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Federated MIMO in NTN mega-constellations: an overview

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Mega-Constellation Non-Terrestrial Network for 6G

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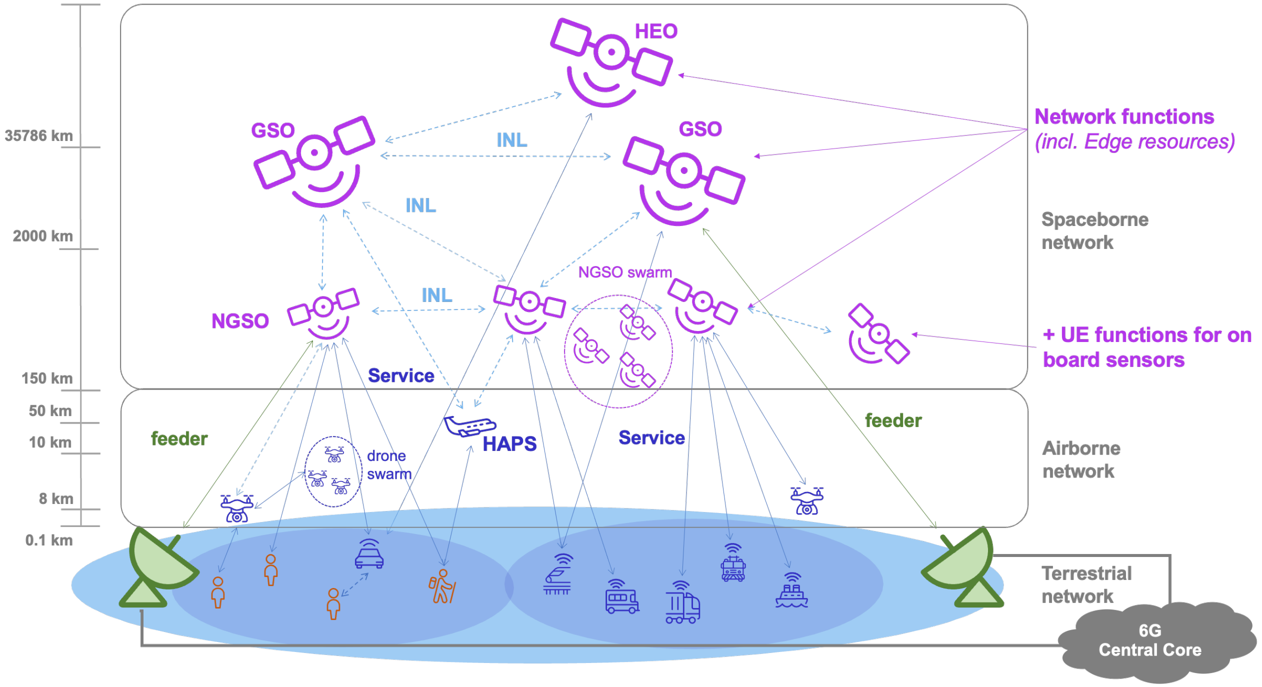
The role of Non-Terrestrial Networks in 6G

- 6G systems are expected to achieve more than "just" extremely fast connectivity
  - **digital twinning** for process/product/service virtualisation
  - AI-based **connected intelligence**
  - **immersive communications**: high-resolution visual/spatial, tactile/haptic, and other sensory data



A. Guidotti et al., "Role and Evolution of Non-Terrestrial Networks towards 6G systems," submitted to IEEE Access, June 2023.

Architecture and system design

Multilayered constellation from GEO to drones, Innovative LEO and vLEO orbits, optical inter and intra node-links design, cell-free MU-MIMO, traffic-driven coverage

Networking, edge computing and communications

Softwarization, virtualization, and orchestration of network resources, functional split, advanced IP, routing in the sky, resource management, integrated edge communication and computing

Flexible and integrated waveforms

Low PAPR and low OOBE solutions, Non-orthogonal techniques to increase the connection density, novel RA procedures to allow multiple transmissions per beam, multipoint transmission from the sky, distributed beamforming

Dynamic Spectrum Access and New spectrum

Coordinated and uncoordinated sharing among different access technologies, inter and intra layer, higher frequency bands, Q/V and above

Positioning

Network based positioning

AI/ML

Network and system orchestration, Radio Resource Management, Network traffic forecasting, Physical layer management, Channel estimation,

