Beyond the Cone Model: Quantifying the Impact of Beam-Level Constraints on LEO Satellite Networks

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Challenge whether Starlink had sufficient capacity to close the digital divide

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Anyone, Anywhere, not Everyone, Everywhere: Starlink Doesn't End the Digital Divide

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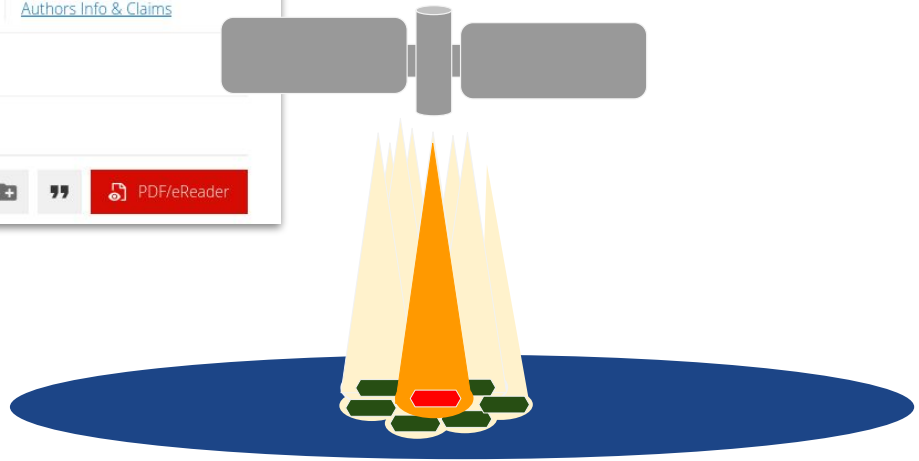
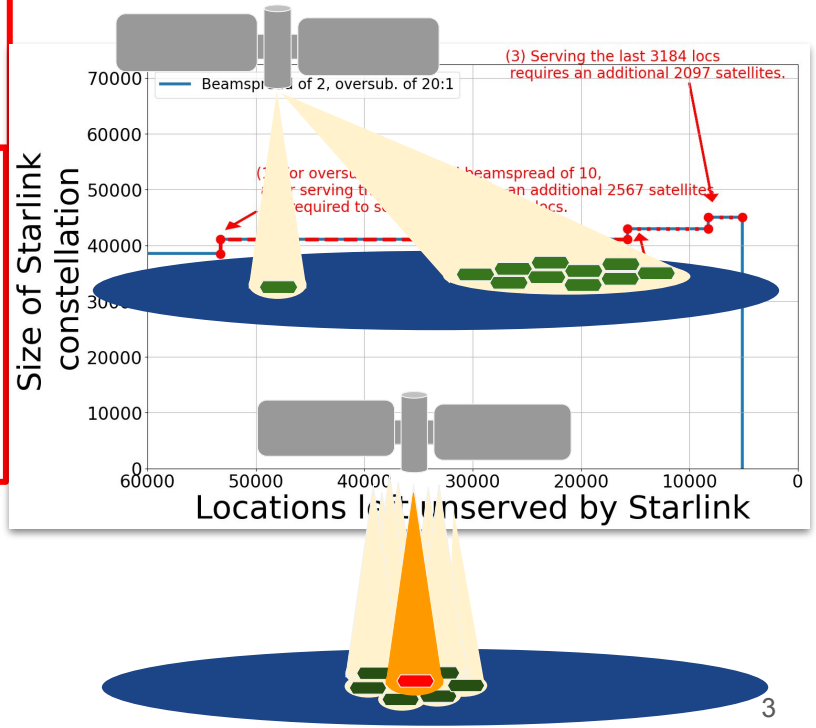


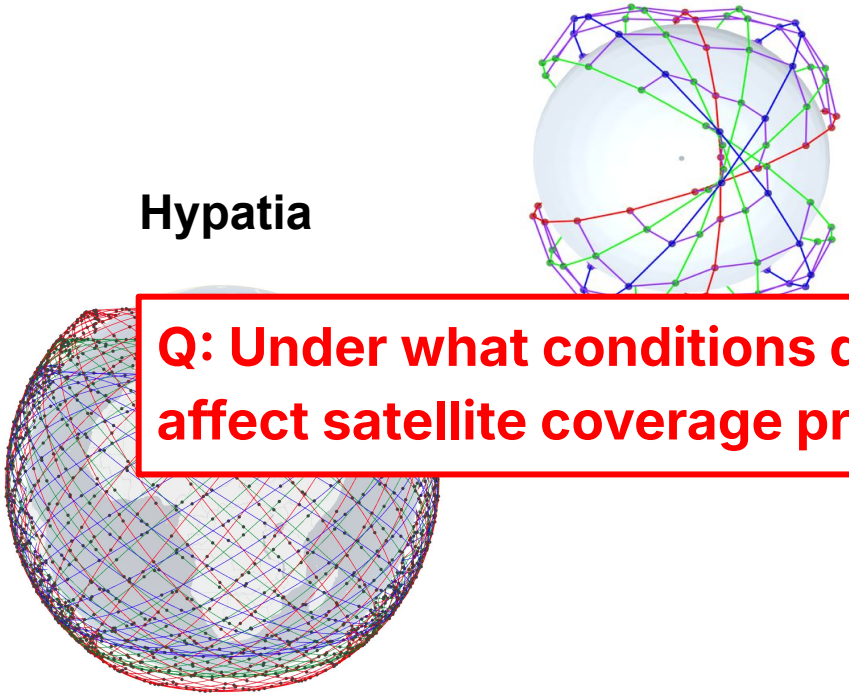
Takeaways:

