

Beyond coverage:

how mega-constellations will shape the future of non-terrestrial networks

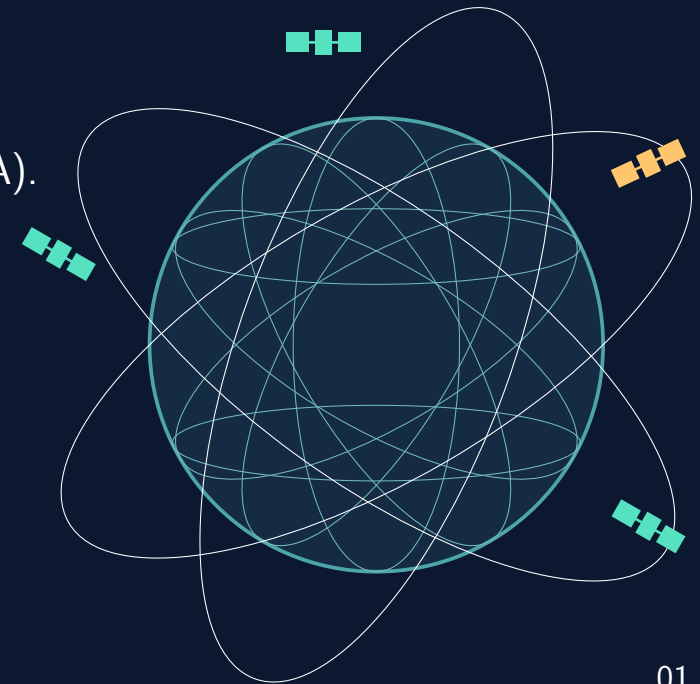
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Joint research on Walker constellations; dimensioning work also with Glorieli Nino (IPSA).

Satellite geometry → **Interference** → **Design**

A mathematical and engineering view of the mega-constellation era.



The mega-constellation race is accelerating

FCC | 09 JAN 2026

**FCC Approves
Next-Gen Satellite
Constellation**

+7,500

additional Starlink Gen2 satellites
authorized

[N1] FCC official release (PDF) →

AMAZON LEO | 09 SEP 2026

**Amazon Leo and
Arianespace strengthen
launch partnership**

+6 launches

Ariane 64 launches ordered; now
24 planned in total

[N2] Arianespace release →

ONEWEB | 10 SEP 2026

**Eutelsat selects
Arianespace for OneWeb
renewal**

+2 launches

Ariane 64 missions contracted for
2027 and 2028

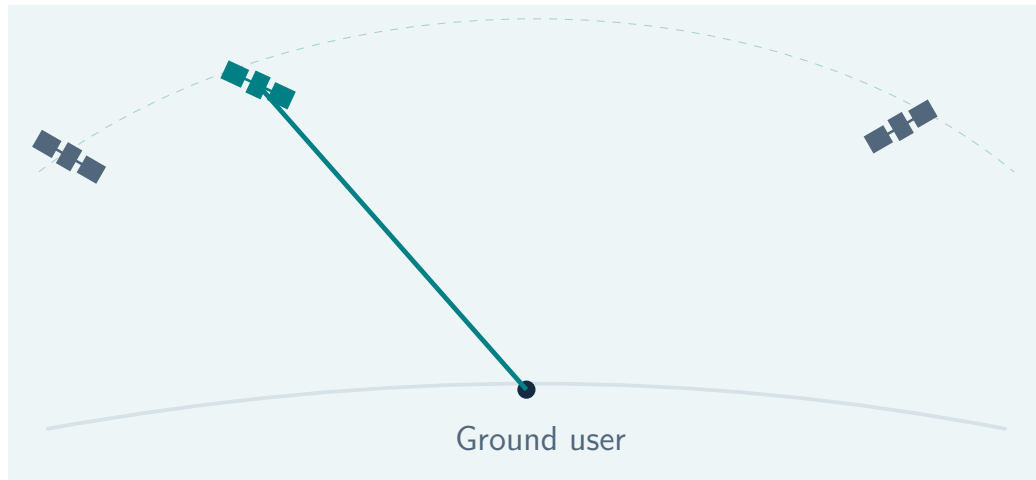
[N3] Arianespace release →

What does larger constellation density mean for an individual radio link?

Do more satellites always mean better service?

