NTN Days 2026 Cnam, Paris 13 October 2026

# Beyond coverage:

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

**Ali Khalesi** IPSA & LINCS

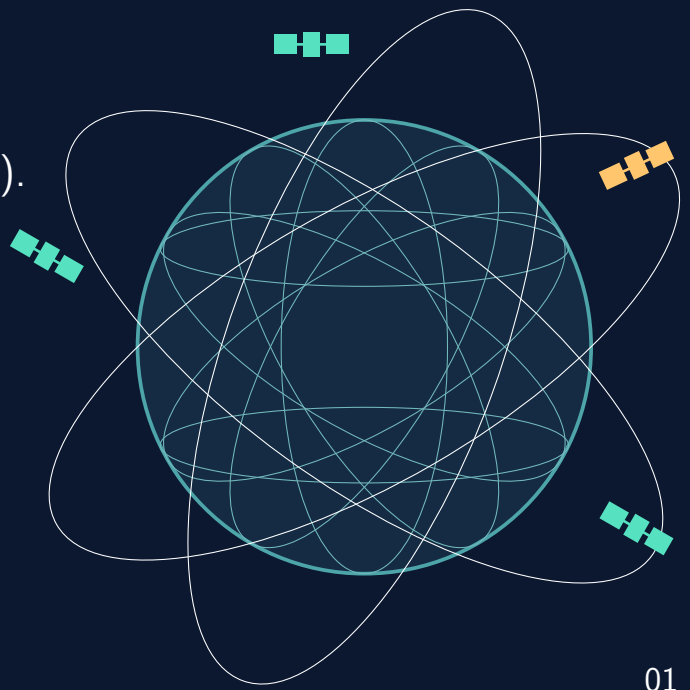
**Prof. François Baccelli** Inria Paris, Télécom Paris & LINCS

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

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**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

