Joint Graph-based User Scheduling and Beamforming in LEO-MIMO Satellite Communication Systems

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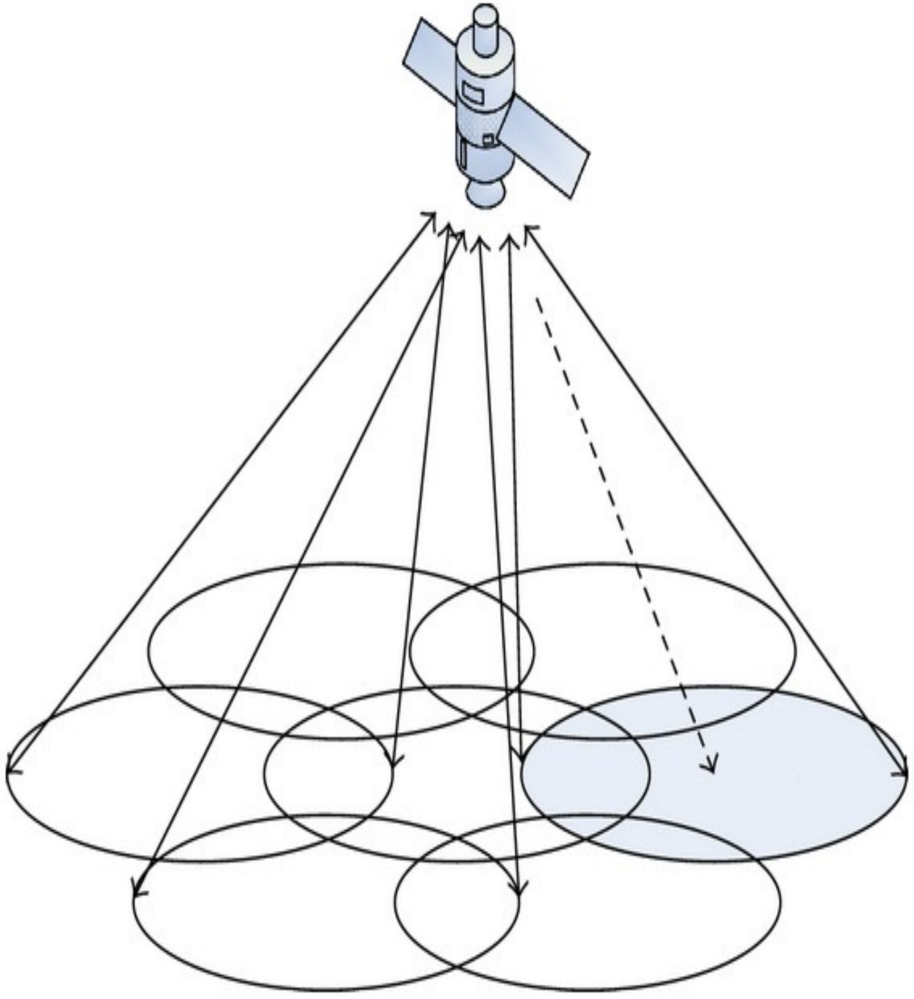
Objective

- We have considered a LEO MU-MIMO HTS with the objective to minimize the inter-beam interference among the users in the downlink.
- Since there are many more UT's on Earth than transmit antennas available on the satellite, user scheduling is necessary.
- Scheduling can be implemented either by user selection or user grouping.
- The paper presents a novel solution for user grouping based on Graph theory.