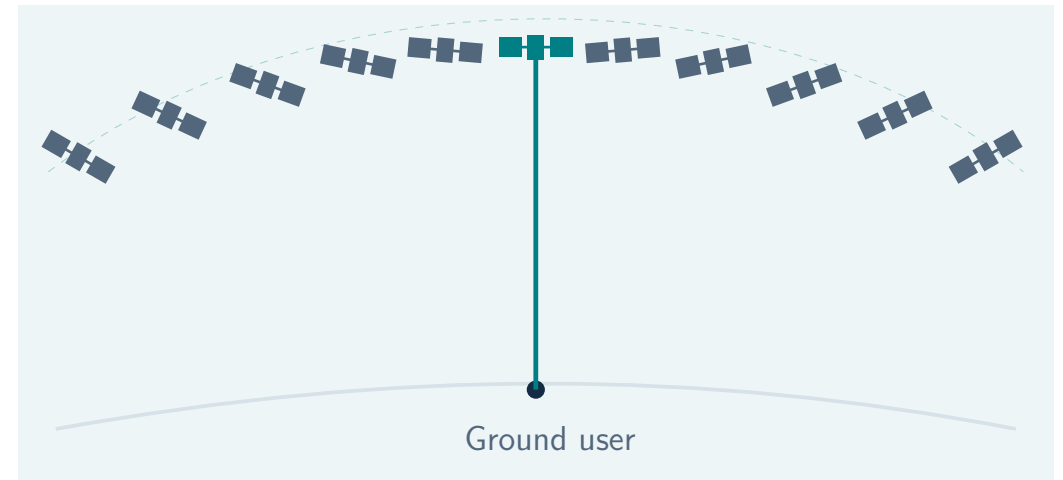
One ground user. The same altitude. The same radio resource.

A sparse sky



More visibility and a nearer serving satellite.

A denser sky



Also more satellites transmitting on the same resource.

Which effect wins as the constellation grows?

First, the serving link gets better

Densification reduces typical serving distance in the evaluated Walker family.

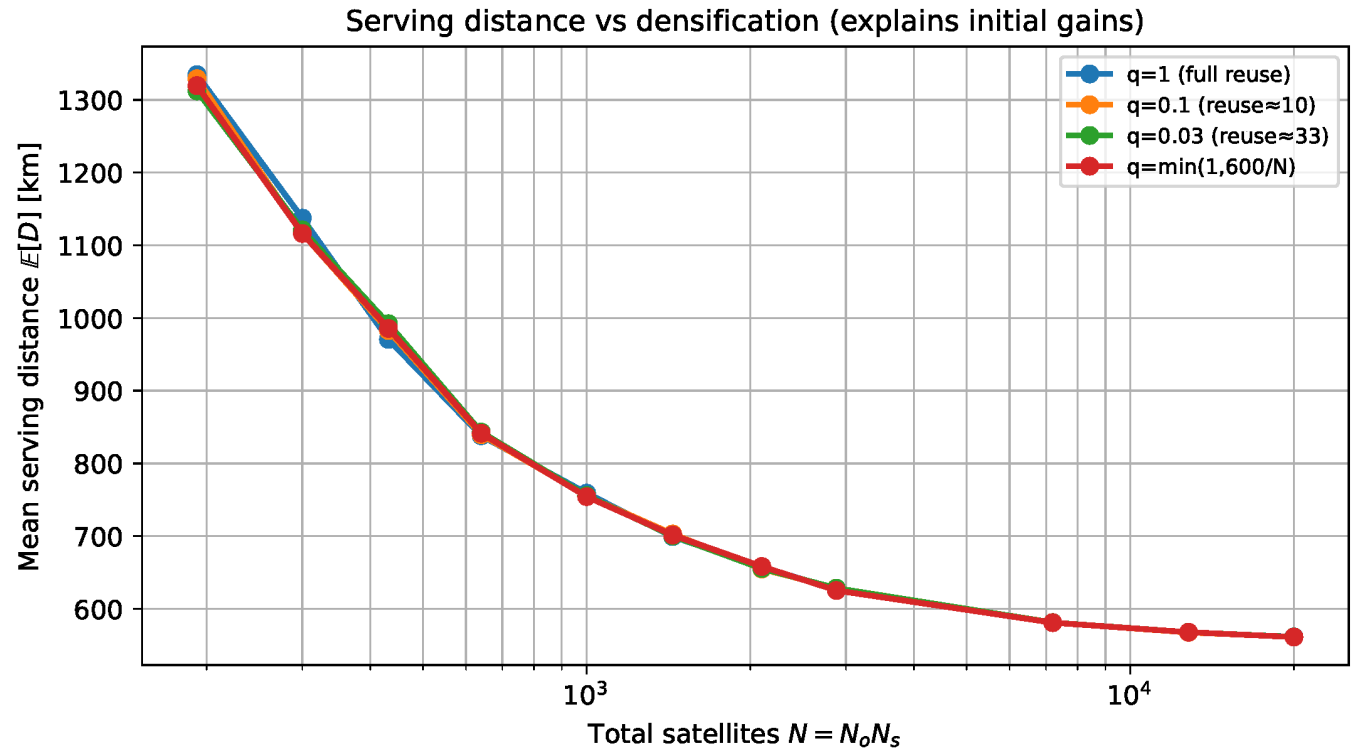
Closer satellite,
stronger useful signal

