Joint Clustering and Uplink Power Control for Cell-free Massive MIMO in LEO Satellite Networks

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Can Zheng, Korea University
T. Fitsum Debebe, Korea University
Chung G. Kang, Korea University
{zc331_, fitsum_debebe,ccgkang}@korea.ac.kr

WISELAB
Korea University

Motivation: Space Broadband Internet (1)

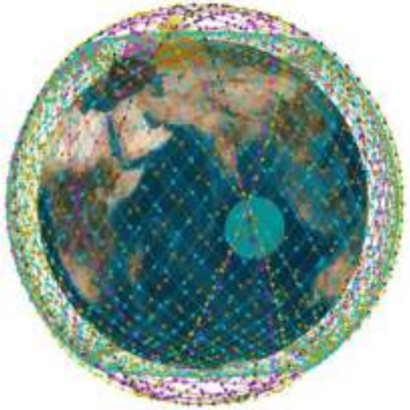
Definition

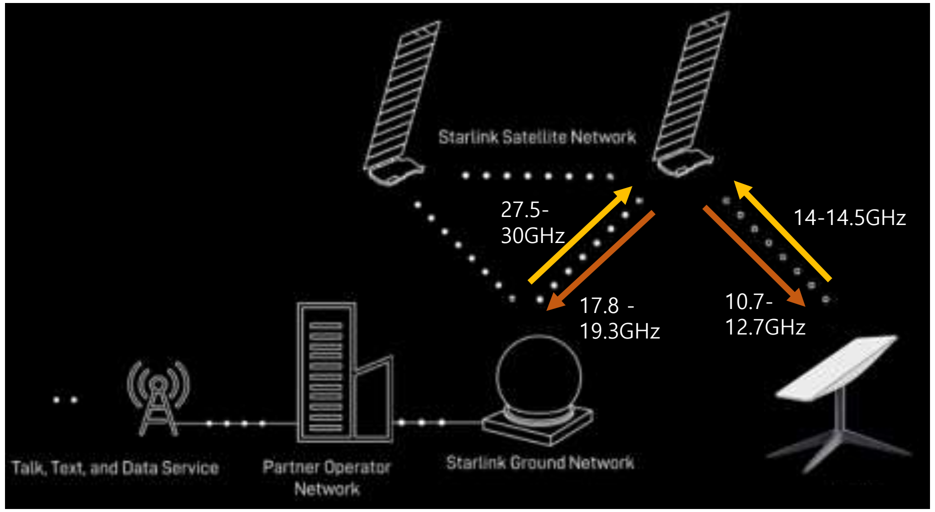
- Broadband-level data connectivity to users on Earth by using a constellation of satellites, primarily in low Earth orbit (LEO), to enable low-latency, high-throughput communications

Key Characteristics

- **LEO Satellite Constellations**: Hundreds to thousands of satellites (e.g., Starlink, OneWeb) orbiting at altitudes of ~300–1,200 km/Low latency (~20–50 ms) compared to GEO (~600 ms).
- **Global Coverage**: Capable of serving remote, rural, maritime, and airborne users beyond the reach of fiber or cellular networks
- **High Throughput**: Uses frequency reuse and spot beamforming to provide broadband speeds (~100 Mbps or more per user in optimal conditions)
- **Ground Segment**: Includes user terminals (e.g., phased-array antennas), ground gateways, and network management infrastructure.

STARLINK

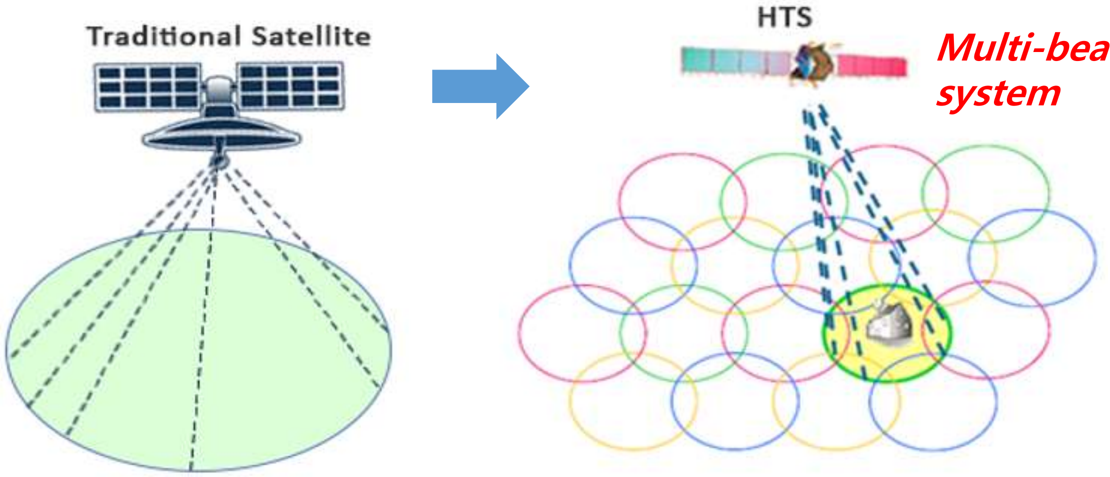




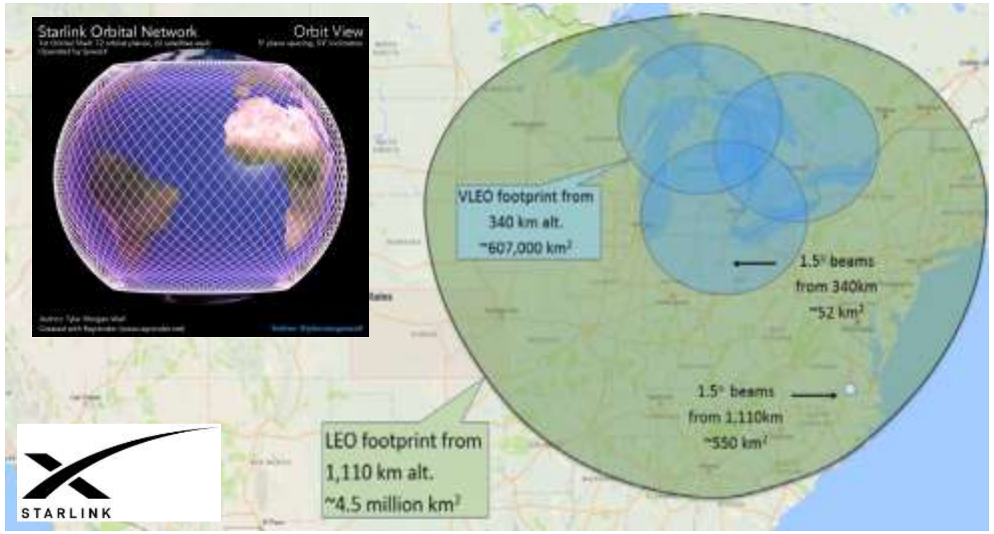
Motivation: Space Broadband Internet (2)

Toward Capacity Enhancement

- Wider bandwidth
- More beams to be supported by each satellite
- A reduced beam size to improve frequency reuse efficiency
- More satellites to deploy



Multi-beam system



Capacity (Mbps) = (Data Rate/Channel) * (# of Beams/Satellite) * (# of Channels/Beam) * (Frequency Reuse Efficiency) * (# of Satellites)

The core technology for capacity enhancement is phased array antennas-based beamforming and interference control for efficient frequency reuse.

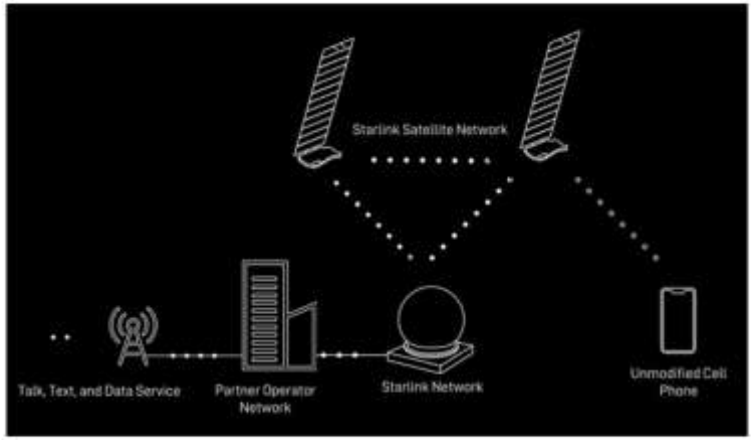
Example: Starlink v1.5

Bandwidth	**Downlink: 250MHz * 8 Channels/Uplink: 100MHz * 4 Channels**
# of Beams	**Downlink:** 3 antennas * 8 beams/antenna * 2 (dual polarization) = 48 beams; Reuse factor = 8
	Uplink: 1 antenna * 8 beams/antenna * 2 (dual polarization) = 16 beams; Reuse factor = 4
Satellite Capacity (Gbps/SAT)	**Downlink:** 48 beams/SAT * 1 Channel/beam * **500Mbps/Channel (16-QAM)** = 24Gbps
	Uplink: 12Gbps

*Scheduler & beam controller in cloud-based centralized monitoring & control system to to decide dynamically where, when, and how beams are allocated to ground cells and users (**beam-hopping**), based on demand, link quality, satellite availability, and regulatory constraints*

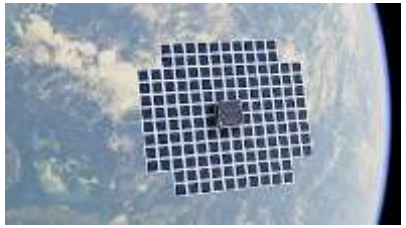
Motivation: Space Broadband Internet (3)

- **Satellite-direct-to-phone Telecommunication: Direct-to-Cell (D2C) Connectivity**
  - **Direct Link to Standard Mobile Devices:** No specialized satellite phones or external antennas/no terrestrial base stations required ➔ Cell tower in space
  - Utilizes existing cellular protocols (e.g., 4G LTE, 5G NR) with minor adaptations on the satellite side
- **D2C for LEO Satellite Architecture**



