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Evaluation of MU-MIMO Digital Beamforming Algorithms in B5G/6G LEO Satellite Systems

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Introduction

The integration of the (**NTNs**) component within the 5G (**NR**) terrestrial ecosystem is to

- improve the system flexibility, adaptability, and resilience
- extend the 5G coverage
- satisfy the high user demand

To this aim ⟹ efficient exploitation of the spectrum:

1. By adding unused or underused spectrum chunks by means of flexible spectrum usage paradigms (Cognitive Radio solutions)
2. Or by decreasing the frequency reuse factor down to full frequency reuse **(FFR) in multi-beam systems**.

- The more aggressive frequency reuse (FFR) ⟹ the more improvement of the system spectral efficiency
- The main transmission techniques that allow to use FFR are the advanced precoding/**beamforming techniques** for MU-MIMO schemes.

System Model

- The latency between the channel/location estimation phase and the transmission phase:

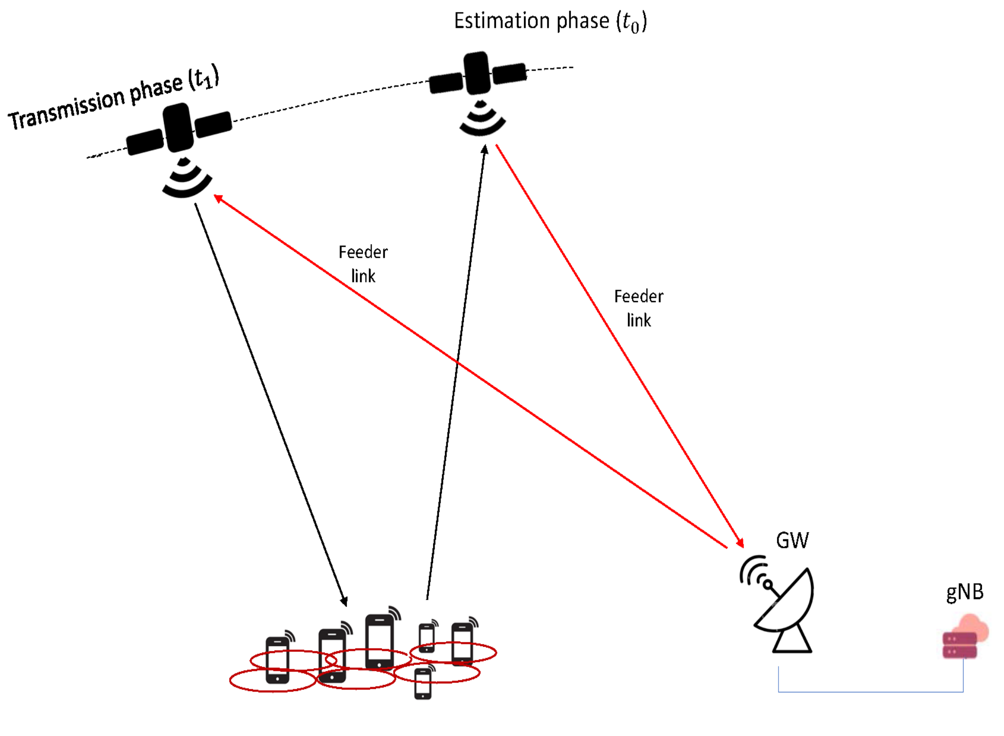
$$\Delta t = t_1 - t_0$$
$$= t_{ut,max} + 2t_{feeder} + t_p + t_{ad}$$

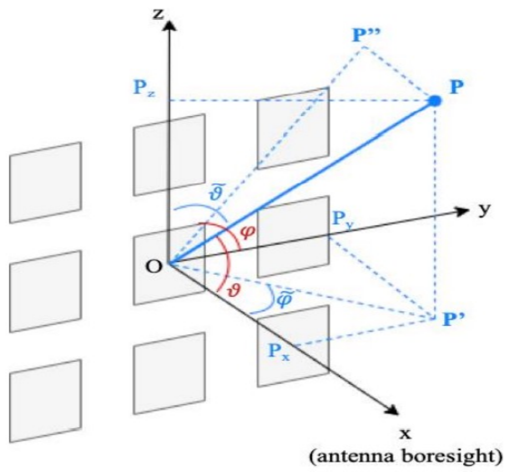
- The Channel coefficients:

$$h_{i,n} = g_{i,n}^{(tx)} g_{i,n}^{(rx)} \frac{\lambda}{4\pi d_{i,n}} \sqrt{\frac{L_{i,n}}{\kappa B T_i}} e^{-j\frac{2\pi}{\lambda} d_{i,n}}$$

$$g^{(tx)}(u,v) = g_E(u,v) \sum_{m=1}^{N_H} \sum_{q=1}^{N_V} e^{jk_0(m d_H u + q d_V v)}$$