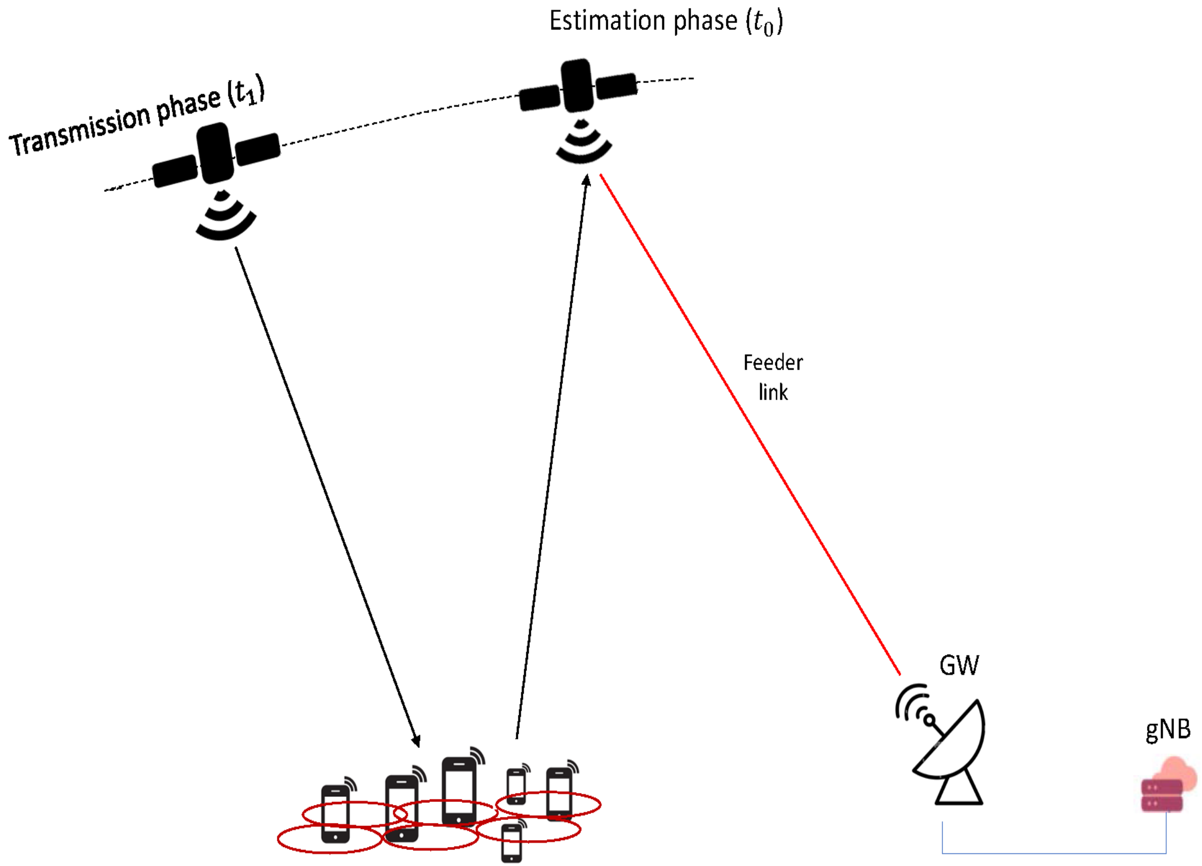
LEO-HTS Spot Beams

System Model

- We consider a single multi-beam LEO satellite equipped with an on-board planar antenna array with N radiating elements, providing connectivity to K single-antenna uniformly distributed on-ground UT's.

- We further assume that the LEO satellite always maintains a logical link with an on-ground gNB.

- Both scheduling and beamforming require the estimation of the Channel State Information (CSI) provided by the UT's.



System architecture with a single LEO satellite

System Model (Contd.)

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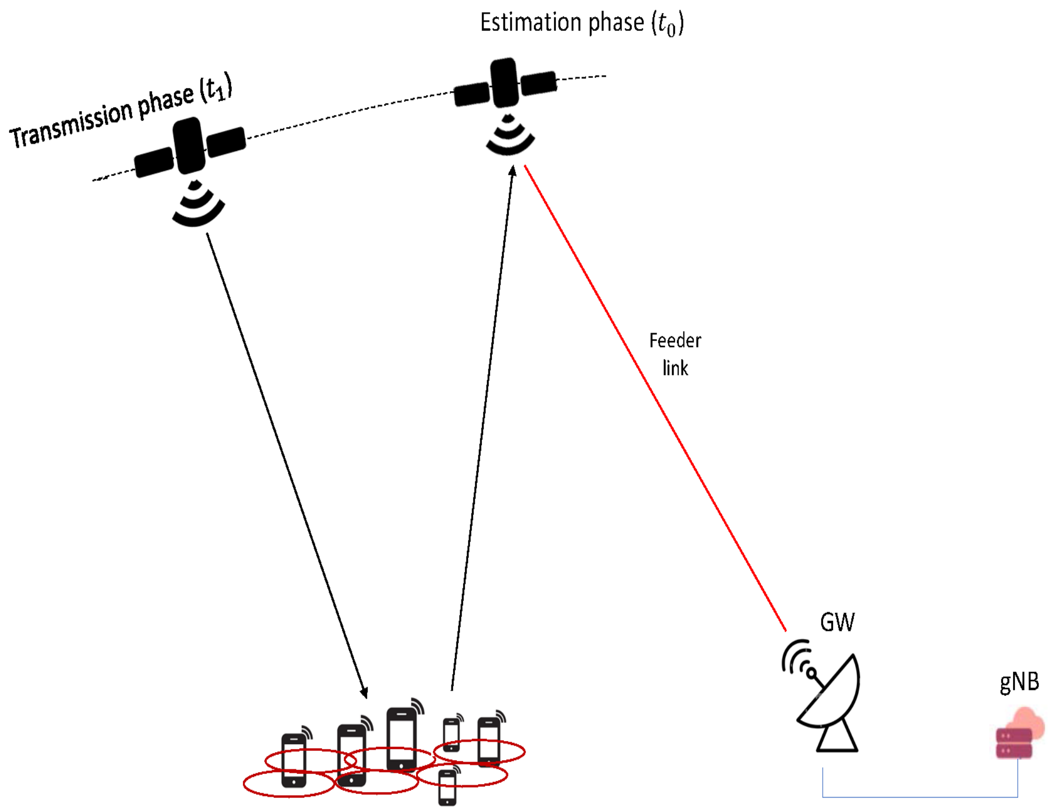
- The Radio Resource Management (RRM) scheduling and beamforming coefficients are computed at the on-ground gNB.