  - **Integration with Terrestrial Networks:** Acts as a complementary layer to ground-based cellular networks (Non-Terrestrial Network, NTN, under 3GPP
  - **Use Cases:** Supports voice, SMS, and eventually broadband data services for emergency communication in disaster zones, maritime and aviation connectivity, rural and isolated communities, and IoT device backhaul
- **Examples**

AST SpaceMobile



LYNK

An Android phone received the first text from space

Technical Background for D2C (1)

Simplified Link Budget Analysis

Parameter	Downlink (LEO → UE)	Uplink (UE → LEO)
Distance	600 km	600 km
Operating Frequency	3.5 GHz	3.5 GHz
Free Space Path Loss (FSPL)	158.9 dB	158.9 dB
Transmit Power	36.7 dBW (= 66.7 dBm EIRP)	**23 dBm**
Transmit Antenna Gain	37.1 dBi (included in EIRP)	**0 dBi**
Receive Antenna Gain	0 dBi	37.1 dBi
Atmospheric & Rain Loss	5 dB	5 dB
Transmitter Losses	2 dB	2 dB
Receiver Losses	2 dB	2 dB
Total Losses (non-FSPL)	9 dB	9 dB
Calculated Received Power	–101.2 dBm	–107.8 dBm
Receiver Sensitivity (3GPP TS 38.101-1)	Noise Floor + required SNR = Thermal Noise + NF + ~18.5dB = (N_0 * Bandwidth) + NF + 18.5dB = - 174dBm + 52.22dB + 6dB + ~18.5dB	
	~ –96.5 dBm	
Link Margin	~ –4.7 dB	~ –11.3 dB

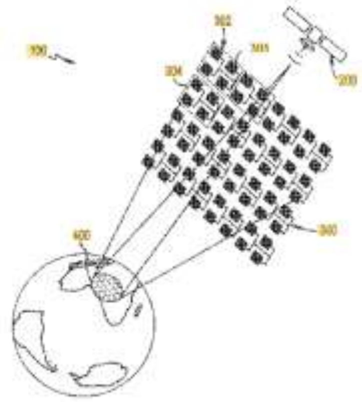
- Link gain of L/S band over Ka band
  - FSPL advantage: ~18.1 dB
  - Rain attenuation advantage: ~4–5 dB

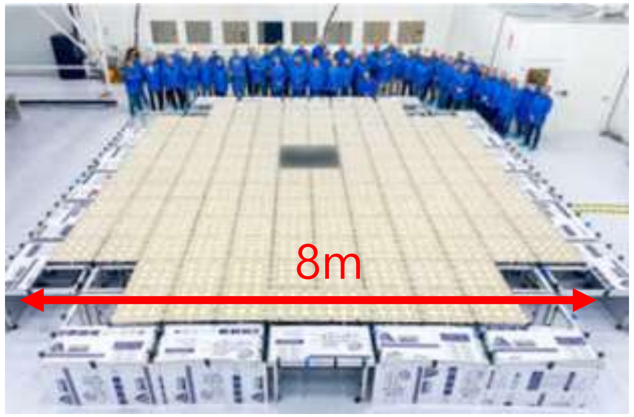
Closing the Link between the Endpoints

- The LEO satellite to compensate with **large receive antenna arrays**, e.g., large phase antenna array, and sensitive receivers

- Example

AST SpaceMobile

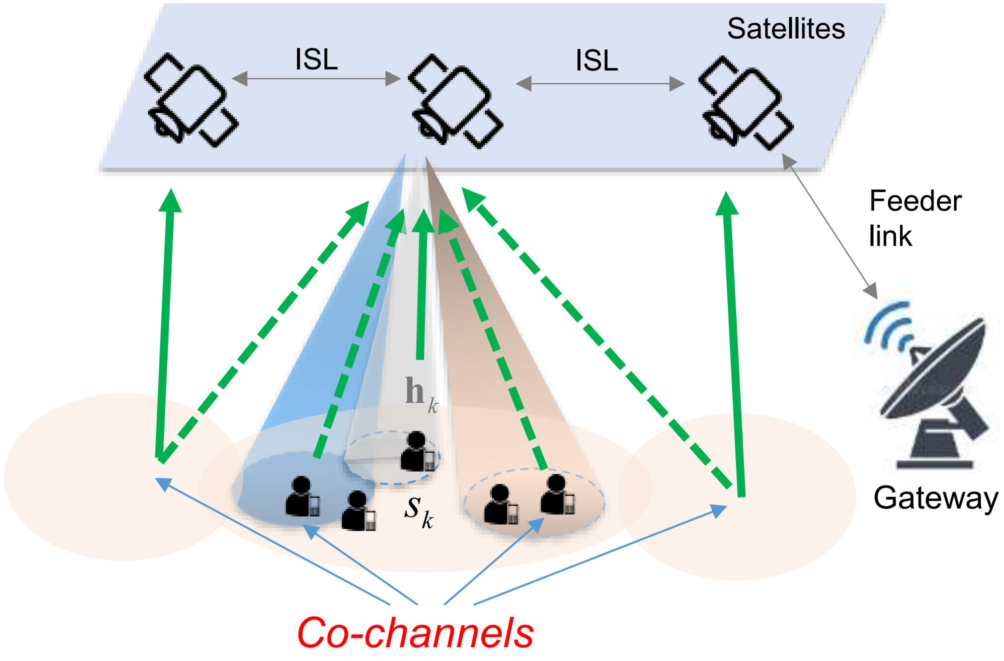


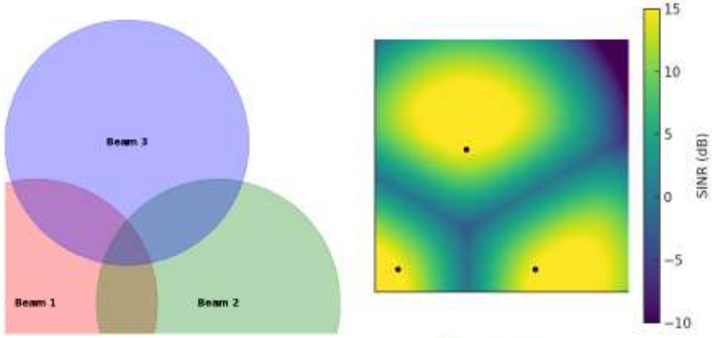


- 148 tiles * 16 elements/tile = 2368 elements/64m^2
- Element distance = 0.155m

Technical Background for D2C (2)

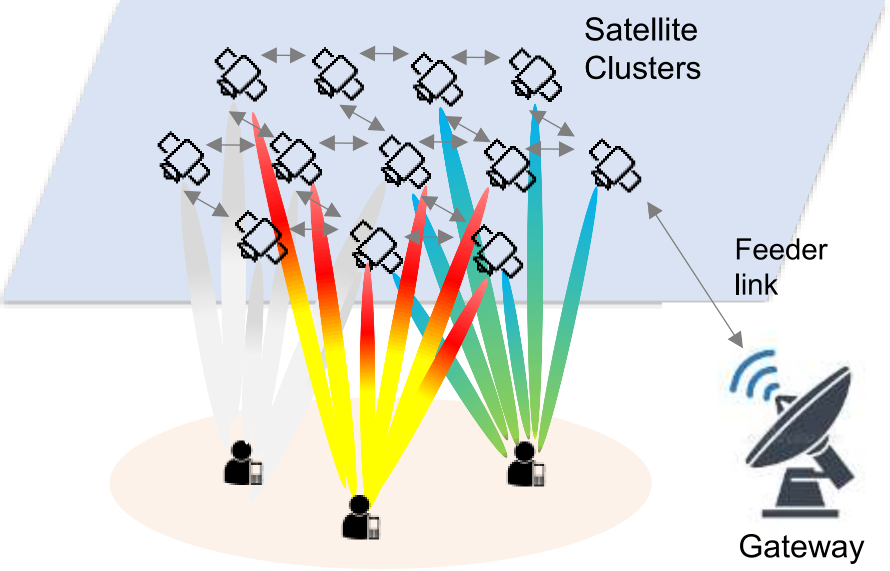
- **Multi-beam D2C Satellite**



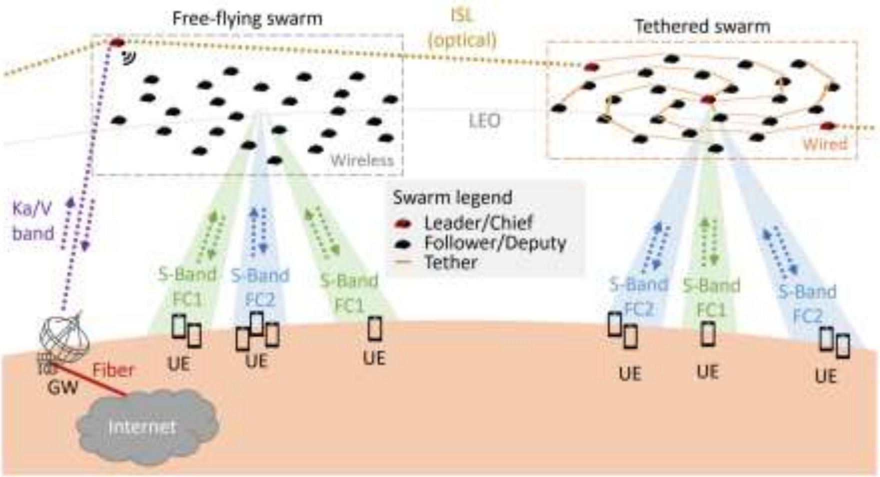


(a) Overlapping beam footprint (b) Uplink SINR map (dB)