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





System model

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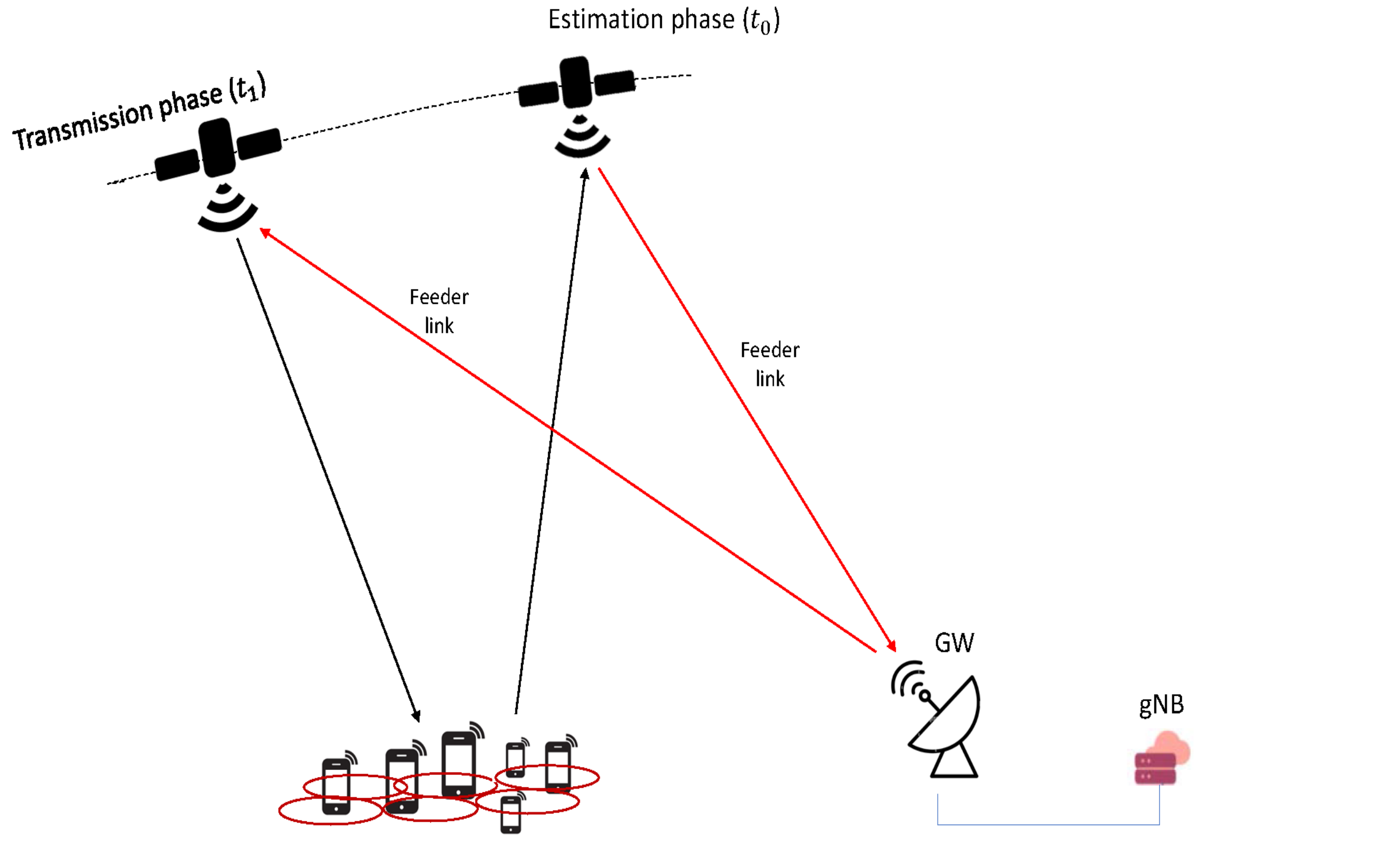
- The signal received by the k_{th} user can be expressed as follows:

$$y_k = \underbrace{\mathbf{h}_k \mathbf{W}_{:,k}\, s_k}_{\text{intended}} + \underbrace{\sum_{i=1, i\neq k}^{K_{sch}} \mathbf{h}_k \mathbf{W}_{:,i}\, s_i}_{\text{interfering}} + z_k$$

$$\mathbf{y} = \mathbf{H}_{t_1} \mathbf{W}_{t_0} \mathbf{s} + \mathbf{z}$$

- $\mathbf{H}_{t_1}$ → Scheduled Channel matrix, $K_{sch} \times N$
- $\mathbf{W}_{t_0}$ → Beamforming Matrix, $N \times K_{sch}$
- $\mathbf{s}$ → $\mathbf{s} = [s_1, \dots, s_{K_{sch}}]^T$



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Benchmark Beamforming Algorithms

