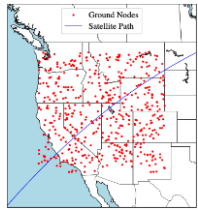
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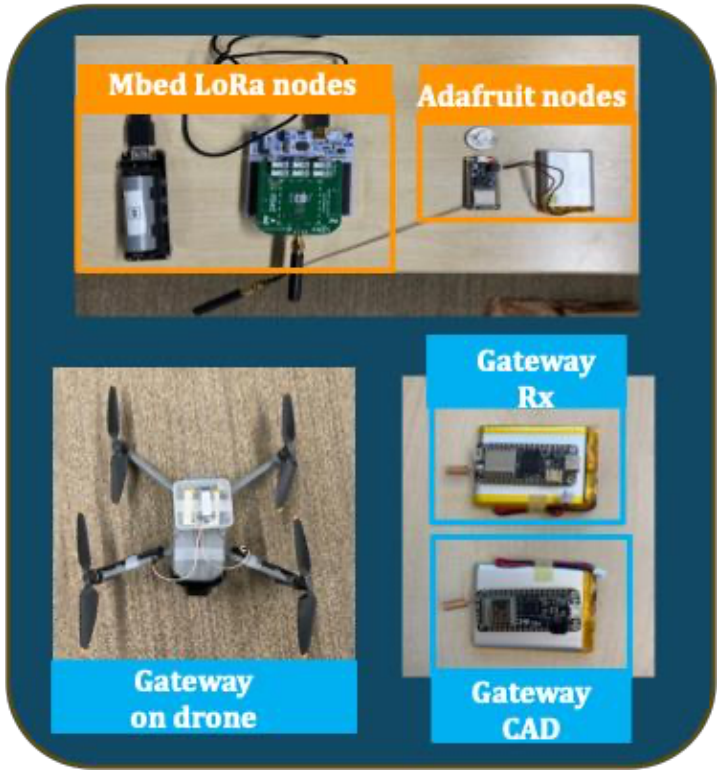
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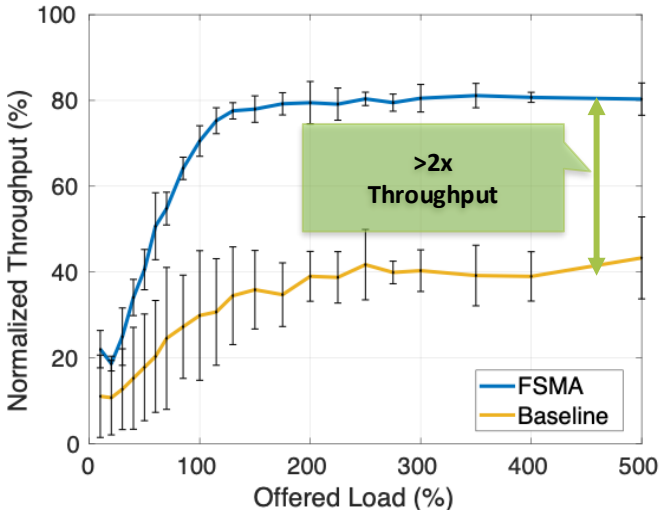
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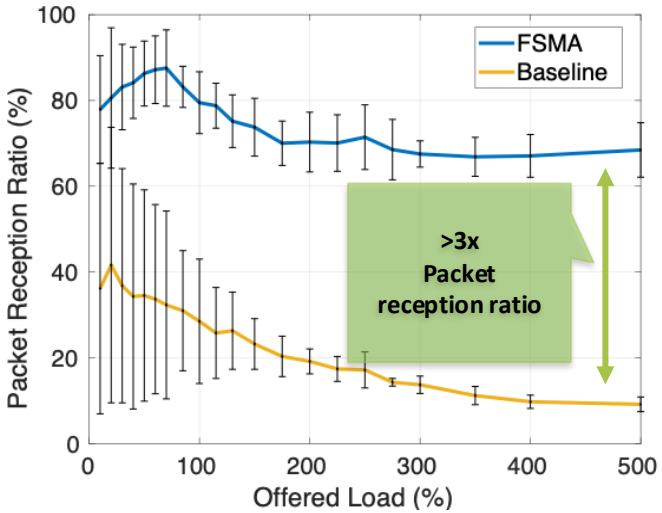


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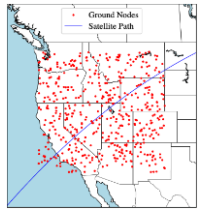






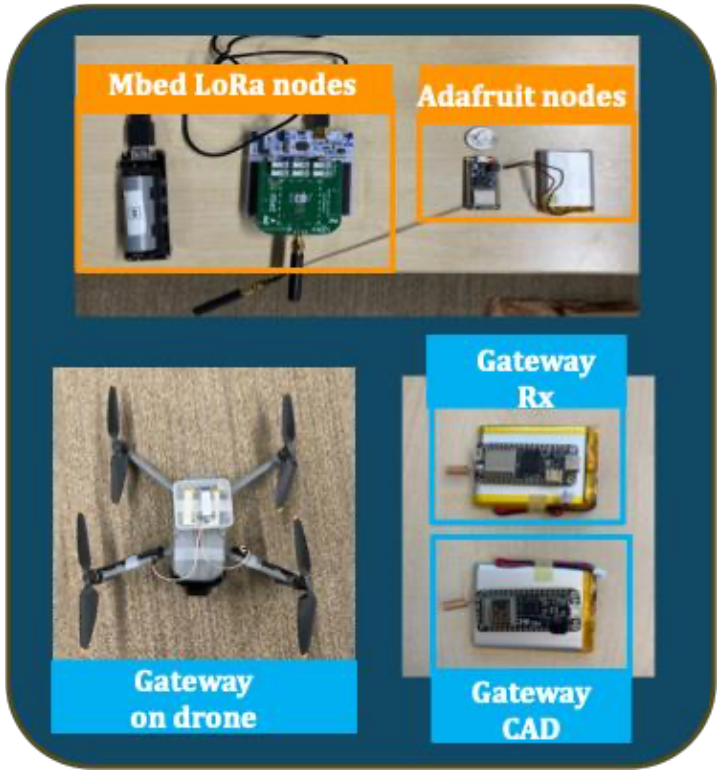
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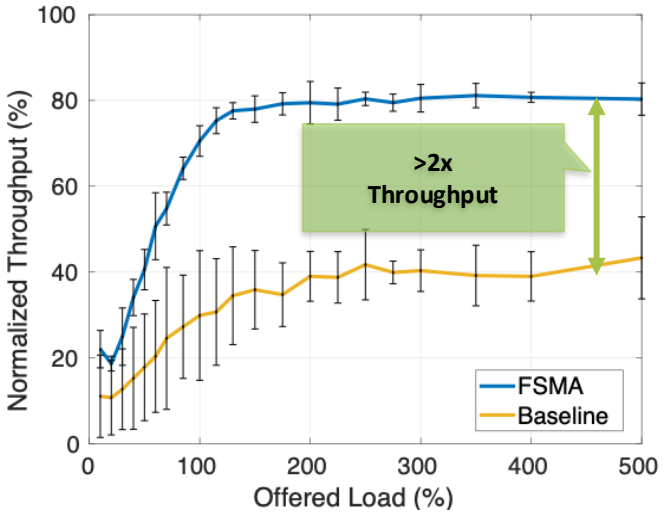
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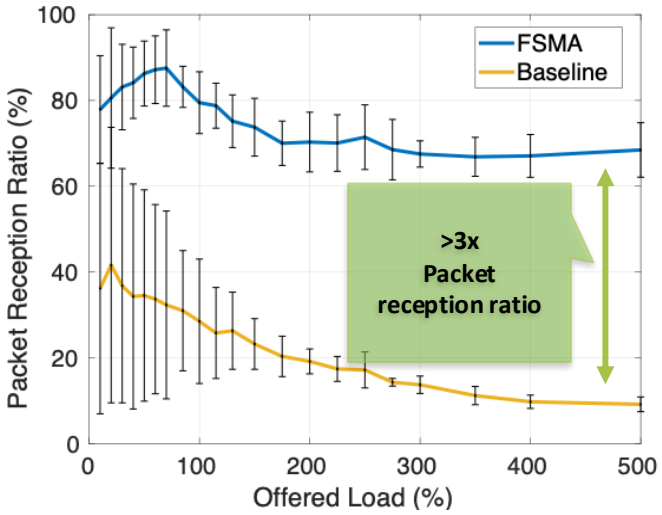


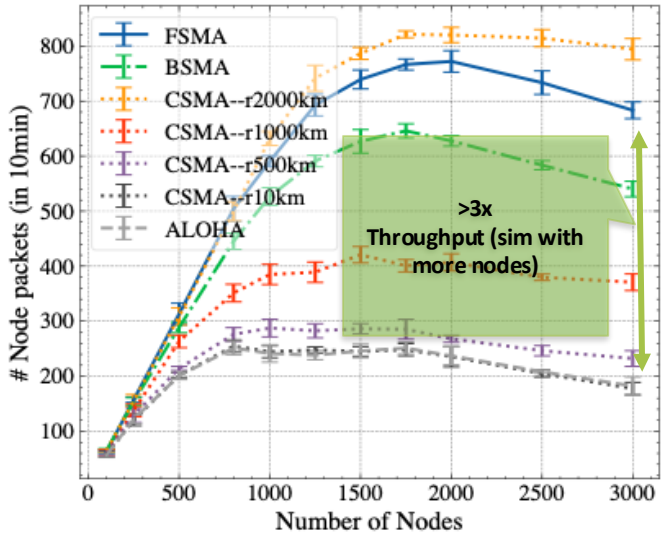
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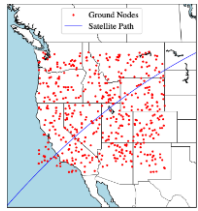






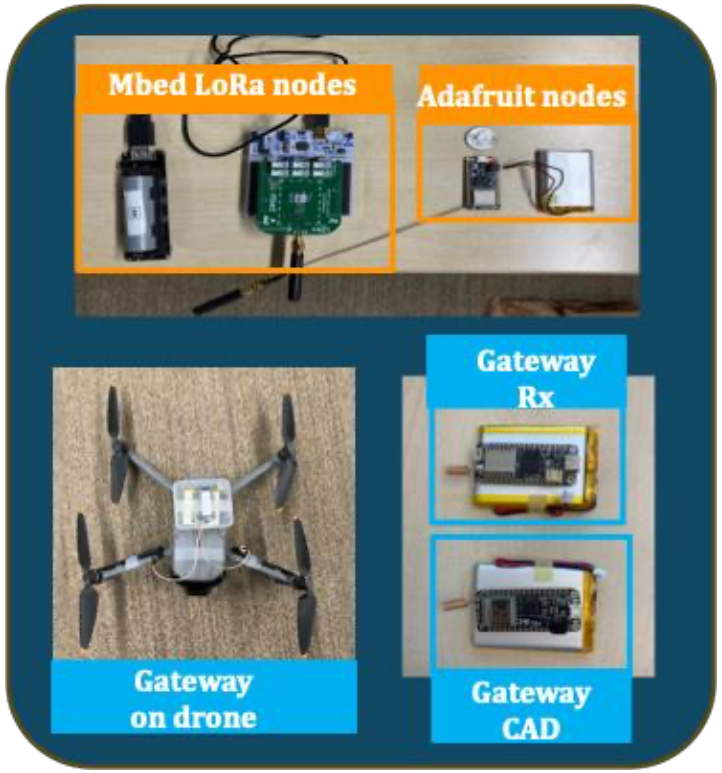
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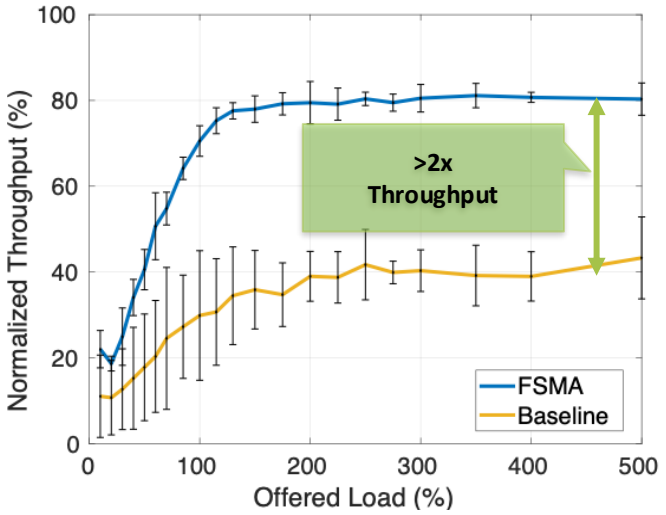
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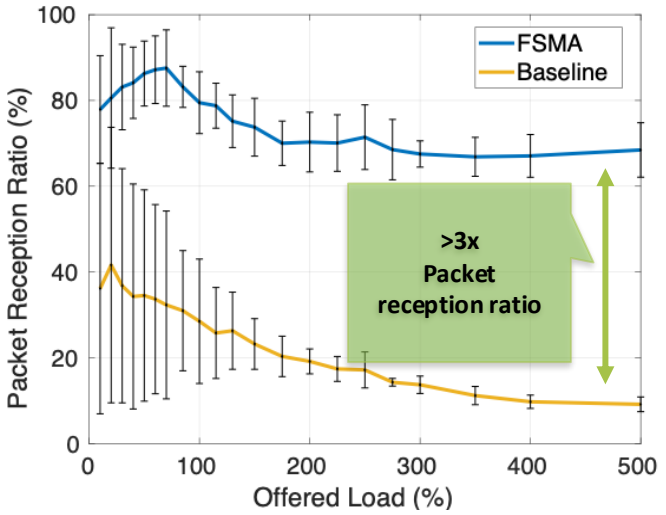
Evaluations: FSMA performance over baselines approaches

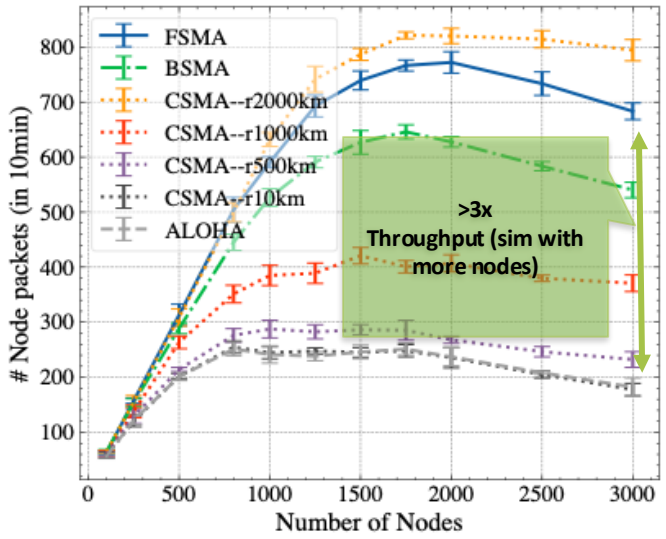


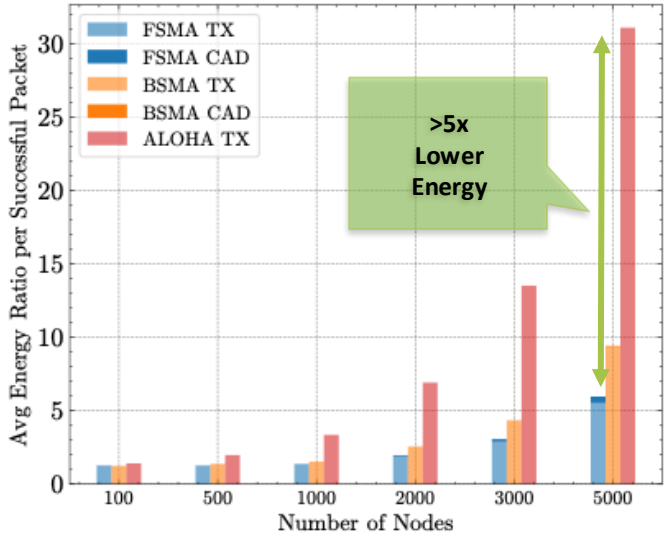
Evaluations

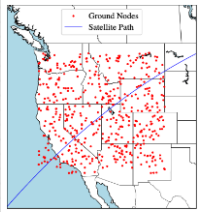
- ***Small-scale hardware experiments:*** static and drone-based moving experiments with 25 COTS LoRa nodes
- ***Large-scale simulations:*** custom satellite IoT simulator modeling satellite orbital mechanics and deploying up to 5000 nodes