- Different groups of users are served in different time slots via TDMA, while users within the same group are simultaneously served by the satellite via SDMA, i.e., the implementation of feed space digital beamforming techniques.

- The latency between the channel estimation phase and the transmission phase is computed as:

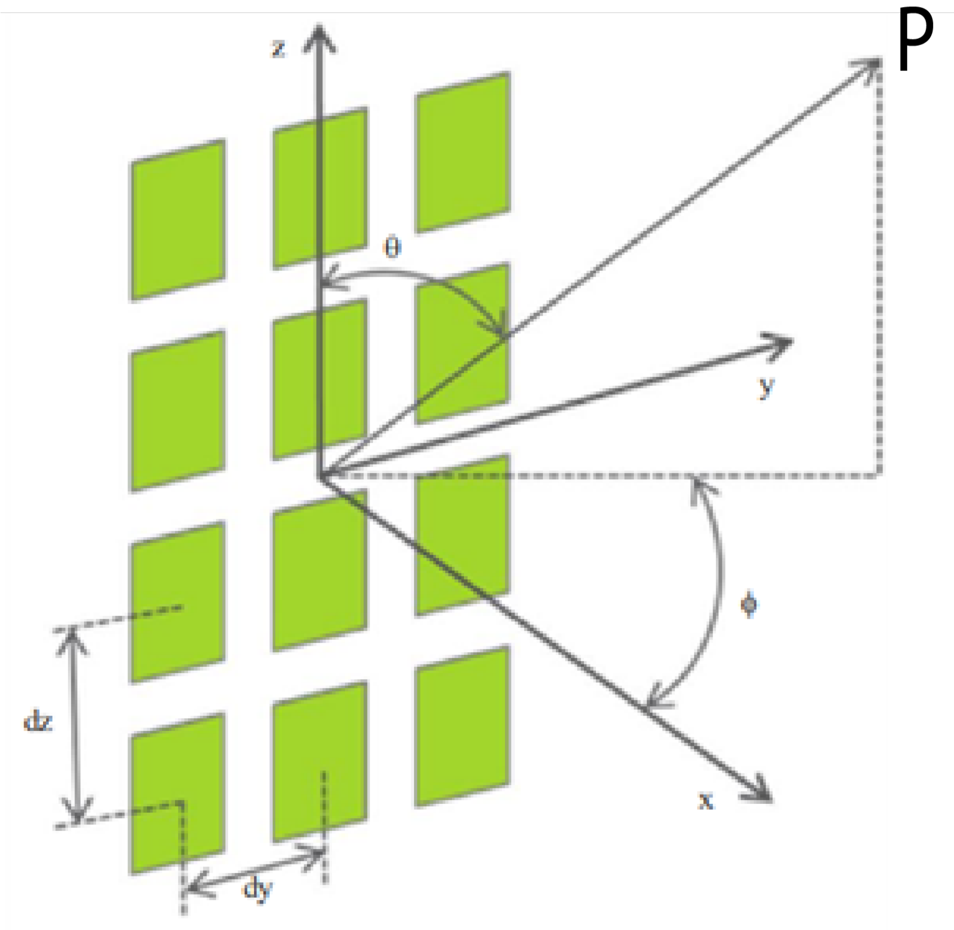
$$\Delta t = t_{ut,max} + 2t_{feeder} + t_p + t_{ad}$$



System architecture with a single LEO satellite

Antenna Model

- The deployed antenna array model is based on ITU-R Recommendation M.2101.
- The antenna boresight directions is defined by the direction of the Sub Satellite Point (SSP).
- The point P is the position of the user terminal on the ground. The user directions are identified by (θ, φ) angles where the boresight direction is (0,0).
- The total array response of the UPA for the generic direction (θ_i, φ_i) can be expressed as the Kronecker product of the two ULA steering vectors along the horizontal and vertical directions.



Antenna Array Model

Antenna Model (Contd.)

$$\mathbf{a}_H(\vartheta_i, \varphi_i) = \left[1, e^{jk_0 d_H \sin\vartheta_i \sin\varphi_i}, \ldots, e^{jk_0 d_H (N_H - 1)\sin\vartheta_i \sin\varphi_i}\right]$$

$$\mathbf{a}_V(\vartheta_i) = \left[1, e^{jk_0 \cos\vartheta_i}, \ldots, e^{jk_0 d_V \pi (N_V - 1)\cos\vartheta_i}\right].$$

Where;

$K_o = 2\pi\lambda$ is the wave number, $N_{H,}$ N_v denotes the number of array elements on the horizontal (y-axis) and vertical (z-axis) directions with $N = N_H \cdot N_V$.

d_H , d_V denote the distance between adjacent array elements on the y- axis and z- axis, respectively.