CSI based Algorithms

- <u>ZF</u>

$$\mathbf{W}_{ZF} = (\mathbf{H}^H\mathbf{H})^{\dagger}\mathbf{H}^H$$

- <u>MMSE (RZF)</u>

$$\mathbf{W}_{MMSE} = \arg\min_{\mathbf{W}} \mathrm{E}||\mathbf{H}\mathbf{W}\mathbf{s} + \mathbf{z} - \mathbf{s}||^2$$

$$\mathbf{W}_{MMSE} = \mathbf{H}(\mathbf{H}\mathbf{H}^H + \mathrm{diag}(\boldsymbol{\alpha})\mathbf{I}_{K_{sch}})^{-1}$$

User's location algorithm

- MB

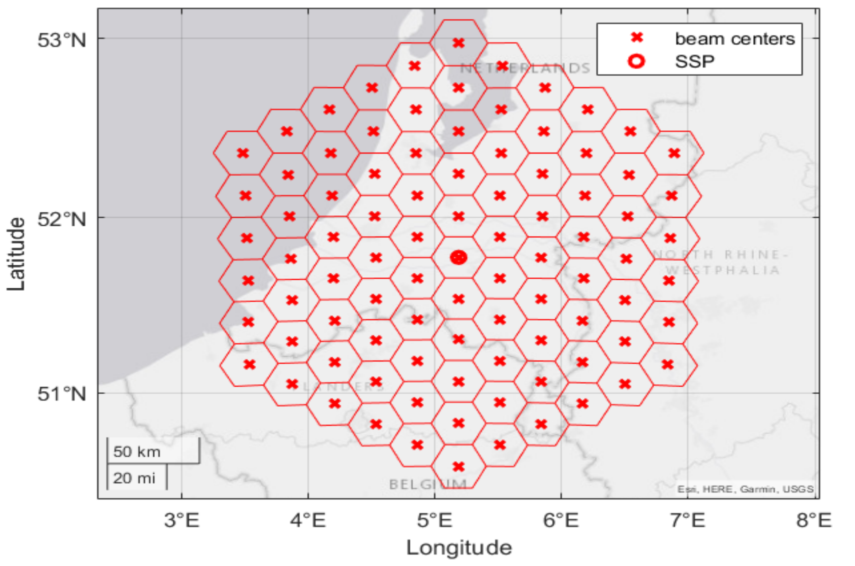
$$\mathbf{B} = [\mathbf{b}_1, \dots, \mathbf{b}_q, \cdots, \mathbf{b}_S]$$

$$\mathbf{W}_{MB} = [\mathbf{W}_{:,1}, \cdots, \mathbf{W}_{:,q}, \cdots, \mathbf{W}_{:,S}]$$

where

$$\mathbf{W}_{:,k} = \mathbf{B}_{:,j}$$

$$j = \arg\min_{\mathrm{i}=1,\cdots,N} ||\mathbf{C}_i - \mathbf{P}_k||^2$$



The Proposed SLNR-based Beamforming

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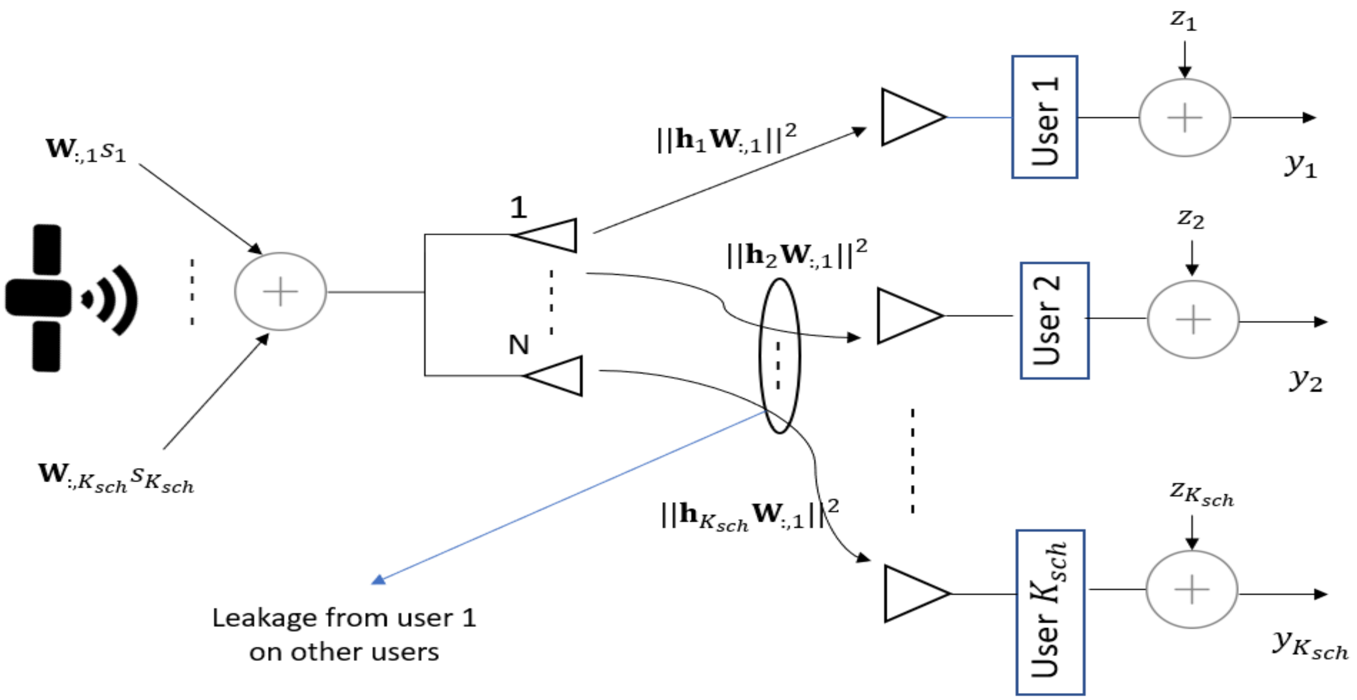
The main motivation is to overcome