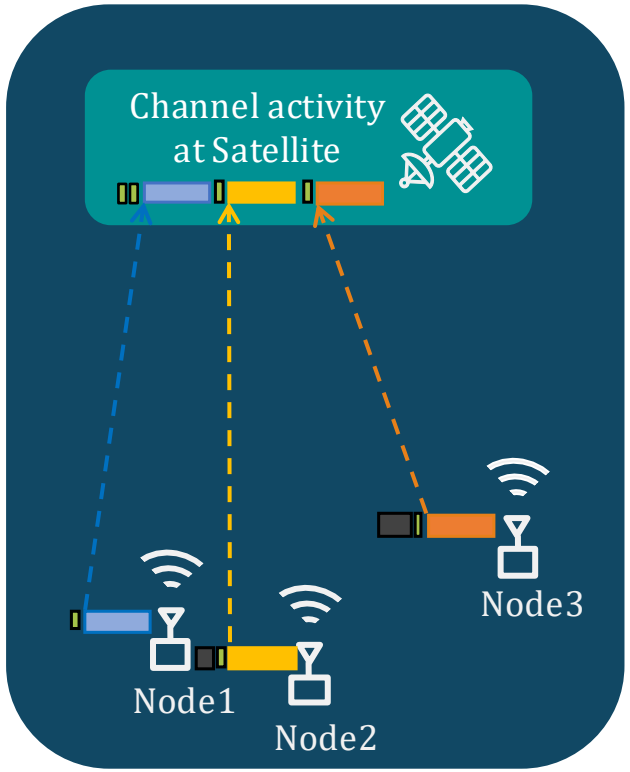




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Summary: Gateway controlled PHY-MAC Access

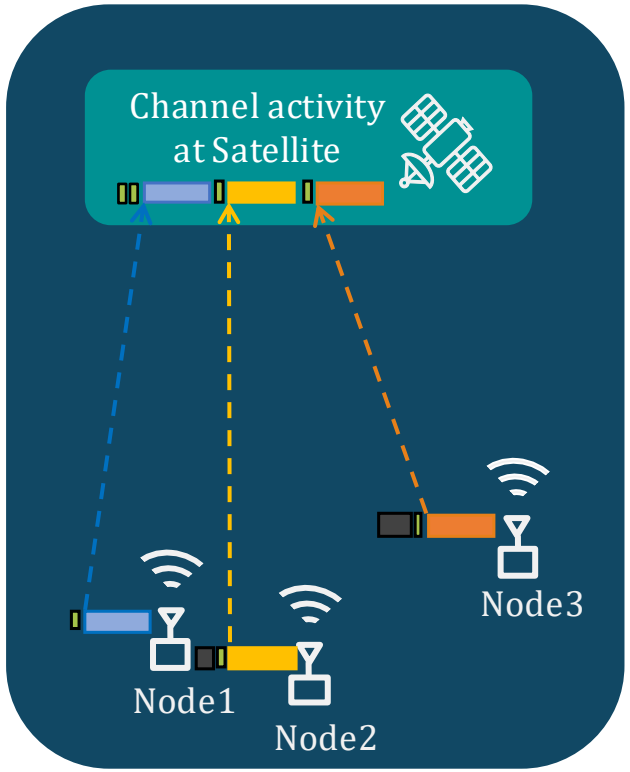
Enables Scalable, Efficient and Deployable (COTs compatible) IoT



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Summary: Gateway controlled PHY-MAC Access

Enables Scalable, Efficient and Deployable (COTs compatible) IoT

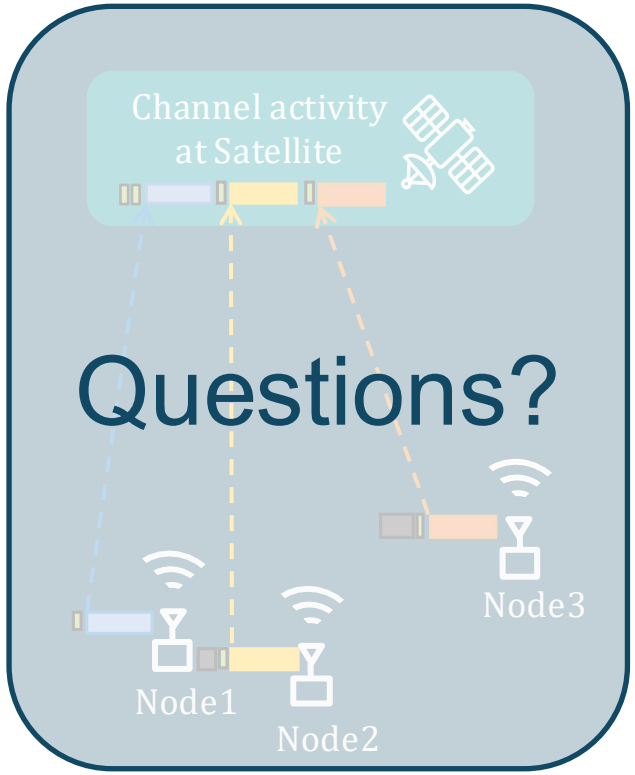


Requirements	Aloha	CSMA	BSMA	FSMA
Collisions mitigation	✗	✗	✓	✓
Link-aware access	✗	✗	✗	✓
Energy efficient (nodes)	✗	✗	✓	✓
Energy efficient (gateway)	✓	✓	✗	✓
Off-the-shelf hardware	✓	✓	✗	✓

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Summary: Gateway controlled PHY-MAC Access

Enables Scalable, Efficient and Deployable (COTs compatible) IoT



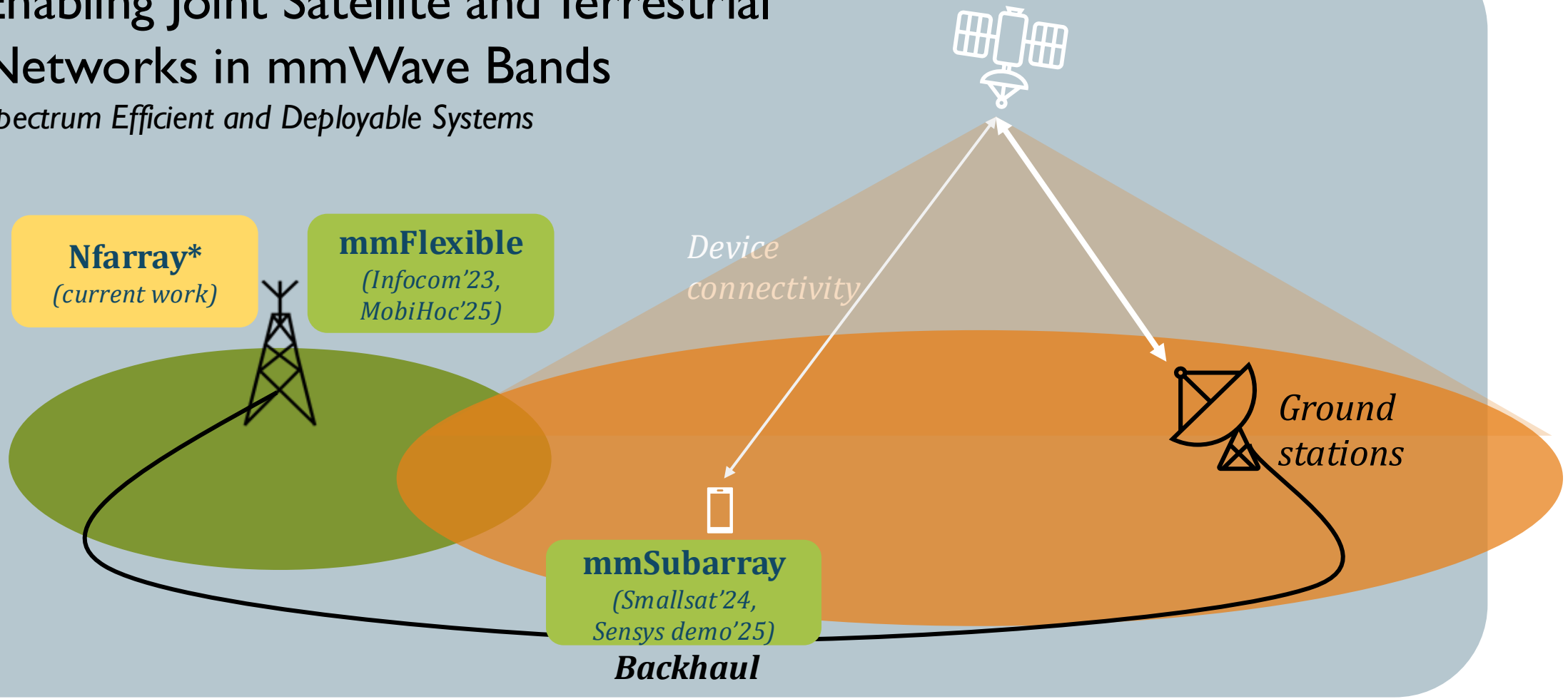
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Energy efficient (gateway)	✓	✓	✗	✓
Off-the-shelf hardware	✓	✓	✗	✓

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Part3: Backhaul and Spectrum Coexistence

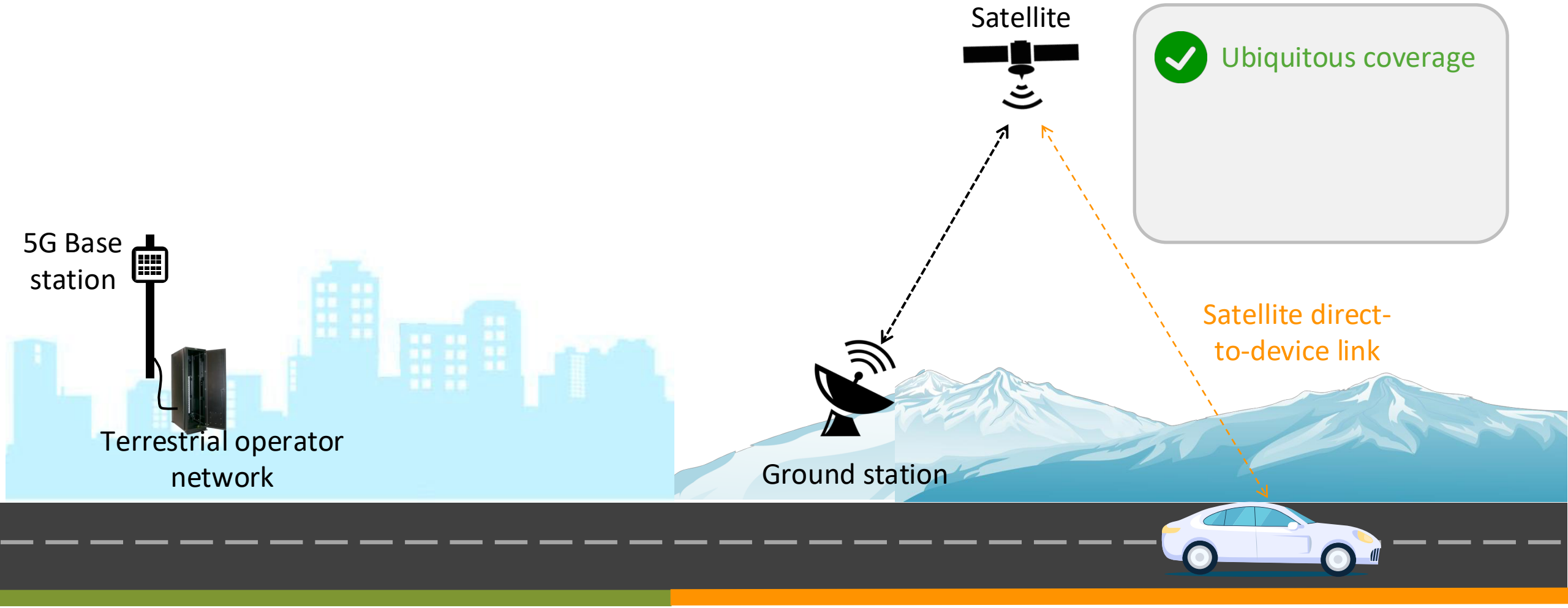
Enabling Joint Satellite and Terrestrial Networks in mmWave Bands

Spectrum Efficient and Deployable Systems



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*under review/submission

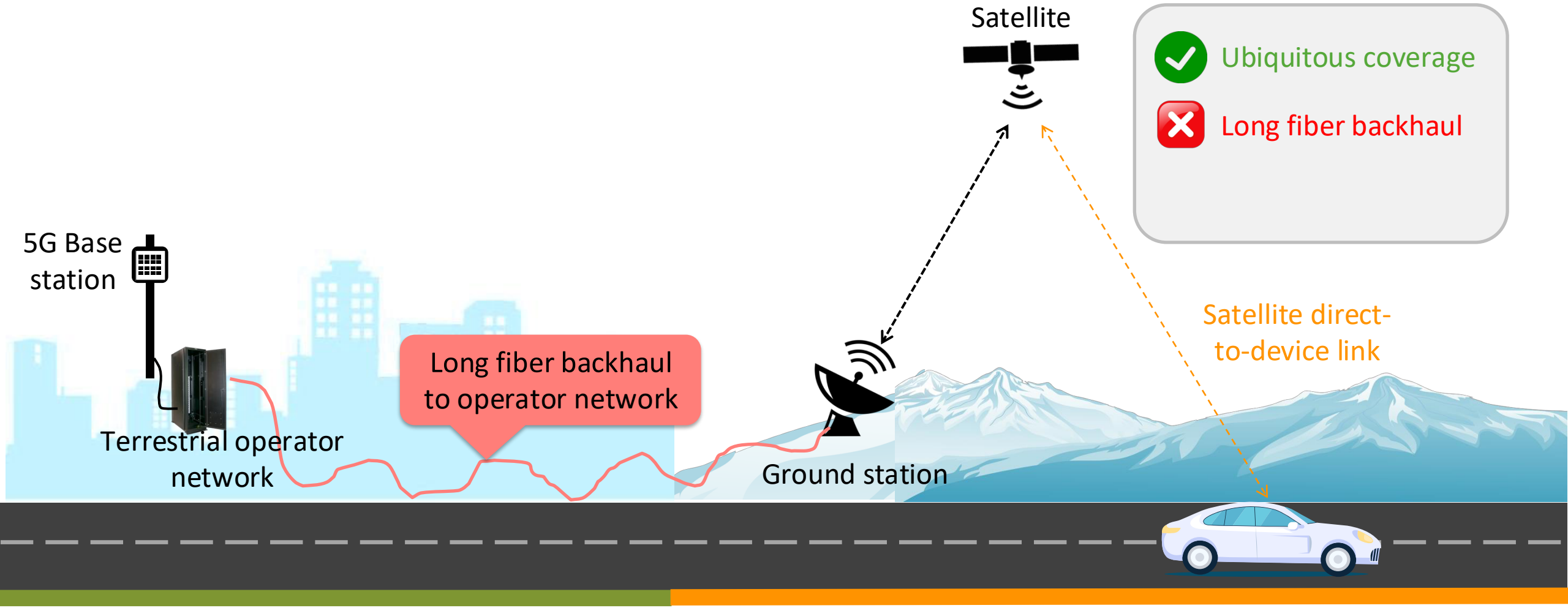
Satellite direct-to-device connectivity: *challenges*



Ref: *starlink.com/business/direct-to-cell*

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Satellite direct-to-device connectivity: *challenges*