(1) High diminishing returns to serve the tail end of users

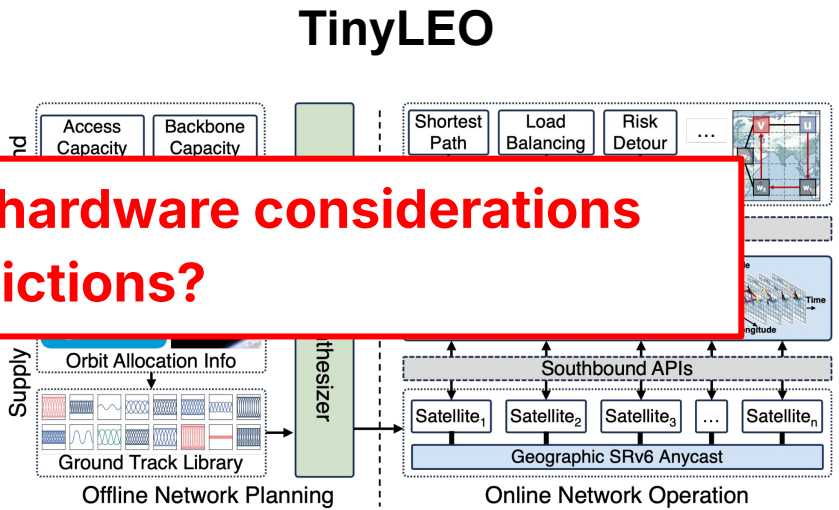
(2) Only possible to accurately evaluate capacity with the right conceptualization of how capacity is served to users



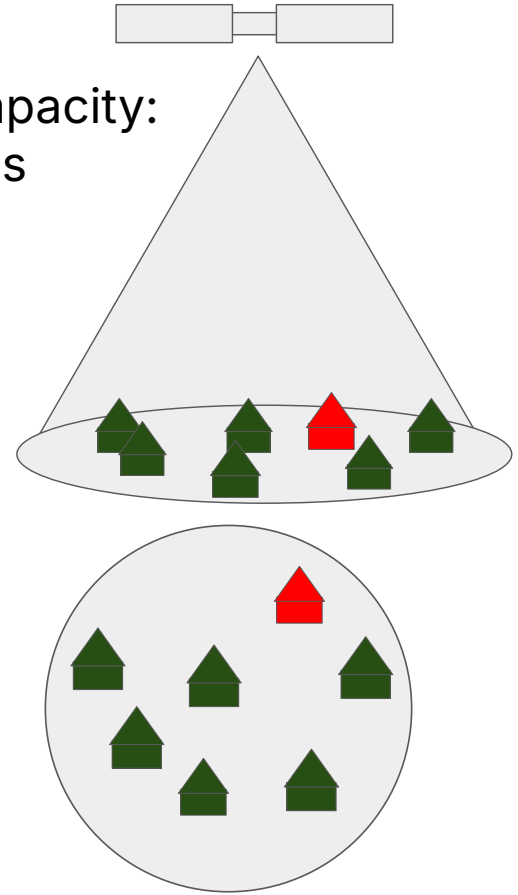
Modeling, simulation, and emulation approaches have grown, but many ignore the constraints of hardware.



Q: Under what conditions do hardware considerations affect satellite coverage predictions?

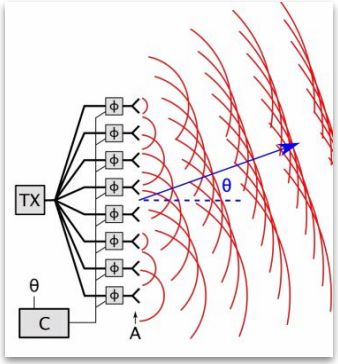


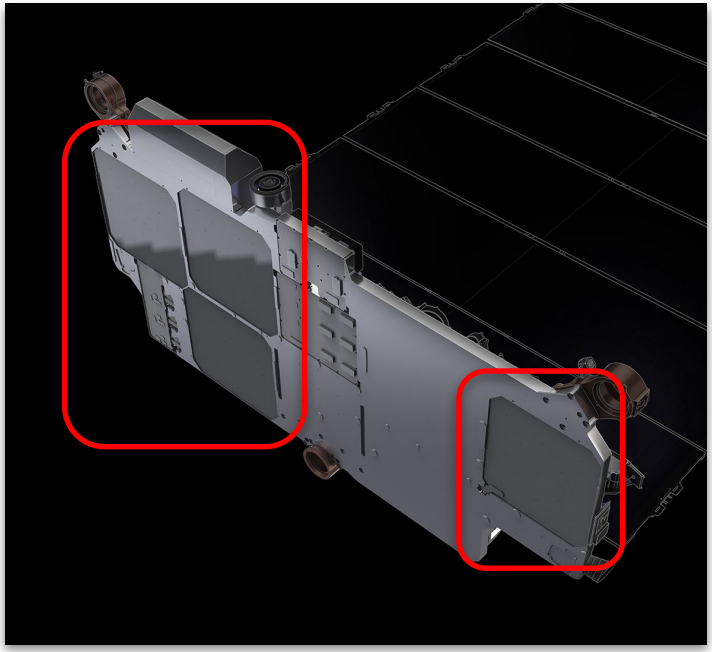
Current approaches assume a “Cone Model”