- **Swarm D2C Satellites**



  - Swarm-based antenna array

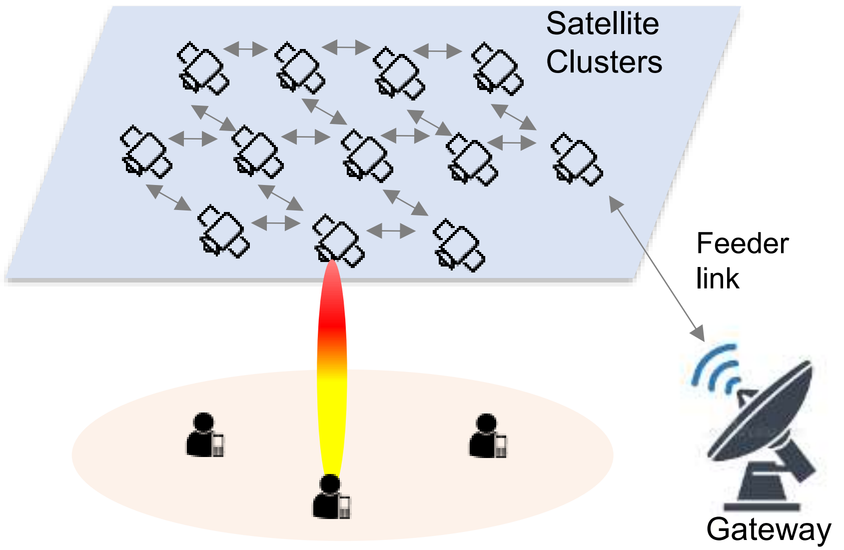


Several small and lightweight satellites, equipped with a single commercial low gain patch antenna to create a large equivalent aperture providing a huge gain and a narrow beam

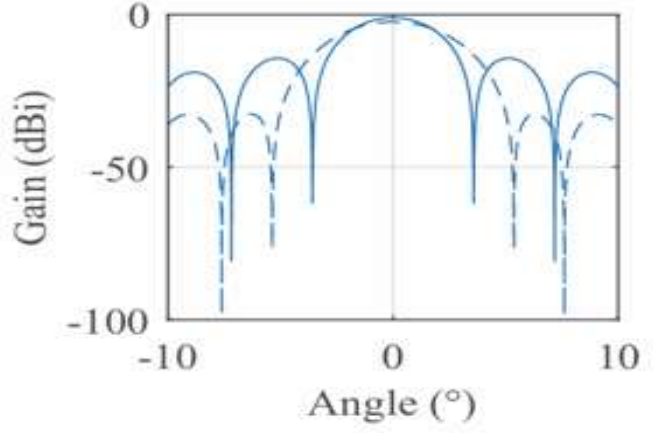
Beamforming vs. Diversity

Beamforming Gain (Array Gain)

- Phase array antenna with a virtual aperture



Beam Pattern for URA



$$\mathrm{SNR}_{\mathrm{BF}} = \frac{P \cdot |\mathbf{h}^H \mathbf{w}|^2}{\sigma^2}$$

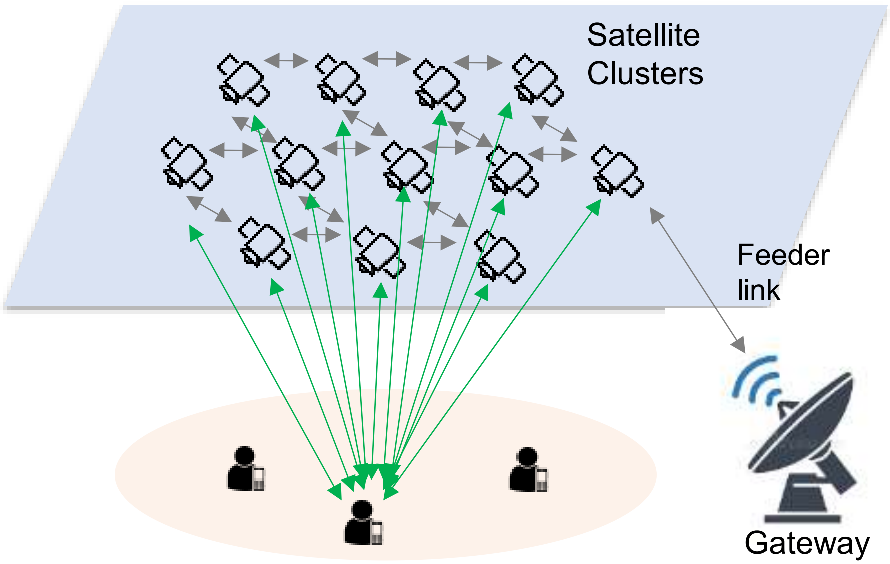
No CSI

$$P_e \sim \mathrm{SNR}^{-1}$$

Beamforming gain *improves* ***average SNR*** *through* ***coherent addition,*** i.e. with $\mathbf{w} = \mathbf{h}$ *(constructive interference)*

Diversity Gain (Combining Gain)

- Distributed massive MIMO



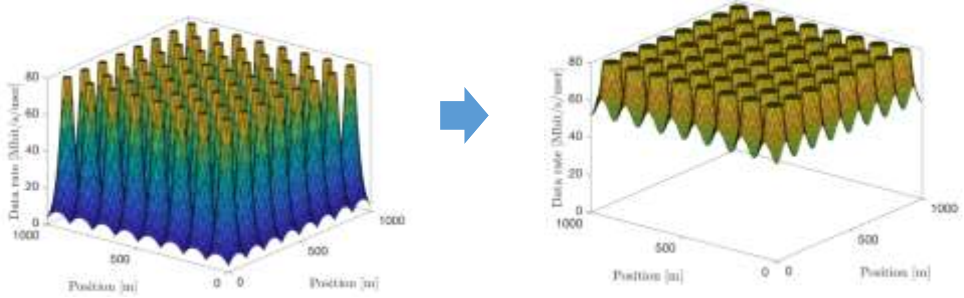
$$\mathrm{SNR}_{\mathrm{MRC}} = \frac{P \cdot \sum_{i=1}^{N} |h_i|^2}{\sigma^2}$$

$$P_e \sim \left(\frac{1}{\mathrm{SNR}}\right)^N$$

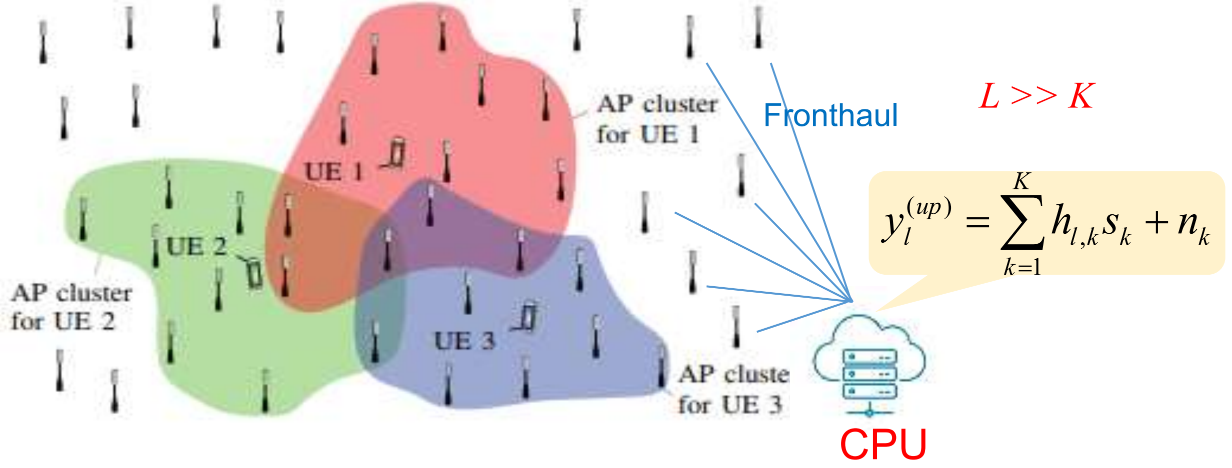
Combines independent faded paths to achieve a diversity gain of N

Cell-free Massive MIMO

▪ Terrestrial Network



- User-centric clustering for combining



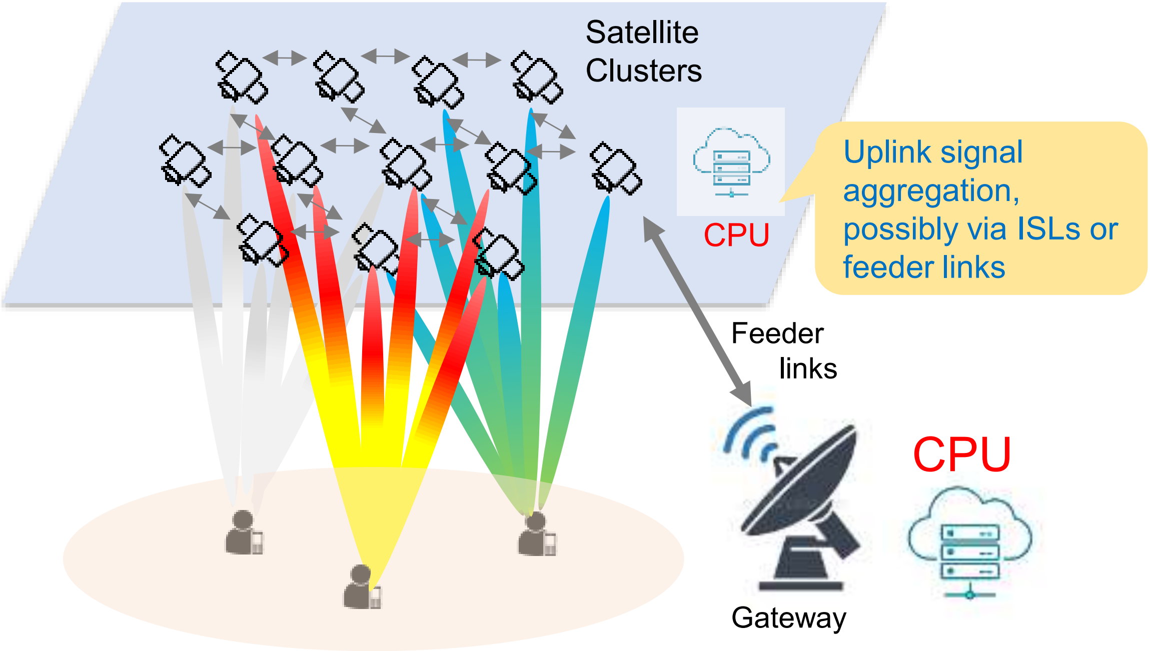
$L >> K$

$$y_l^{(up)} = \sum_{k=1}^{K} h_{l,k} s_k + n_k$$

- Uplink combining in CPU:

$$\hat{s}_k = \sum_{l \in \mathcal{M}_k} v_{l,k}^* y_l^{(up)} = \sum_{l \in \mathcal{M}_k} v_{l,k}^* h_{l,k} s_k + \sum_{i=1, i \neq k}^{K} \sum_{l \in \mathcal{M}_i} v_{l,i}^* h_{l,i} s_i + \sum_{i=1}^{K} \sum_{l \in \mathcal{M}_i} v_{l,i}^* n_i$$