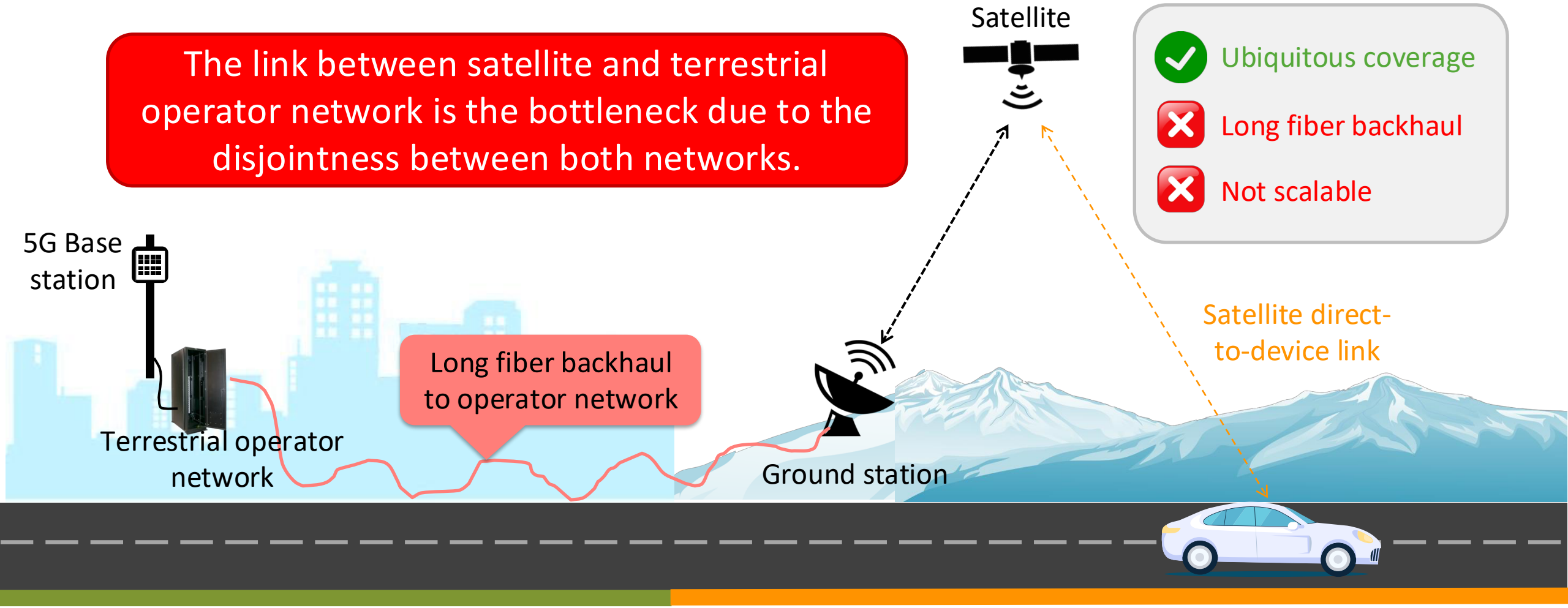


Ref: *starlink.com/business/direct-to-cell*

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Satellite direct-to-device connectivity: *challenges*

The link between satellite and terrestrial operator network is the bottleneck due to the disjointness between both networks.

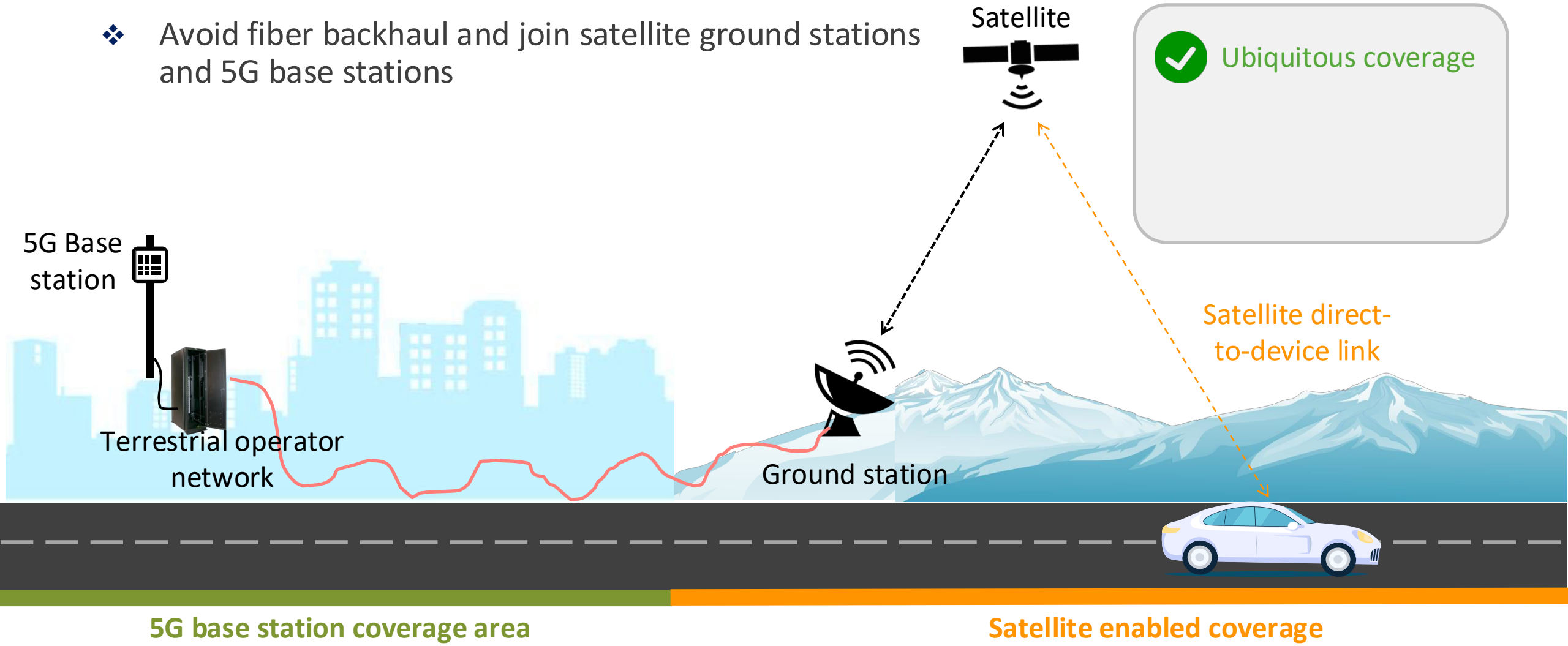


Ref: *starlink.com/business/direct-to-cell*

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Proposed Joint satellite and terrestrial networks *(JointNets)*

- Avoid fiber backhaul and join satellite ground stations and 5G base stations

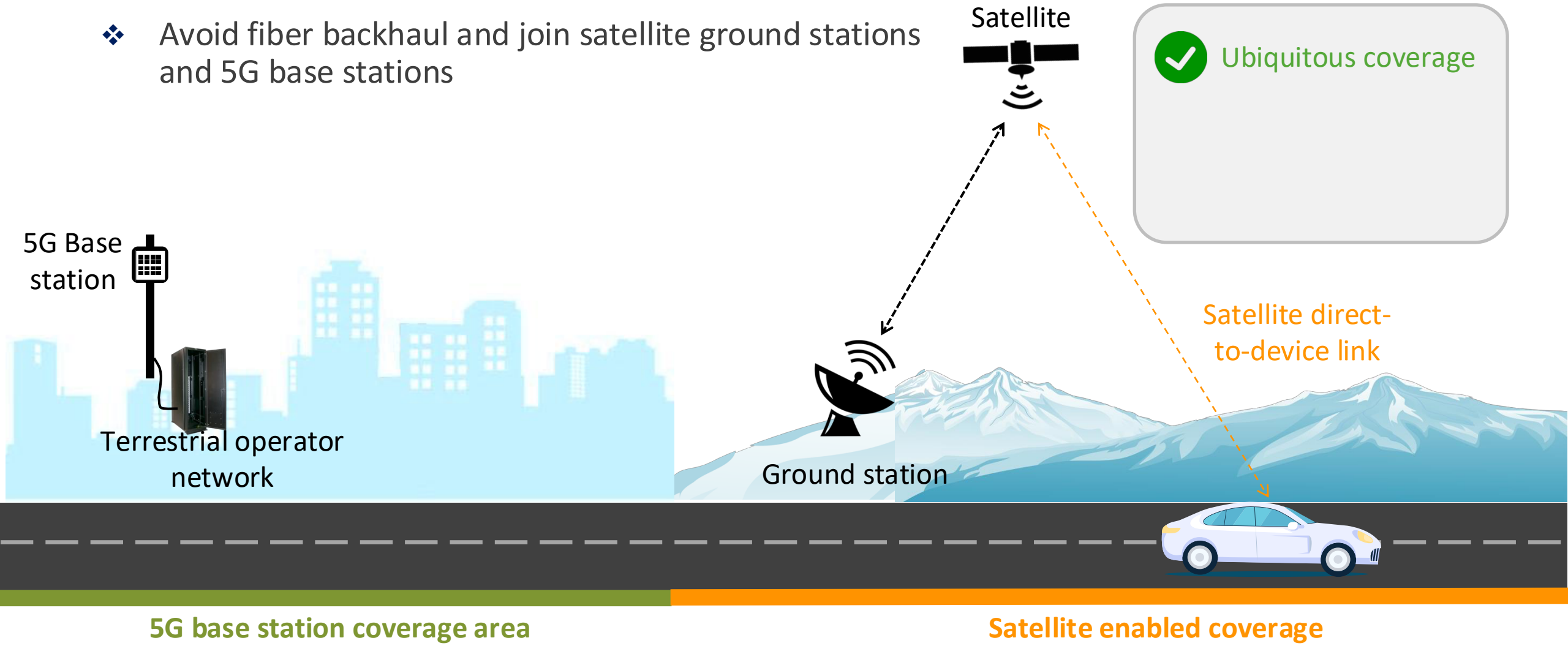


Ref: *starlink.com/business/direct-to-cell*

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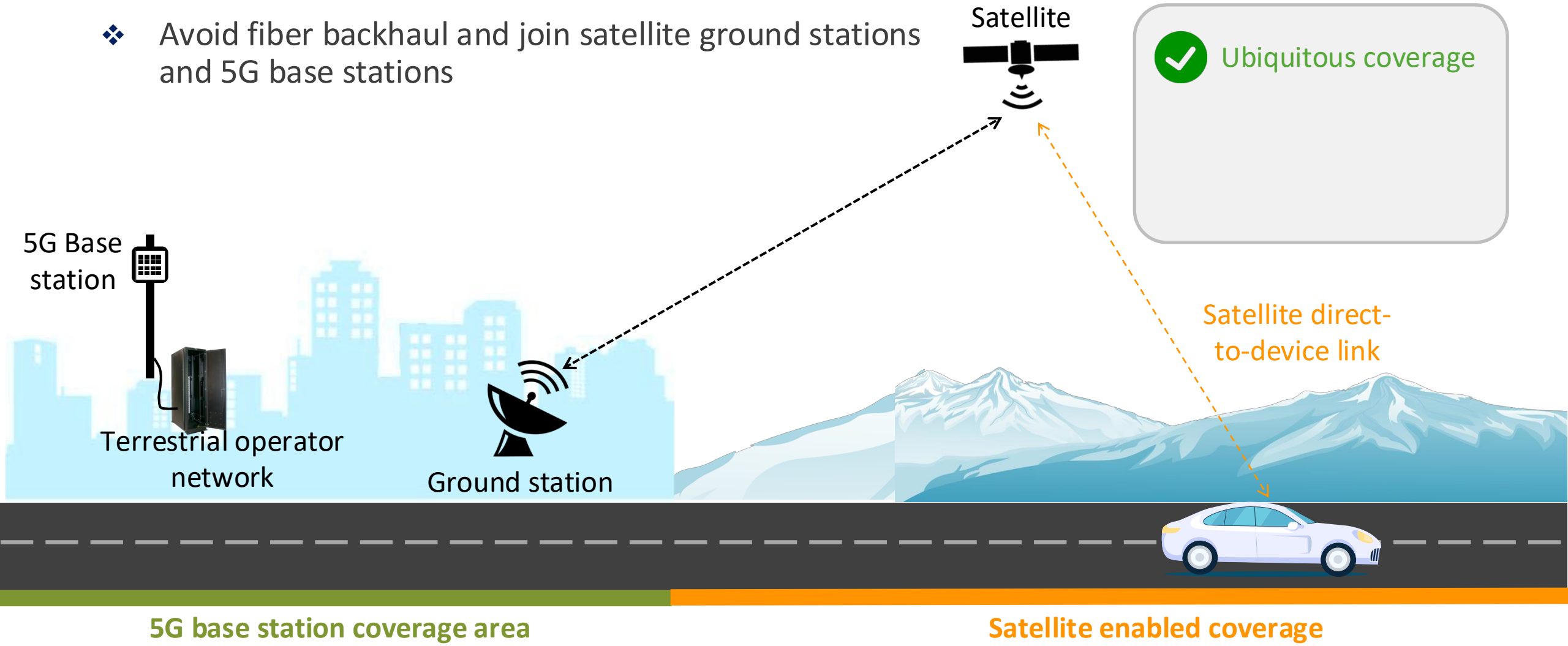


Ref: *starlink.com/business/direct-to-cell*

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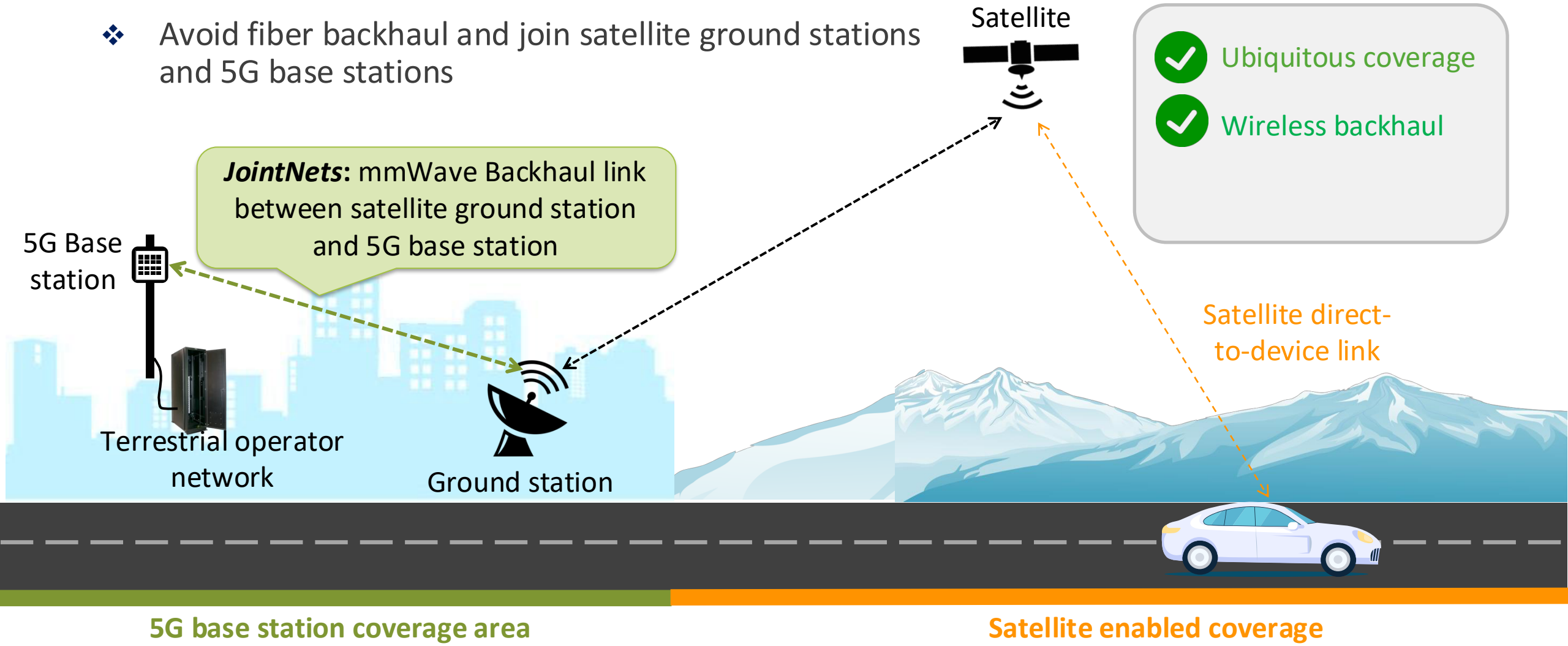