- The $1\times N$ steering vector of the UPA targeted at the i_{th} user is given by

$$\mathbf{a}(\vartheta_i, \varphi_i) = g_E(\vartheta_i, \varphi_i)\, \mathbf{a}_H(\vartheta_i, \varphi_i) \otimes \mathbf{a}_V(\vartheta_i)$$

Channel Model

- The Channel State Information (CSI) vector $\mathbf{h}_i$ at feed level represents the channel between the N radiating elements and the generic i_{th} on-ground UT, with $i = 1, \dots, K$ can be written as

$$\mathbf{h}_i = G_i^{(rx)} \frac{\lambda}{4\pi d_i} \sqrt{\frac{L_i}{\kappa B T_i}} e^{-j\frac{2\pi}{\lambda} d_i} \mathbf{a}(\vartheta_i, \varphi_i)$$

in which, d_i is the slant range between the generic i_{th} user and the satellite, λ is the wavelength, KBT_i denotes the equivalent thermal noise power, K the Boltzmann constant, B the user bandwidth (assumed to be the same for all users)
T_i the equivalent noise temperature of the i_{th} UT.
L_i denotes all the additional losses per user, such as for example atmospheric, antenna, and cable losses.
$G_i^{(rx)}$ denotes the receiving antenna gain for the i_{th} UT.

- The additional losses are computed as per 3GPP TR 38.821

$$L_i = L_{sha,i} + L_{atm,i} + L_{sci,i}$$

Channel Matrix Computation

- Collecting all the K CSI vectors makes it possible to build a $K \ X \ N$ complex channel matrix at the System level.

$$\mathbf{H} = [\mathbf{h}_1^{\mathsf{T}}, \mathbf{h}_2^{\mathsf{T}}, \ldots, \mathbf{h}_K^{\mathsf{T}}]^{\mathsf{T}}$$

- Given the set of all users to be scheduled $\mathcal{U} = \{U_1, U_2, \ldots, U_K\}$, the RRM algorithm defines a possible users' partitioning $\{\mathcal{C}_1, \mathcal{C}_2, \ldots, \mathcal{C}_P\}$ where $\mathcal{C}_p \subseteq \mathcal{U}$ is defined as a cluster.

- The cardinality of the p_{th} cluster is defined as $|\mathcal{C}_p| = K_p$

- Clusters are not necessarily disjoint sets of users $|\mathcal{C}_1 \ \cup \ \mathcal{C}_2 \ \cup \ldots \cup \ \mathcal{C}_P| = K$

- The total time frames available at the RRM is given by

$$T_{tot} = \sum_{p=1}^{P} |\mathcal{C}_p| \geq K$$

Beamforming Matrix

- The selected beamforming algorithm computes for each cluster a $N \times K_p$ complex beamforming matrix given as

$$\mathbf{W}_p = [\mathbf{w}_1^{(p)}, \mathbf{w}_2^{(p)}, \ldots, \mathbf{w}_{K_p}^{(p)}]$$

  where $\mathbf{w}_i^{(p)}$ denotes the $N \times 1$ beamformer designed for the i_{th} user in the p_{th} cluster.

- The matrix $\mathbf{W}_p$ projects the K_p dimensional column vectors contains the unit-variance user symbols onto the *N*- dimensional space defined by the antenna feeds.

$$\mathbf{s}_p = [s_1, s_2, \ldots, s_{K_p}]^{\mathsf{T}}$$

- Thus, in the feed space, the computation of the beamforming matrix allows for the generation of a dedicated beam towards each user direction.

Received Signal and SINR

- The received signal by the i_{th} user in the p_{th} cluster is given as

$$y_k^{(p)} = \mathbf{h}_k \mathbf{w}_k^{(p)} s_k + \sum_{\substack{i=1 \\ i \neq k}}^{K_p} \mathbf{h}_k \mathbf{w}_i^{(p)} s_i + z_k^{(p)}$$

where $z_k^{(p)}$ is a circularly symmetric Gaussian Random Variable with zero mean and unit variance.

- The K_p dimensional vector of the received symbol in the p_{th} cluster is given as

$$\mathbf{y}_p = \mathbf{H}_p^{(t_1)} \mathbf{W}_p^{(t_0)} \mathbf{s}_p + \mathbf{z}_p$$

- The Signal-to-Interference-plus-Noise ratio for user *k* belonging to cluster *p* can be computed as

$$\mathrm{SINR}_k^{(p)} = \frac{\left\| \mathbf{h}_k \mathbf{w}_k^{(p)} \right\|^2}{1 + \sum_{\substack{i=1 \\ i \neq k}}^{K_p} \left\| \mathbf{h}_k \mathbf{w}_i^{(p)} \right\|^2}$$