▪ Non-Terrestrial Network



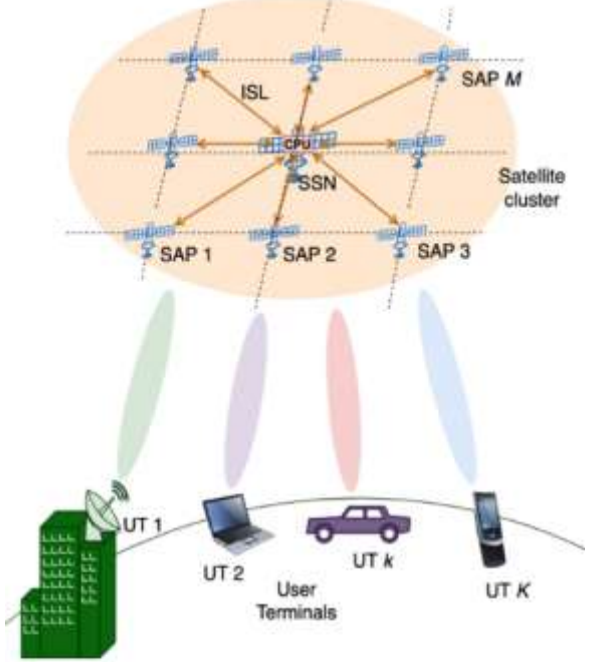
Uplink signal aggregation, possibly via ISLs or feeder links

- Joint decoding to suppress interference and boost SNR
- User-centric clustering ($\mathcal{M}_k$) to select a set of access points (satellites)
- Uplink power control

Previous Work: Handover-aware Distributed Massive MIMO

System Model

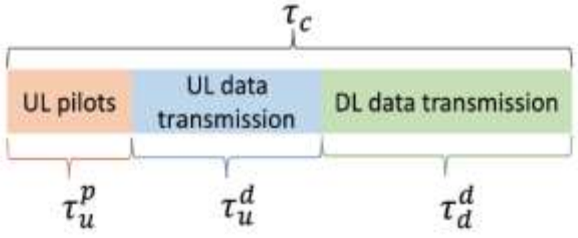
- Downlink transmission model



Precoding: $v_{m,k} = \sqrt{p_{m,k}}\hat{h}_{m,k}$

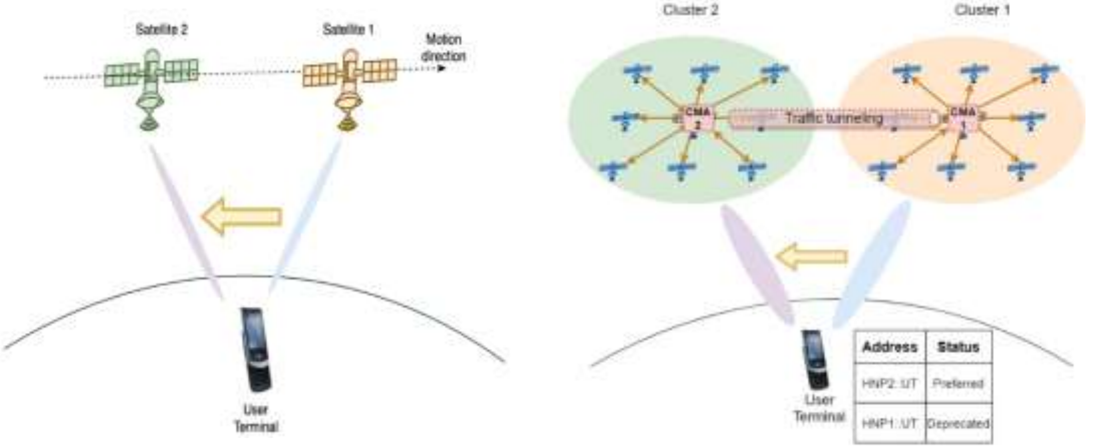
$$\mathbf{x} = \mathbf{V}\mathbf{s} = \mathbf{v}_1 s_1 + \mathbf{v}_2 s_2 + \cdots + \mathbf{v}_K s_K$$

$$\begin{aligned} y_k &= \mathbf{h}_k^H \mathbf{x} \\ &= \mathbf{h}_k^H \mathbf{v}_k s_k + \sum_{k' \in \mathcal{K} \setminus k} \mathbf{h}_k^H \mathbf{v}_{k'} s_{k'} + n_k \end{aligned}$$



Handover Model

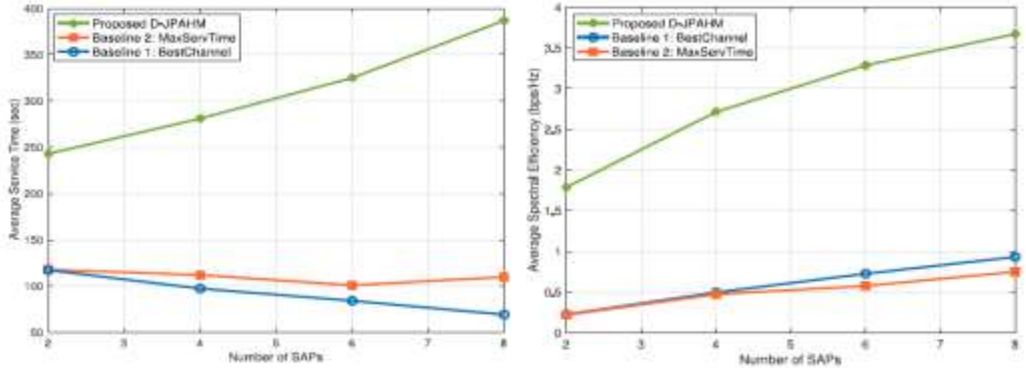
- Single-satellite versus cluster handover



Problem Formulation

$$\begin{aligned} \max_{p_{m,k}, I_k} \quad & (1-\alpha)\sum_{k=1}^{K} R_k[t] I_k[t] + \alpha \sum_{k=1}^{K} I_k[t] \\ \text{s.t.} \quad & R_k[t] \geq R_k^{\min} I_k[t], \ \forall k \in \mathcal{K} \\ & \sum_{k=1}^{K} p_{m,k} \leq P_m^{\max}, \ \forall m \in \mathcal{M} \\ & I_k[t] \in \{0,1\}, \ \forall k \in \mathcal{K} \\ & p_{m,k} \geq 0, \ \forall m \in \mathcal{M}, \ k \in \mathcal{K}, \end{aligned}$$

Performance Analysis

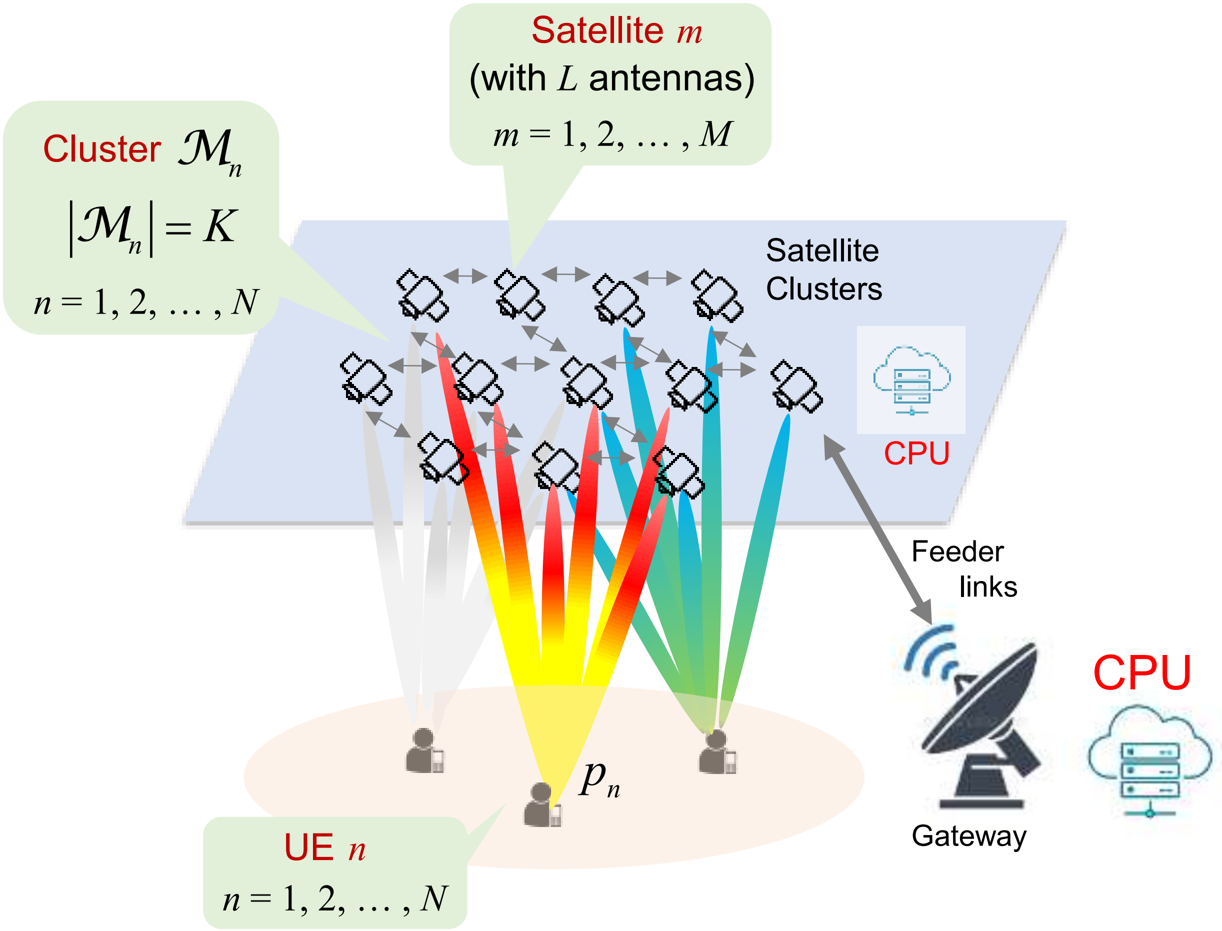


M. Y. Abdelsadek, G. K. Kurt and H. Yanikomeroglu, "Distributed Massive MIMO for LEO Satellite Networks," in IEEE Open Journal of the Communications Society, vol. 3, pp. 2162-2177, 2022,