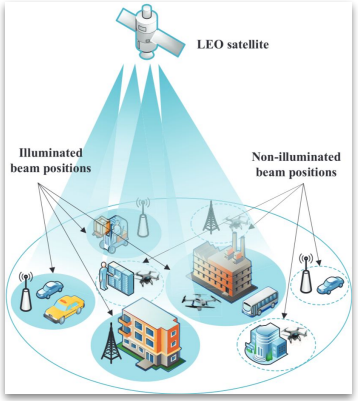


- Assumes that a LEO sats’ capacity can be distributed arbitrarily within its field of view
- Service not possible if total satellite capacity already reached

This model abstracts away the RF beam hardware that enables connectivity





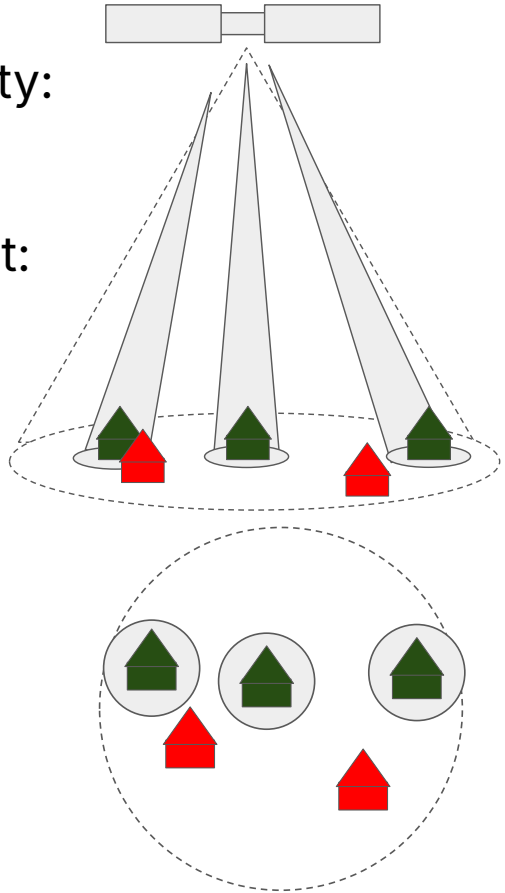


We propose a “Beam Model” for higher accuracy