Ref: *starlink.com/business/direct-to-cell*

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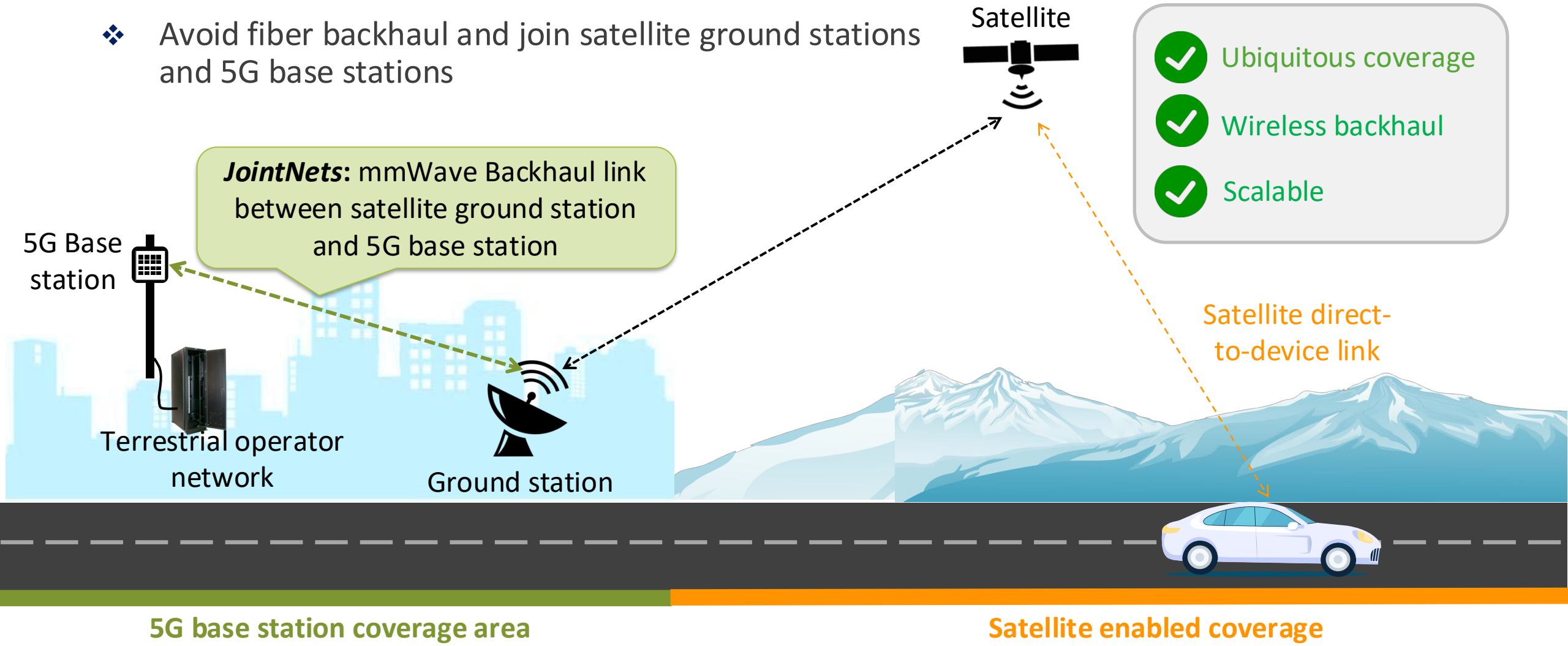


Ref: *starlink.com/business/direct-to-cell*

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Proposed Joint satellite and terrestrial networks *(JointNets)*

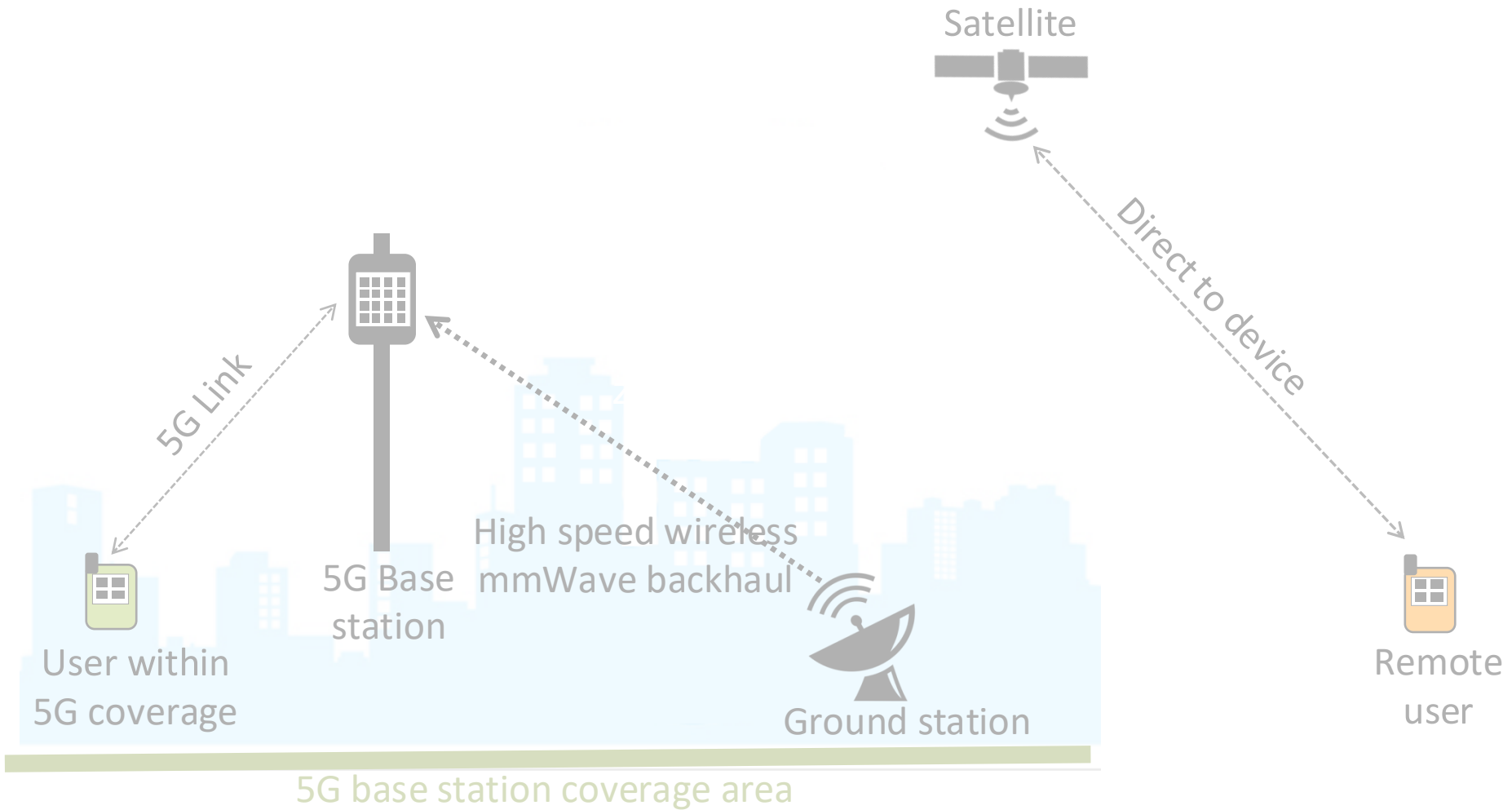
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Ref: *starlink.com/business/direct-to-cell*

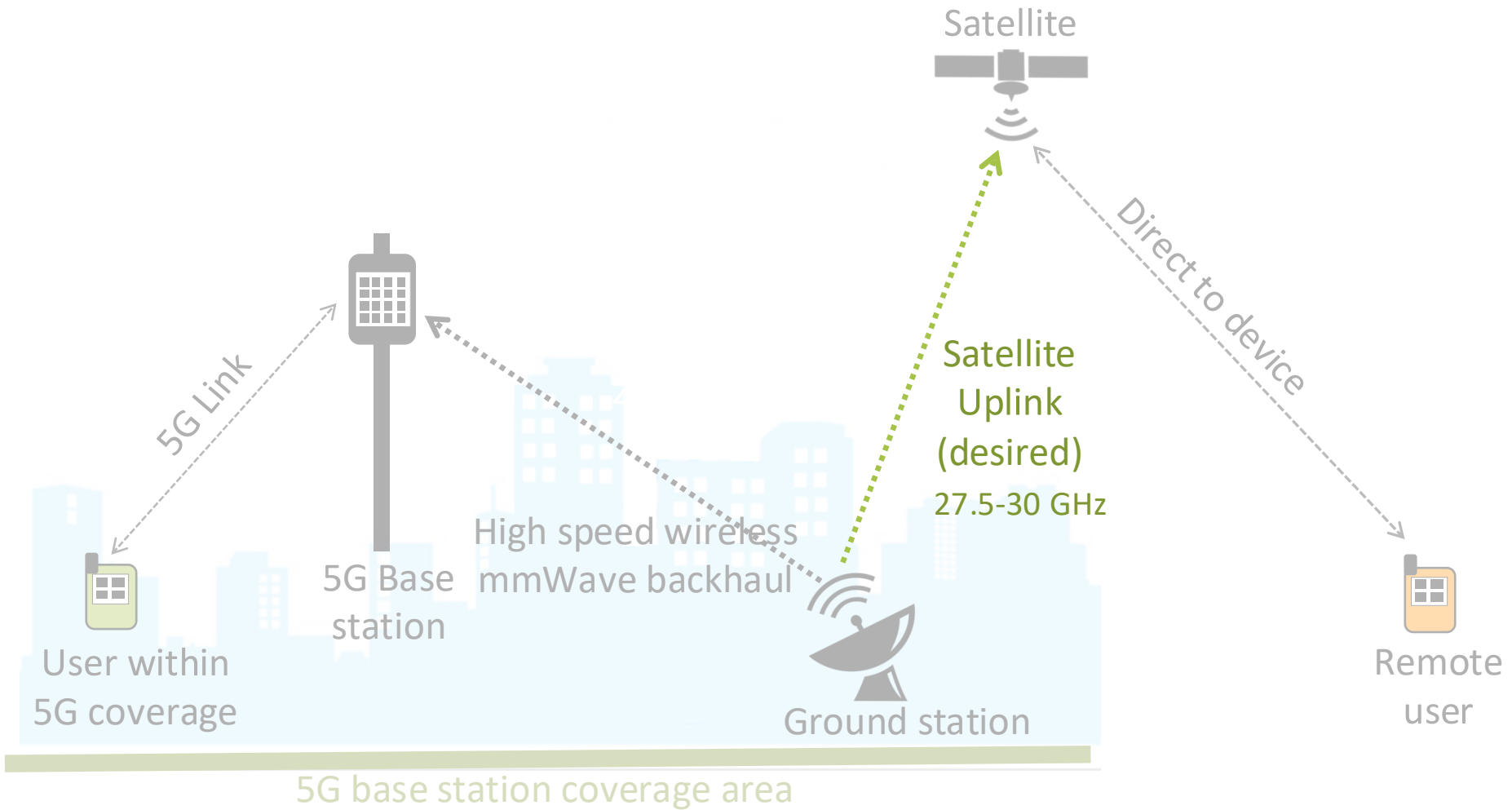
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JointNets challenge: Interference



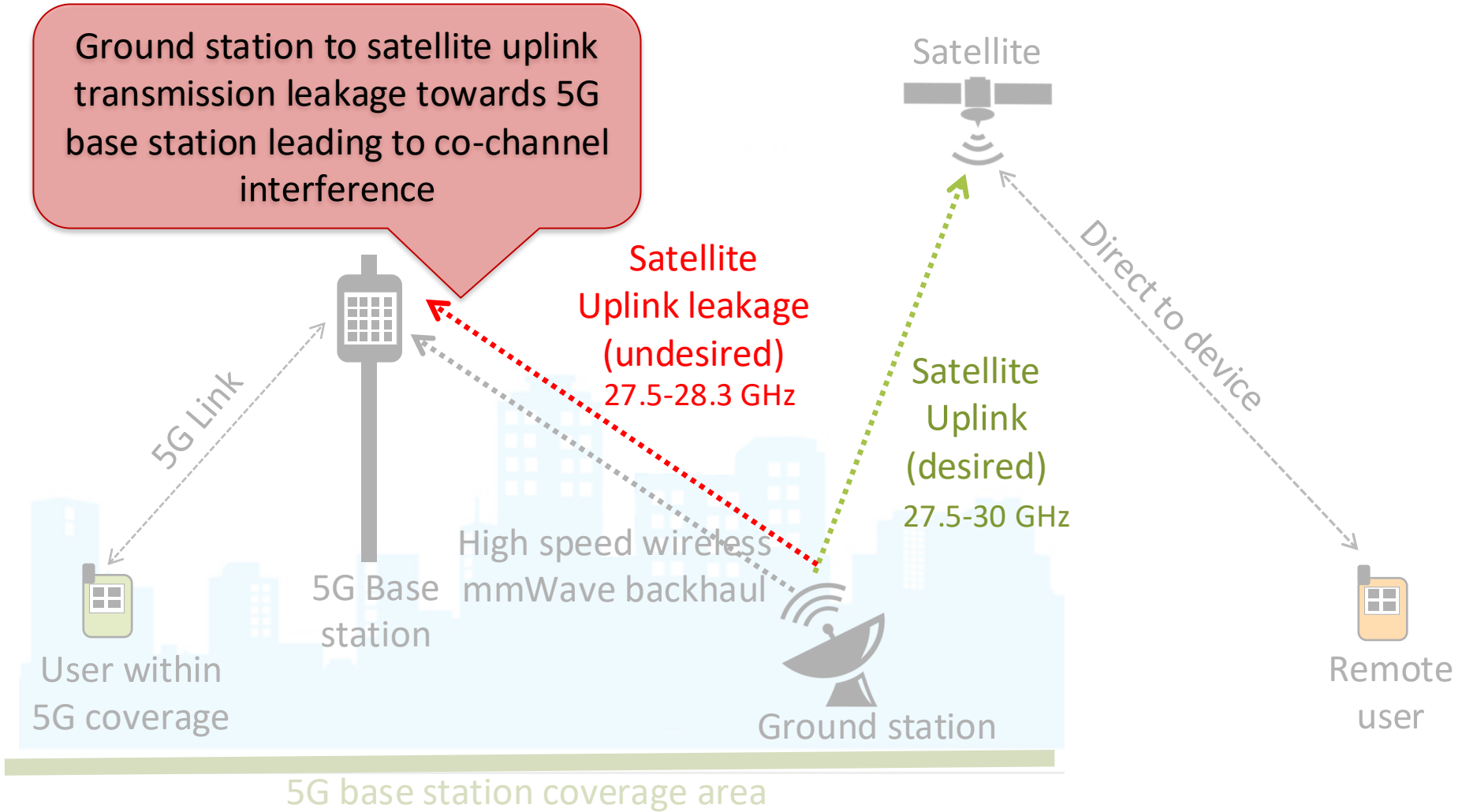
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JointNets challenge: Interference