System Model (1)

Uplink Configuration

- Each UE to be served by a cluster of satellites, which must be dynamically configured to maximize the overall system throughput



Uplink Transmission Model

- The received signal by the m-th satellite”

$$\mathbf{y}_m^{UL} = \sum_{n=1}^{N} \sqrt{p_n}\,\mathbf{h}_{nm} s_n + \mathbf{n}_m \quad \text{where} \quad \mathbf{n}_m \sim \mathcal{CN}(\mathbf{0}, \sigma_{UL}^2 \mathbf{I}_L)$$

- The local estimate in the m-th satellite:

$$\hat{s}_{nm} = I_{nm}\mathbf{v}_{nm}^H \mathbf{y}_m^{UL} \quad \text{where} \quad I_{nm} = \begin{cases} 1, & m \in \mathcal{M}_n \\ 0, & m \notin \mathcal{M}_n \end{cases}$$

- The combined signal at CPU

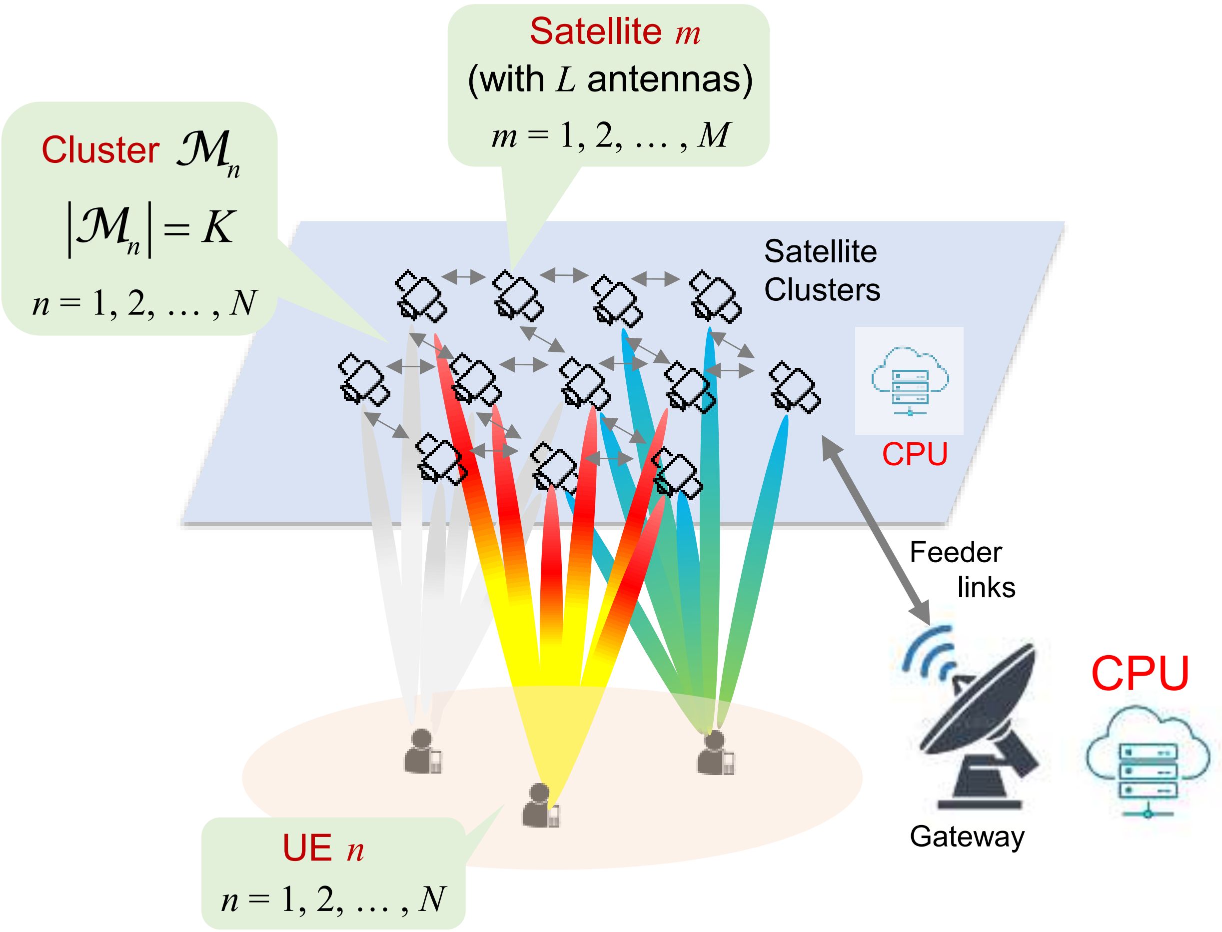
$$\hat{s}_n = \sum_{m=1}^{M} \hat{s}_{nm} = \left(\sum_{m=1}^{M} I_{nm}\sqrt{p_n}\,\mathbf{v}_{nm}^H \mathbf{h}_{nm} \right) s_n + \sum_{n' \neq n}^{N} \left(\sum_{m=1}^{M} I_{n'm}\sqrt{p_{n'}}\,\mathbf{v}_{nm}^H \mathbf{h}_{n'm} \right) s_{n'} + \sum_{m=1}^{M} I_{nm}\mathbf{v}_{nm}^H \mathbf{n}_m$$

- Signal-to-interference & noise ratio (SINR)

$$SINR_n^{UL} = \frac{\sum_{m=1}^{M} I_{nm} p_n \left| \mathbf{v}_{nm}^H \mathbf{h}_{nm} \right|^2}{\sum_{m=1}^{M} \sum_{\substack{n'=1 \\ n' \neq n}}^{N} I_{n'm} p_{n'} \left| \mathbf{v}_{nm}^H \mathbf{h}_{n'm} \right|^2 + \sum_{m=1}^{M} I_{nm} \sigma_{UL}^2 \left| \mathbf{v}_{nm}^H \mathbf{h}_{n'm} \right|^2}.$$

System Model (2)

- ## Uplink Configuration



- ## Channel Model: Rician K-fading
  - The channel between satellite m and user n

$$\mathbf{h}_{nm} = \sqrt{L_{nm}} \left(\sqrt{\frac{\kappa_{nm}}{\kappa_{nm}+1}} \mathbf{h}'_{nm} + \sqrt{\frac{1}{\kappa_{nm}+1}} \mathbf{h}''_{nm} \right)$$

LOS

$$\mathbf{h}'_{nm} = \begin{bmatrix} 1 \\ e^{-j\frac{2\pi d}{\lambda}\sin\theta_{nm}} \\ \vdots \\ e^{-j(L-1)\frac{2\pi d}{\lambda}\sin\theta_{nm}} \end{bmatrix}^T$$

NLOS

$$\mathbf{h}''_{nm} \sim CN(\mathbf{0}, \boldsymbol{I}_L)$$

  - Large-scale fading:

$$L_{nm}[dB] = L_{nm}^{FSPL}(d_{nm}, f_c) + L_{nm}^{SF}$$

Free Space Path Loss

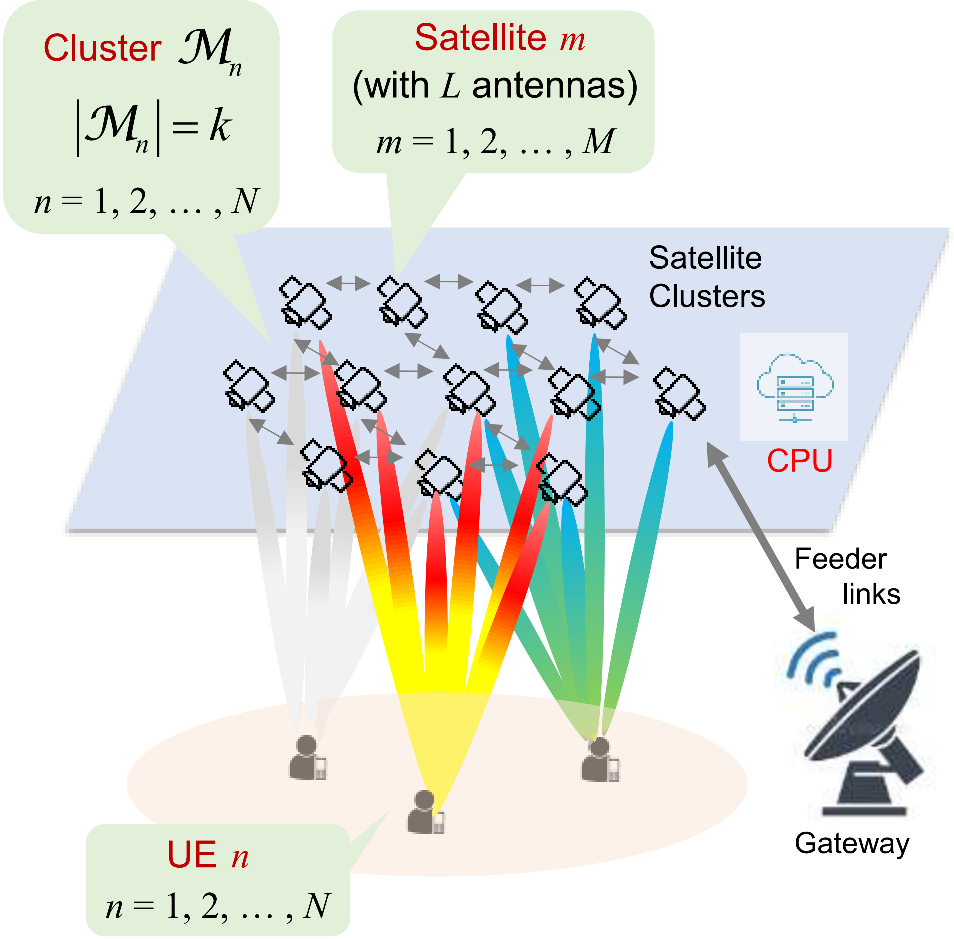
$$L_{nm}^{FSPL}(d_{nm}, f_c) = 32.45 + 20\log_{10}(f_c) + 20\log_{10}(d_{nm})$$

