

RESILIENT SPECTRUM SHARING AMONG NON-GEOSYNCHRONOUS SATELLITES

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RESEARCH GOALS FOR THIS PROJECT

- Multiple constellations of NGSO satellites will share spectrum with each other and with GSO satellites
- In this project, we will
 - Quantify risk that an NGSO satellite constellation will cause harmful interference to other systems
 - Design novel algorithms that determine how NGSO constellations access spectrum and manage resources
 - Propose new strategies to mitigate the effects of interference among NGSO satellite constellations
 - Assess both new and existing strategies to mitigate interference among NGSO satellite constellations
 - Derive implications for national spectrum policy, international spectrum policy, and business arrangements between satellite operators

RESEARCH RESULTS FOR THIS YEAR

- This year, we
 - Developed radio resource management (RRM) algorithms that determine how NGSO constellations manage spectrum resources and access spectrum
 - Simulated constellations that use these RRM algorithms to determine what data rates can be achieved, and how this depends on constellation characteristics
- Next, we will show results when multiple satellite constellations using these algorithms share spectrum, including
 - the risk of harmful interference to other systems in the absence of mitigation strategies
 - how the effects of inter-constellation interference change with different mitigation strategies

RADIO RESOURCE MANAGEMENT (RRM)

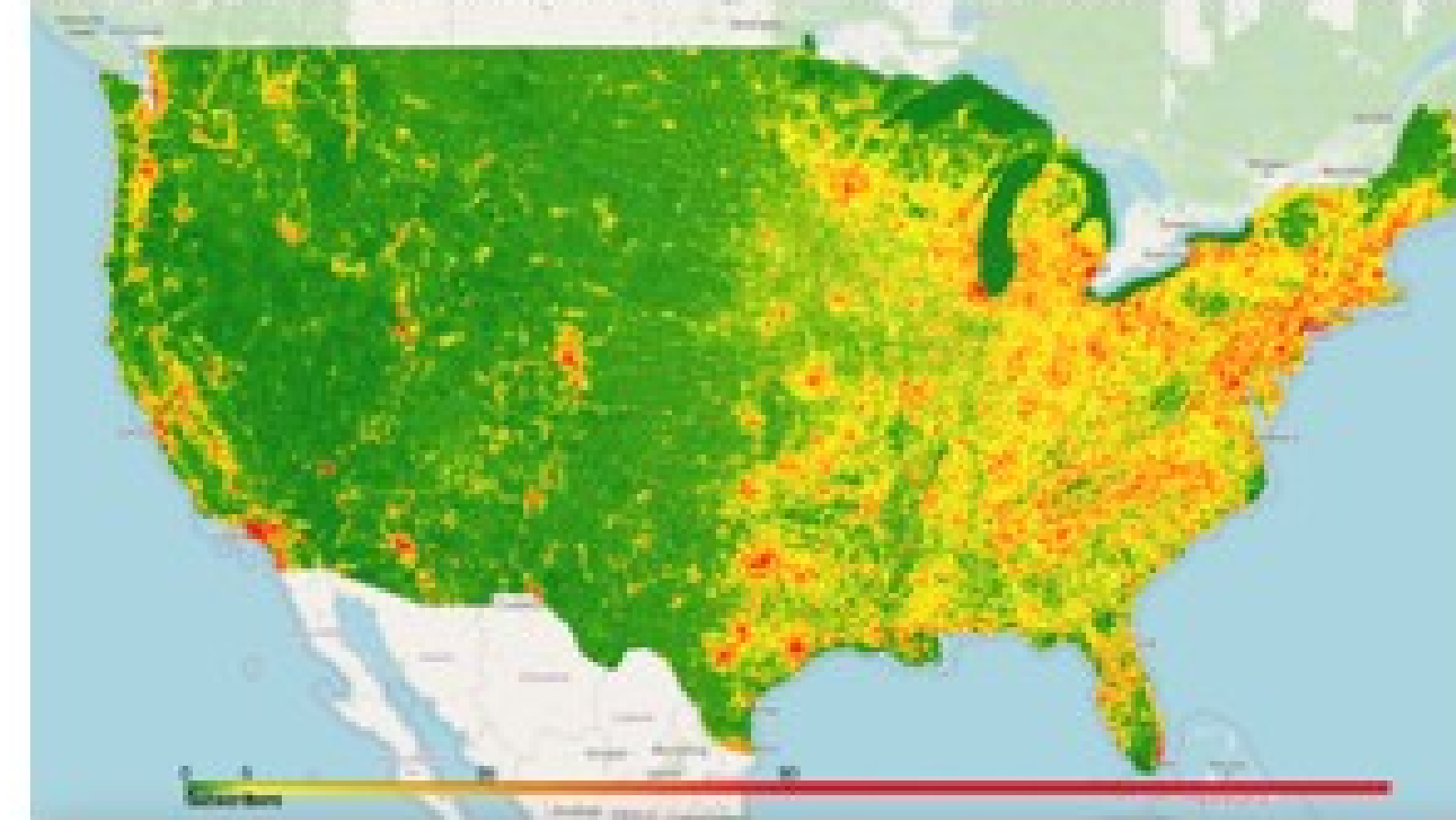
- Challenges:
 - Large constellation with thousands of satellites
 - Flexible payload with vast configuration possibilities in multiple dimensions, e.g., beam size, beam location, time, frequency, power, etc.
 - User distribution is highly uneven; fairness is needed
 - High complexity; problems are usually NP hard
- Goals: An RRM solution that balances **efficiency**, **fairness**, and **complexity**
- Solutions:
 - Optimize the 5th percentile of subscriber data rate
 - Divide the problem into three subproblems: beam placement, satellite assignment, and frequency-time resource allocation
 - Use heuristics to solve each subproblem