- The problem of maximizing SINR for all users
- No closed form solution of the optimization problem (the beamformers are jointly optimized)

$$\mathrm{SLNR}_k = \frac{||\mathbf{h}_k \mathbf{W}_{:,k}||^2}{1+\sum_{i=1, i\neq k}^{K_{sch}} ||\mathbf{h}_i \mathbf{W}_{:,k}||^2} \qquad \mathrm{SINR}_k = \frac{||\mathbf{h}_k \mathbf{W}_{:,k}||^2}{1+\sum_{i=1, i\neq k}^{K_{sch}} ||\mathbf{h}_k \mathbf{W}_{:,i}||^2}$$



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The Proposed SLNR-Based Beamforming

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$$\mathrm{SLNR}_k = \frac{||\mathbf{h}_k \mathbf{W}_{:,k}||^2}{1+\sum_{i=1,i\neq k}^{K_{sch}} ||\mathbf{h}_i \mathbf{W}_{:,k}||^2}$$

$$\mathrm{SLNR}_k = \frac{||\mathbf{h}_k \mathbf{W}_{:,k}||^2}{1+||\mathbf{Z}_k \mathbf{W}_{:,k}||^2}$$ where $$\mathbf{Z}_k = [\mathbf{h}_1|\cdots|\mathbf{h}_{k-1}|\mathbf{h}_{k+1}|\cdots|\mathbf{h}_{K_{sch}}]$$

- The beamforming matrix targeted for the user k that maximizes its SLNR is given by:

$$\hat{\mathbf{W}}_{:,k} = \arg\max_{\mathbf{W}} \mathrm{SLNR}_k = \arg\max_{\mathbf{W}} \frac{||\mathbf{h}_k \mathbf{W}_{:,k}||^2}{1+||\mathbf{Z}_k \mathbf{W}_{:,k}||^2}$$

- The optimal beamformer is linked to closed-form solution of the generalized eigenvalue problem

$$\hat{\mathbf{W}}_{:,k} \propto \mathrm{max.eigenvector}((1+\mathbf{Z}_k^H \mathbf{Z}_k)^{-1}\mathbf{h}_k^H \mathbf{h}_k) \Longrightarrow \mathrm{SLNR} = \lambda_{max}$$

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Performance Evaluation Through Numerical Results and Simulation

System Parameters_Simulation Basis

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- A comparative analysis are shown using the following parameters as system KPIs:

✓ Signal to Noise and Interference Ratio (SINR)

$$SINR_k = \frac{SNR_k}{1+INR_k}$$

✓ Spectral Effeciency (Rate)

$$\eta_k = \log_2(1 + SINR_k)$$

Power normalization: power that can be emitted by both the satellite and per antenna

SPC Normlization

- upper bound is imposed on the total on-board power
- Orthogonality is preserved

MPC Normalizaation

- The power per antenna is upper bounded
- Not the entire available on-board power is exploited

Parameter	**Range**
Carrier frequency	2GHz
System Band	S band (30 MHz)
Beamforming space	Feed
Receiver type	VSAT
Receiver scenario	Fixed
Propagation scenario	LOS, NLOS
System scenario	Urban
Number of tiers	5
Number of beams	91
Num. of scheduled users	91
Number of transmitters	1024
User density	0.5 users/Km^2