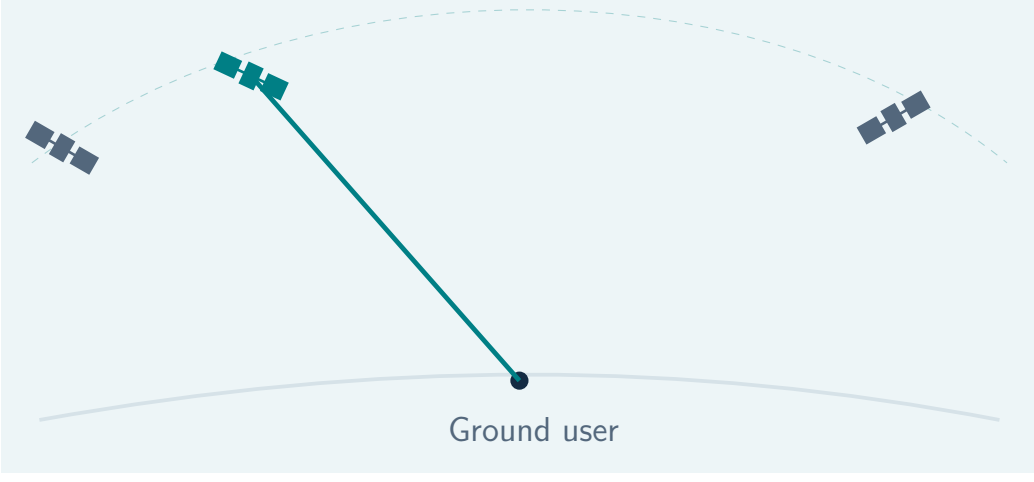
[N3] Arianespace release →

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

# Do more satellites always mean better service?

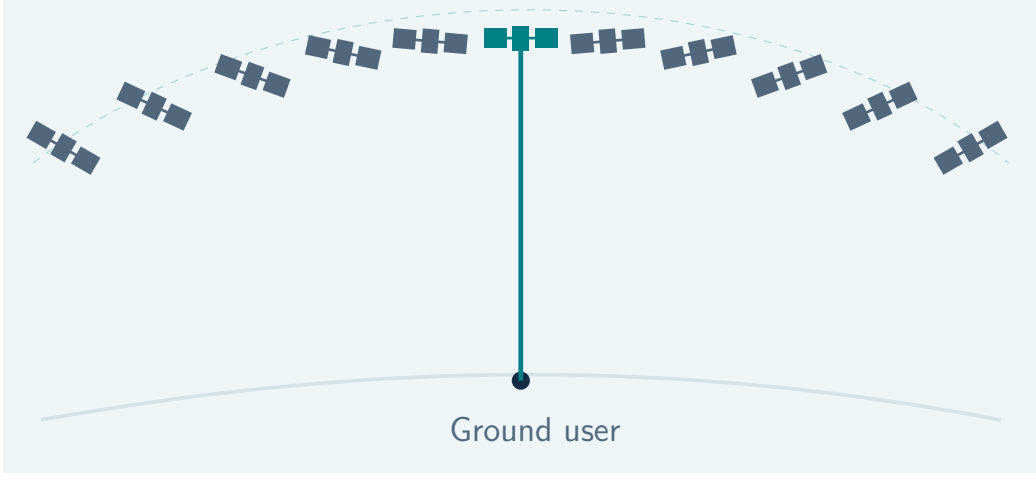
One ground user. The same altitude. The same radio resource.

## 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.

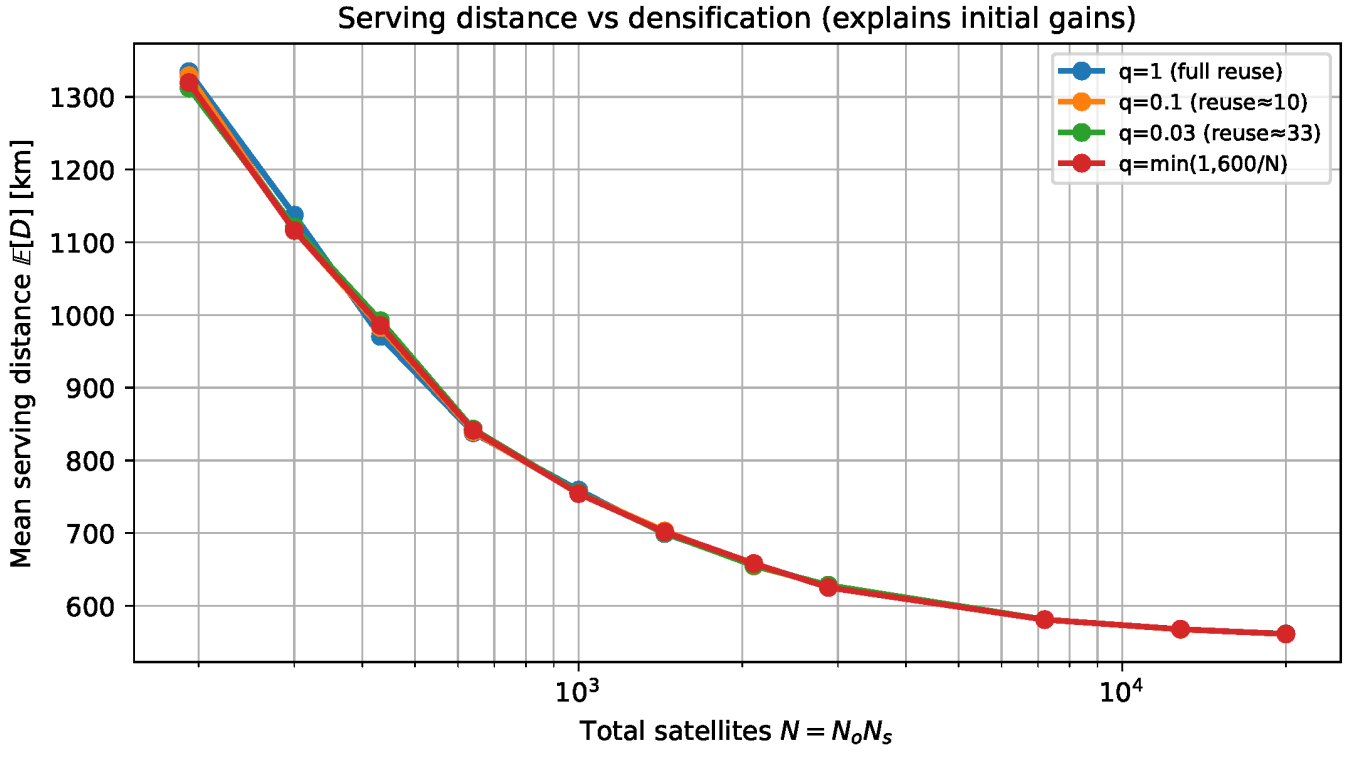
## Closer satellite, stronger useful signal