OVERVIEW OF ALGORITHMS

- Step 1: Cell Layout
 - Divide surface of the earth into cells, each of which can be served by a separate satellite beam
 - Cells should be smaller where subscriber density is greater
- Step 2: Satellite Assignment
 - At each selected instant in time, assign each cell to a satellite
 - Considering factors such as
 - Satellite visibility
 - Distance from each cell to each satellite at that instant
 - Co-channel interference for beams from same satellite
- Step 3: Resource Allocation
 - Divide bandwidth into channels, and time into timeslots, forming resource units
 - Allocate specific resource units to each satellite-cell beam
 - Considering factors such as fairness and efficiency

USE REALISTIC USER DISTRIBUTION

- Subscriber density based on population density
- 1.43 million simultaneously active subscribers.
- Rural subscription rate = 20 * urban rate. (Like Starlink)



VARIABLE CELL SIZE BETTER THAN FIXED

- Variable-size cells yield 5% higher median data rate although lower data rates for the top 10%

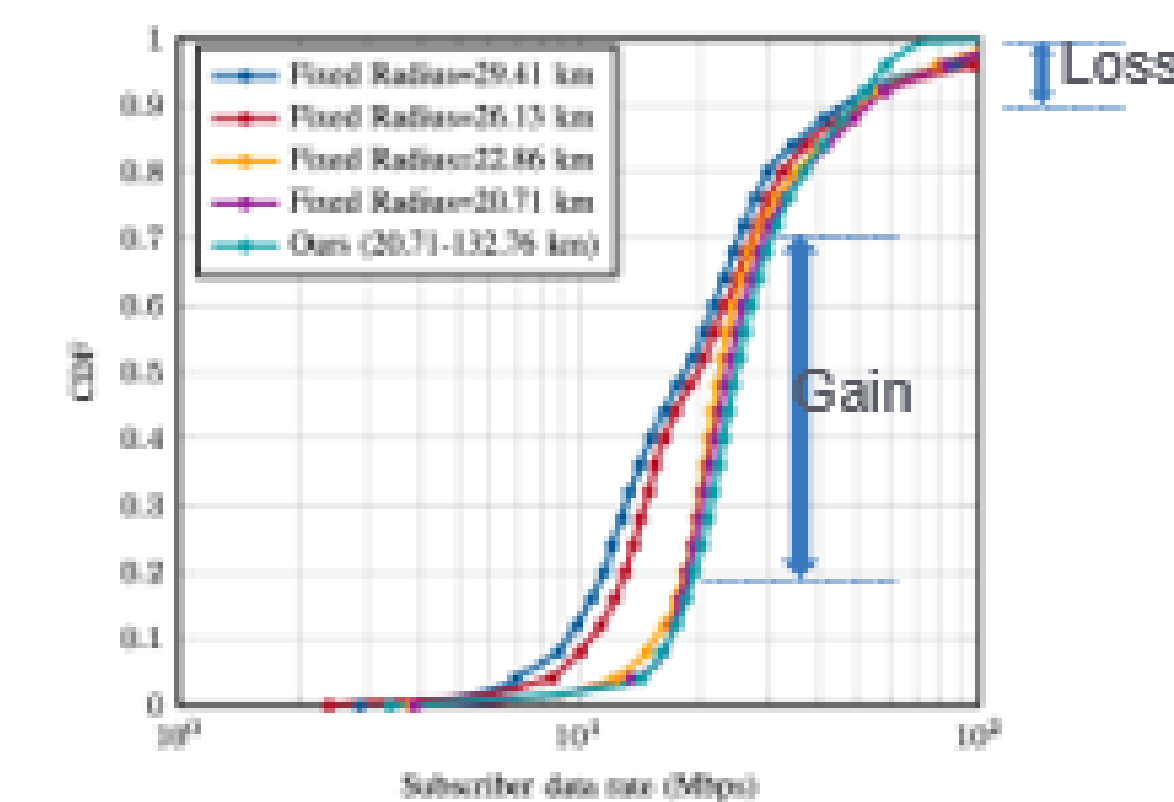


Fig. 3. CDF of subscriber data rate of constellation A with different cell layouts

NOVEL HEURISTIC TO ASSIGN SATELLITES

- First, sort cells by a metric that reflects number of satellite options available and demand from that cell
 - $P = \log(\text{no. of satellites}) + \log(\text{cell's rank by no. of customers})$
- Second, for each cell, going from lowest P to highest P
 - Identify satellites that are visible and have sufficient capacity left
 - Choose "best" satellite, where "best" means balancing 2 objectives
 - Load balancing, i.e. choose satellite now serving fewest subscribers
 - Maximizing frequency reuse, i.e. choose satellite to minimize extent to which the new cell assignment makes other cells unserviceable due to intra-satellite interference
 - Balance is captured in the Resource Contention Index (RCI)

$$RCI_v = \sum_{C \in S^*} \text{subs}(C) \cdot \deg_v(C)$$
 - The "best" satellite is the one that minimizes combination of RCI and how much RCI changes with assignment of new cell

$$[\alpha \cdot RCI_v + (1 - \alpha) \cdot \Delta RCI_v(C_{new})]$$

RCI OUTPERFORMS TRADITIONAL ASSIGNMENT STRATEGIES

- Compare with algorithms that prioritize higher elevation angle, better load balance, and lower cell count
- 99% higher at 5th percentile; 50% higher median