Capacity computation

- In order to design a fair-proportional scheduler the per-user achievable capacity is computed as

$$C_k = \; B \sum_{\substack{p \\ U_k \in \mathcal{C}_p}} \gamma_p \log_2 \left(1 + \mathrm{SINR}_k^{(p)}\right)$$

- The clusters weights are computed as

$$\gamma_p = \frac{|\mathcal{C}_p|}{\sum_{p=1}^{P} |\mathcal{C}_p|} = \frac{K_p}{T_{tot}}$$

- The beamforming matrix is based on Linear Minimum Mean Square Error (MMSE)

$$\mathbf{W}_p = \left(\mathbf{H}_p^H \mathbf{H}_p + \alpha \mathbf{I}_N\right)^{-1} \mathbf{H}_p^H$$

Power Normalizations

Sum Power Constraint (SPC)

$$\tilde{\mathbf{W}}_p = \frac{\sqrt{P_t}\mathbf{W}_p}{\sqrt{\mathrm{tr}(\mathbf{W}_p\mathbf{W}_p^H)}}$$

→ An upper bound is imposed on the total on-board power. It preserves the orthogonality of the beamformer columns but does not guarantee that the power transmitted from each feed will be upper bounded.

Per Antenna Power Constraint (PAC)

$$\tilde{\mathbf{W}}_p = \sqrt{\frac{P_t}{N}}\left(\mathrm{diag}\left(\mathrm{diag}\left(\mathbf{W}_p\mathbf{W}_p^H\right)\right)\right)^{-\frac{1}{2}}\mathbf{W}_p$$

→ The limitation is imposed per antenna, however the orthogonality in the beamformer columns here is disrupted.

Maximum Power Constraint (MPC)

$$\tilde{\mathbf{W}}_p = \frac{\sqrt{P_t}\mathbf{W}_p}{\sqrt{N\ \max_j\left[\mathbf{W}_p\mathbf{W}_p^H\right]_{j,j}}}$$

→ The power per antenna is upper bounded and the orthogonality is preserved, but not the entire available on-board power is exploited.

Graph based User Clustering

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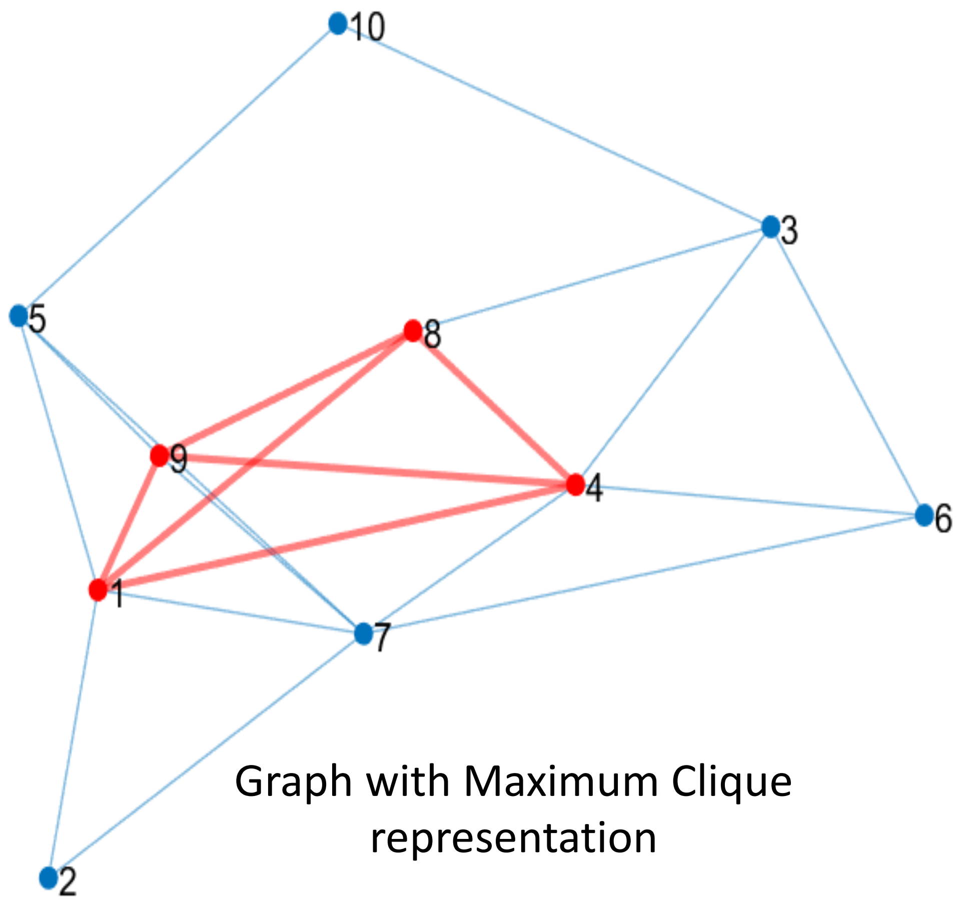
- The clustering problem is modelled as an undirected and unweighted graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$
- Users constitute the vertices of the graph, and edges are based on a dissimilarity measure of their channels. Computed from

$$[\mathbf{\Psi}]_{i,j} = \frac{\left|\mathbf{h}_i \mathbf{h}_j^H\right|}{\|\mathbf{h}_i\| \, \|\mathbf{h}_j\|} \quad (18)$$