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

But altitude sets a floor:

$D_0 \geq h > 0.$

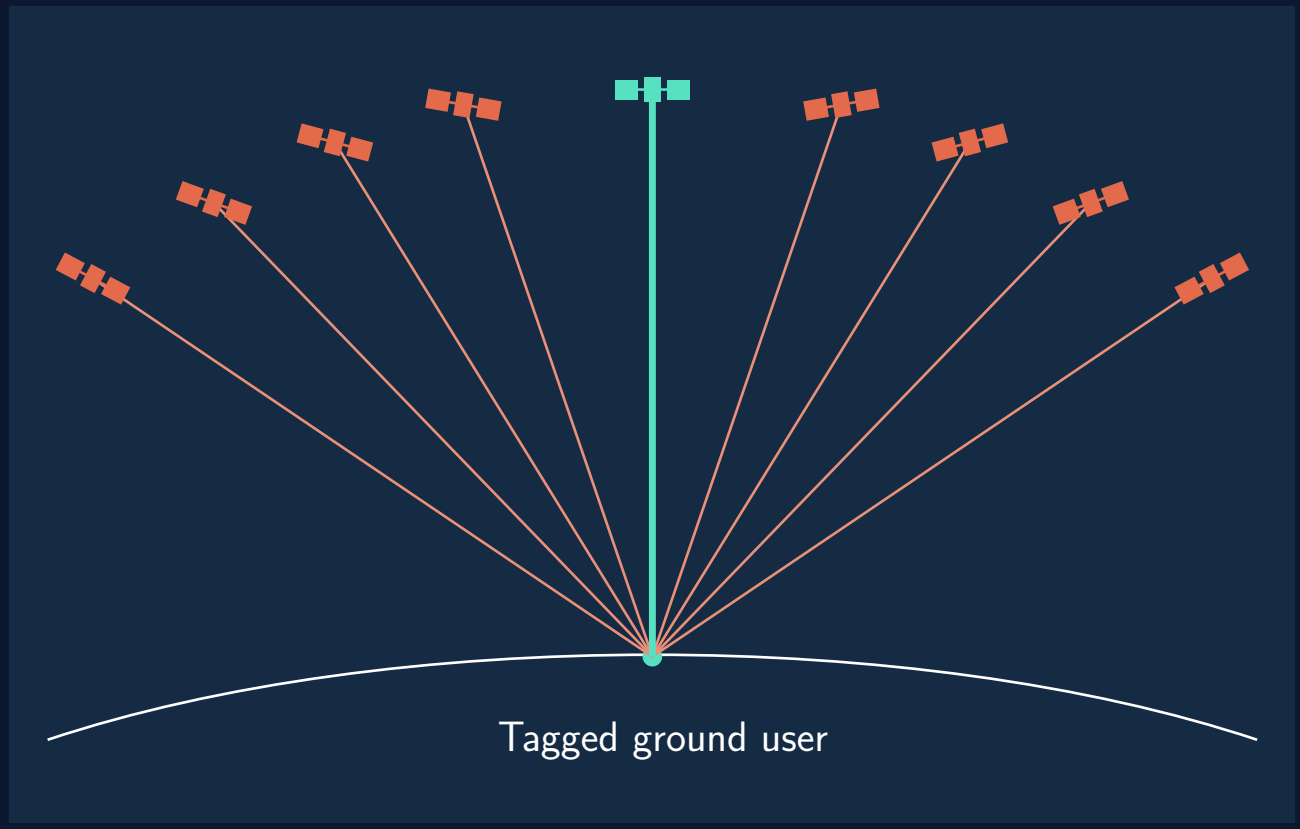
The mean SNR gain saturates when the serving distance approaches its geometric minimum.