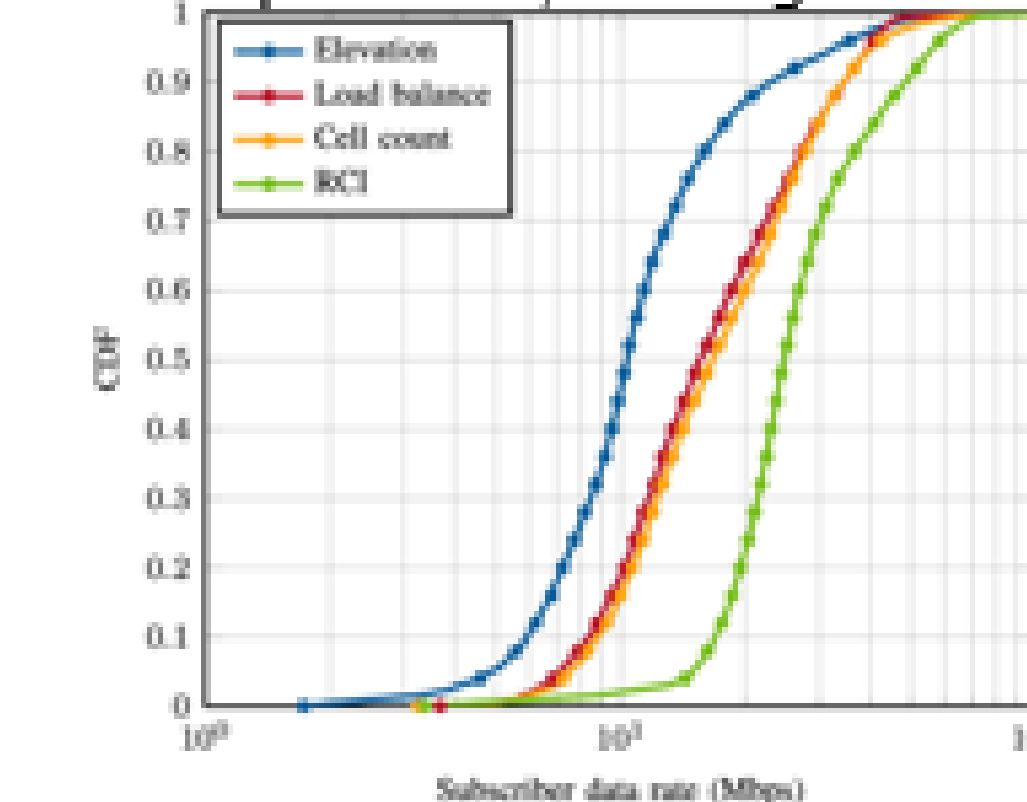


Fig. 4. CDF of subscriber data rate of constellation A with different assignment metrics

ALLOCATION OF RESOURCE UNITS

- Satellites allocate frequency-time resource units to cells
- Fairness: Each iteration selects the cell with lowest resource-to-subscriber ratio, then advances this ratio to the median value
- Efficiency: Resource unit allocation minimizes conflicts with neighboring cells

Baseline Beam hopping:

- Periodic: serve cells in a fixed order
- Random: serve cells randomly
- Greedy: serve cells with minimum resource/subscriber ratio

Baseline channel assignment

- Random: select channel randomly
- Best fit: select channel with minimum conflict with neighboring cells

Compared to baselines

- 12% higher 5th percentile
- 50% higher median

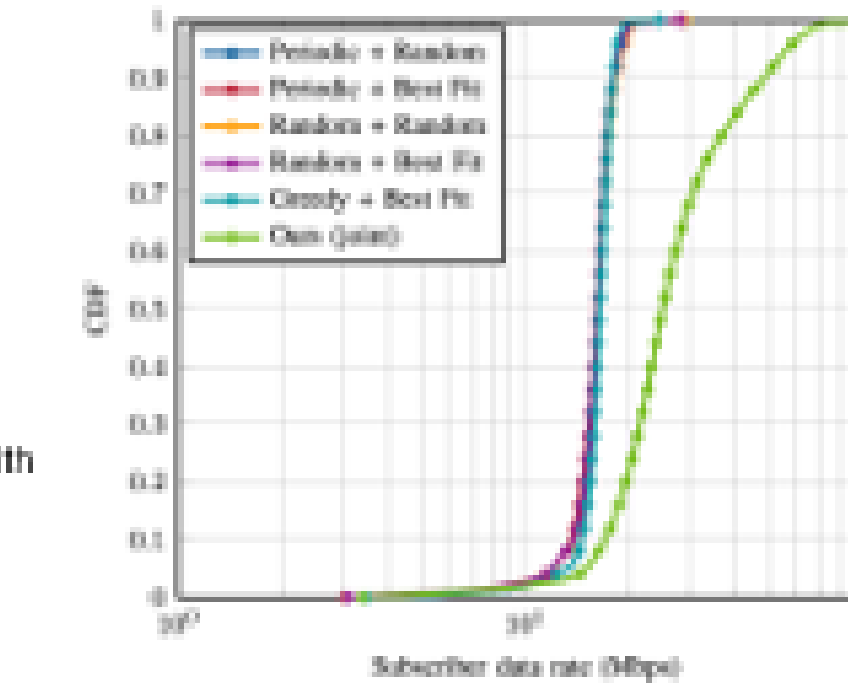


Fig. 5. CDF of subscriber data rate of constellation A with different frequency-time allocation algorithms

INTER VS INTRA SAT INTERFERENCE

- Inter-satellite interference: interference from satellites other than the serving satellite
- Intra-satellite interference: interference from the beams intended for other cells transmitted by the serving satellite