LOS Scenario, VSAT terminals, BF in feed space, $P_t = 4\ \mathrm{dBW/MHz}$

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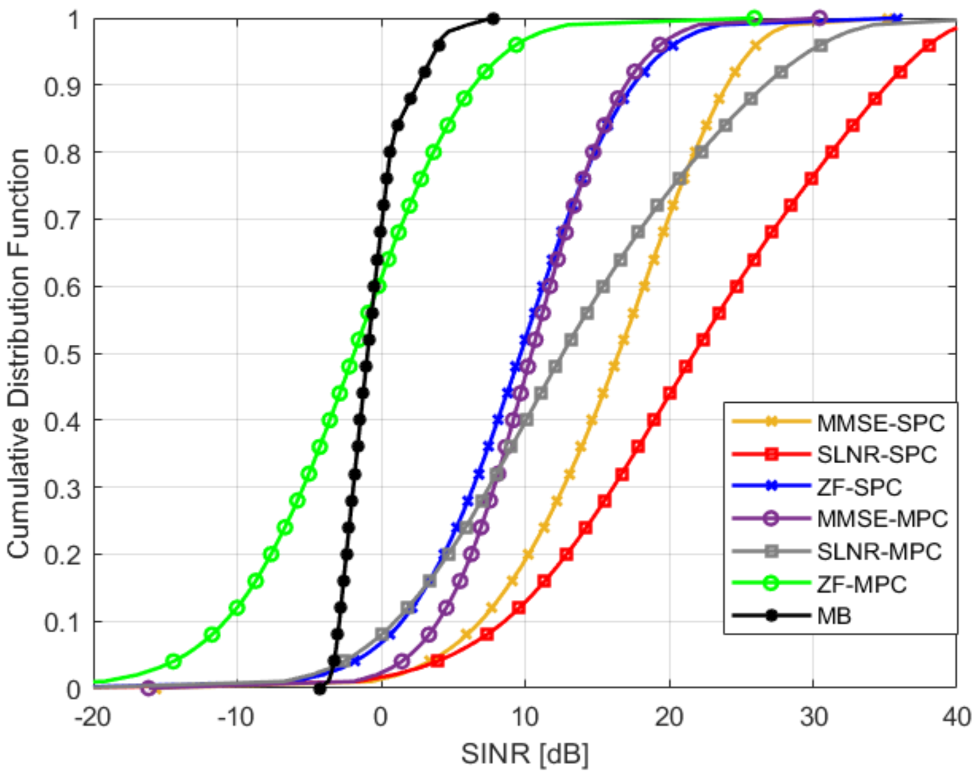

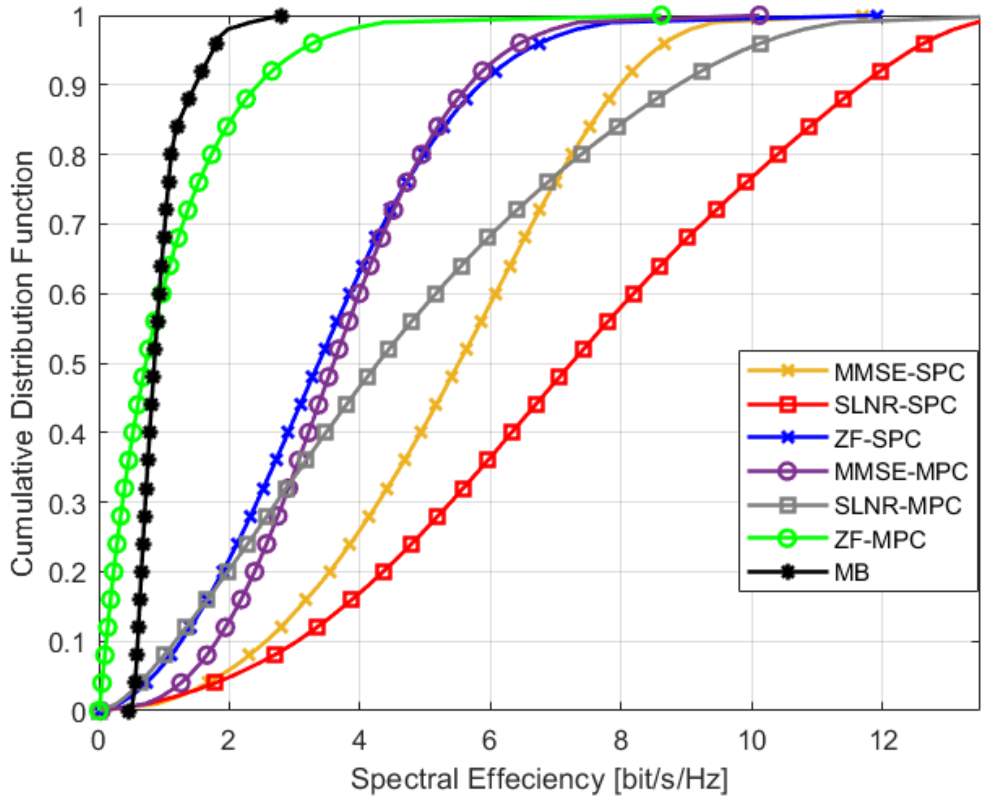

- The proposed SLNR beamforming provides better performance than MMSE, followed by ZF and MB
- In terms of normalization, SPC shows a good results for all beamforming schemes

NLOS Scenario, **VSAT** terminals, BF in **feed** space, $P_t = 4\ \mathrm{dBW/MHz}$