**Here: the distance approaches 550 km.**

# Then, interference keeps accumulating

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




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

**Useful power is bounded in mean.**

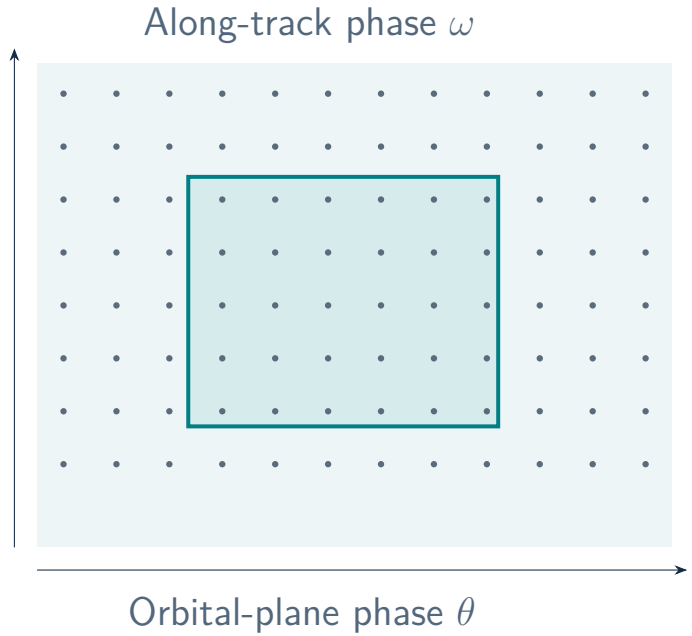
**Aggregate interference grows with density.**

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

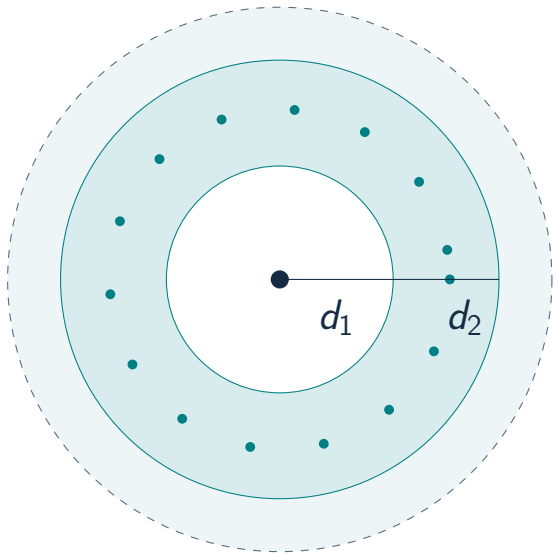
# A fixed piece of sky contains a growing crowd

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

## 1. A regular phase grid




## 2. A visible distance annulus




Strictly inside the visible region

## 3. A uniform count

At least $\beta N$ satellites in the patch

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

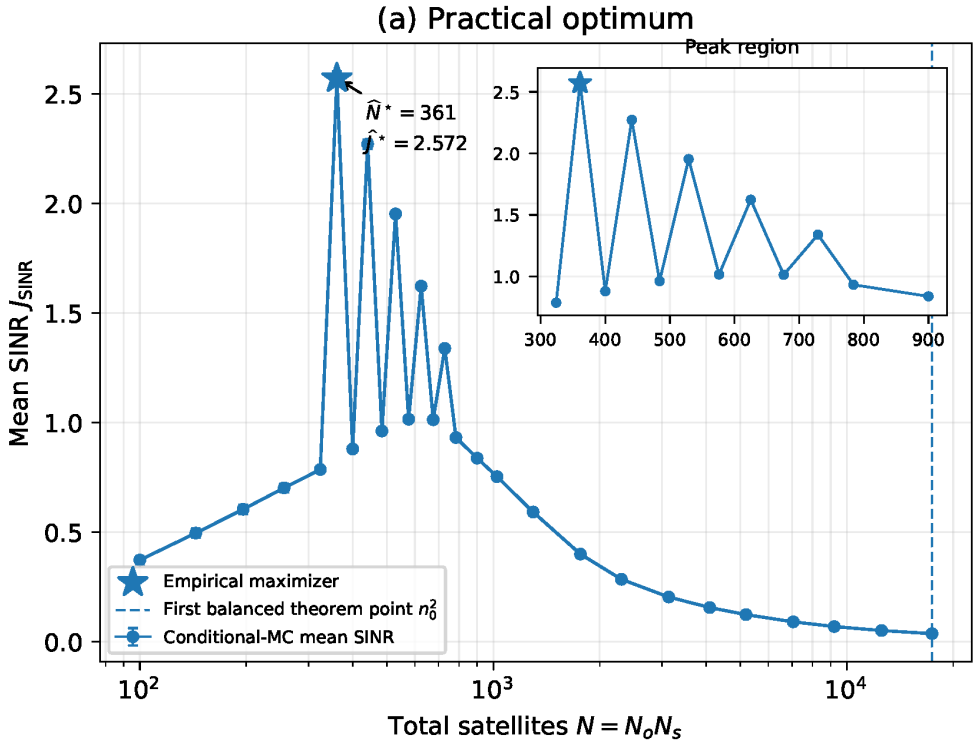
Positive coupling in this patch forces interference growth.