Shadow Fading

$$L_{nm}^{SF} \sim \mathcal{N}(0, \sigma_{SF}^2)$$

Problem Formulation

Uplink Configuration



Outage-Fair Optimization Problem

- Joint clustering and uplink power control subject to outage-fairness constraint

$$
\begin{aligned}
\max_{\substack{\mathbf{p}=\{p_n\} \\ \mathbf{I}=\{I_{nm}\}}} \quad & \sum_{n=1}^{N} \mathrm{SE}_n^{\mathrm{UL}} \\
\text{s.t.} \quad & \boxed{\Pr\{\mathrm{SINR}_n \geq \gamma\} \geq \alpha,} \quad \forall n, \\
& \boxed{0 \leq p_n \leq p_{\max}, \quad \forall n,} \\
& I_{nm} \in \{0, 1\}, \quad \forall n, m, \\
& \boxed{I_{nm} = 0 \text{ if } \phi_{nm} < \phi_{\mathrm{th}},} \quad \forall n, m, \\
& \boxed{\sum_{m=1}^{M} I_{nm} = k, \quad \forall n.}
\end{aligned}
$$

Outage-fairness constraint

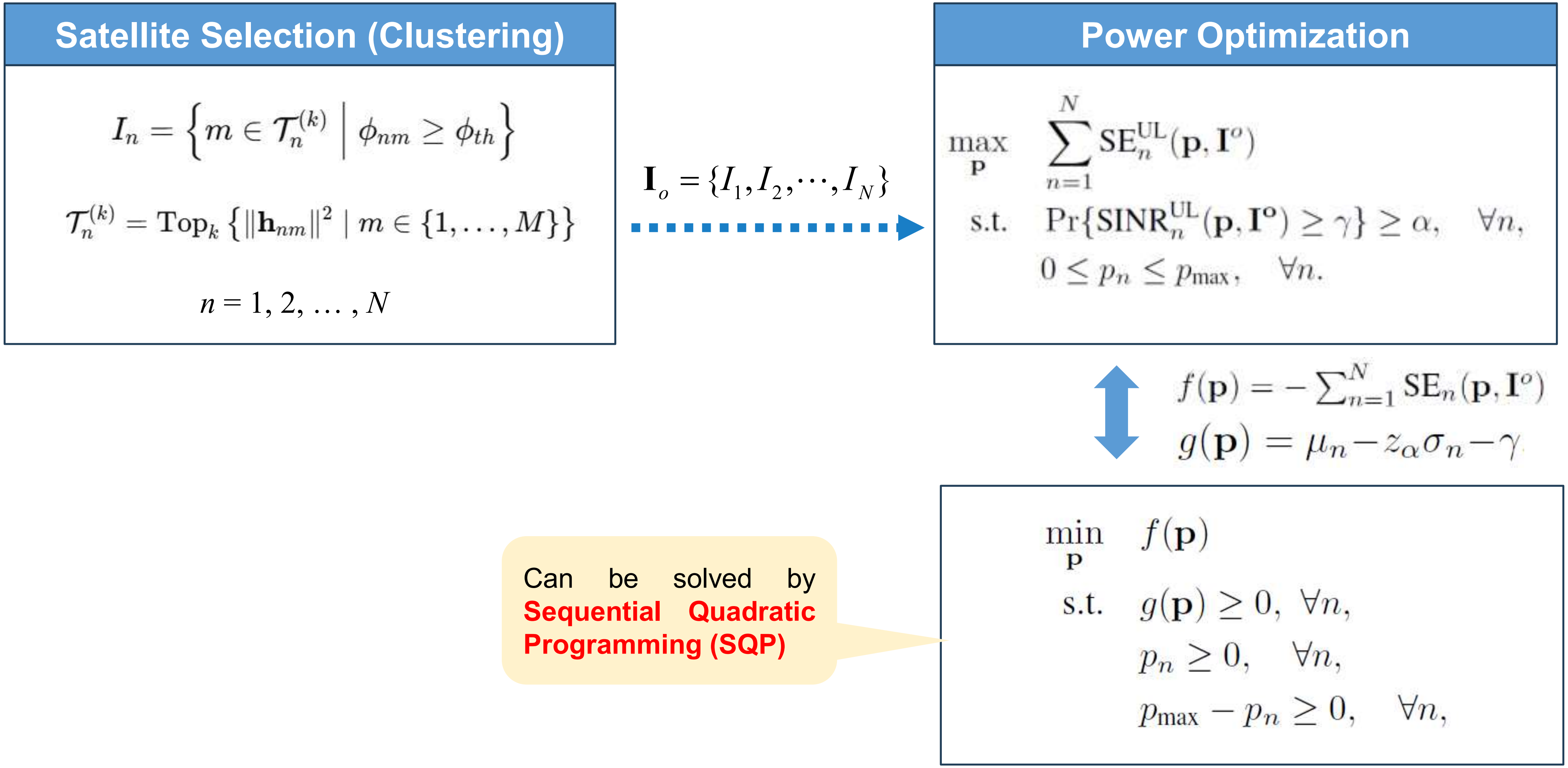
Power constraint

Minimum elevation angle constraint

The maximum number of satellites constraint

Greedy Algorithm

- **Two-Phase Heuristic Approach**



Satellite Selection (Clustering)

$$I_n = \left\{ m \in \mathcal{T}_n^{(k)} \,\middle|\, \phi_{nm} \geq \phi_{th} \right\}$$

$$\mathcal{T}_n^{(k)} = \mathrm{Top}_k \left\{ \|\mathbf{h}_{nm}\|^2 \mid m \in \{1, \ldots, M\} \right\}$$

$$n = 1, 2, \ldots, N$$

$$\mathbf{I}_o = \{I_1, I_2, \cdots, I_N\}$$

Power Optimization

$$\begin{aligned} \max_{\mathbf{p}} \quad & \sum_{n=1}^{N} \mathrm{SE}_n^{\mathrm{UL}}(\mathbf{p}, \mathbf{I}^o) \\ \text{s.t.} \quad & \Pr\{\mathrm{SINR}_n^{\mathrm{UL}}(\mathbf{p}, \mathbf{I}^o) \geq \gamma\} \geq \alpha, \quad \forall n, \\ & 0 \leq p_n \leq p_{\max}, \quad \forall n. \end{aligned}$$

$$f(\mathbf{p}) = -\sum_{n=1}^{N} \mathrm{SE}_n(\mathbf{p}, \mathbf{I}^o)$$

$$g(\mathbf{p}) = \mu_n - z_\alpha \sigma_n - \gamma$$

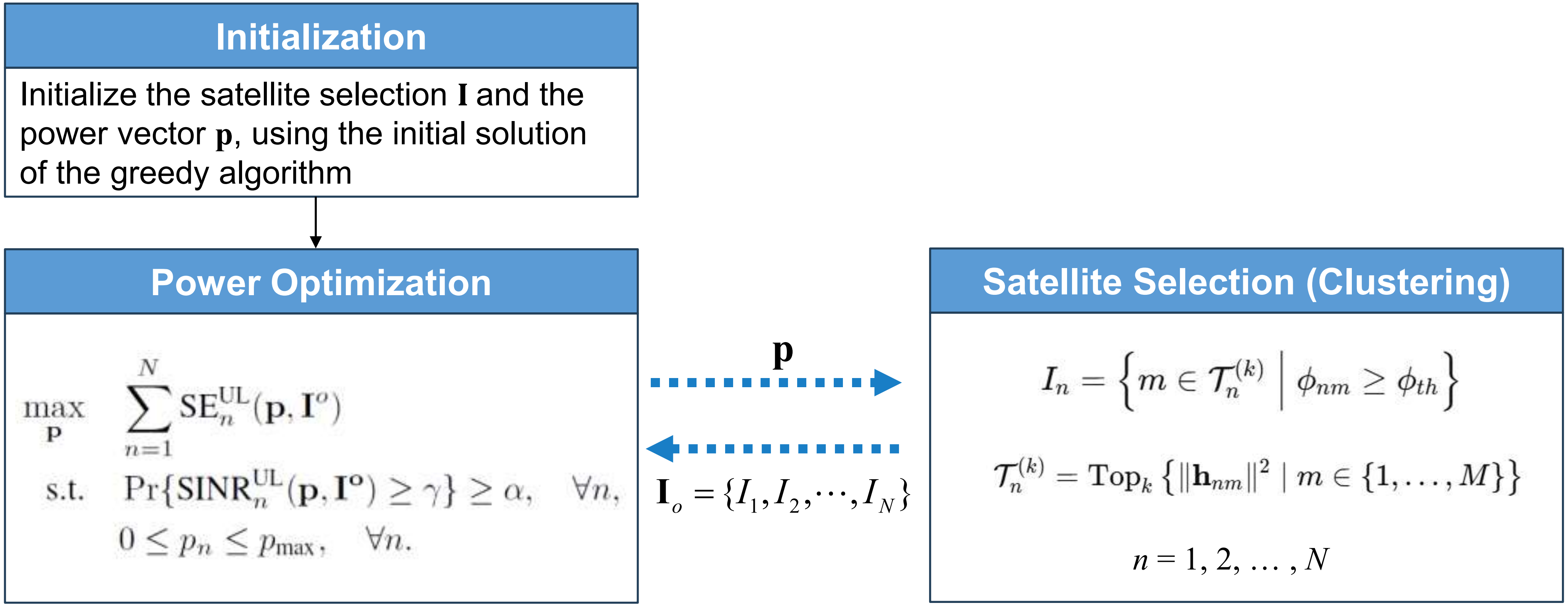
$$\begin{aligned} \min_{\mathbf{p}} \quad & f(\mathbf{p}) \\ \text{s.t.} \quad & g(\mathbf{p}) \geq 0, \ \forall n, \\ & p_n \geq 0, \quad \forall n, \\ & p_{\max} - p_n \geq 0, \quad \forall n, \end{aligned}$$