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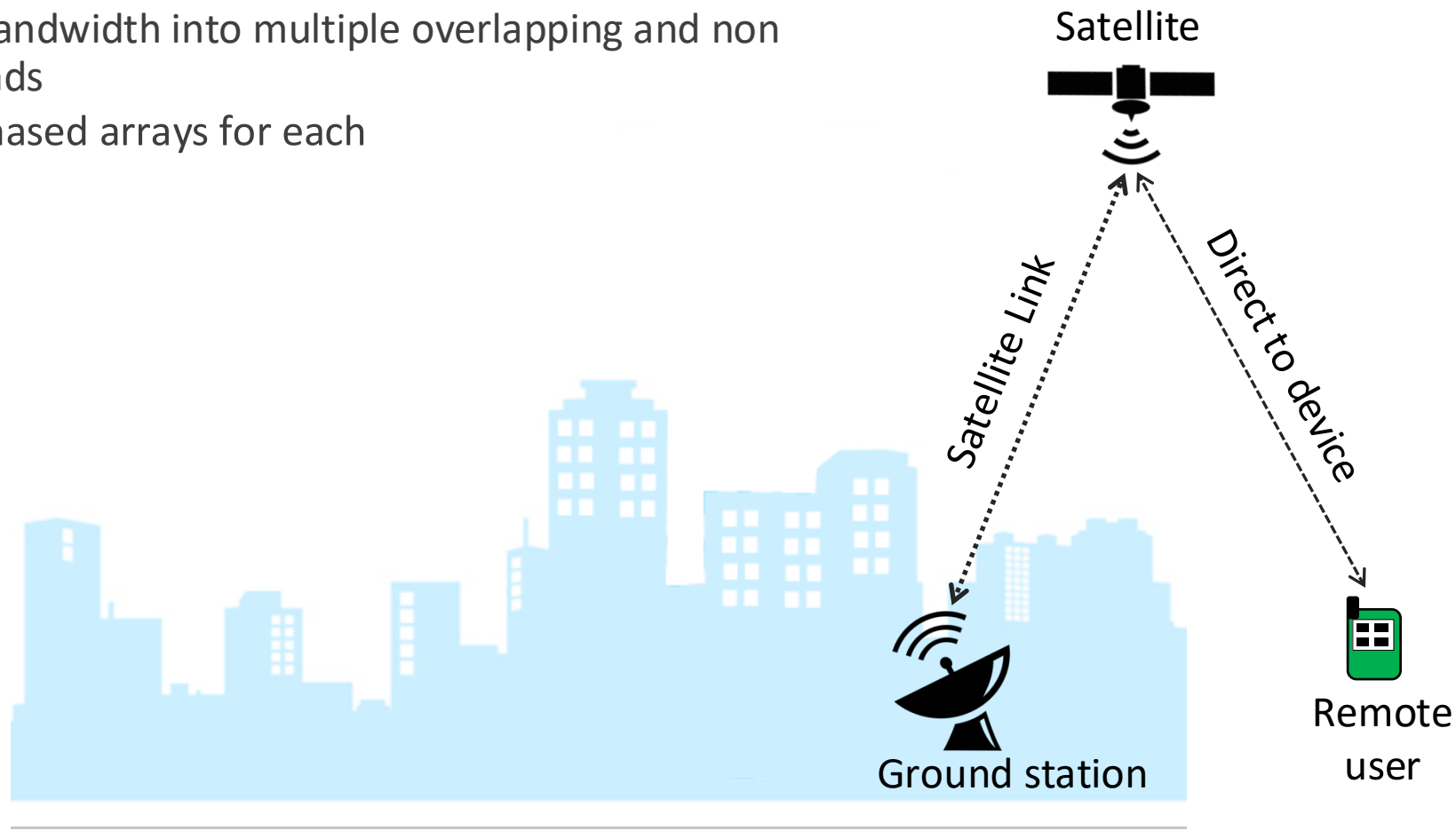
JointNets challenge: Interference



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Proposed ***mmSubArray*** solution

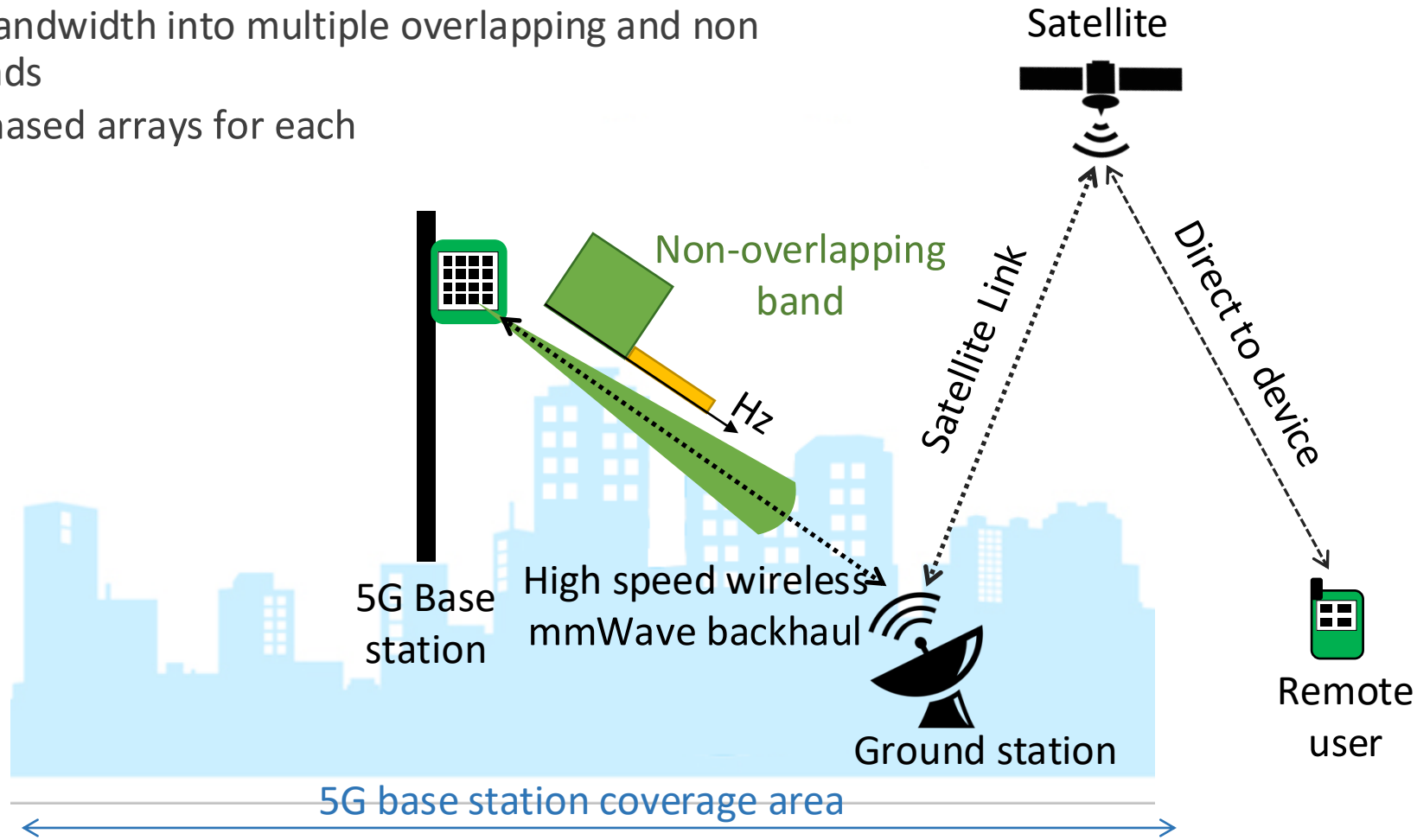
- ***mmSubArray*** approach
  - Divide overall bandwidth into multiple overlapping and non overlapping bands
  - Use different phased arrays for each



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Proposed ***mmSubArray*** solution

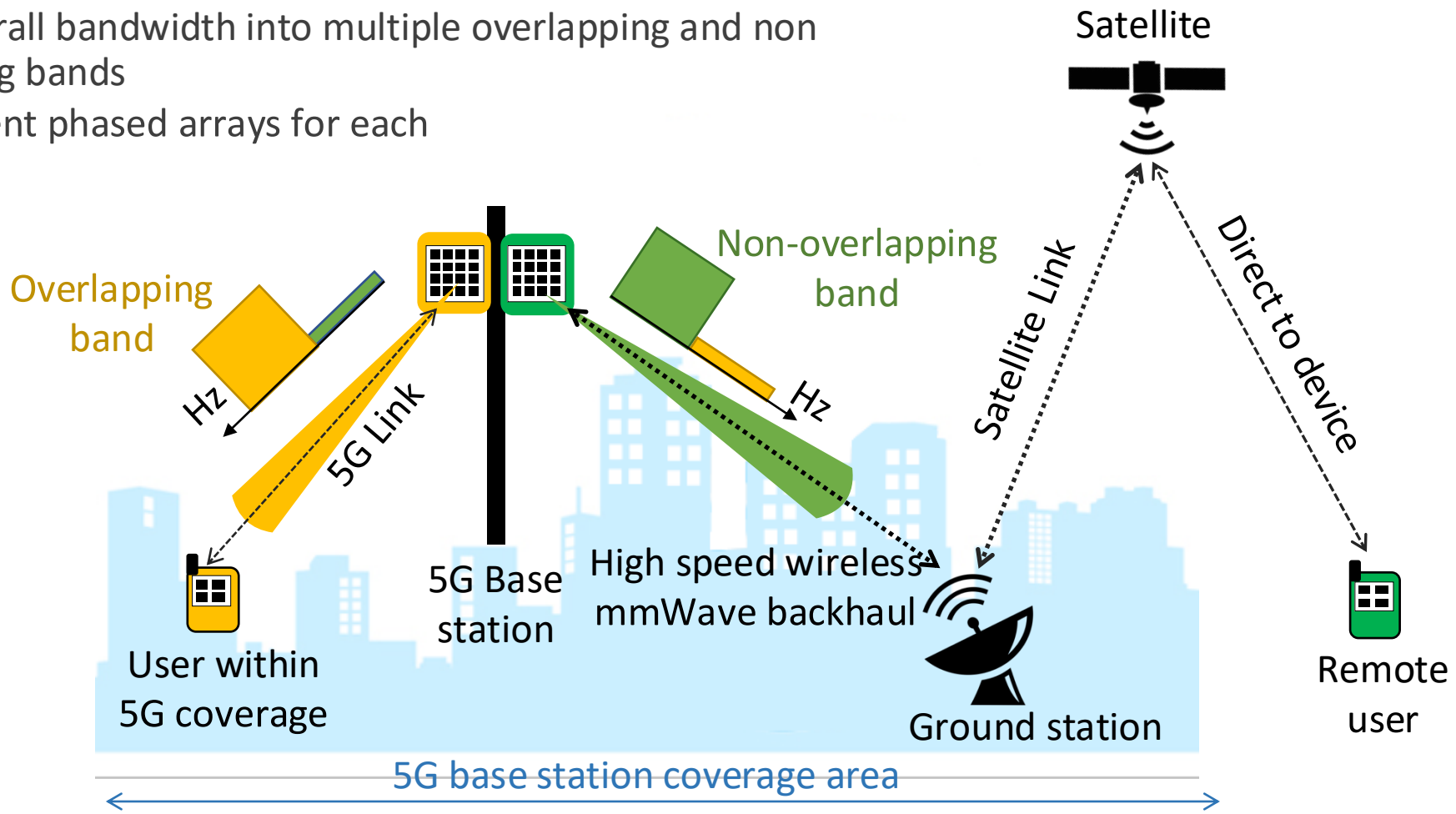
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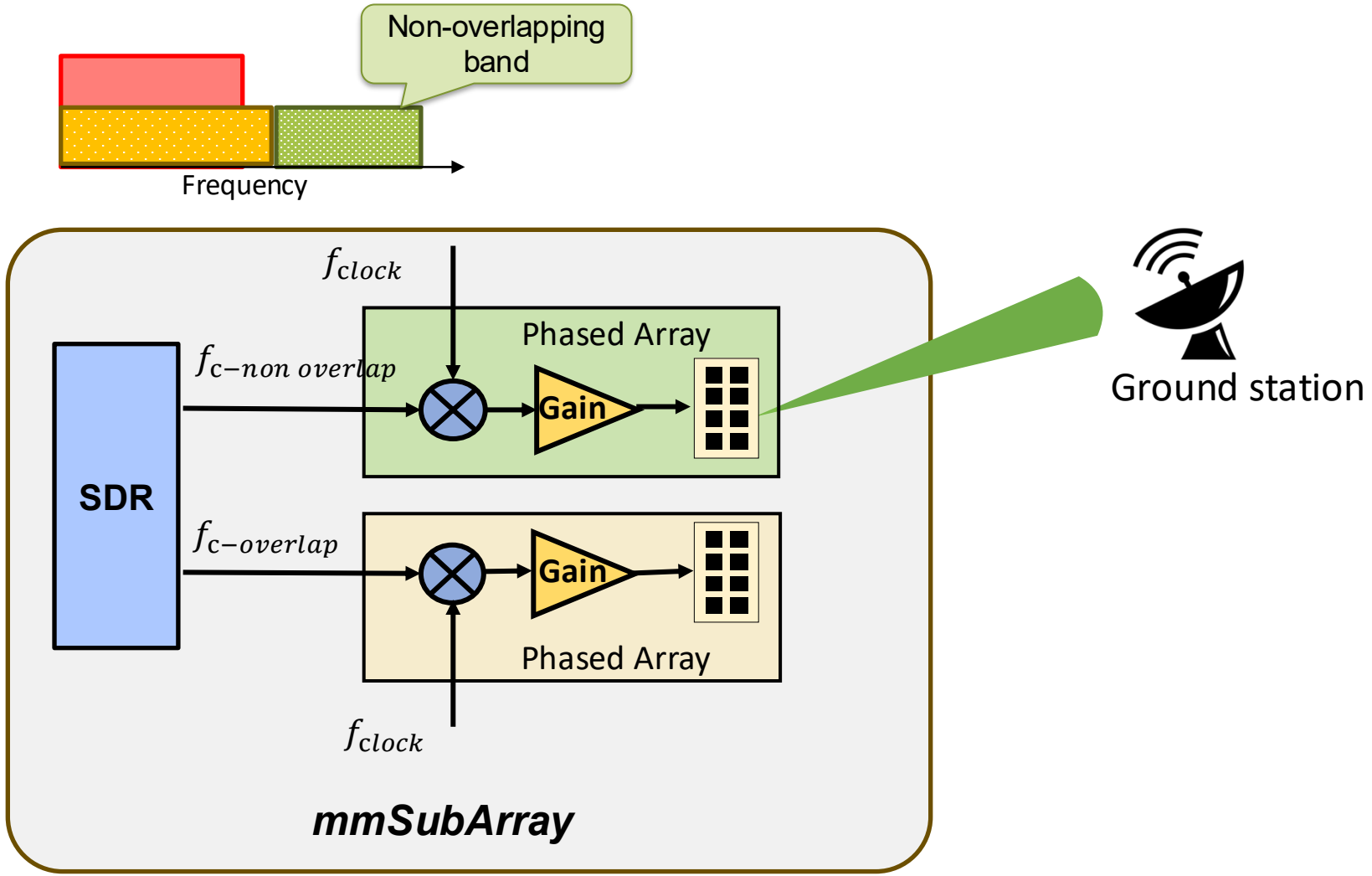
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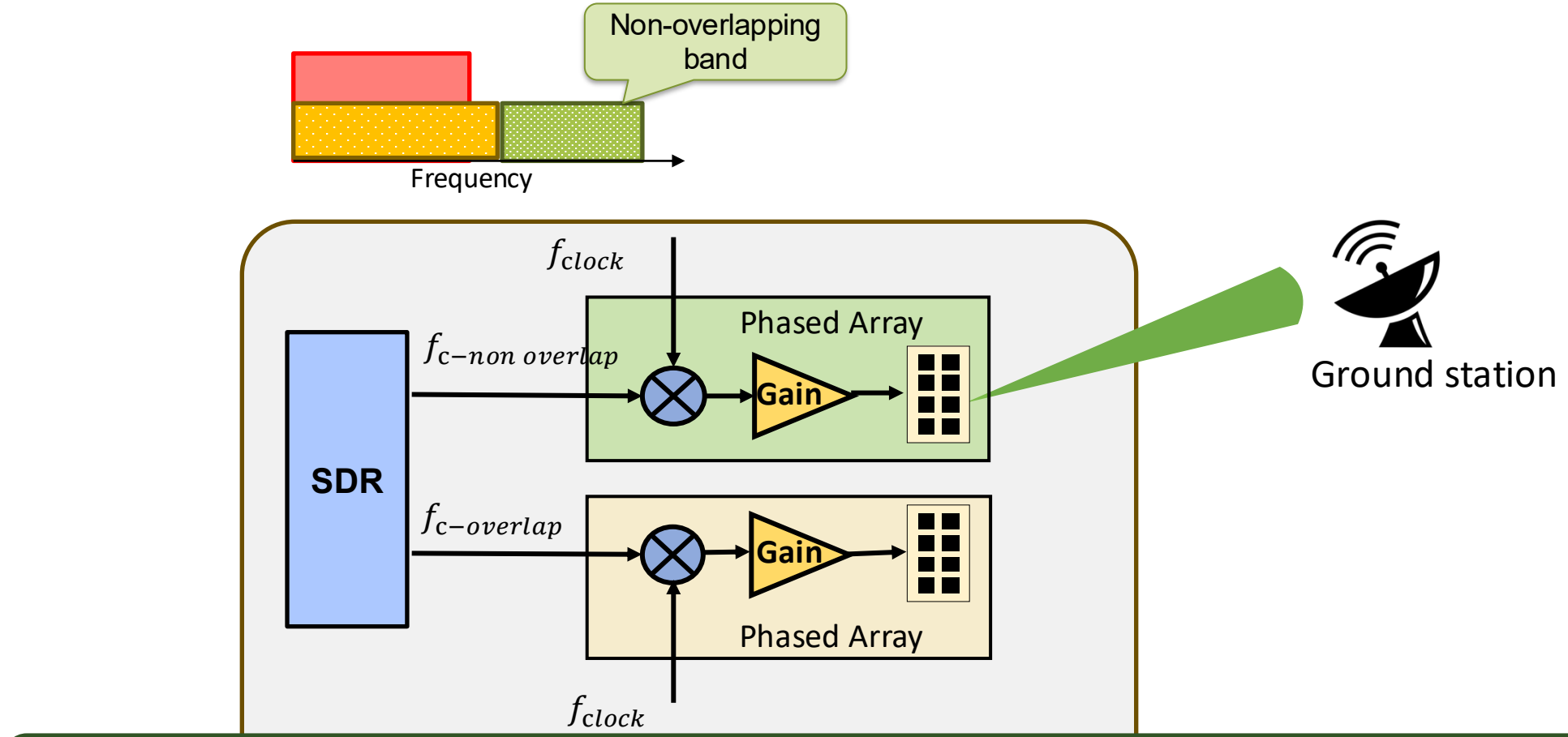
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Proposed ***mmSubArray*** solution: *Beaming non-overlapping band to satellite ground station*