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

# Theory predicts the decay; simulations reveal the turn

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

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




## 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?

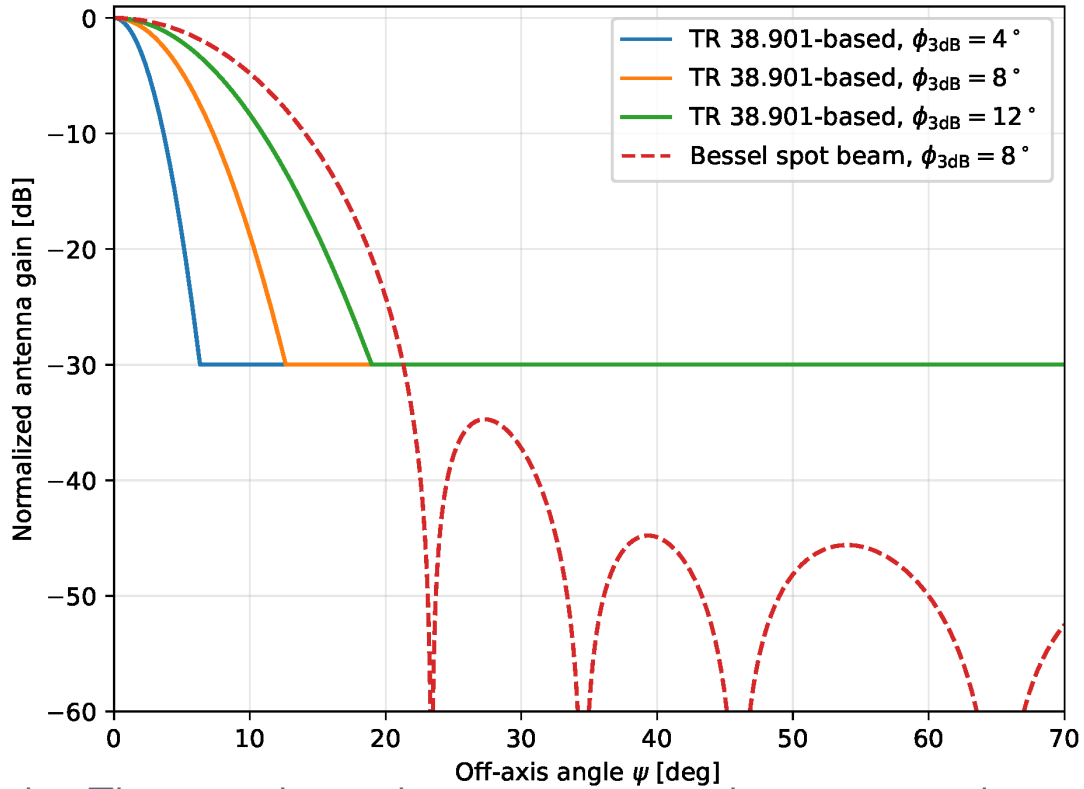
A controlled 3GPP-inspired robustness experiment.

## Continuous angular gain

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

Circularized TR 38.901 law
Baseline parameter $\phi_{3\mathrm{dB}} = 8°$
Bessel spot beam as a second test