Total Capacity:
6 houses

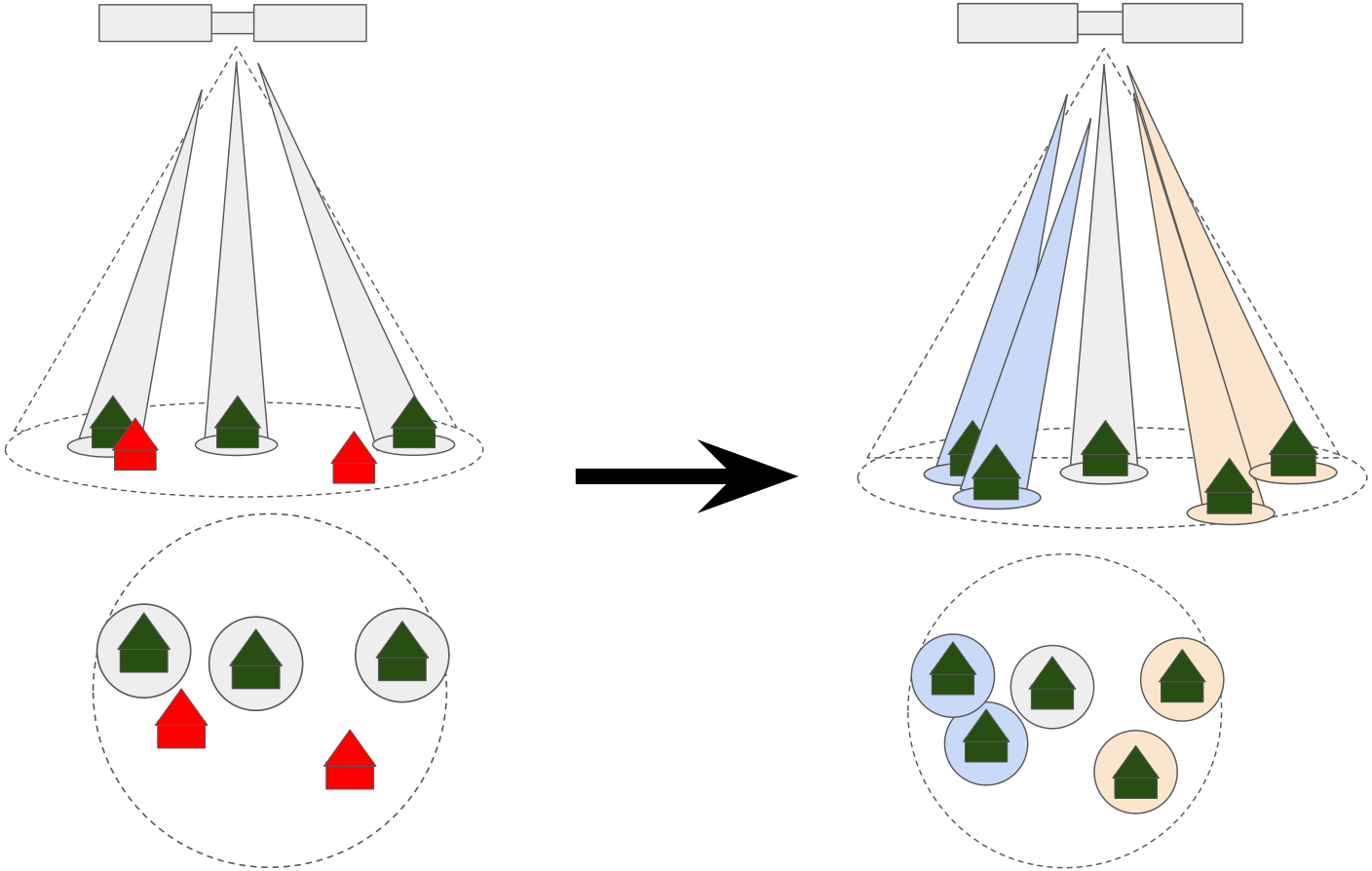
Beam budget:
3 beams

Beam Capacity:
2 houses per beam

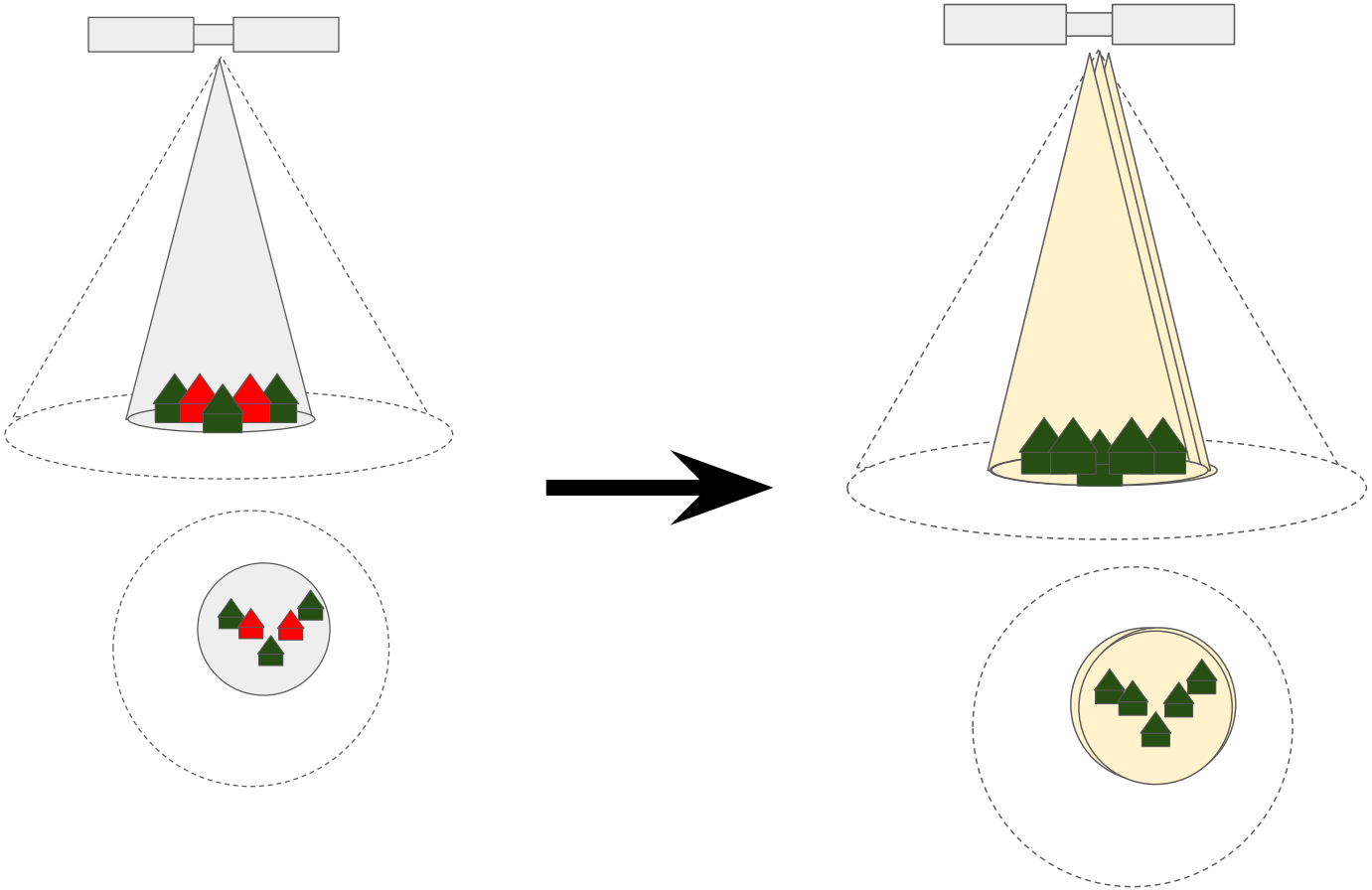


- Discretizes total satellite capacity into individual beams
- Service not possible if satellite’s beam budget AND beam capacity is reached
- Service capabilities expanded by **beam hopping** and **beam stacking**