$$\text{SNR} = \frac{pGH_0D_0^{-\alpha}}{\sigma^2}$$

But altitude sets a floor:

$$D_0 \geq h > 0.$$

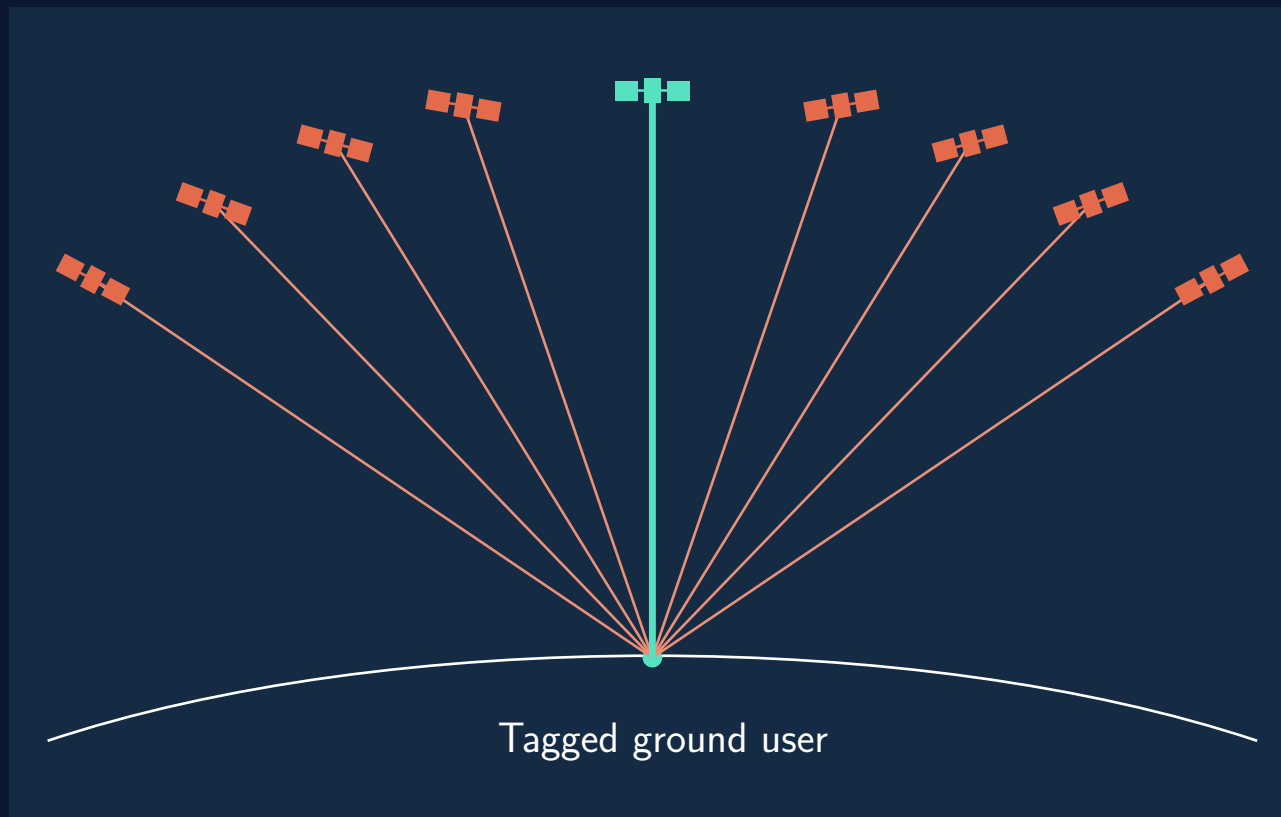
The mean SNR gain saturates when the serving distance approaches its geometric minimum.



Here: the distance approaches 550 km.

Then, interference keeps accumulating

A better serving link shares the sky with more active co-channel transmissions.



$$\text{SINR} = \frac{S}{I + \sigma^2}$$

Useful power is bounded in mean.

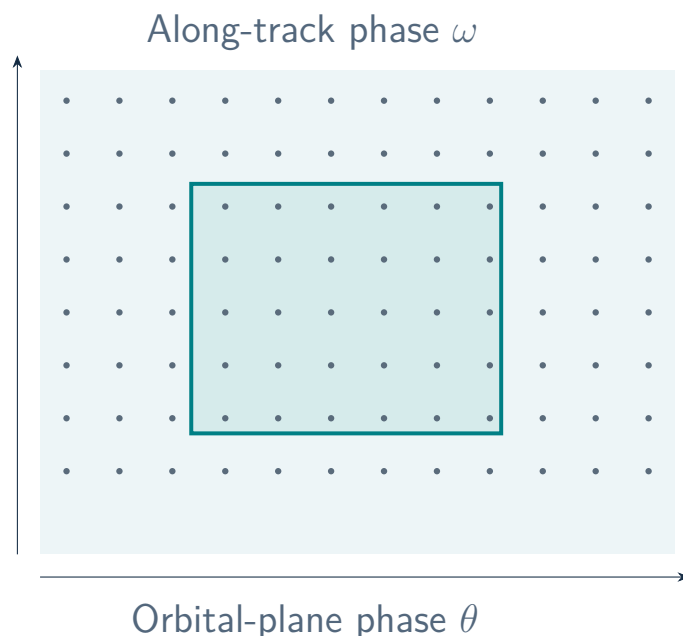
Aggregate interference grows with density.