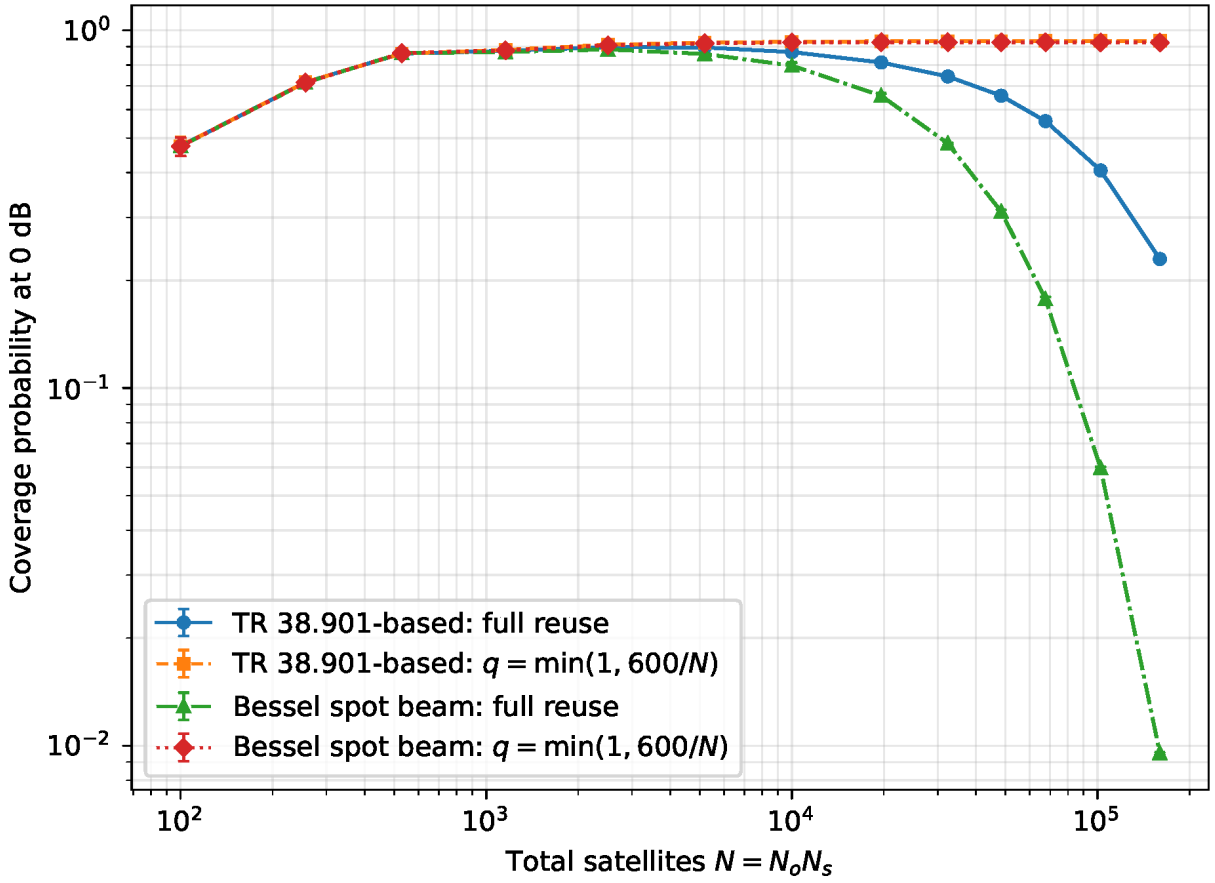
550 km altitude  53° inclination
Equatorial user  Rayleigh fading
Zenith SNR 12 dB  $\alpha = 2.5$