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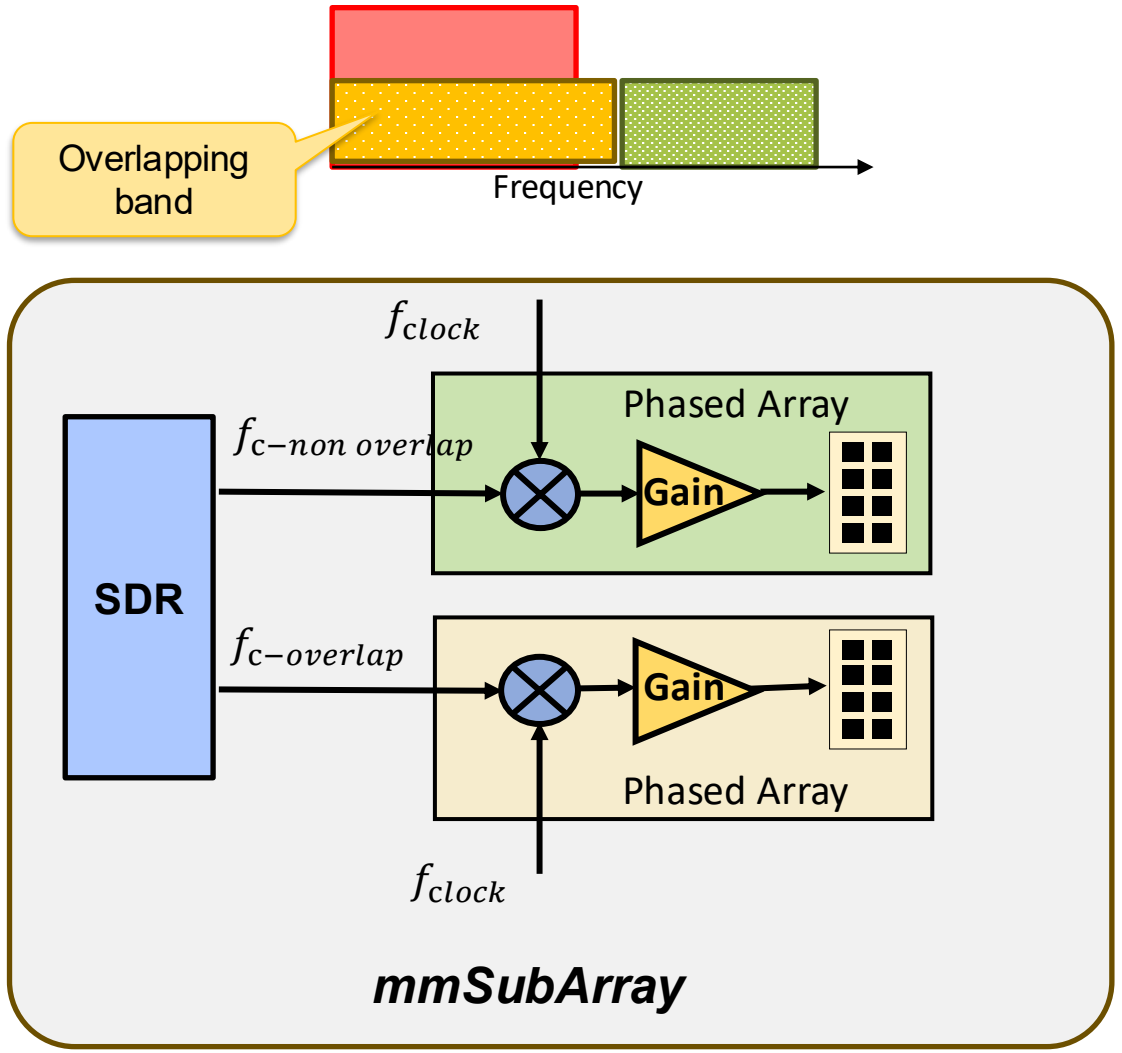
Proposed ***mmSubArray*** solution: *Beaming non-overlapping band to satellite ground station*



Enabling backhaul through non-overlapping band

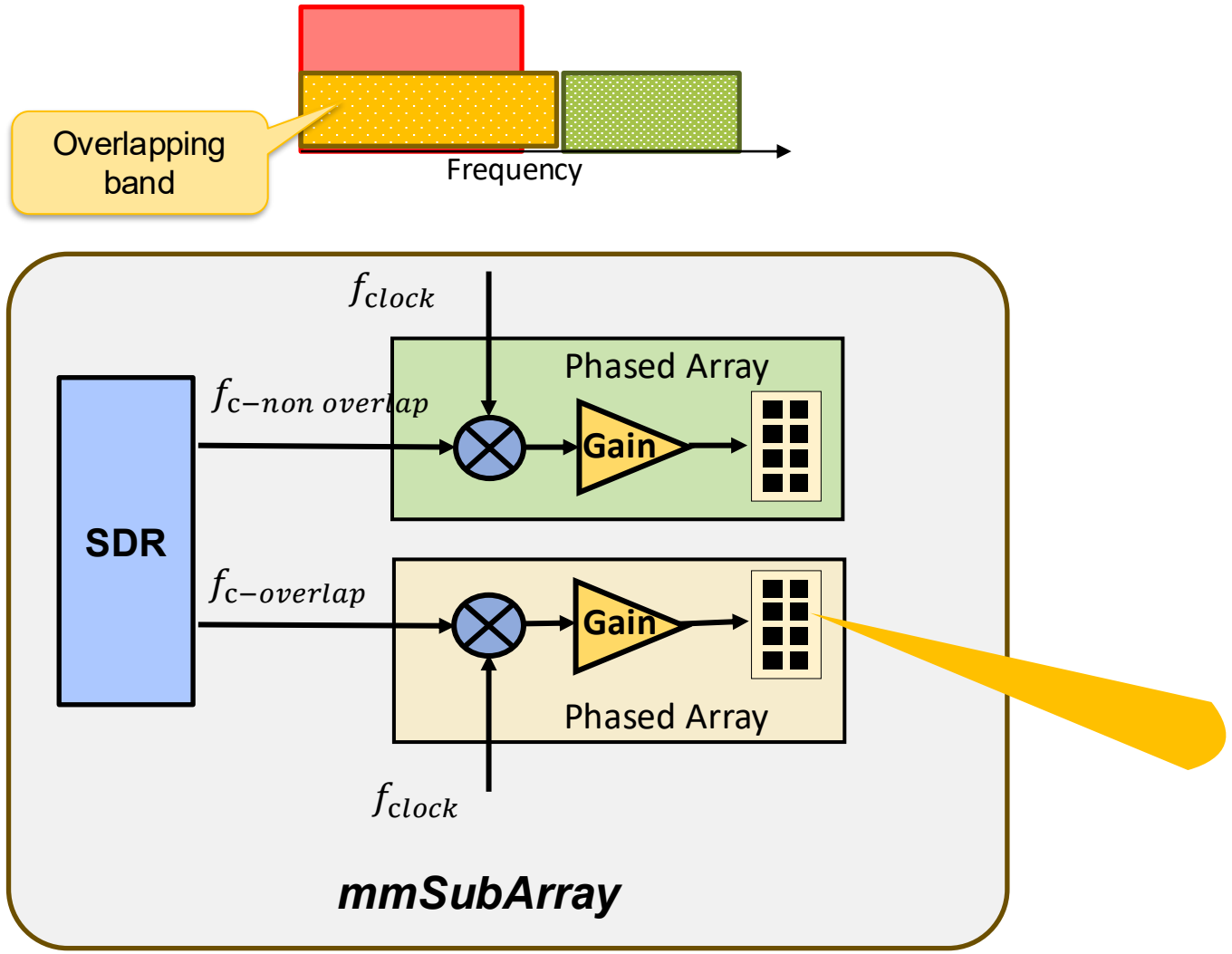
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Proposed ***mmSubArray*** solution: *Suppressing interference and supporting users*



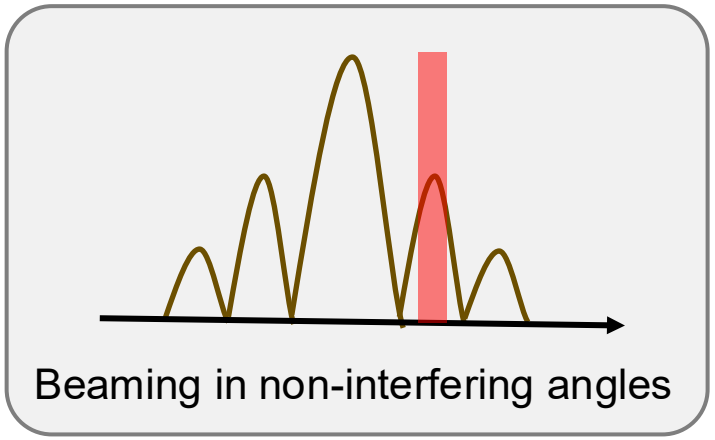
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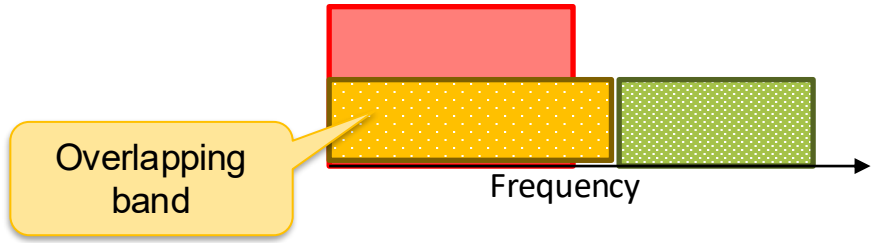
Proposed ***mmSubArray*** solution: *Suppressing interference and supporting users*

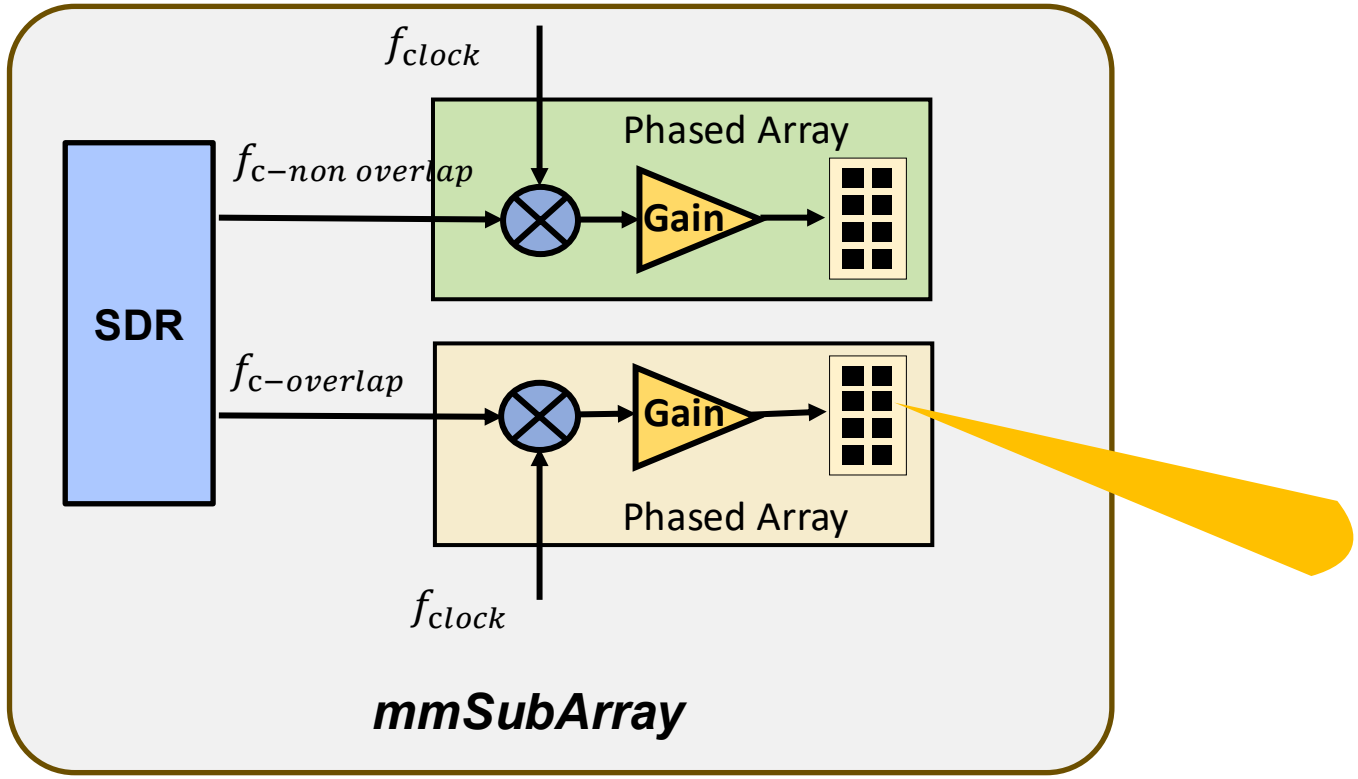


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Proposed ***mmSubArray*** solution: *Suppressing interference and supporting users*