Antennas and components

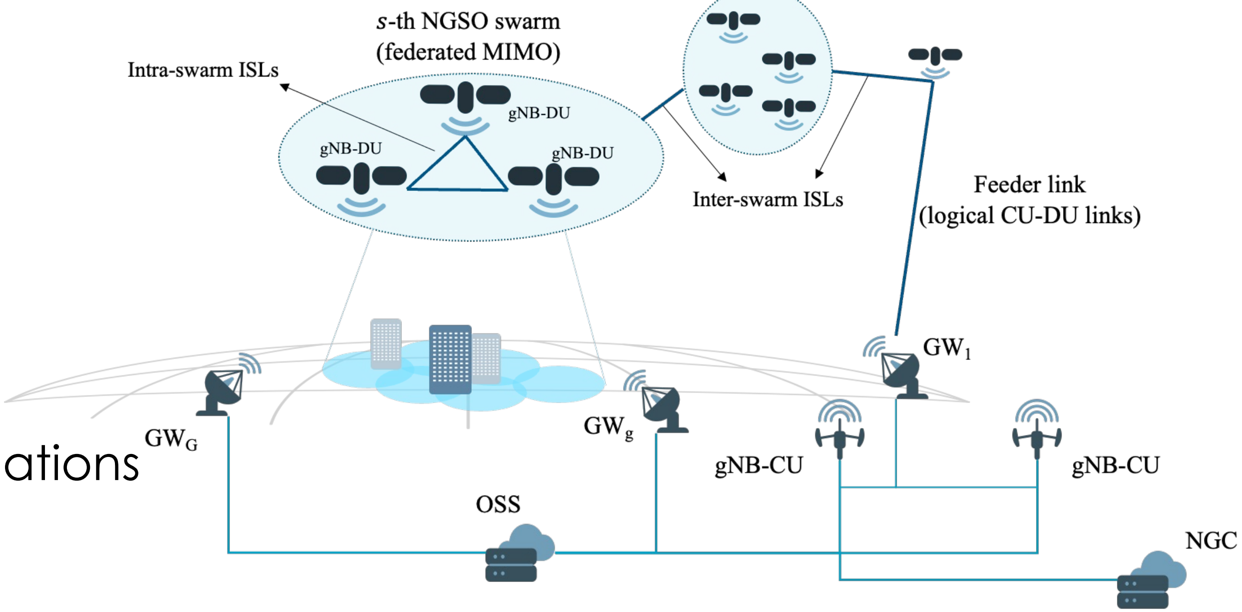
Active antennas for link budget and flexible coverage, Refracting RIS for indoor coverage, regenerative payload, high-parallel energy efficient HW, Optical devices

Multi-point transmission from space: Federated CF-MIMO

- Legacy SatCom systems: geographical coverage through co-located radiating elements

- Cell-Free in 6G NTN: **centralised/federated feed space beamforming**
  - **single multi-beam satellite**: co-located radiating elements, on-board/on-ground CPU
  - **multiple multi-beam satellites**: radiating elements distributed in a **NGSO swarm,** on-ground/on-board CPU

- Architecture design choices
  - type of payload: regenerative or transparent
  - type of **functional split**
  - availability of **ISLs**
  - where BF is applied: **OBBF** or **OGBF**