- Tested with 2 Walker constellations of size 3,236 and 10,000

Inter-satellite interference is negligible

- Due to directivity of Rx antenna

Intra-satellite interference is the main source of interference

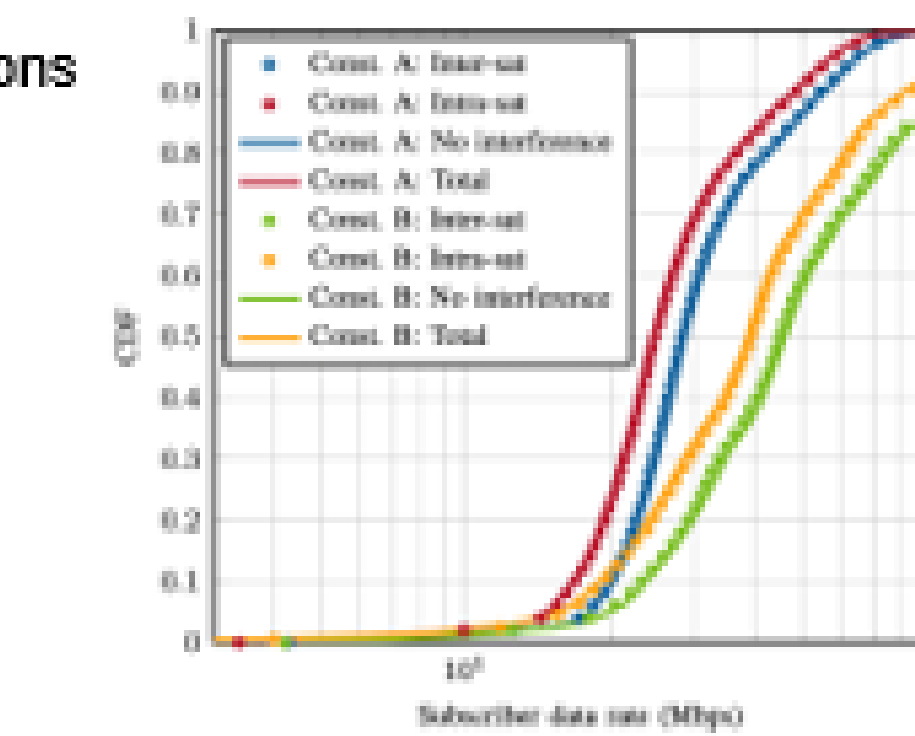


Fig. 6. CDF of subscriber data rate with different interference types. Constellation B has 10,000 satellites in this experiment.

ANTENNA TAPERING HELPS

- We used 32x32 MIMO antenna with and without tapering
- Tapering reduces sidelobe levels but increases beamwidth
- The subscriber data rate distribution benefits from lower sidelobe levels despite less focused beams

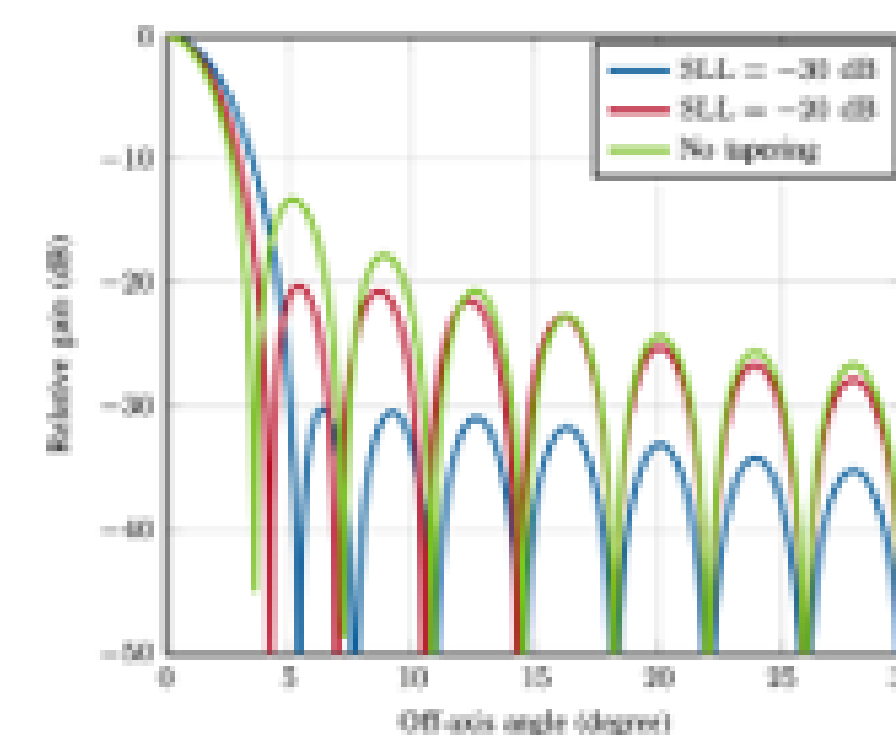


Fig. 8. Antenna pattern with and without Taylor tapering.