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 $N = 160{,}000$

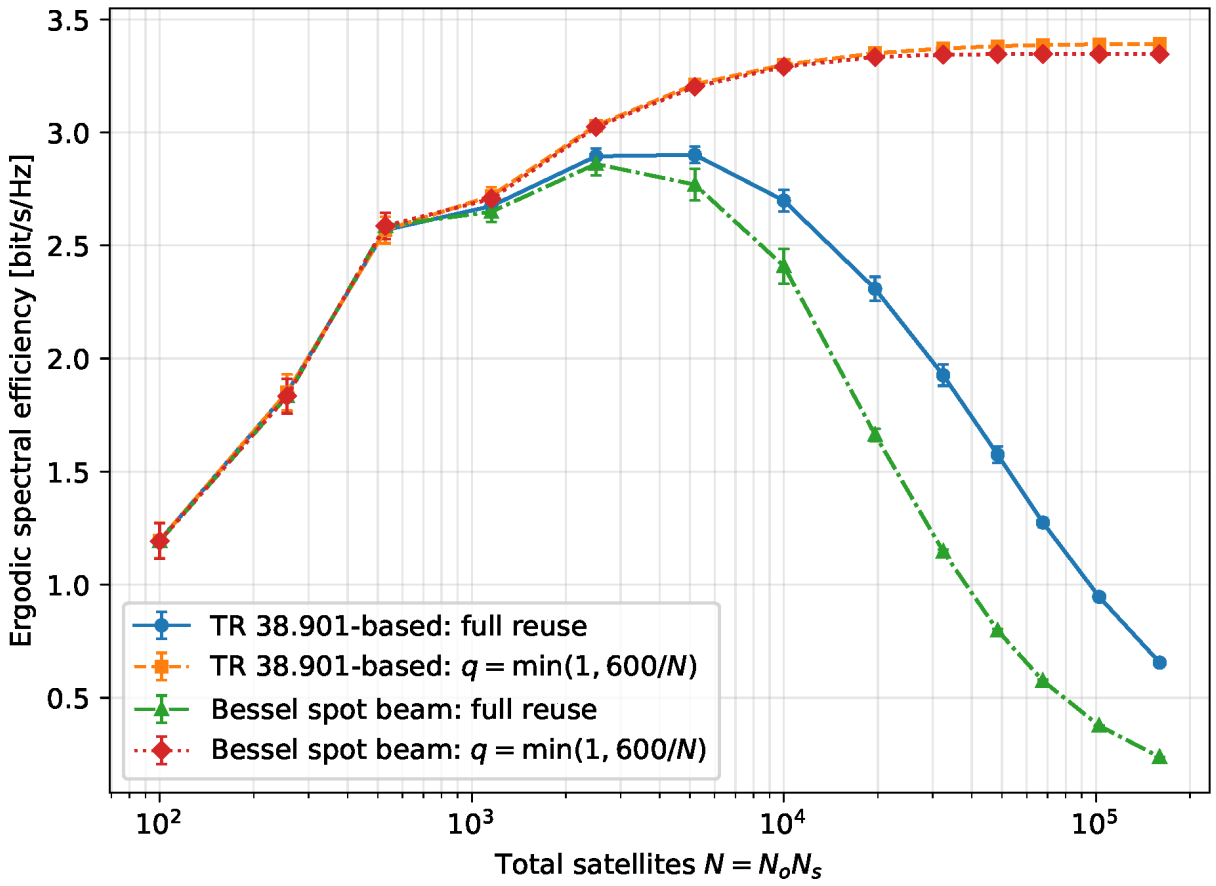
TR 38.901-based: $\approx 0.2$

Bessel: $\approx 0.01$

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**

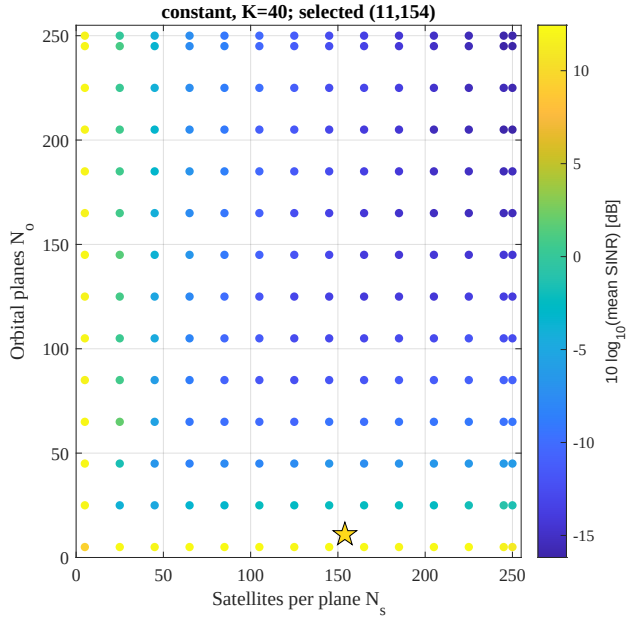
Observed plateau under density-dependent activity.