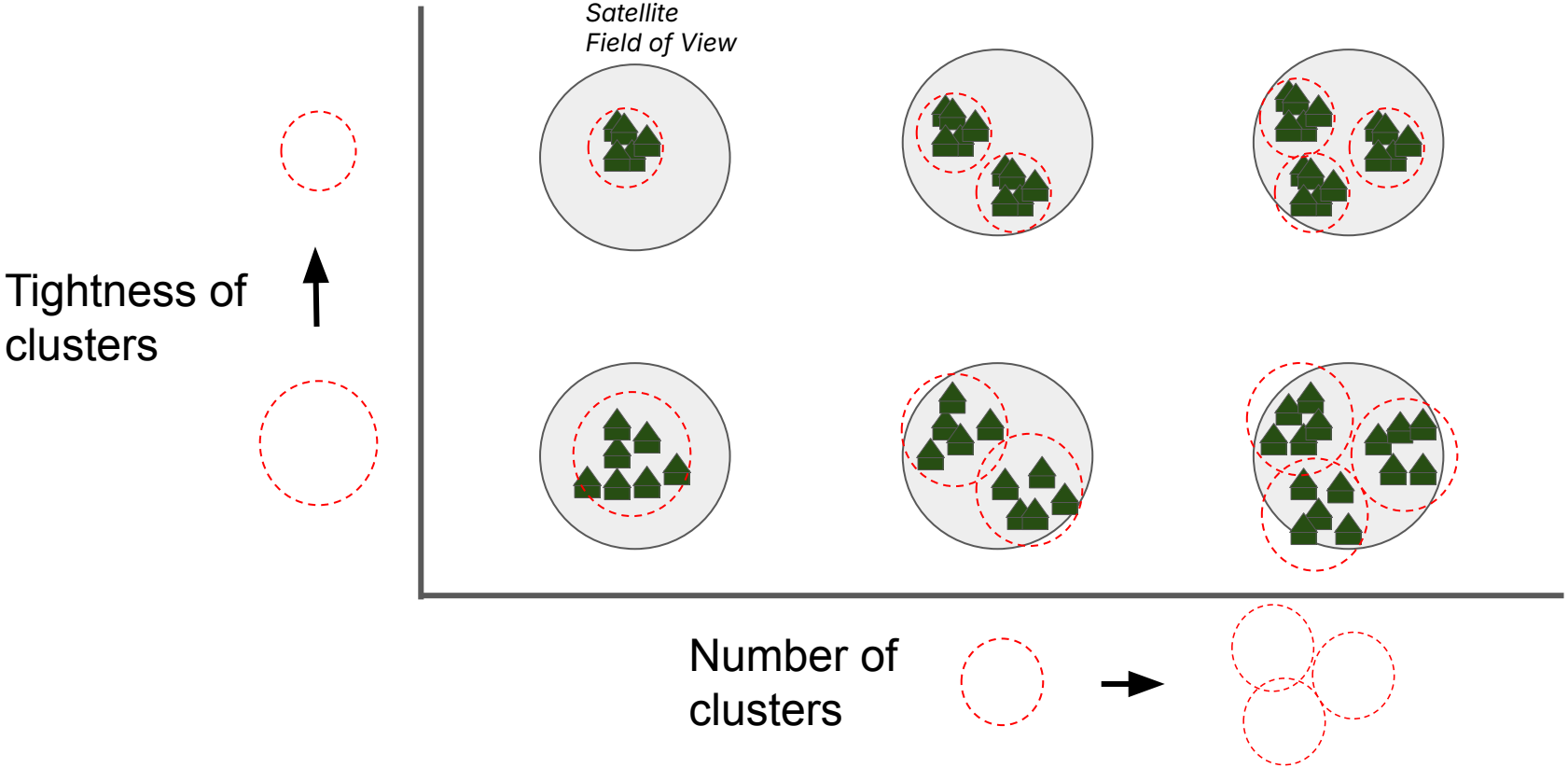
Beam Hopping: Splitting a beam’s capacity over multiple regions



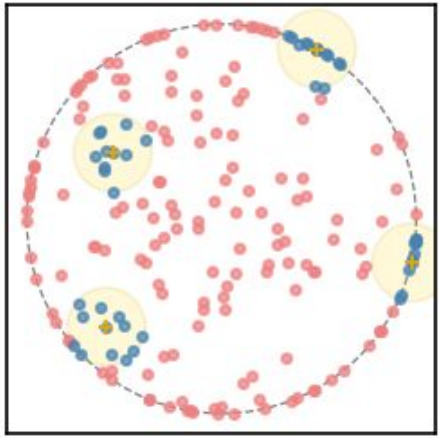
Beam Stacking: Increasing capacity over single region