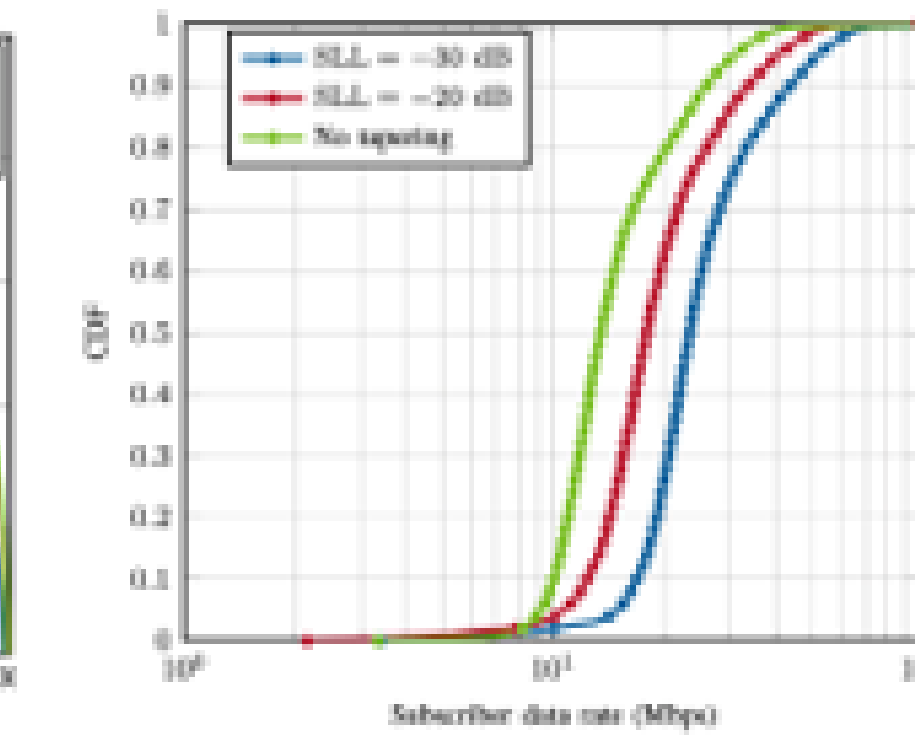


Fig. 9. CDF of subscriber data rate of constellation A with different tapering configurations.

INCREASING NUMBER OF SATELLITES

- Increasing the number of satellites improves performance initially, but then saturates.
 - 5th percentile saturates earlier than the median.
- Decreasing cell size by adding elements in MIMO array mitigates saturation.