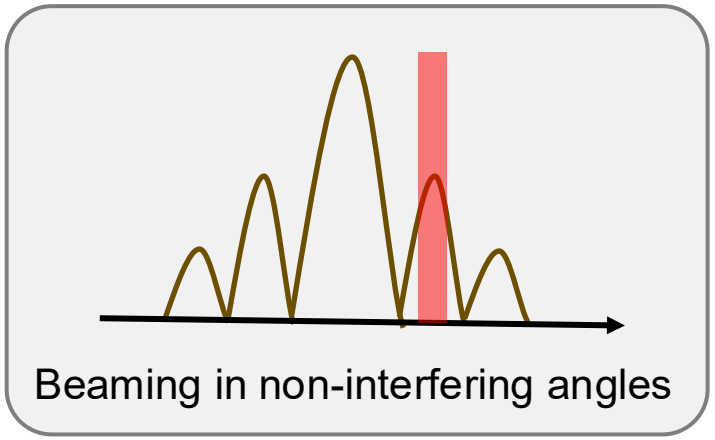


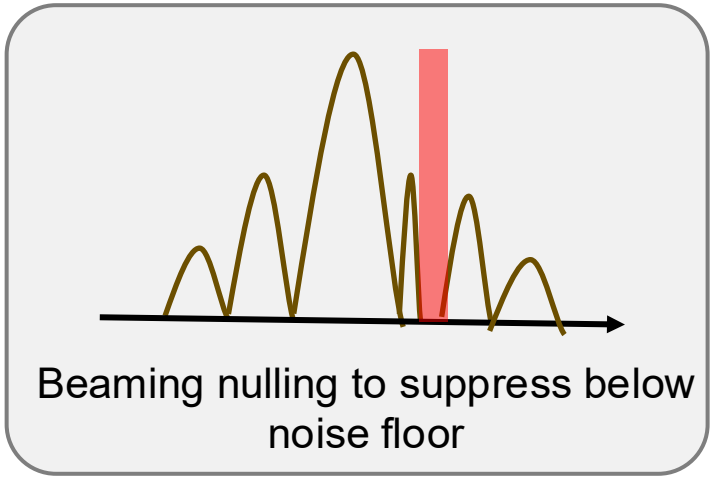


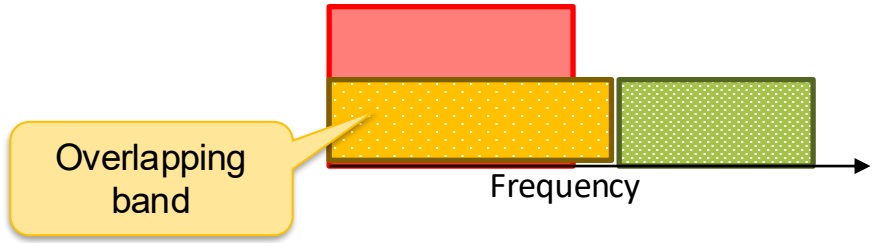


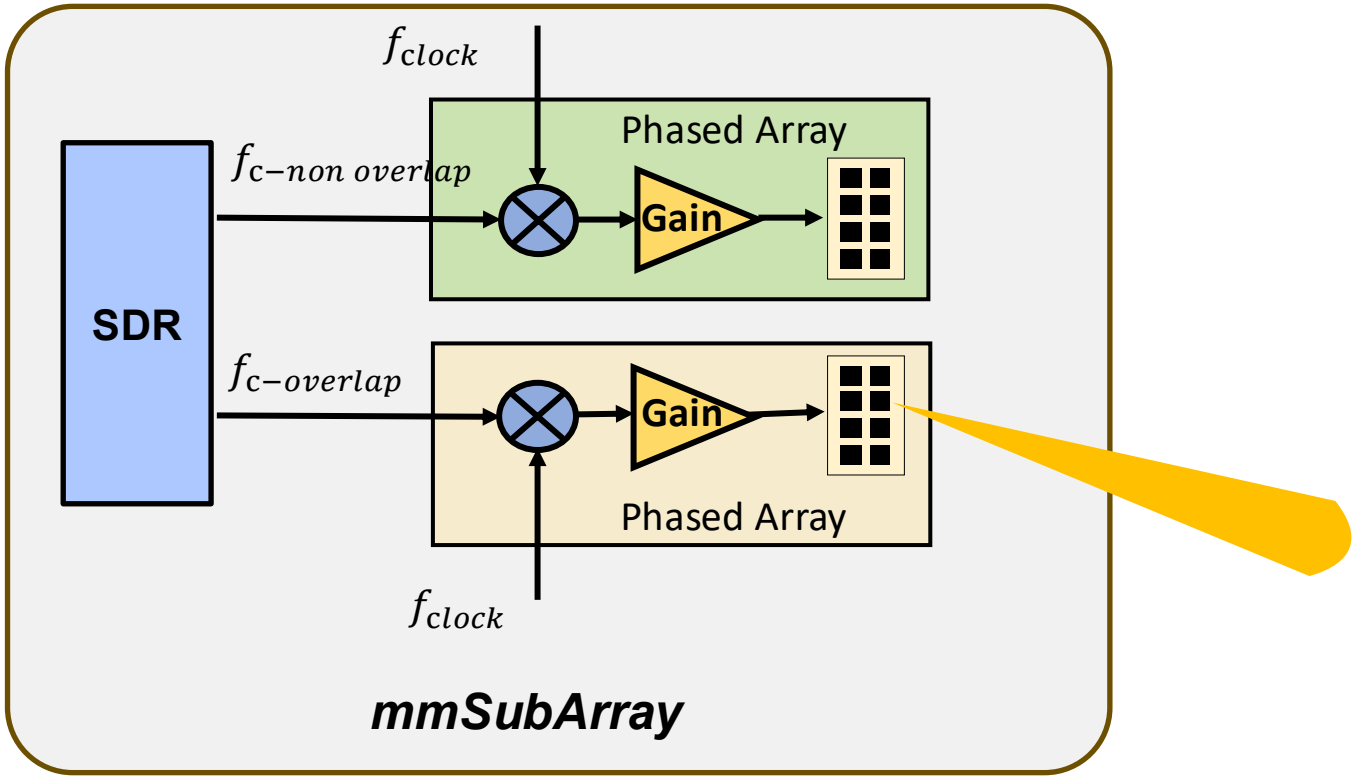
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Proposed ***mmSubArray*** solution: *Suppressing interference and supporting users*



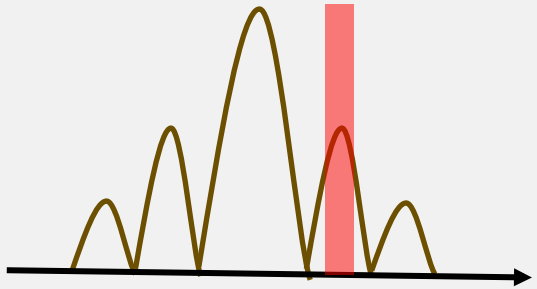




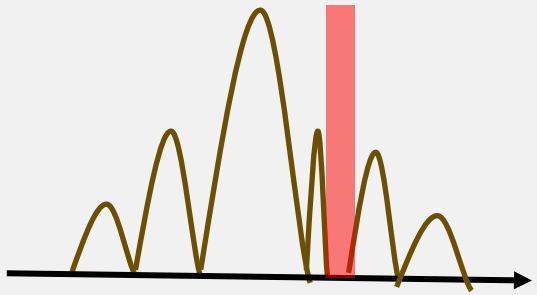


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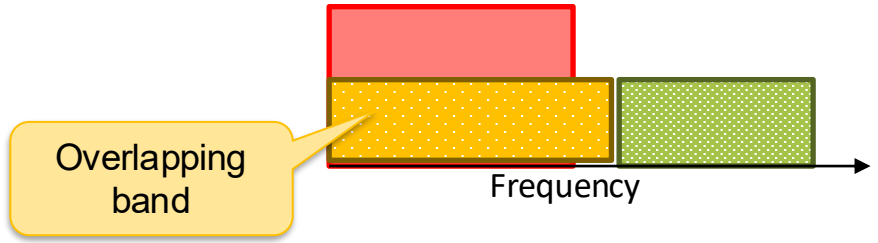
Proposed ***mmSubArray*** solution: *Suppressing interference and supporting users*

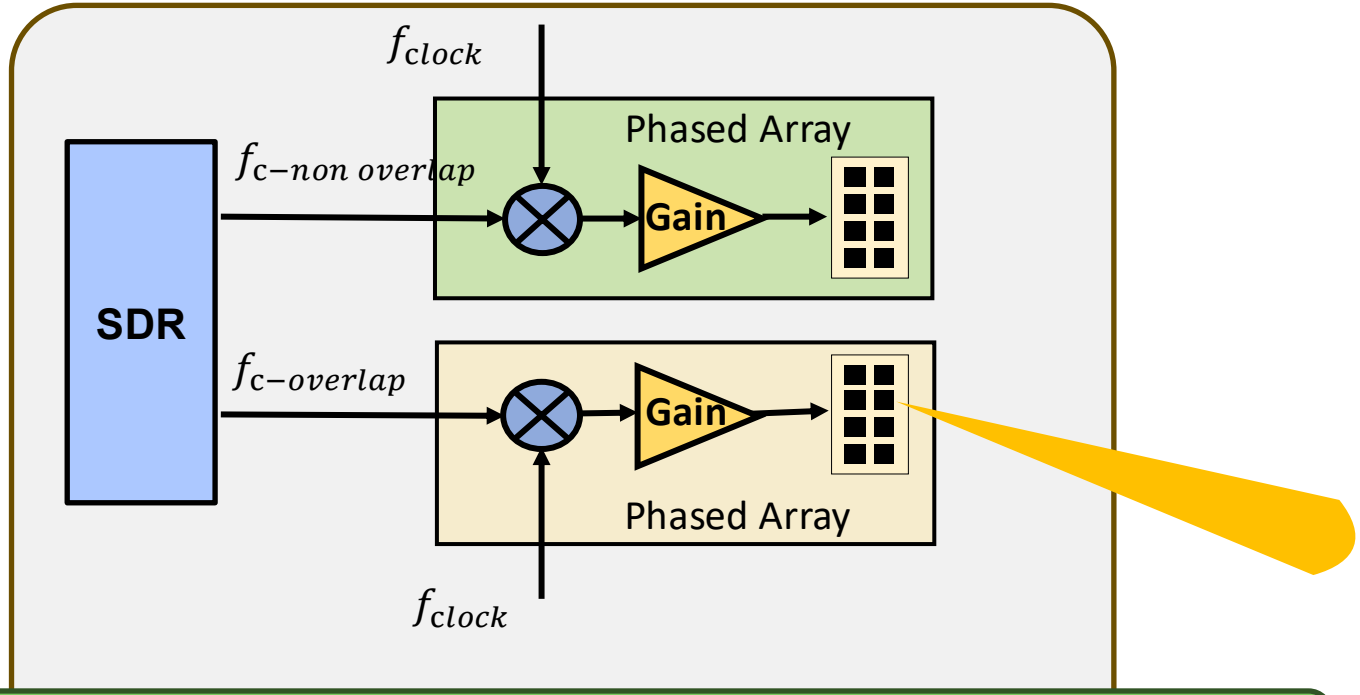


Beaming in non-interfering angles



Beaming nulling to suppress below noise floor







user

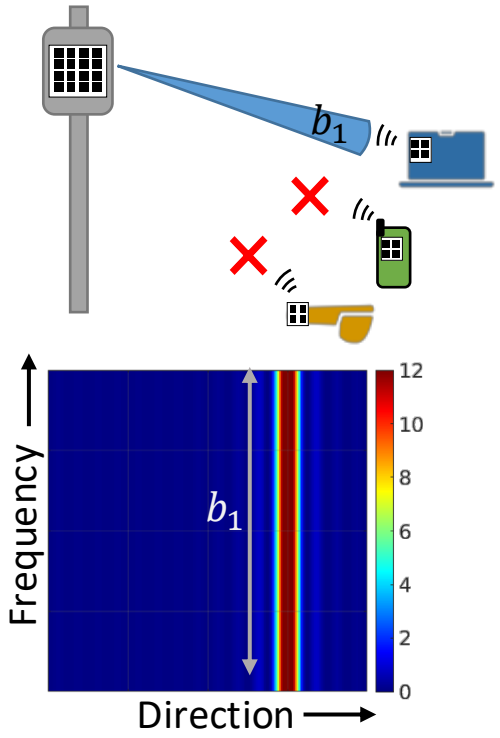
Enabling coexistence by suppressing interference and effectively supporting users in non interfereing directions

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Satellite-Terrestrial-Coexistence Demo

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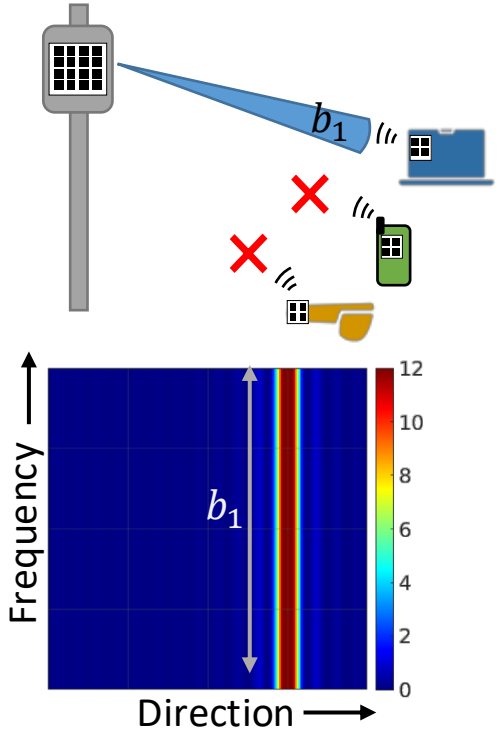
mmFlexible: Flexible time-frequency resource allocation



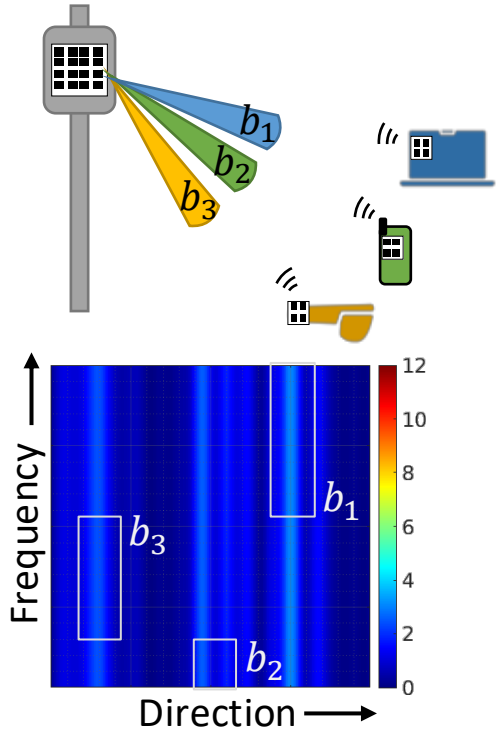
Single beam
(cannot serve concurrent users)

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mmFlexible: Flexible time-frequency resource allocation