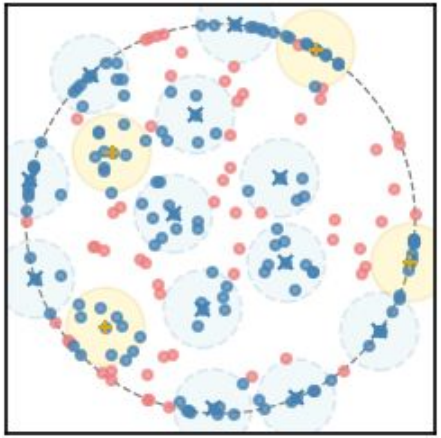
Generating differing geographical user distributions



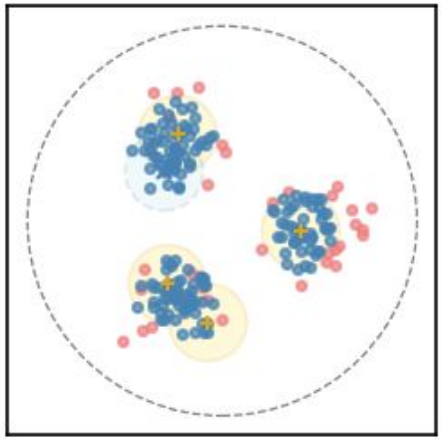
Generating coverage predictions from the beam model