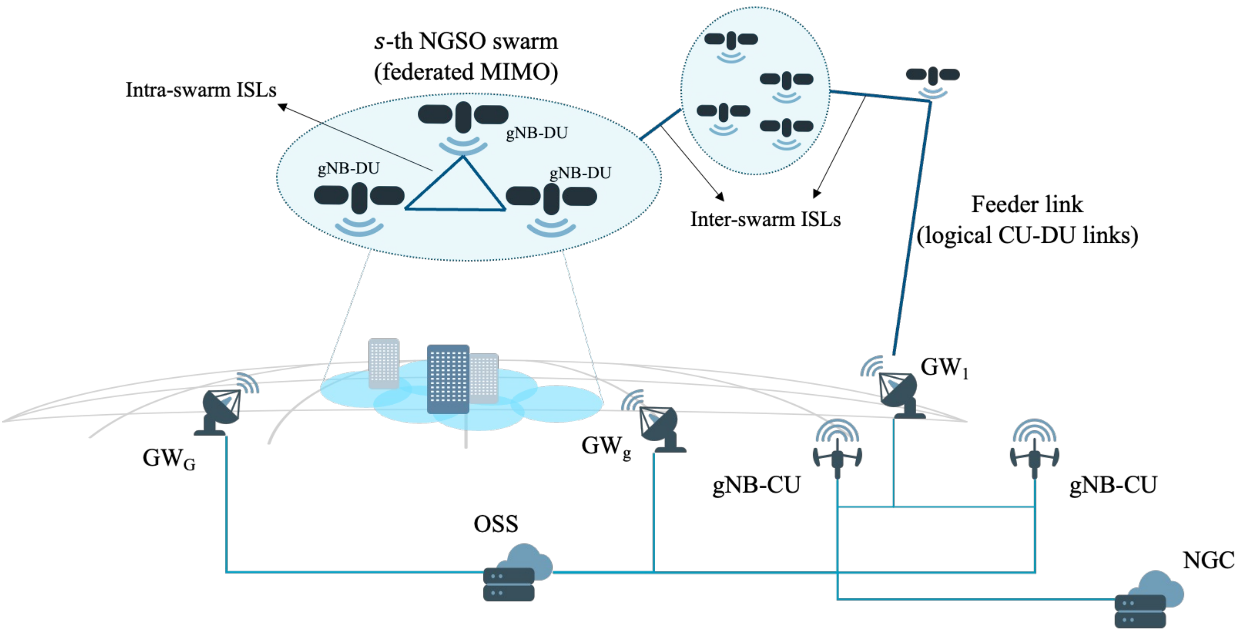


- ISLs are needed to manage (very) large constellations
  - **logical links** between the satellites (gNB-DU) and the GWs (gNB-CU)
  - each gNB can manage tens of logical connections
    - **multiple gNB-CUs** and **beam management procedures**

A. Guidotti, A. Vanelli-Coralli, C. Amatetti., "Federated Cell-Free MIMO in Non-Terrestrial Networks: Architectures and Performance," submitted to IEEE Transactions on Aerospace and Electronic Systems, June 2023.

Multi-point transmission from space: Federated CF-MIMO

- **On-Ground Beamforming and Scheduling Computation (OGBSC)**
  - scheduling and beamforming are computed **at the gNB-CUs**
  - the beamforming matrix can be applied at the gNB-DUs (OBBF) or at the gNB-CU (OGBF)
  - intra-swarm ISLs not strictly necessary



- **On-Board Beamforming and Scheduling Computation (OBBSC)**
  - scheduling and beamforming are computed at a **master gNB-DU**
  - significantly reduced latency, but the complexity is increased
  - intra-swarm ISLs needed

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Multi-point transmission from space: Federated CF-MIMO

Payload type	Architecture option			Computation	Application	Δt factors
Transparent	OGBSC	OGBF	centralised	gNB (on-ground)	gNB (on-ground)	user+feeder(+ISLs)
		OBBF			on-board	
Regenerative	OGBSC	OGBF	federated or centralised	gNB-CU (on-ground)	gNB-CU (on-ground)	user+feeder(+ISLs)
		OBBF			gNB-DU (on-board)	
	OBBSC	OBBF		gNB-DU (on-board)	gNB-DU (on-board)	user(+ISLs)[1]

[1]: The ISLs with OBBSC solutions are intra-swarm and, thus, might be negligible in terms of additional latency.

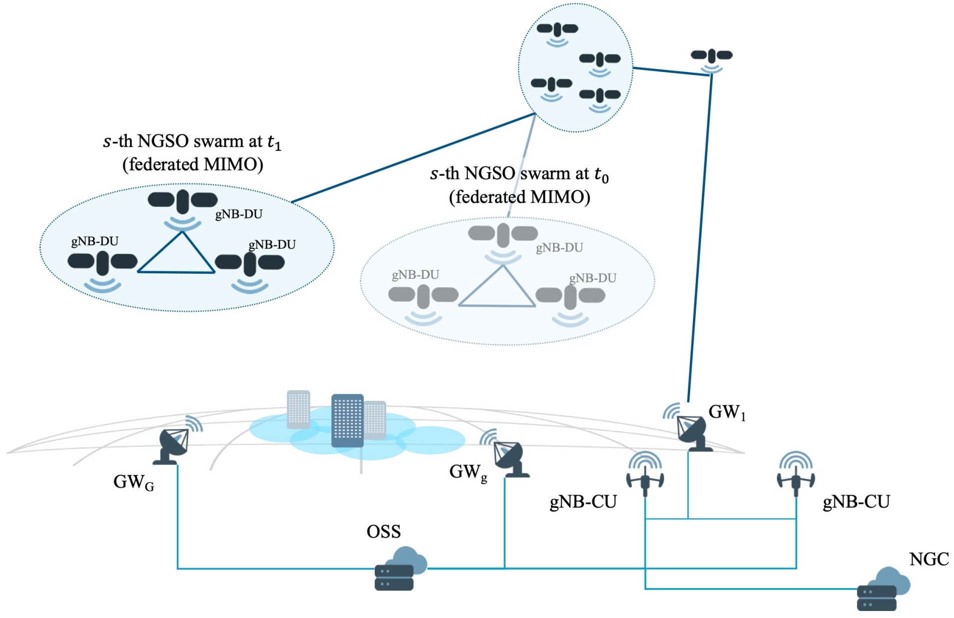
- Ancillary information is needed for beamforming and scheduling: CSI or location estimates