Can be solved by **Sequential Quadratic Programming (SQP)**

Alternating Optimization Algorithm

Iterative Approach

- Decompose the original problem into two subproblems, power optimization & clustering



Initialization

Initialize the satellite selection $\mathbf{I}$ and the power vector $\mathbf{p}$, using the initial solution of the greedy algorithm

Power Optimization

$$\max_{\mathbf{p}} \quad \sum_{n=1}^{N} \mathrm{SE}_n^{\mathrm{UL}}(\mathbf{p}, \mathbf{I}^o)$$
$$\text{s.t.} \quad \Pr\{\mathrm{SINR}_n^{\mathrm{UL}}(\mathbf{p}, \mathbf{I}^o) \geq \gamma\} \geq \alpha, \quad \forall n,$$
$$0 \leq p_n \leq p_{\max}, \quad \forall n.$$

$\mathbf{p}$

$\mathbf{I}_o = \{I_1, I_2, \cdots, I_N\}$

Satellite Selection (Clustering)

$$I_n = \left\{ m \in \mathcal{T}_n^{(k)} \;\middle|\; \phi_{nm} \geq \phi_{th} \right\}$$

$$\mathcal{T}_n^{(k)} = \mathrm{Top}_k \left\{ \|\mathbf{h}_{nm}\|^2 \mid m \in \{1, \ldots, M\} \right\}$$

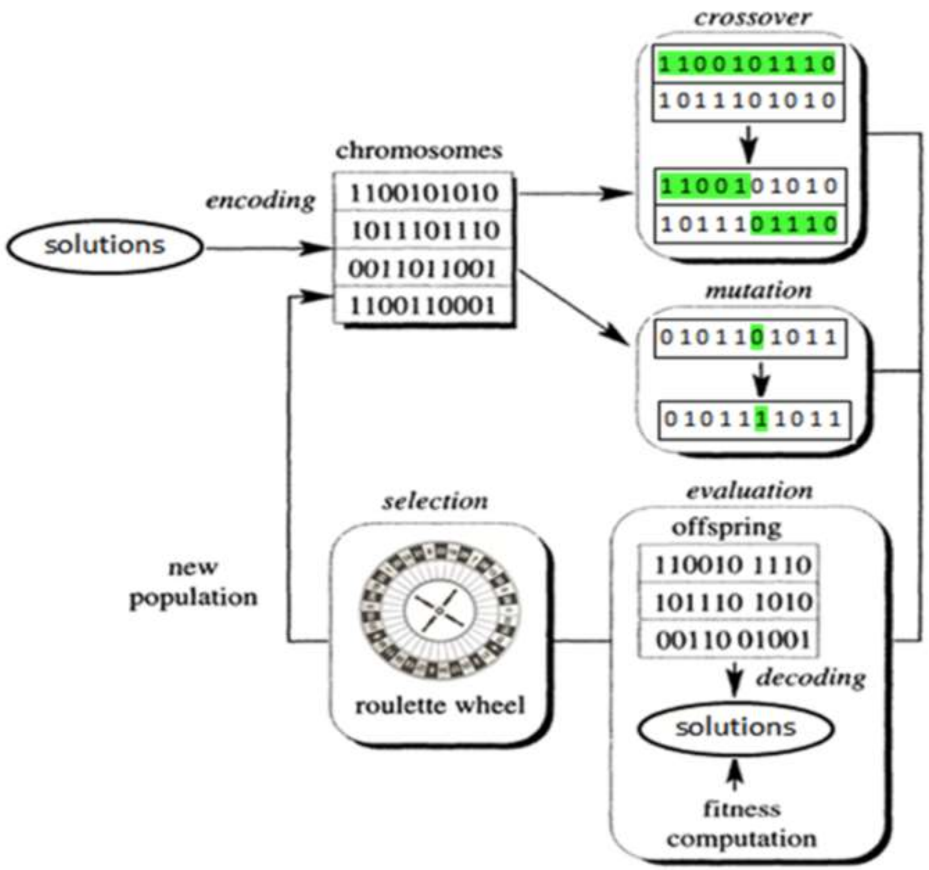
$$n = 1, 2, \ldots, N$$

- Repeat until the improvement in total SE is less than the tolerance or the maximum number of iterations (e.g., 100) is reached

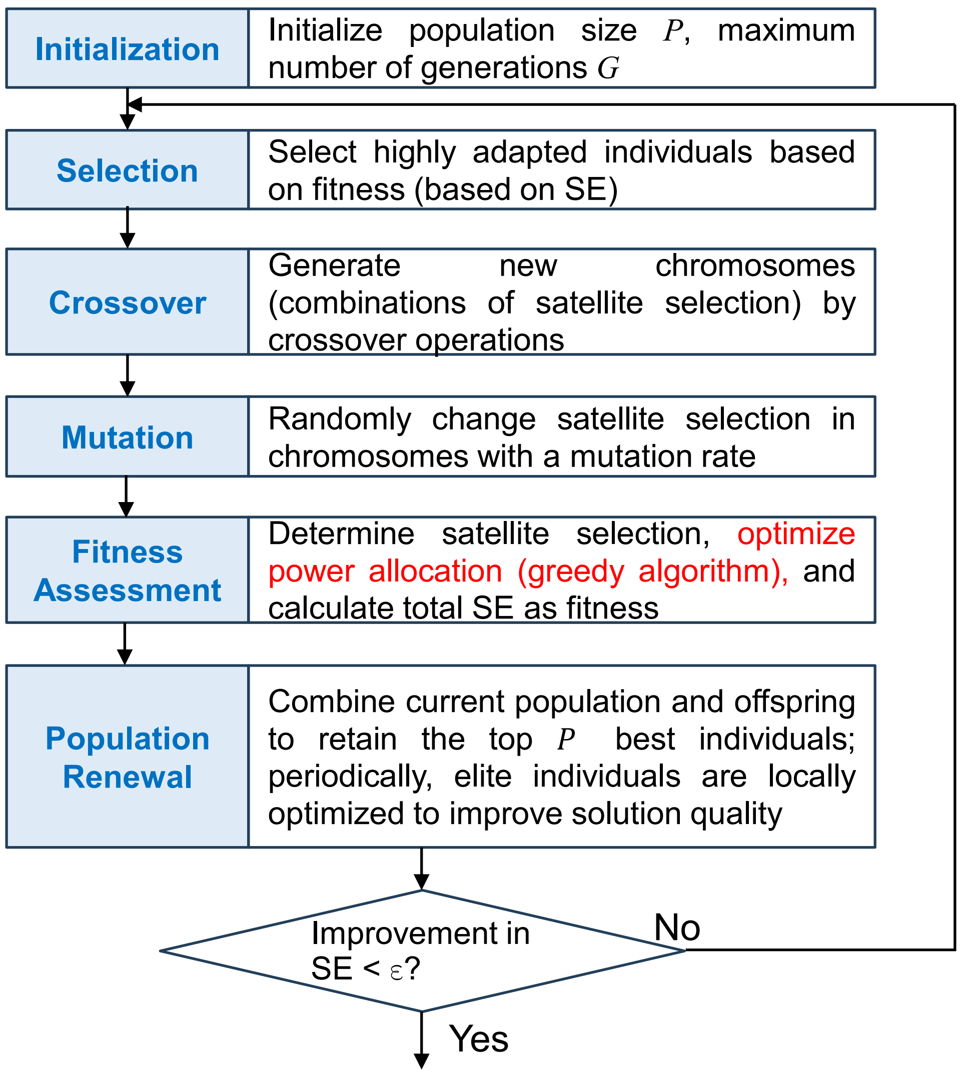
Genetic Algorithm

Meta-Heuristic Algorithm

- Each user's satellite selection $\mathbf{I}_n$ is encoded as a chromosome
- The initial solution is generated by a greedy algorithm



- GA Iteration



Initialization	Initialize population size P, maximum number of generations G
Selection	Select highly adapted individuals based on fitness (based on SE)
Crossover	Generate new chromosomes (combinations of satellite selection) by crossover operations
Mutation	Randomly change satellite selection in chromosomes with a mutation rate
Fitness Assessment	Determine satellite selection, optimize power allocation (greedy algorithm), and calculate total SE as fitness
Population Renewal	Combine current population and offspring to retain the top P best individuals; periodically, elite individuals are locally optimized to improve solution quality

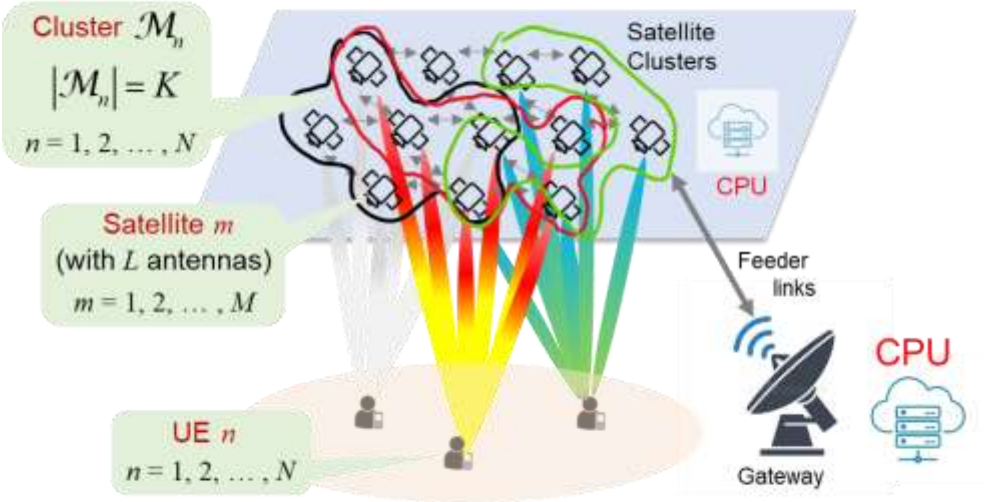
Improvement in SE < ε?