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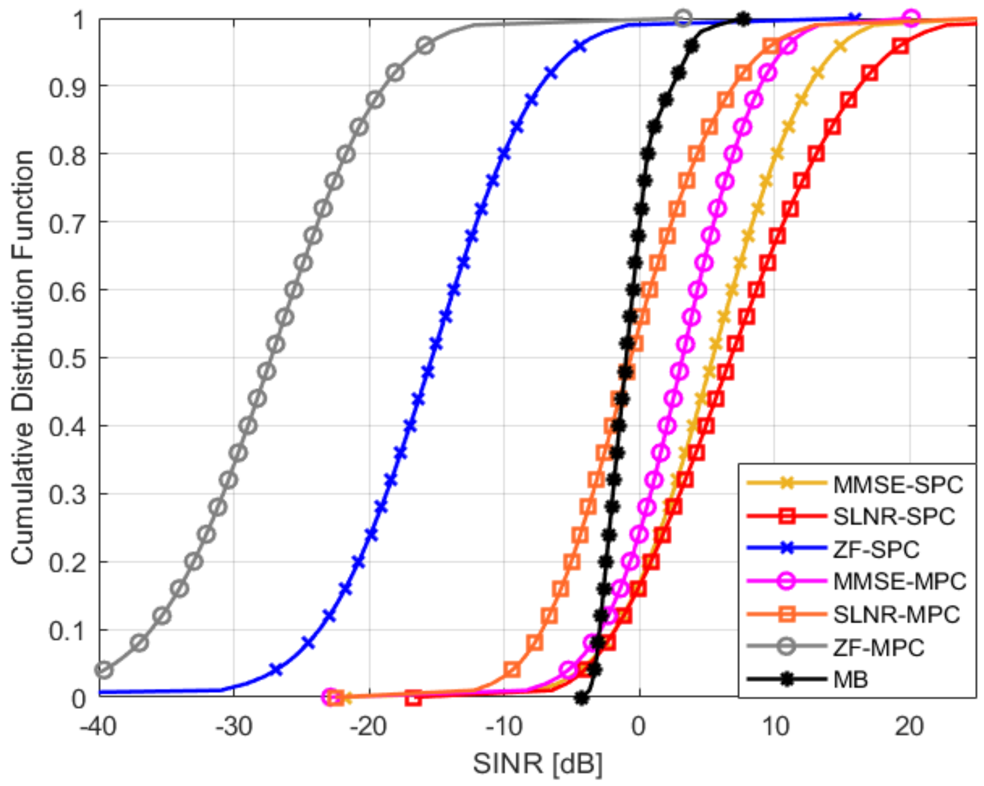

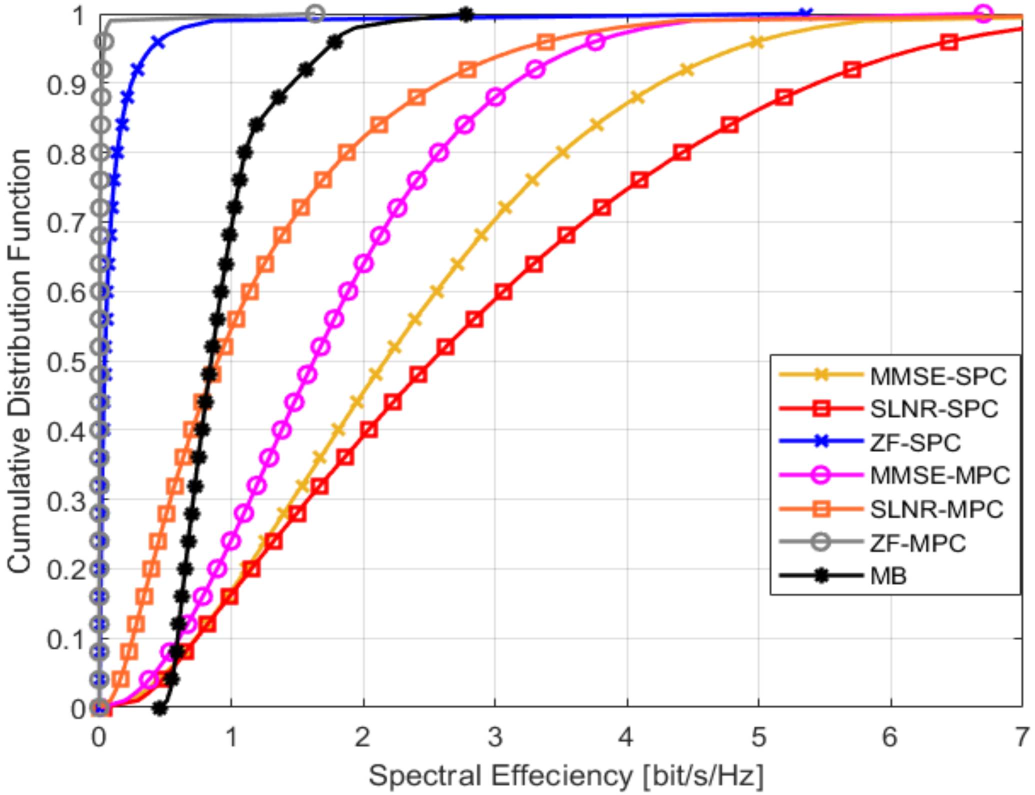

- The proposed SLNR beamforming provides better performance than MMSE, followed by MB and ZF (is the worst)
- In terms of normalization, SPC shows a better results for all beamforming schemes, followed by MPC and PAC.