Place beams to maximize coverage



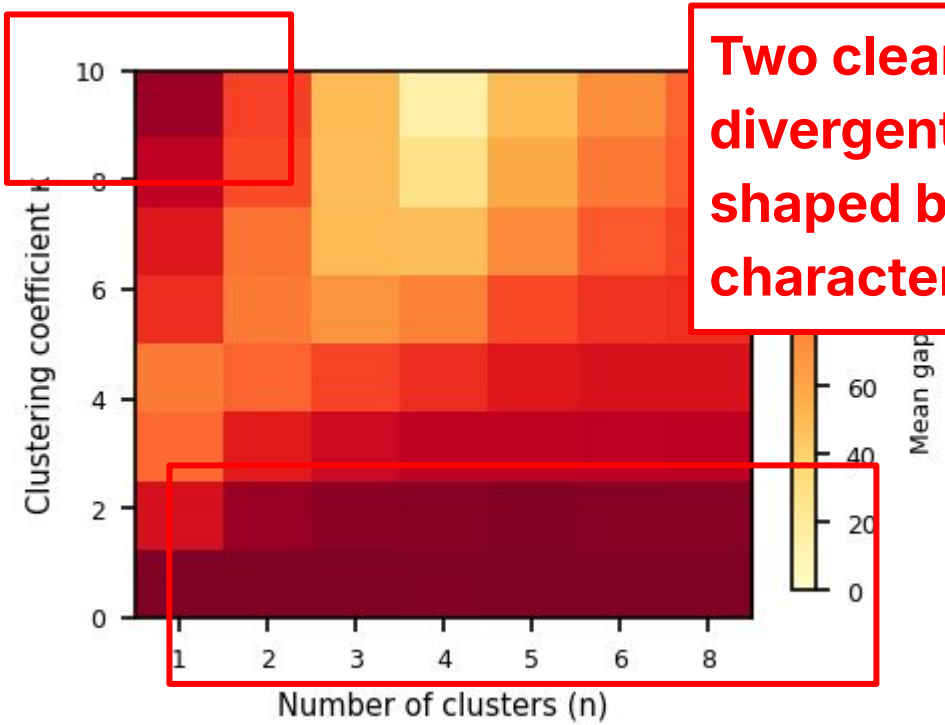
Hop beams to extend coverage



Allow stacking as appropriate

Comparing coverage predictions from the two models

Few, tight clusters

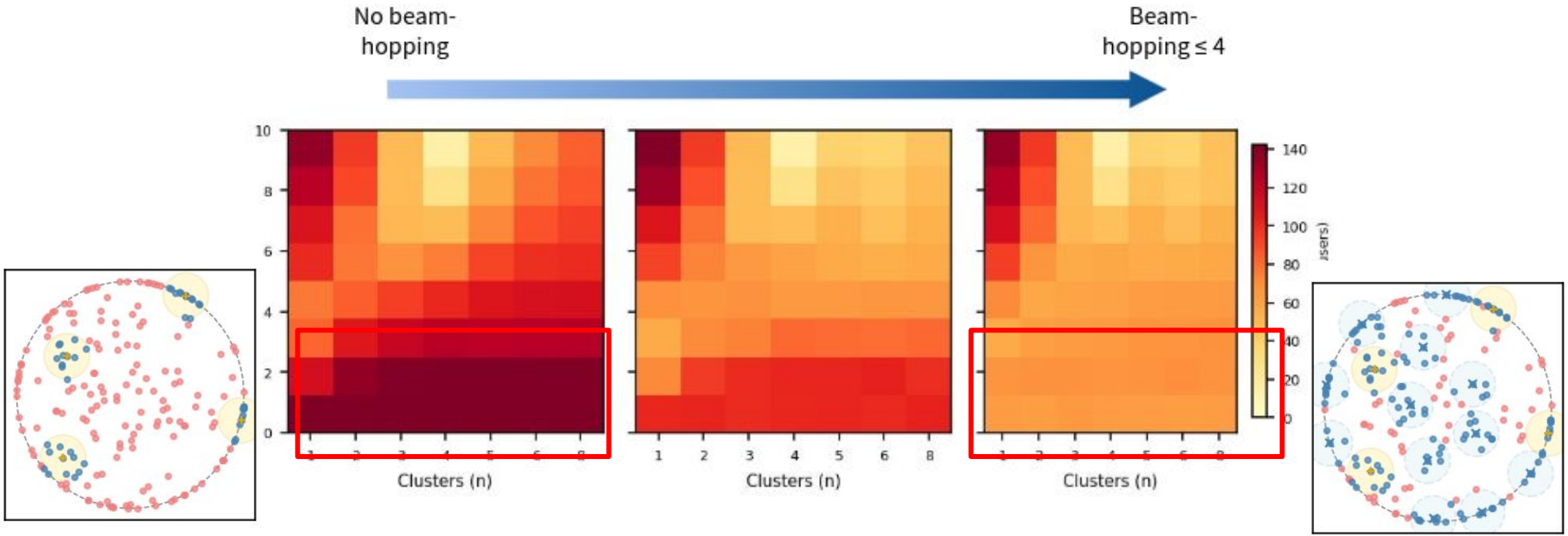


Two clear areas of divergent prediction shaped by beam characteristics

Uniform distribution

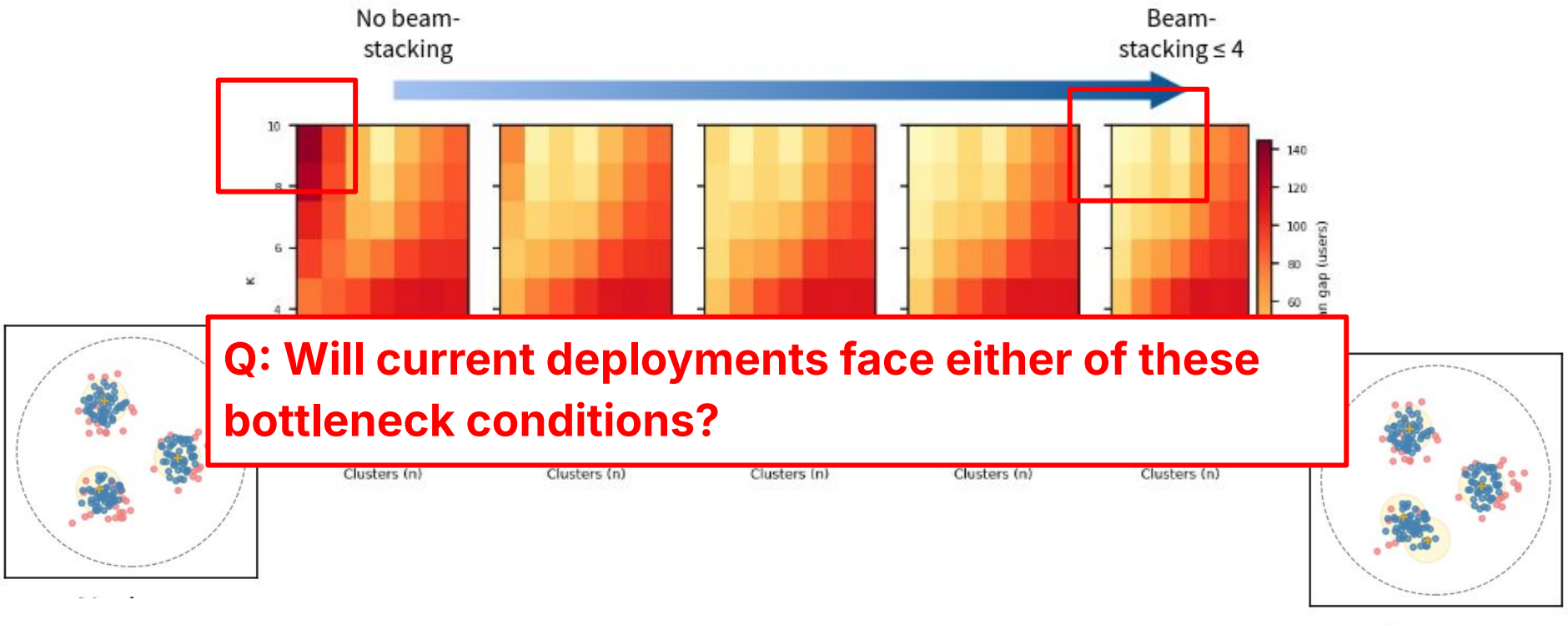
Region 1: Beam Count Exhaustion

Addressed with beam hopping



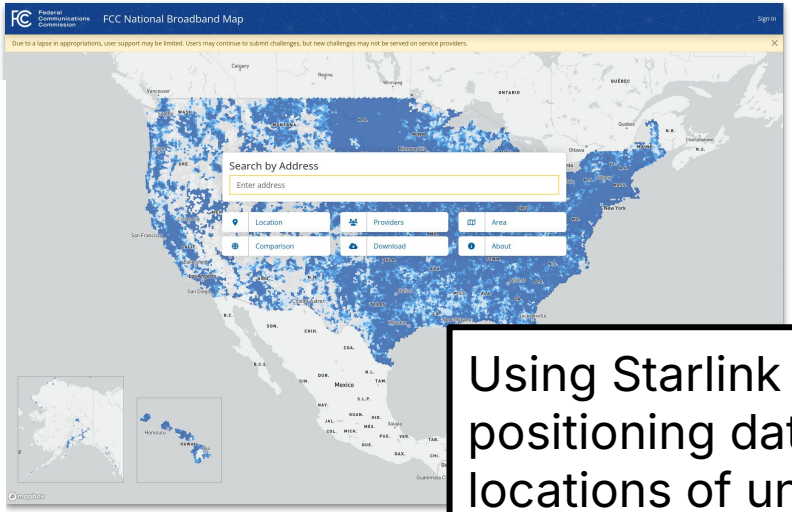
Region 2: Beam Capacity Exhaustion

Addressed with beam stacking



Q: Will current deployments face either of these bottleneck conditions?

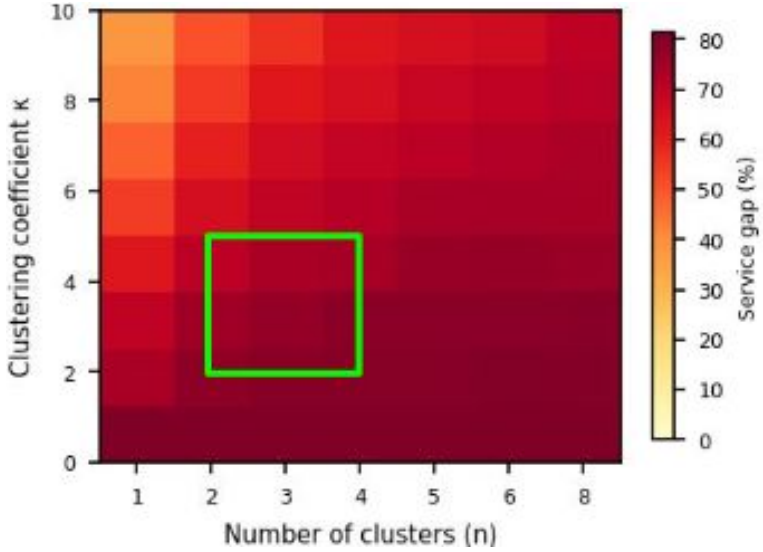
Setup: Serving all currently unserved locations within the US (again)



Using Starlink sat. positioning data and locations of unserved users in the US, identify **2 to 4 clusters** and **κ** (tightness coef.) of **2 to 5**