Fixed beams and fixed reuse can delay the crossover. They do not remove it under the model assumptions.

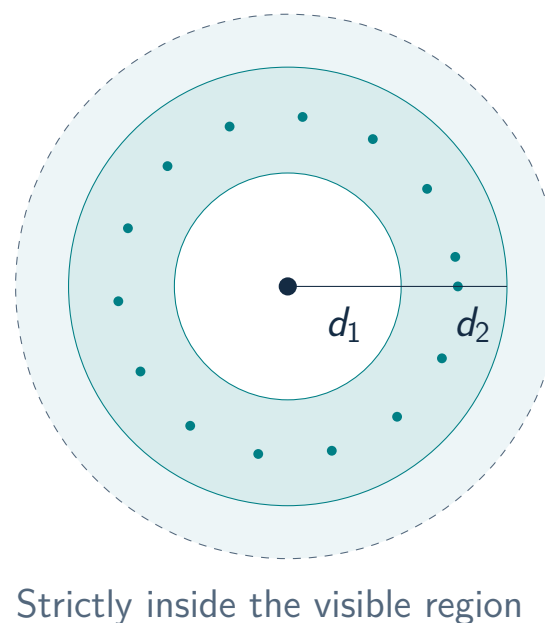
A fixed piece of sky contains a growing crowd

Proof intuition: stochastic geometry with the exact Walker lattice and invariant phase averaging.

1. A regular phase grid



2. A visible distance annulus



3. A uniform count

At least βN
satellites in the patch

For every phase state once
both Walker dimensions are
sufficiently large.

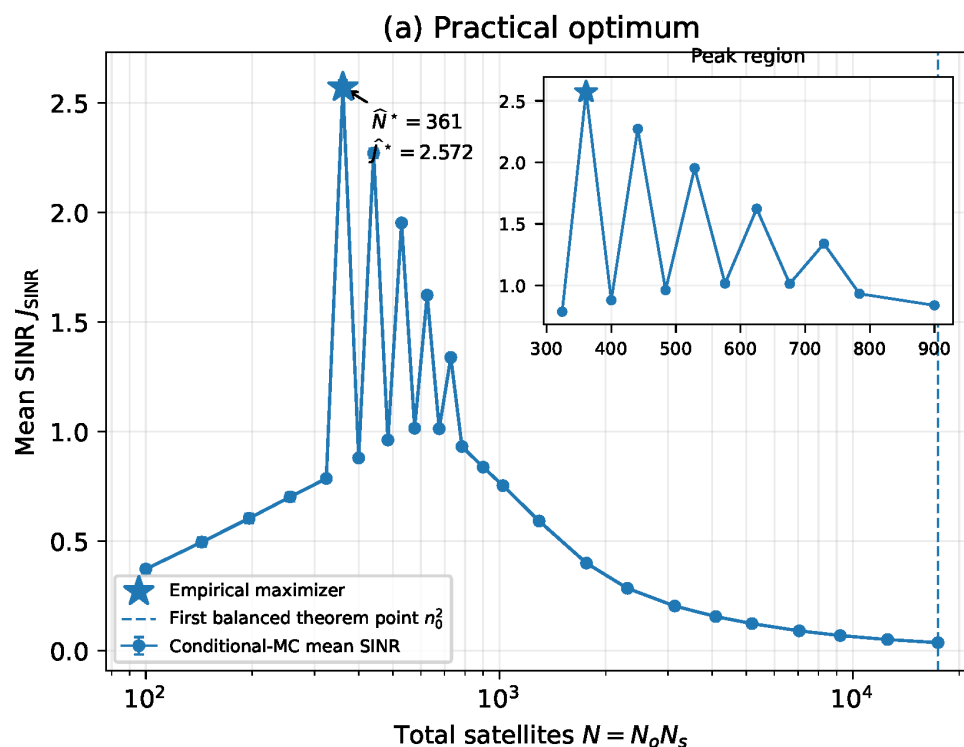
Positive coupling in this
patch forces interference
growth.

$$\mathbb{E}[I] \geq c_I N \quad \text{while} \quad \mathbb{E}[S] \leq S_{\max}.$$

Theory predicts the decay; simulations reveal the turn

Fixed altitude, fixed antenna pattern and full reuse on one resource block.

$$P_{\text{cov}}(\tau) = O(N^{-1}), \quad C_{\text{erg}} = O(N^{-1}), \quad J = \mathbb{E}[\text{SINR}] \longrightarrow 0.$$



A finite optimum

$19 \times 19 = 361$ satellites
on this tested balanced
grid.