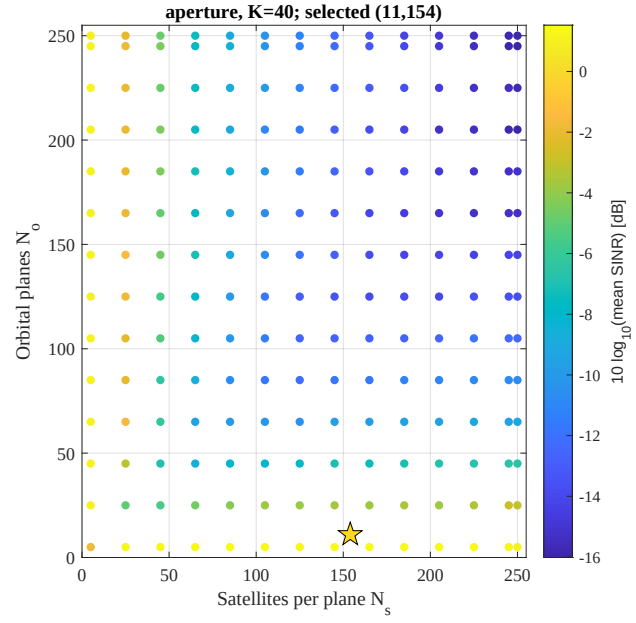
Per active link and resource. Scheduling duty cycle and frequency partitioning still cost resources.

# 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  $K = 40$




$11 \times 154$

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

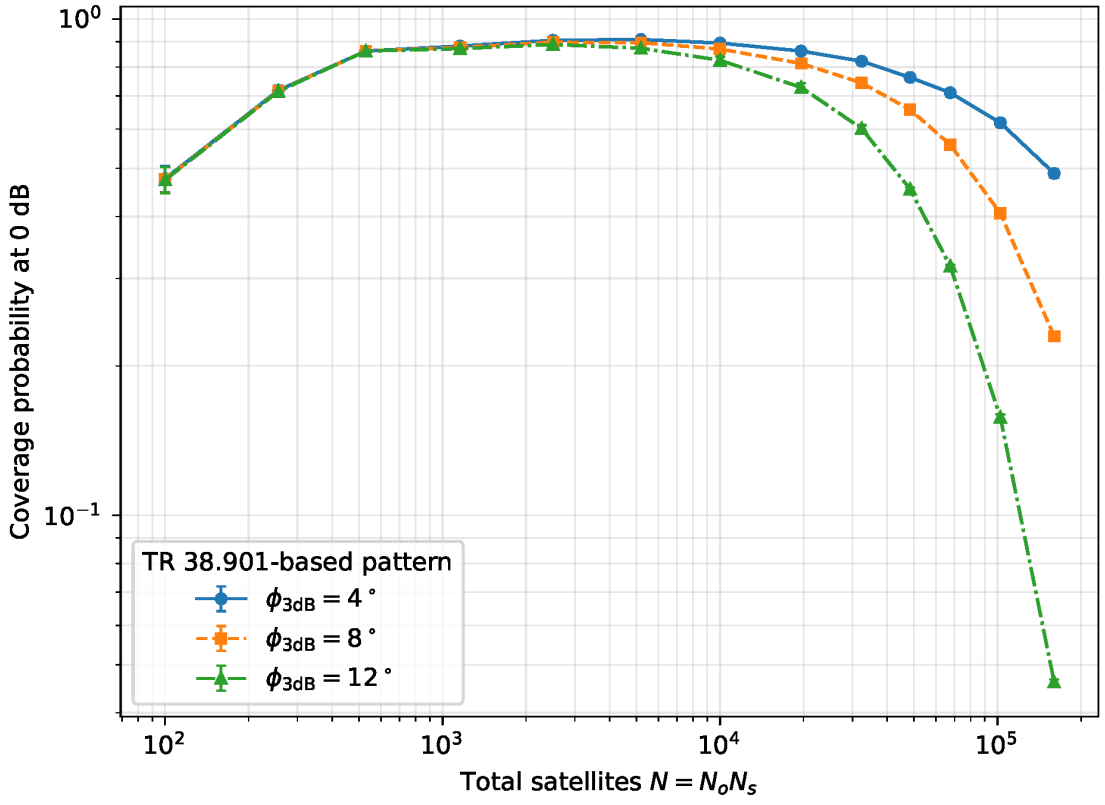
2.185 GHz / n256
80 RBs / 14.4 MHz occupied
TR 38.811 aperture pattern

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 Khalesi & François Baccelli

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arXiv:2604.24656

Full text and proofs available on arXiv.

Scan to read the paper

**Thank you!  Questions?**

ali.khalesi@ipsa.fr