The Proposed SLNR-based Beamforming

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SLNR based beamforming

- considering noise power in implementing beamforming vectors ☺

- Is a regularized channel inversion scheme, with regularization factors customized to each user based on their operating SNR ☺

ZF beamforming

- not considering noise power in implementing beamforming vectors

→ Noise enhancement ☹

MMSE beamforming

- the same regularization for all users (factor equal to the inverse of average SNR) ☹

Comparison **LOS** and **NLOS** scenario

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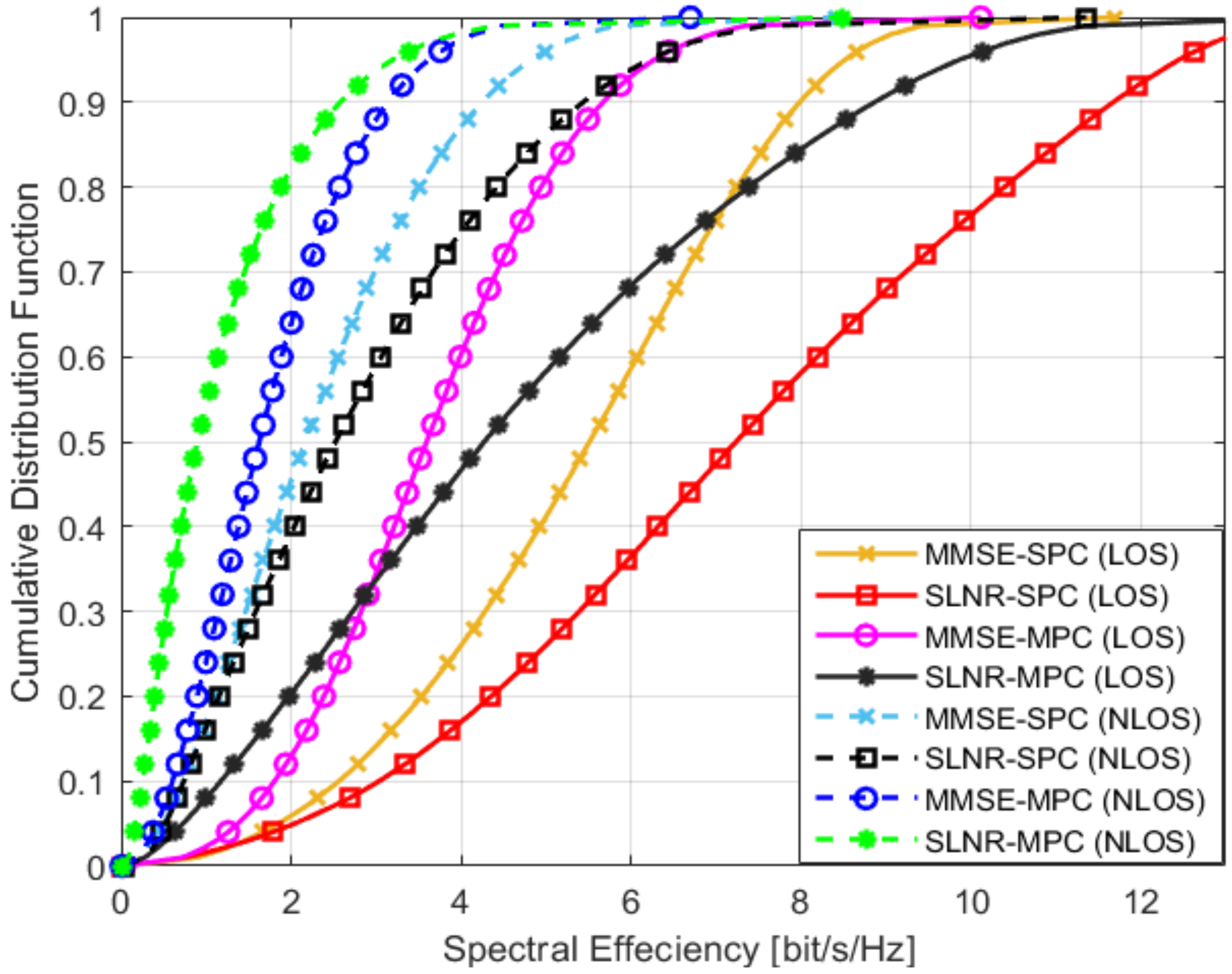