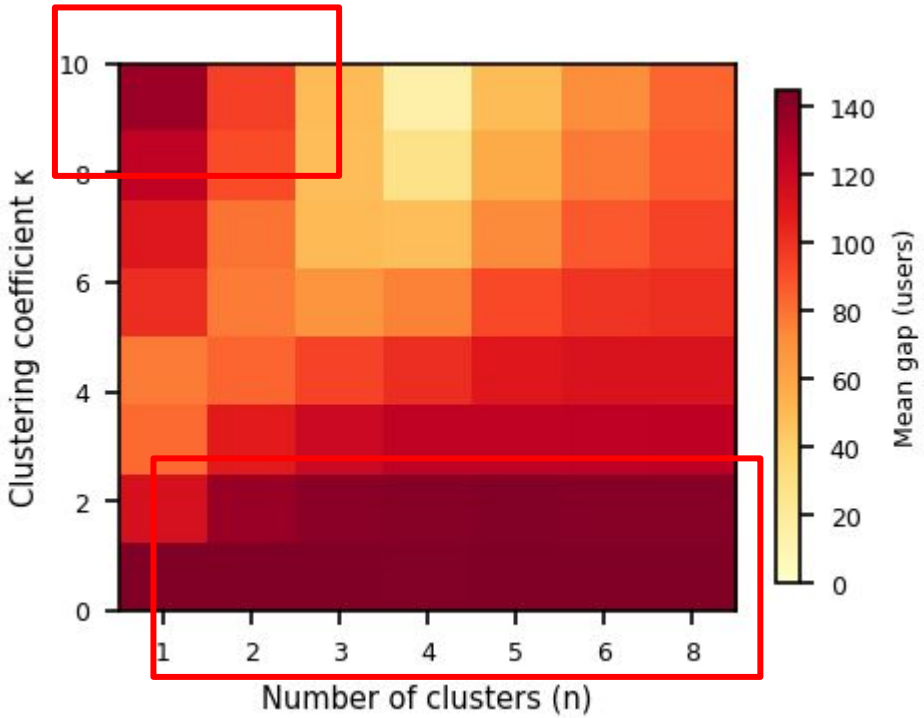
A: In the worst case, prediction gap of **68 to 80%**, approaching beam count exhaustion region

Using Starlink Schedule S filings with the FCC, we assume a highly-constrained scenario with 24 beams and minimal hop/stack



Summary

- Propose a new paradigm for more accurate satellite coverage modeling
- Divergent predictions when number of beams and beam capacity are constrained
- For real deployments, up to 80% overestimation in the worst case



Future work

- Extend current work
  - Take into consideration physical layer constraints
  - Various beam scheduling algorithms

- Constellation planning tool
  - Input: user demand
  - Output: Number of beams required + constellation topology necessary to satisfy the demand

Thank you!

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