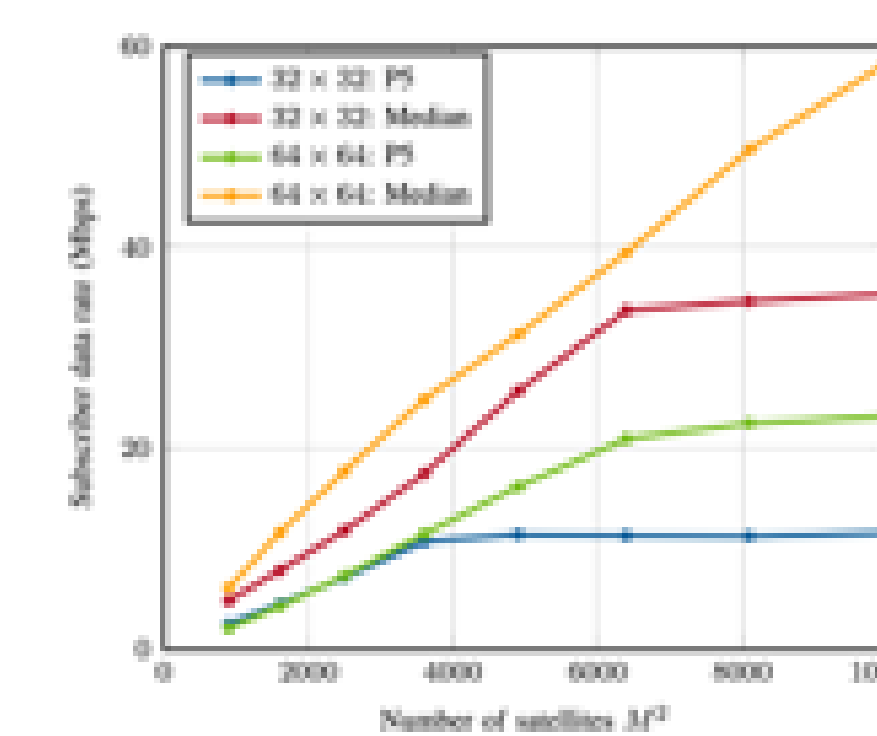
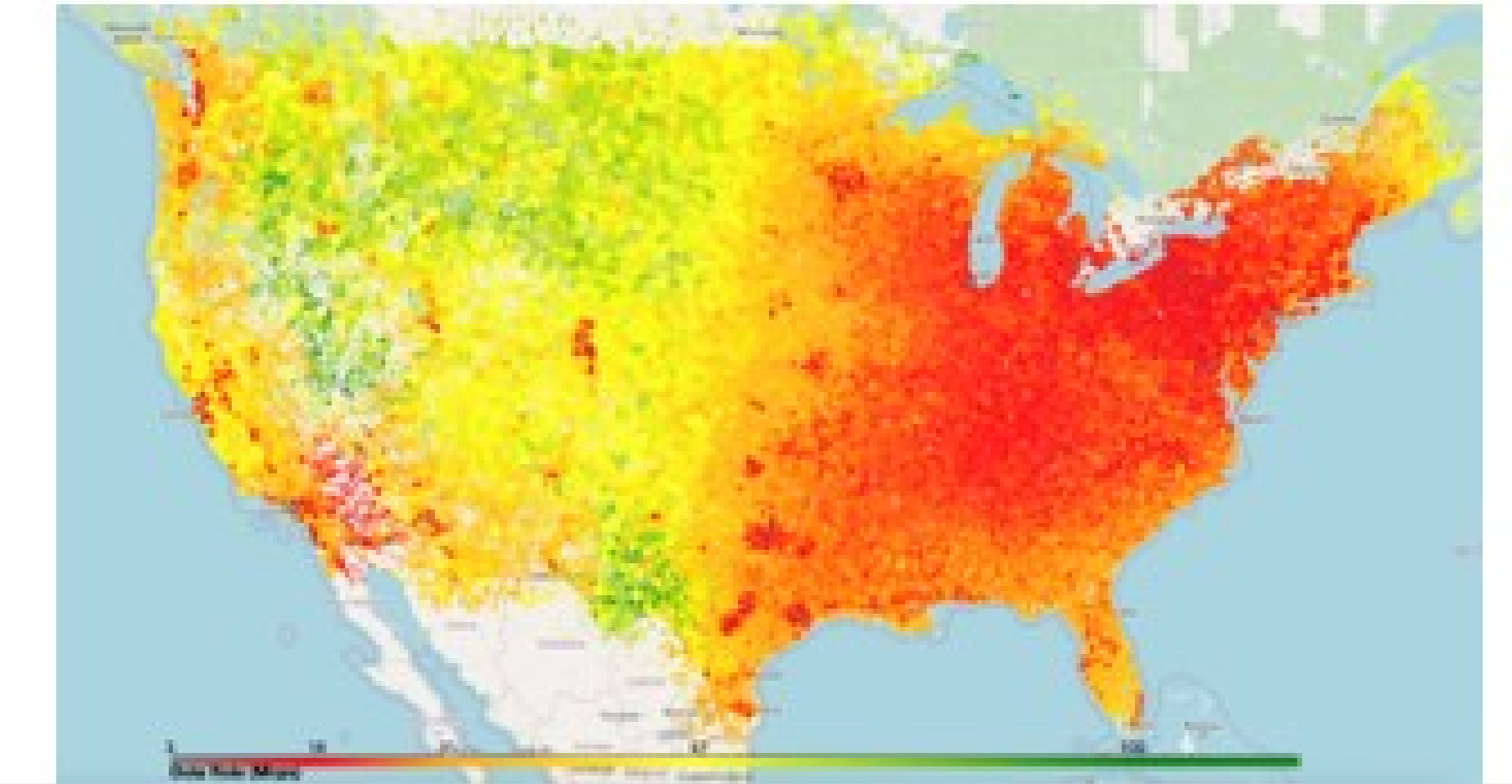


Fig. 10. Subscriber data rate performance of various constellation size across different percentiles. Two transmit antenna configurations are tested, i.e., 32 x 32 and 64 x 64 UPA.