No universal numerical threshold. The mean-SINR result uses an additional fading small-ball condition, satisfied by Rayleigh fading.

Does the mechanism survive directional antennas?

A controlled 3GPP-inspired robustness experiment.

Continuous angular gain

$$A(\psi) = \min \left\{ 12 \left(\frac{\psi}{\phi_{3\text{dB}}} \right)^2, 30 \right\} \text{ dB}$$

Circularized TR 38.901 law

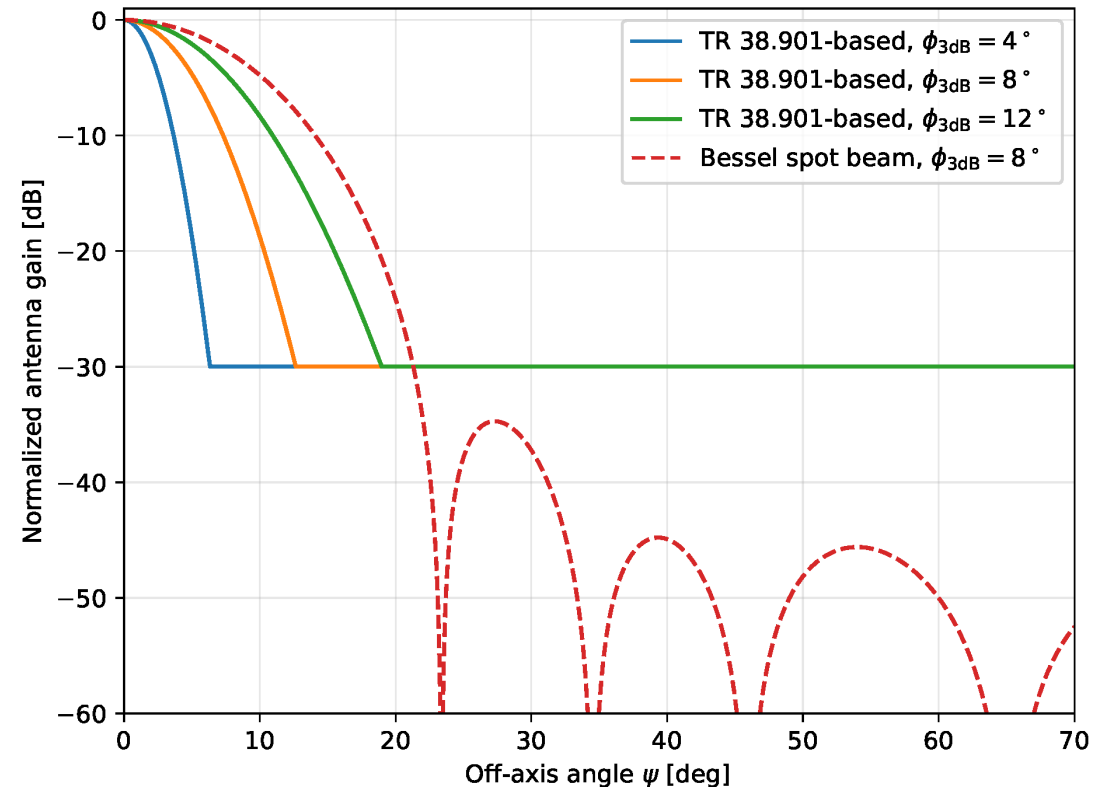
Baseline parameter $\phi_{3\text{dB}} = 8^\circ$