- The set of edges of the graph is completely determined by its adjacency matrix, whose entities are defined as

$$[\mathbf{A}]_{i,j} = \begin{cases} 1, & [\mathbf{\Psi}]_{i,j} \leq \delta_{th} \\ 0, & [\mathbf{\Psi}]_{i,j} > \delta_{th} \end{cases} \quad (19)$$

- δ_{th} denotes a properly designed threshold and finding the optimal threshold value is one of objectives.



Graph with Maximum Clique representation

The Maximum Clique

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- It is a greedy iterative procedure that aims at minimizing the total number of P clusters, given an optimized threshold δ_{th}.

This is accomplished by:

I. Maximizing the size of each cluster by iteratively finding the maximum clique of the updated graph.

II. Creating disjoint sets of scheduled users, which also minimizes the total users.

$$\mathcal{C}_i \cap \mathcal{C}_j = \varnothing, \ \forall i, j$$

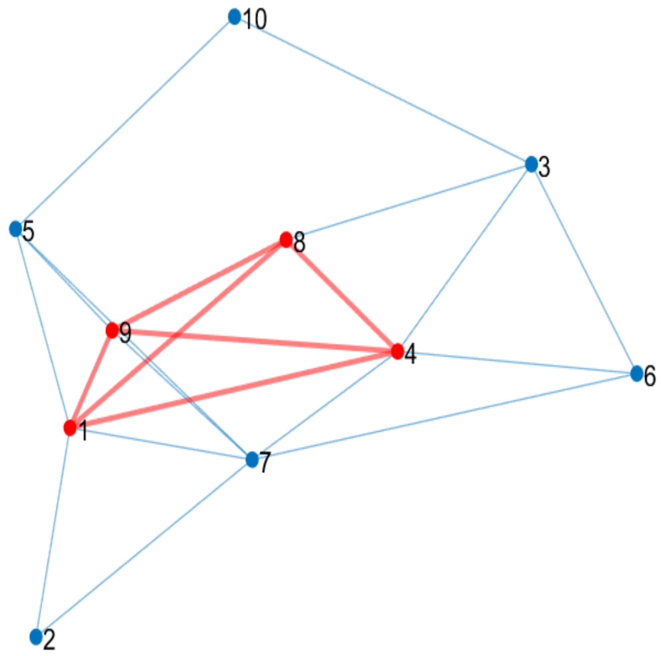
- Fairness is guaranteed among users by setting the cluster weights

$$\gamma_p = \frac{K_p}{K}$$

Algorithm 1 Iterative clique-based user scheduling algorithm

Input: Channel matrix $\mathbf{H}$, threshold δ_{th}
Output: Cluster sets $\mathcal{C}_p$ and cluster weights γ_p for $p = 1, \dots, P$