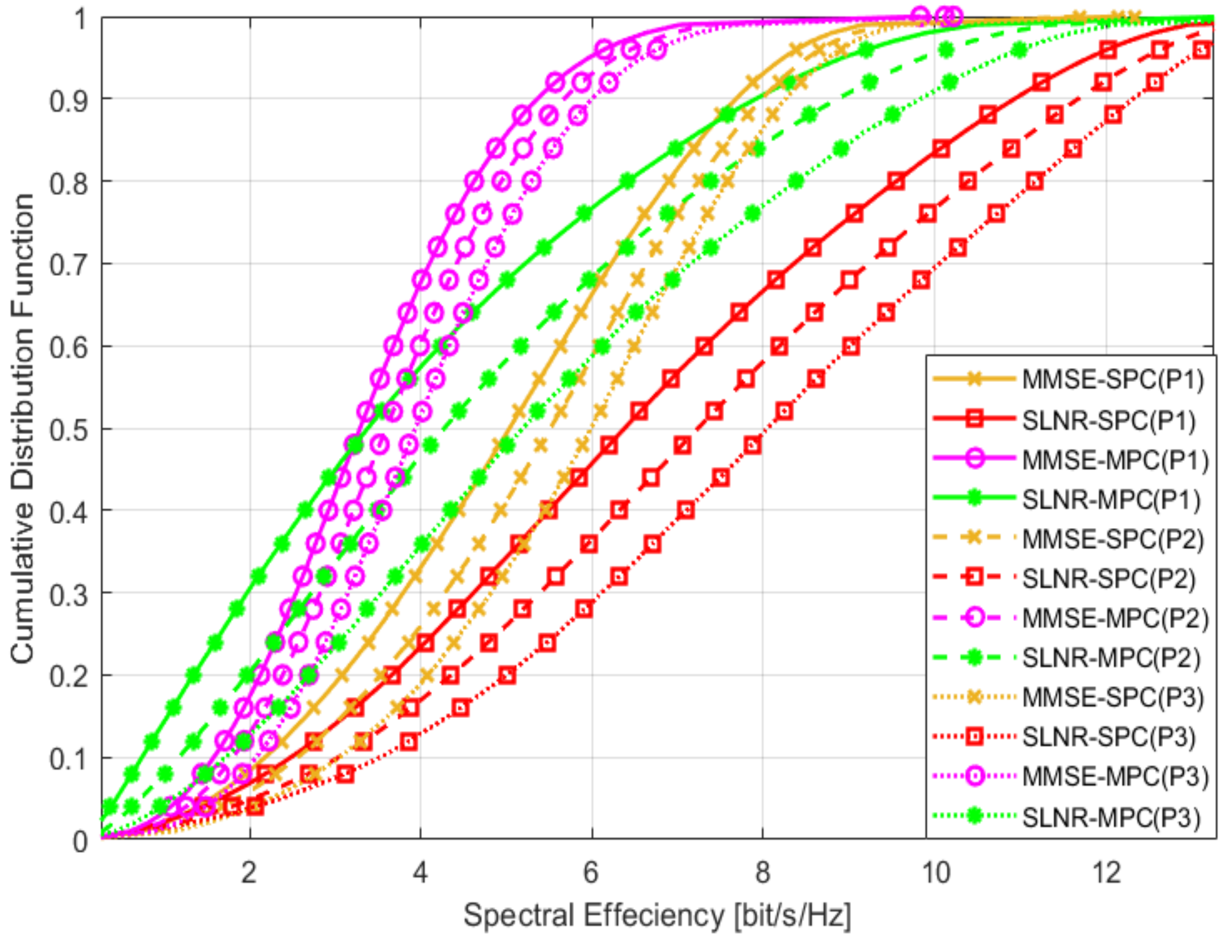
Degradation in the performance when moving from LOS to NLOS scenario

- In the order of 4-5 bit/s/Hz for SLNR-based beamforming
- In the order of 3-4 bit/s/Hz for MMSE-SPC and 1-2 bit/s/Hz for MMSE-MPC.

Performance assessment at different transmitted power densities P_t ={1,4,7} dBW/MHz, LOS scenario

By doubling the transmitted power :

- for SLNR scheme, gain in the order of 0.85-0.95 bit/sec/Hz
- for MMSE in order 0.4-0.5 bit/sec/Hz
- such results give additional advantage of the proposed scheme.



Conclusion

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- Proposing a beamforming algorithm aimed at maximizing the figure of merit (SLNR)
- SLNR-based scheme eliminates the joint coupling between the beamforming vectors into multiple separate optimization problems of the targeting users
- System level assessment and comparison with benchmark solutions
    - CSI-based
    - Location-based
- The numerical results provided a significant better performance of SLNR-based beamforming than the optimal MMSE followed by MB and ZF beamforming in terms of spectral efficiency and SINR
- The power normalization SPC introduced the best performance for all beamforming algorithms followed by MPC
- Degradation in the performance when moving from LOS to NLOS propagation scenario
- The increased transmitted power density introduced slight improvement for SLNR and MMSE beamforming
- **Future Works**: considering multiple satellites in a mega-constellation scenario ⟹ global coverage

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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 infrastrucure, based on advanced NGSO-mega-constellation

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Thank you for your attention

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