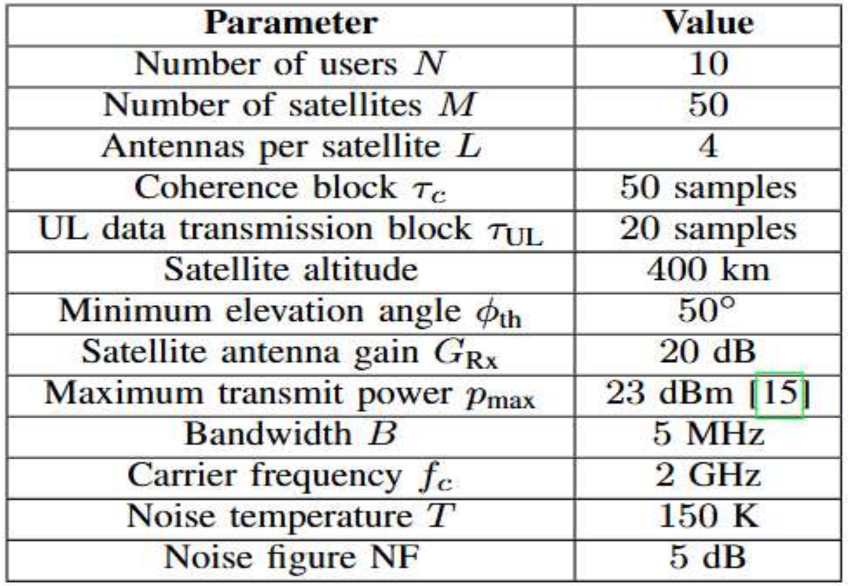
No

Yes

Simulation Results (1)

- **Simulation Parameters**

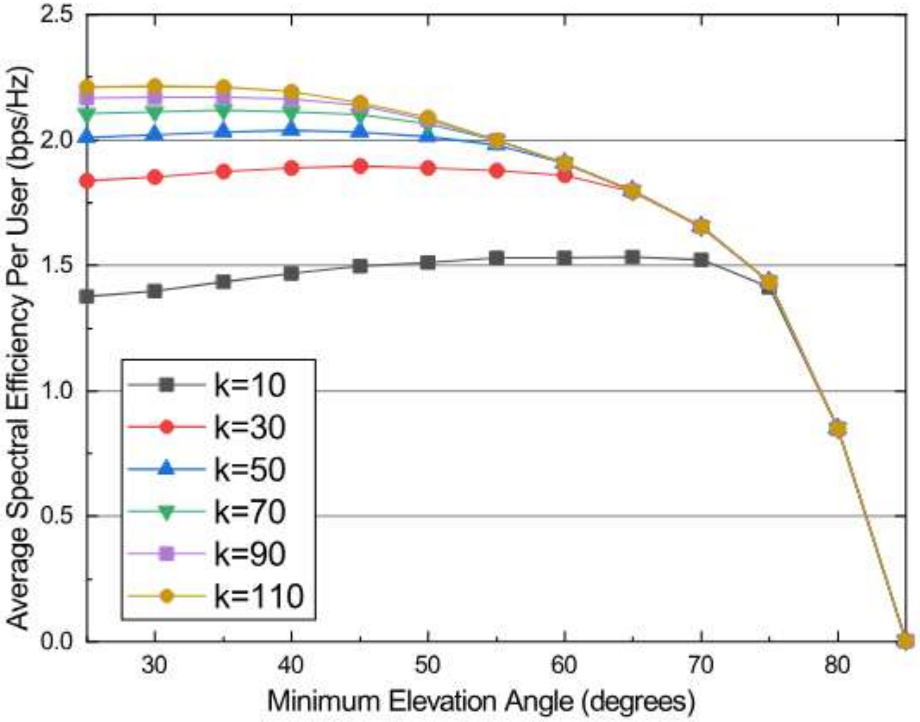




Parameter	Value
Number of users N	10
Number of satellites M	50
Antennas per satellite L	4
Coherence block τ_c	50 samples
UL data transmission block τ_{UL}	20 samples
Satellite altitude	400 km
Minimum elevation angle ϕ_{th}	50°
Satellite antenna gain G_{Rx}	20 dB
Maximum transmit power $p_{\max}$	23 dBm [15]
Bandwidth B	5 MHz
Carrier frequency f_c	2 GHz
Noise temperature T	150 K
Noise figure NF	5 dB

- **Impact of Minimum Elevation Angle**

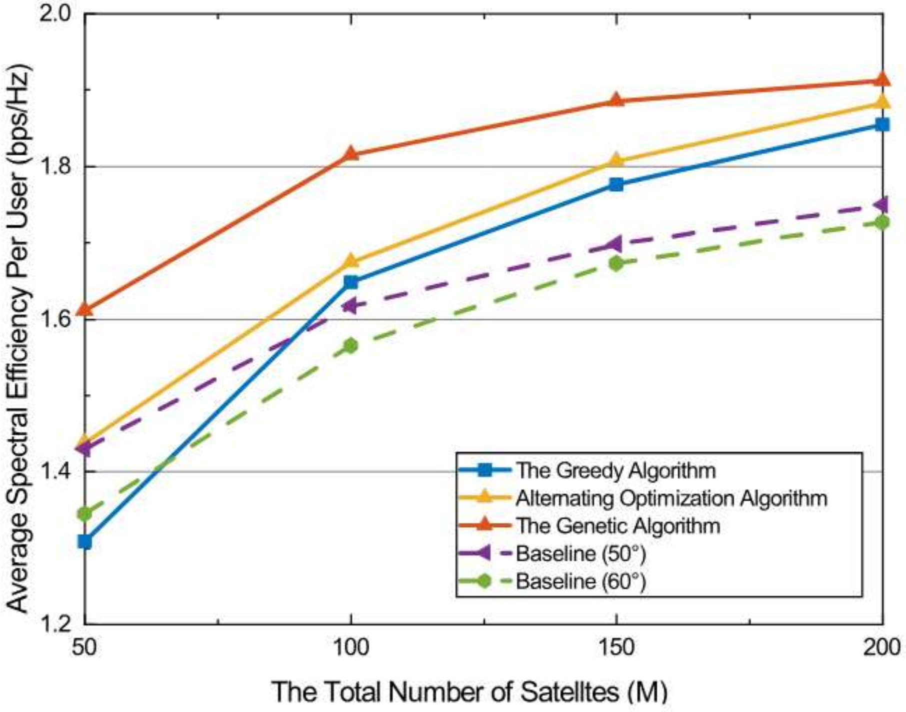
The larger the minimum elevation angle is, the smaller number of satellites to select



- The optimum cluster size varies with the minimum elevation angle
- Some tradeoff observed for the small cluster size

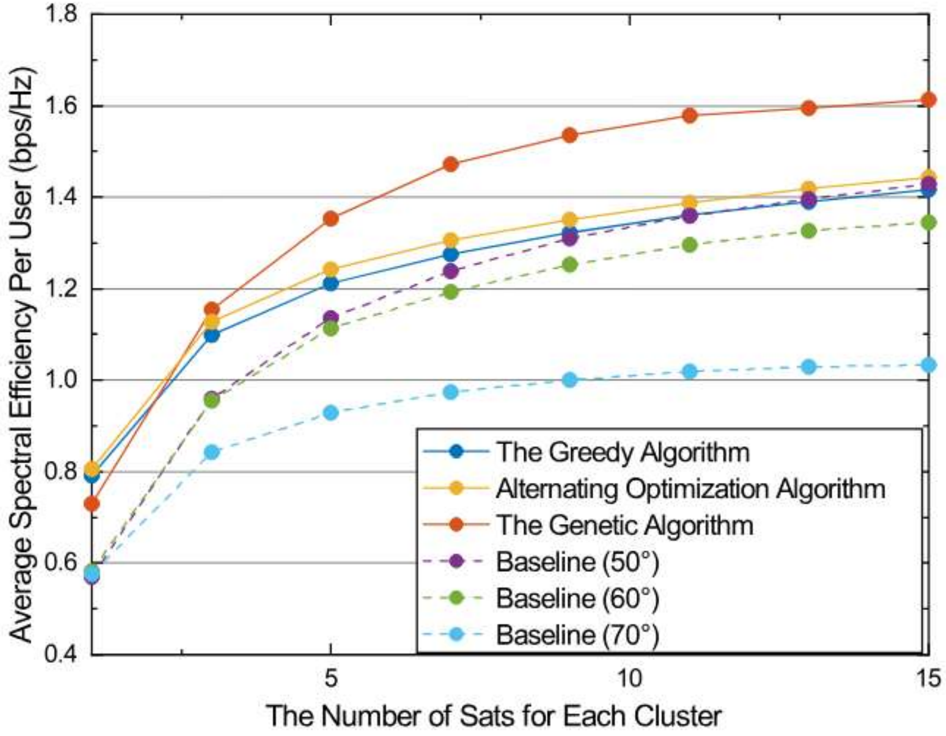
Simulation Results (2)

- **Impact of The Total # of Satellites**



  - GA performs best in all conditions
  - The performance gap narrows as M increases

- **Impact of Cluster Size**



  - As k increases, SE tends to increase
  - Converge when $k > 10$
  - GA consistently outperforms the other algorithms

Conclusions

- **Summary**
  - Proposed a joint clustering and uplink power control framework for CF-mMIMO in LEO satellite networks
  - Formulated a mixed-integer, non-convex optimization problem targeting uplink spectral efficiency (SE) with fairness constraints
  - Developed and evaluated Greedy, Alternating Optimization, and Genetic Algorithms for scalable and efficient solutions.

- **Practical Implications**
  - Our method enables reliable and efficient D2C connectivity, crucial for extending broadband coverage to remote/underserved regions
  - Supports scalable operation under limited power and bandwidth in real LEO satellite environments

- **Future Work**
  - Refine uplink SINR modeling beyond Gaussian approximation
  - Explore real-time adaptive clustering using DRL-based approaches
  - Investigate hybrid ground-satellite scheduling for integrated 6G NTN systems.


Thank you