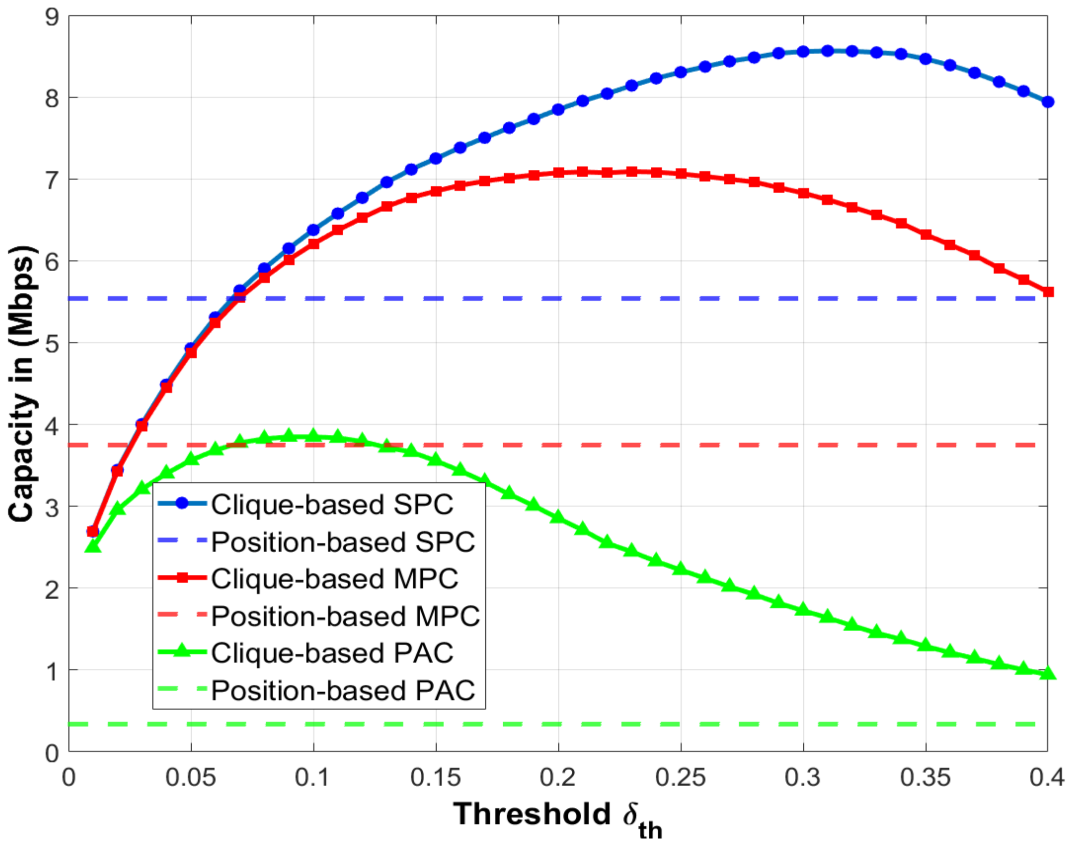
Compute channel correlation distance matrix $\mathbf{\Psi}$ as in (18)
Compute adjacency matrix $\mathbf{A}$ as in (19)
Initialize remaining set of vertices with all users $\mathcal{R} = \mathcal{U}$
Create graph $\mathcal{G}(\mathcal{R}, \mathcal{E})$
Initialize $p = 1$
while $\mathcal{R} \neq \varnothing$ **do**
    $\mathcal{Q}_{\max} = \text{MaxCliqueDyn}(\mathcal{G})$
    $\mathcal{C}_p \leftarrow \mathcal{Q}_{\max}$
    $K_p \leftarrow |\mathcal{C}_p|$
    for all $U_i \in \mathcal{Q}_{\max}$ **do**
        for all $U_j \in \mathcal{R}$ **do**
            $\mathcal{E} = \mathcal{E} - \{U_i, U_j\}$
        end for
    end for
    $\mathcal{R} \leftarrow \mathcal{R} - \mathcal{Q}_{\max}$
    $p \leftarrow p + 1$
end while
$T_{tot} \leftarrow \sum_{p=1}^{P} K_p$
for p:=1 **to** P **do**
    $\gamma_p \leftarrow \frac{K_p}{T_{tot}}$
end for