DATA RATE: SPATIAL DISTRIBUTION

- Higher data rate in the western interior regions
- Significantly lower data rate in the eastern half and parts of the west coast



DATA POP/SUB DENSITY

- Data rates are bounded by subscriber density
- Urban users tend to get worse service than rural users, despite a lower subscription rate

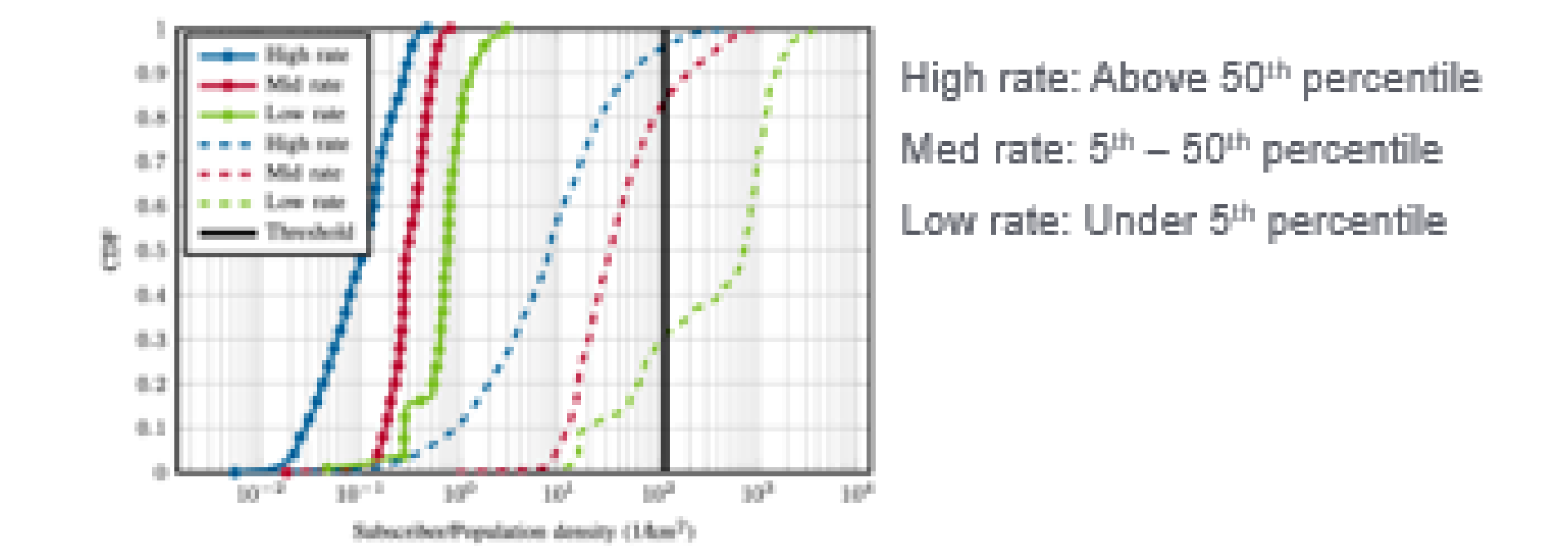


Fig. 13. The distribution of subscriber/population density for users with different data rate ranges. Solid line: subscriber density. Dashed line: population density. Vertical line: rural-urban threshold.

SUMMARY

- We developed a set of RRM algorithms that an NGSO constellation can use to manage spectrum resources and access spectrum
 - Realistic, achieve high data rates, computationally efficient
- We used these algorithms to understand performance
 - Intra-satellite interference worse than inter-satellite interference within a constellation
 - Tapering to reduce sidelobes improves data rates despite increase in beamwidth
 - Urban users tend to receive lower data rates,
 - assuming rural subscription rate is 20 * urban subscription rate
- We can now use these algorithms when evaluating NGSO-NGSO interference in a more realistic setting.
- Our next results will quantify NGSO-NGSO interference, and assess various strategies to mitigate it

REFERENCES

- Research in this paper is described in the following
 - G. Lin, J. M. Peha, M. A. Sirbu, and A. Hills, "Scalable Radio Resource Management for NGSO Satellite Constellations," *13th IEEE International Conference on Wireless for Space and Extreme Environments*, to appear.
- Previous work includes
 - A. Hills, J. M. Peha, J. Munk, "Feasibility of Using Beam Steering to Mitigate Ku-Band LEO-to-GEO Interference," *IEEE Access*.
 - A. Hills, J. M. Peha, J. Munk & S. Pogorelec, "Controlling Antenna Sidelobe Radiation to Mitigate Ku-Band LEO-to-GEO Satellite Interference," *IEEE Access*.