Bessel spot beam as a second test

550 km altitude 53° inclination

Equatorial user Rayleigh fading

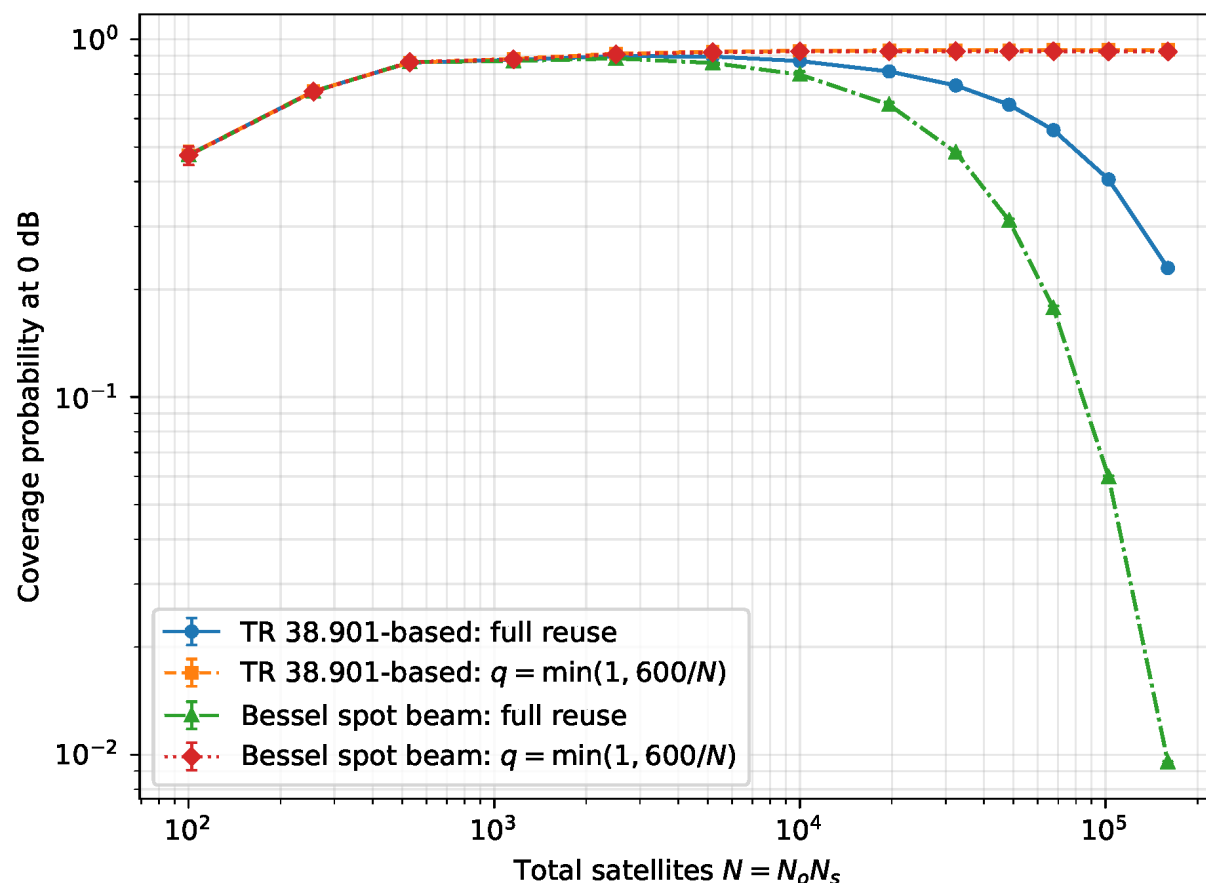
Zenith SNR 12 dB $\alpha = 2.5$



Serving beam points at the user; interfering beams point at nadir. This tests the mechanism, not a complete commercial multi-beam network.

Directional beams delay the coverage decline

Original simulation: probability that downlink SINR exceeds 0 dB.



An initial gain, then a decline.

Under full reuse, coverage eventually turns downward for both patterns.