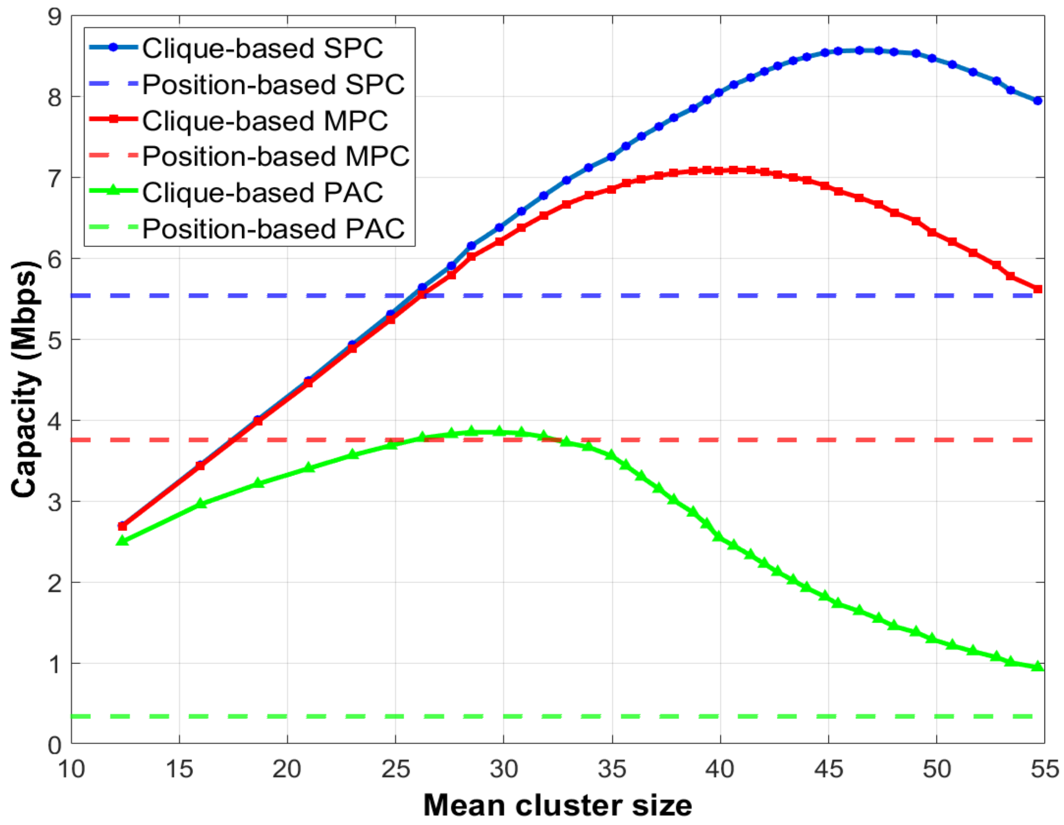


Simulation Parameters

SIMULATION PARAMETERS	
Carrier frequency	2GHz
System Band	S band (30 MHz)
Beamforming space	Feed
Receiver type	VSAT
Receiver scenario	Fixed
Propagation scenario	Non- Line of Sight
System scenario	Urban
Number of tiers	5
Cluster Size for Position-based Scheduler	91
Number of transmitters	1024 (32 x 32 UPA)
User density	$0.05\ \mathrm{users/Km^2}$

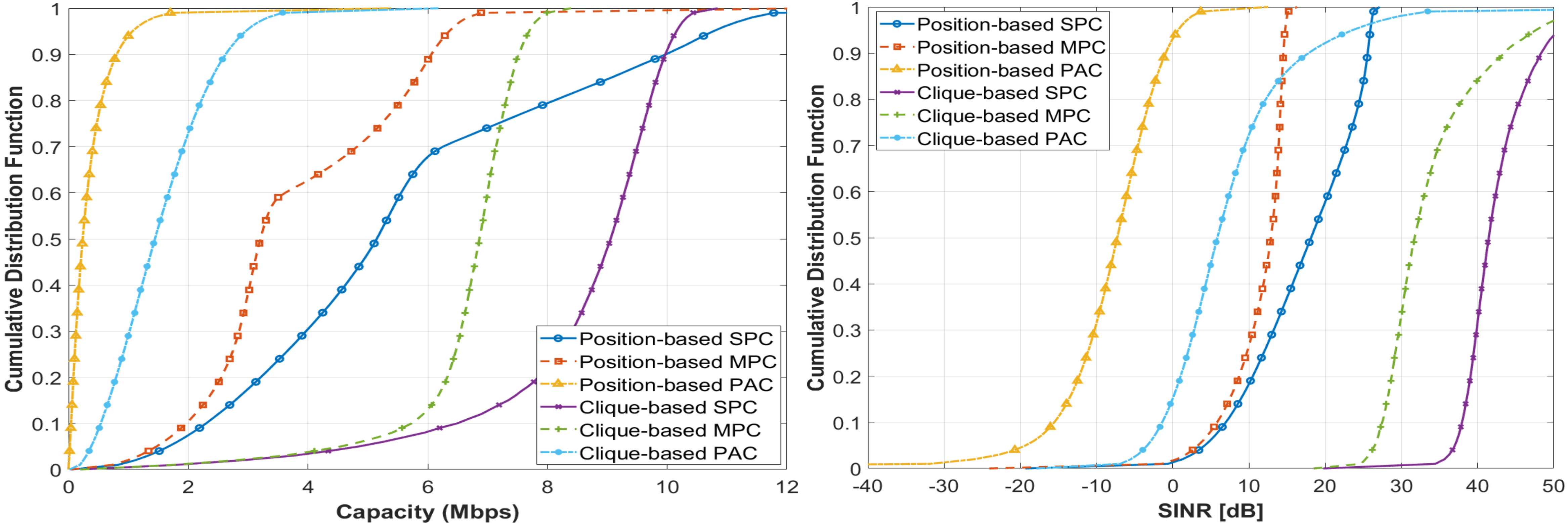
Threshold Optimization





MMSE-	Capacity	Optimized δ_{th}	Average Cluster Size
SPC	7.71 Mbps	0.33	47
MPC	6.70 Mbps	0.25	42
PAC	3.84 Mbps	0.09	28

CDF's



The clique-based scheduler shows an improvement in terms of average per-user capacity of 4 Mbps and in terms of SINR of more than 20 dB with reference to MMSE-SPC normalization method.

Conclusion

- In this work, we have proposed a greedy iterative user scheduling procedure based on the maximum clique algorithm.
- For each time slot, a digital MMSE beamforming matrix allows to spatially separate the scheduled users and we considered three power normalizations for the beamforming matrix: SPC, MPC, and PAC.
- The results have been presented in terms of achievable per-user capacity and SINR and they show that the performance for clique based scheduling is highly improved as compared to the position based scheduling. Future works will improve the presented system model with the inclusion of multiple moving satellites.

Acknowledgement

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- **H2020 DYNASAT** (Dynamic spectrum sharing and bandwidth-efficient techniques for high- throughput MIMO Satellite systems)
  - research, develop, and demonstrate techniques for **bandwidth efficient transmission** and **efficient spectrum usage** for a **high-throughput 5G/6G satellite access** network infrastructure, based on **advanced NGSO-mega-constellations**

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Thanks!

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