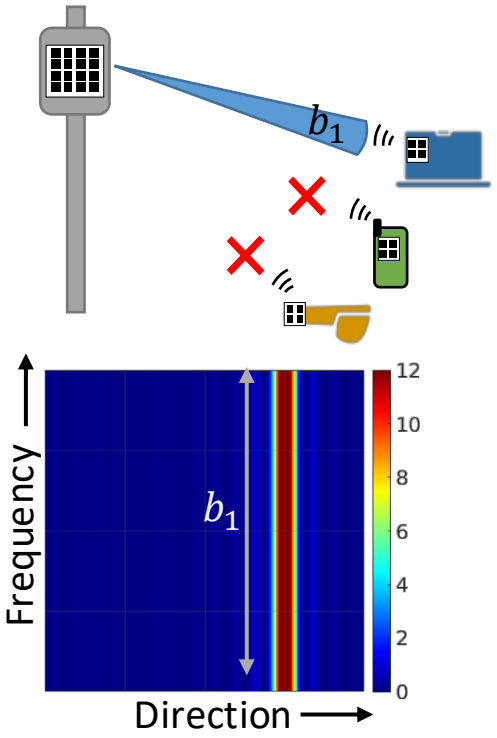
Single beam
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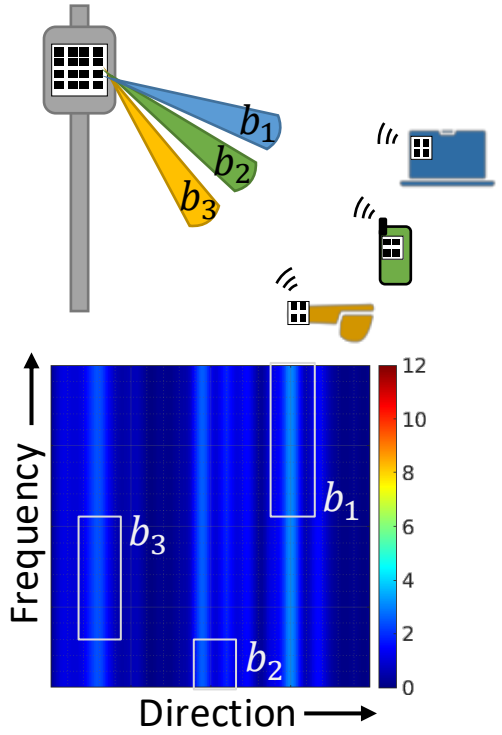
Multi-beam
(low beamforming gain per-beam)

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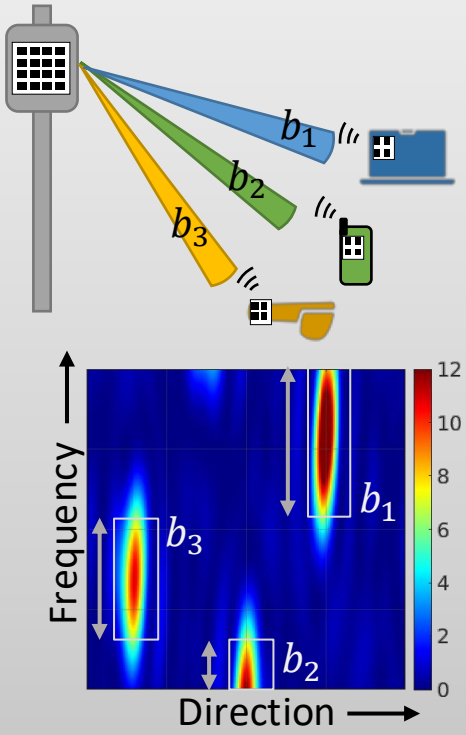
mmFlexible: Flexible time-frequency resource allocation



Single beam
(cannot serve concurrent users)



Multi-beam
(low beamforming gain per-beam)



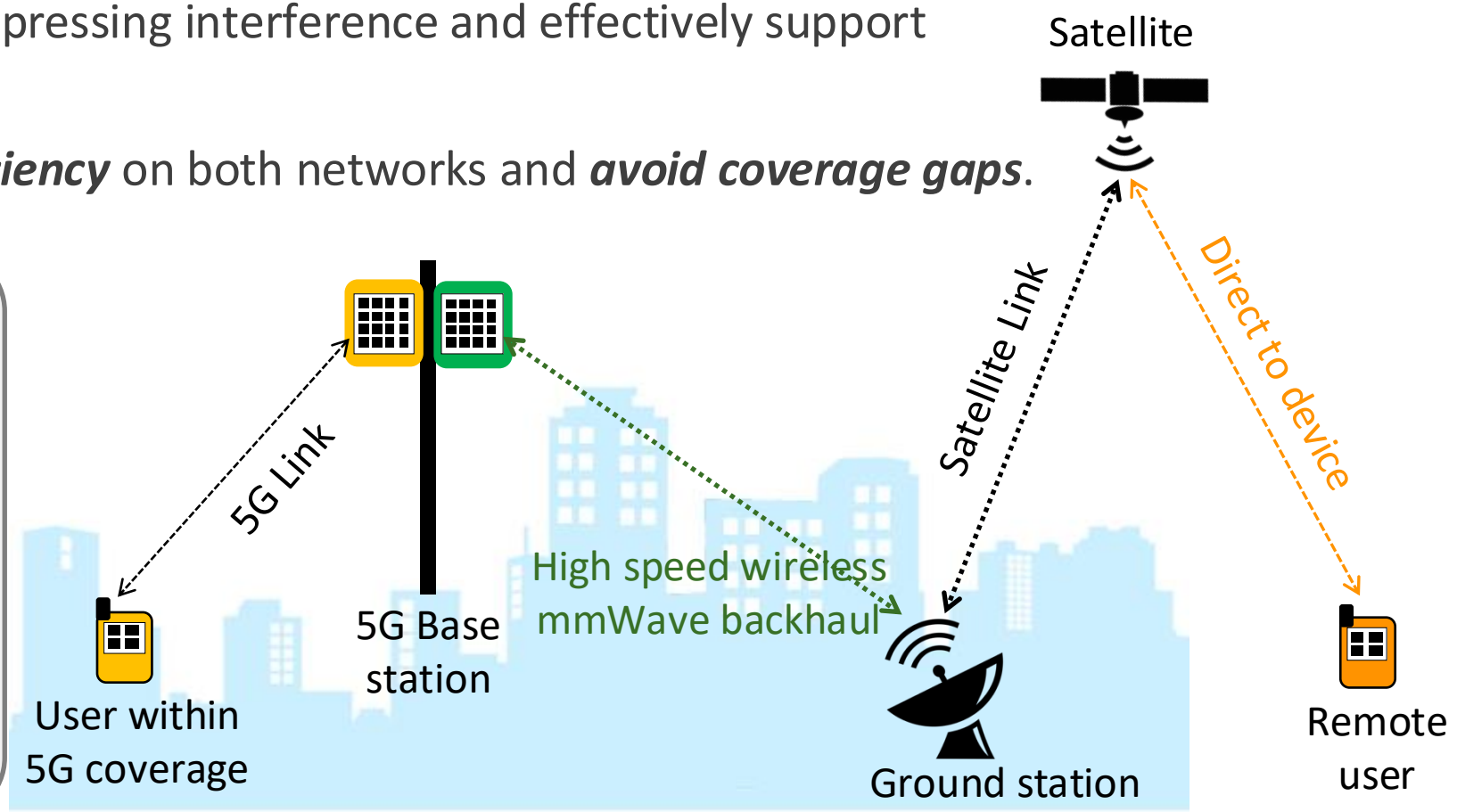
Proposed: Frequency-dependent Multi-beam
(high gain and high beam-bandwidth per-beam)

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Summary

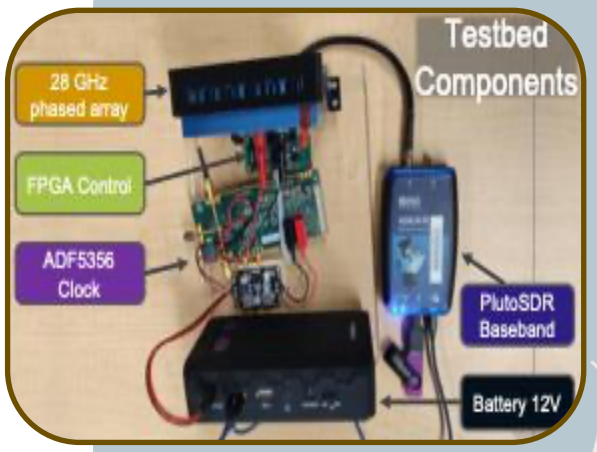
- High speed wireless mmWave backhaul – ***no more expensive fiber backhual***.
- **Enables coexistence** by suppressing interference and effectively support users in other directions
- Achieves ***high spectral efficiency*** on both networks and ***avoid coverage gaps***.

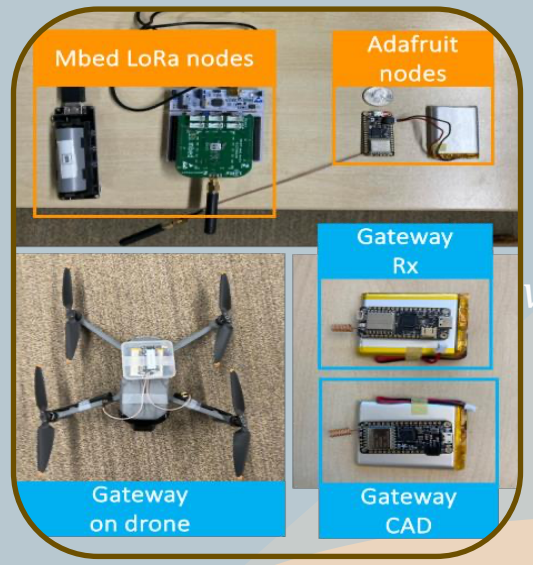
Artifacts and more details at
wcsng.ucsd.edu/mmsubarray



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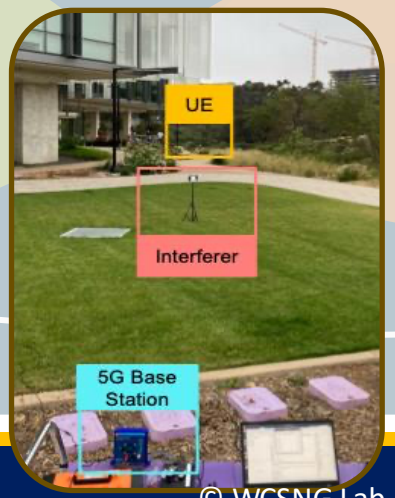
Building Adaptive, Efficient and Deployable Systems









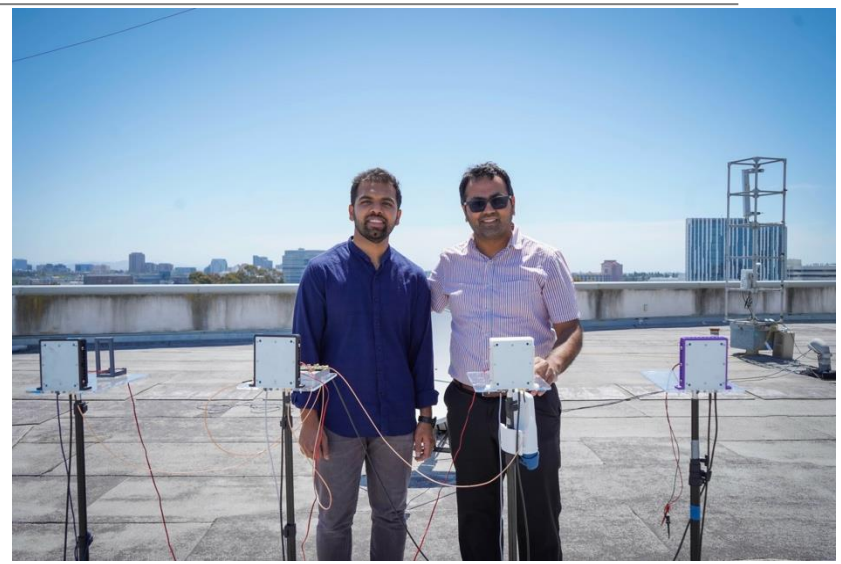




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Acknowledgements

- **Primary Student:** Rohith Reddy Vennam



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Acknowledgements

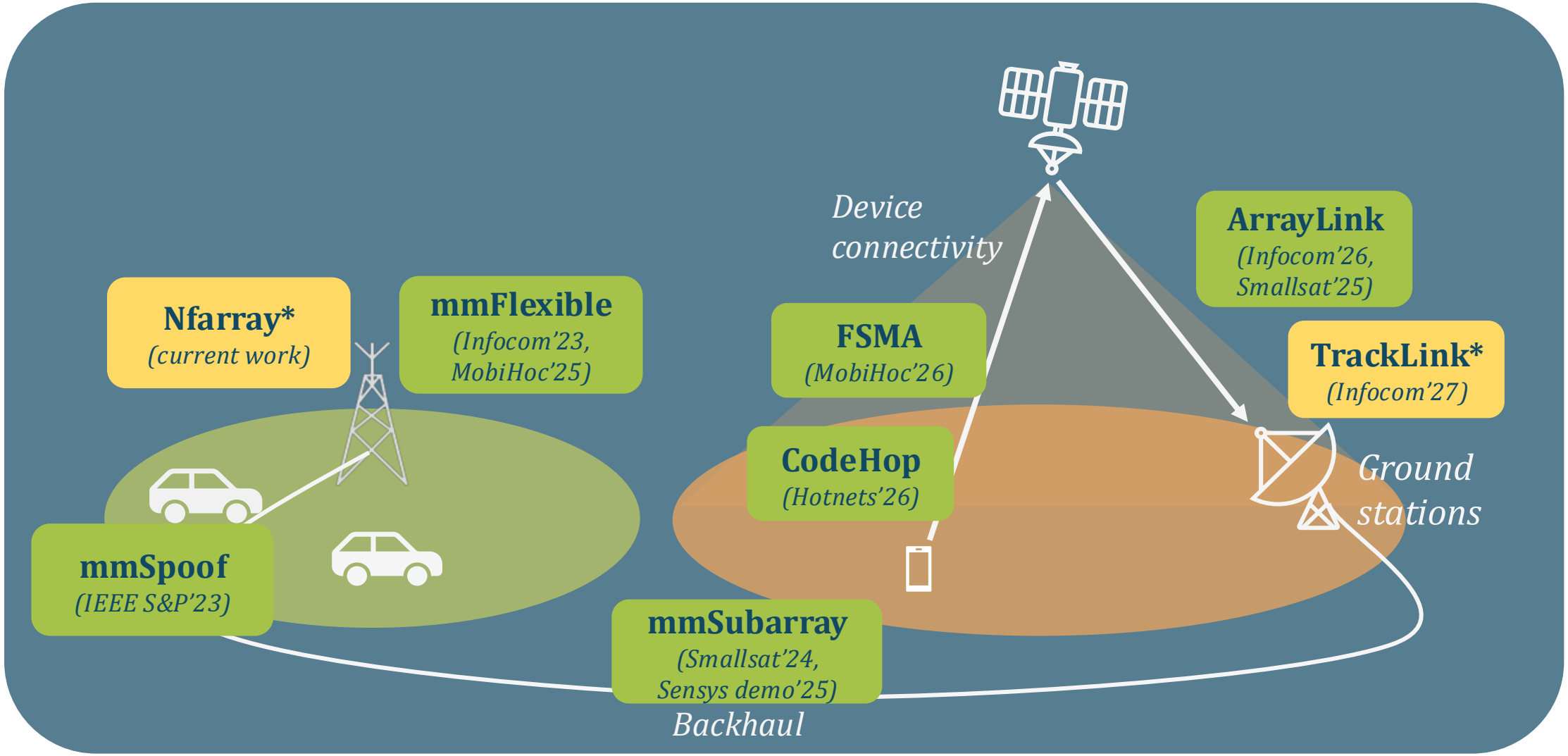
- **Primary Student:** Rohith Reddy Vennam
- **Collaborators (Professors)**: Deepak Vasisht (UIUC), Aanjhan Ranganathan (Northeastern), Ish Kumar Jain (RPI)
- **Collaborators (Students):** Ish Kumar Jain, Raghav Subbaraman, Luke Wilson, Maiyun Zhang, Kshitiz Bansal, Joshua Orozco, Puja Shukla, Nagarjun Bhat, Sesha Sai Rakesh Jonnavithula, Zhongze Xiang, William Hunter
- Claude code was used to make graphics and presentation for this work





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Thank you: Happy to take any questions ☺



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