At $N = 160,000$

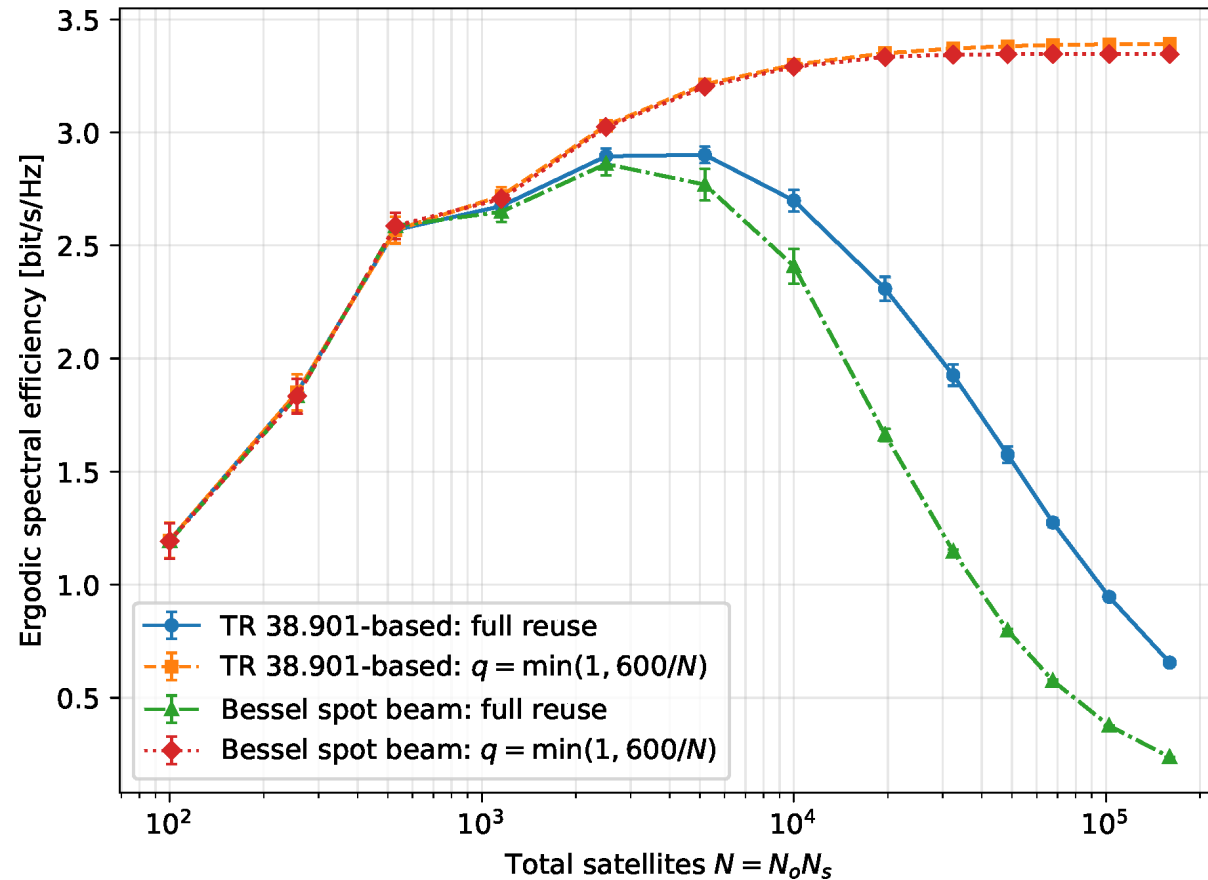
TR 38.901-based: ≈ 0.2

Bessel: ≈ 0.01

The theorem gives the asymptotic limit. These curves show finite-density behavior.

Controlling co-channel activity changes the outcome

The serving link stays active; each potential interferer is active with probability $q(N)$.



$$q(N) = \min\left(1, \frac{600}{N}\right)$$

The effective co-channel population stays of constant order.

3.3–3.4 bit/s/Hz

Observed plateau under density-dependent activity.

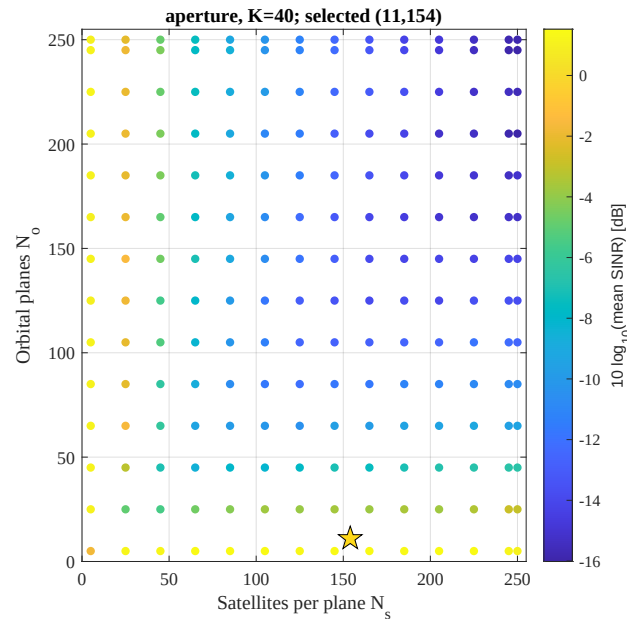
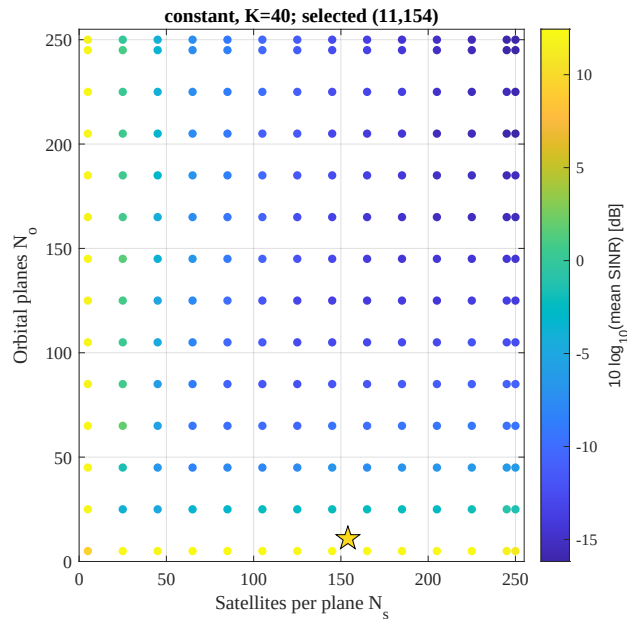
Per active link and resource.
Scheduling duty cycle and frequency partitioning still cost resources.

Constellation shape and frequency reuse matter together

A second study: explicit cyclic frequency assignment $\chi(i, j) = (i + j) \bmod K$.

Paris reference user 629 km altitude 33° inclination $K = 40$

11×154



1,694 satellites
Selected in both models
among tested finalists.

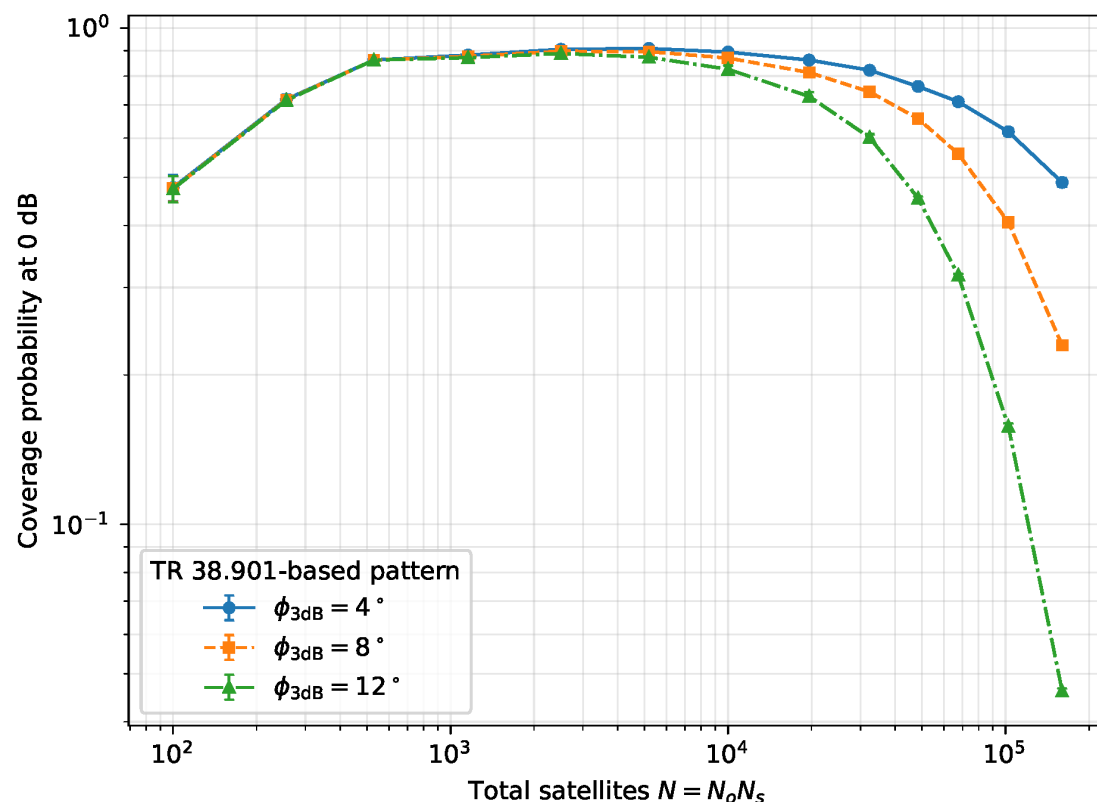
2.185 GHz / n256
80 RBs / 14.4 MHz occupied
TR 38.811 aperture pattern

Other finalists remain statistically
non-excluded. This is a
reference-user design, not a global
service optimum.

Fixed K delays the decline; the eventual mean-SINR bound remains $O(K/N)$.

Interference management must scale with density

Engineering implication: adding satellites and adding radio coordination belong in the same design.



Beamforming

Reduce off-axis coupling. Narrower fixed beams move the knee.

Scheduling

Limit simultaneous strong interferers using predictable orbital motion.

Frequency resources

Coordinate reuse with beam overlap, traffic and constellation geometry.

The converse motivates scalable control; it does not rank existing operators' implementations.

More satellites help when interference control keeps pace.

Geometry

Shorter serving links
have a physical limit.

Theory

Uncontrolled co-channel
densification loses SINR.

Design

Scale beam coordination,
scheduling and reuse.

The result concerns a link on a shared resource, not the total capacity of the whole network.

Thank you. ali.khalesi@ipsa.fr

READ THE FULL PAPER

Densification Converses for Walker Constellations

Ali Khaledi & François Baccelli

[arXiv:2604.24656](https://arxiv.org/abs/2604.24656)

Full text and proofs available on arXiv.



Scan to read the paper

Thank you! Questions?

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