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

- In NGSO systems, **ancillary information aging** is present

$$\Delta t_{OGBSC} = \tau_{user} + \tau_{feeder}^{(DL)} + \tau_{feeder}^{(UL)} + \tau_p + \tau_{rout} + \tau_{ad}$$

$$\Delta t_{OBBSC} = \tau_{user} + \tau_p + \tau_{ad}$$



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CF-MIMO algorithms

Algorithm	Channel coefficient	Beamforming matrix	Information	Errors
MMSE	$h_{k,n,s}^{(t)} = \frac{g_{k,n,s}^{(TX,t)} g_{k,n,s}^{(RX,t)}}{4\pi \frac{d_{k,s}^{(t)}}{\lambda} \sqrt{L_{k,s}^{(t)} \kappa B T_k}} e^{-\jmath \frac{2\pi}{\lambda} d_{k,s}^{(t)}} e^{-\jmath \varphi_{k,s}^{(t)}}$	$\mathbf{H}^H \left(\mathbf{H}\mathbf{H}^H + \text{diag}(\boldsymbol{\alpha}) I_K \right)^{-1}$	CSI	CSI estimation Low-SINR estimation Air interface adj. UE/node movement
LB-MMSE	$\widetilde{h}_{k,n,s}^{(t)} = \frac{\widetilde{g}_{k,n,s}^{(TX,t)} \widetilde{g}_{k,n,s}^{(RX,t)}}{4\pi \frac{\widetilde{d}_{k,s}^{(t)}}{\lambda} \sqrt{\kappa B T_k}} e^{-\jmath \frac{2\pi}{\lambda} \widetilde{d}_{k,s}^{(t)}}$	$\widetilde{\mathbf{H}}^H \left(\widetilde{\mathbf{H}}\widetilde{\mathbf{H}}^H + \text{diag}(\boldsymbol{\alpha}) I_K \right)^{-1}$	Location	Location estimation Radiation pattern model UE/node movement
SS-MMSE	$\widetilde{h}_{k,n,s}^{(BC,t)} = \frac{\widetilde{g}_{k,n,s}^{(BC,TX,t)} \widetilde{g}_{k,n,s}^{(BC,RX,t)}}{4\pi \frac{\widetilde{d}_{k,s}^{(BC,t)}}{\lambda} \sqrt{\kappa B T_k}} e^{-\jmath \frac{2\pi}{\lambda} \widetilde{d}_{BC,k,s}^{(t)}}$	$\widetilde{\mathbf{H}}_{BC}^H \left(\widetilde{\mathbf{H}}_{BC}\widetilde{\mathbf{H}}_{BC}^H + \text{diag}(\boldsymbol{\alpha}) I_K \right)^{-1}$	Location	Location estimation Radiation pattern model Approx. location UE/node movement

Estimated CSI

Estimated location

Approx. location

$$\mathbf{H}^{(feed)} = \left[\mathbf{H}^{(feed,1)}, \ldots, \mathbf{H}^{(feed,N_S)}\right] \Rightarrow \mathbf{W}_x = \left[\mathbf{W}_x^{(sat\ 1)}; \ldots; \mathbf{W}_x^{(sat\ N_S)}\right]$$

Block computation with multiple satellites

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Power distribution

- Notably, proper normalisations of the beamforming matrix are needed aiming at
  1. Not exceeding the **total on-board available power**
  2. Not working in the non-linear regime in the **on-board HPAs**
  3. Preserving the optimal MMSE solution (i.e., **orthogonality** among the matrix columns)

Sum Power Constraint (SPC)

$$\breve{\mathbf{W}}_{MMSE} = \sqrt{\frac{P_t}{\mathrm{tr}(\mathbf{W}_{MMSE}\mathbf{W}_{MMSE}^H)}}\mathbf{W}_{MMSE}$$

- (1) and (3) are guaranteed
- (2) cannot be ensured
- Typically the best performance, but not entirely feasible due to violating (2)

Maximum Power Constraint (MPC)

$$\breve{\mathbf{W}}_{MMSE} = \sqrt{\frac{P_t}{K \max_{k=1,\dots,K} \|\mathbf{w}_{k,:}\|^2}}\mathbf{W}_{MMSE}$$

- (1), (2), (3) are guaranteed
- The total on-board power is not fully exploited
- It might lead to a loss in the SNR and, then, in the SINR

Per Antenna Constraint (PAC)

$$\breve{\mathbf{W}}_{MMSE} = \sqrt{\frac{P_t}{K}}\mathrm{diag}\left(\frac{1}{\|\mathbf{w}_{1,:}\|}, \dots, \frac{1}{\|\mathbf{w}_{K,:}\|}\right)\mathbf{W}_{MMSE}$$

- (1) and (2) are guaranteed
- (3) is violated and it can lead to a significant performance loss in interference-limited scenarios

- Multiple satellites: sSPC and sMPC → implemented per block

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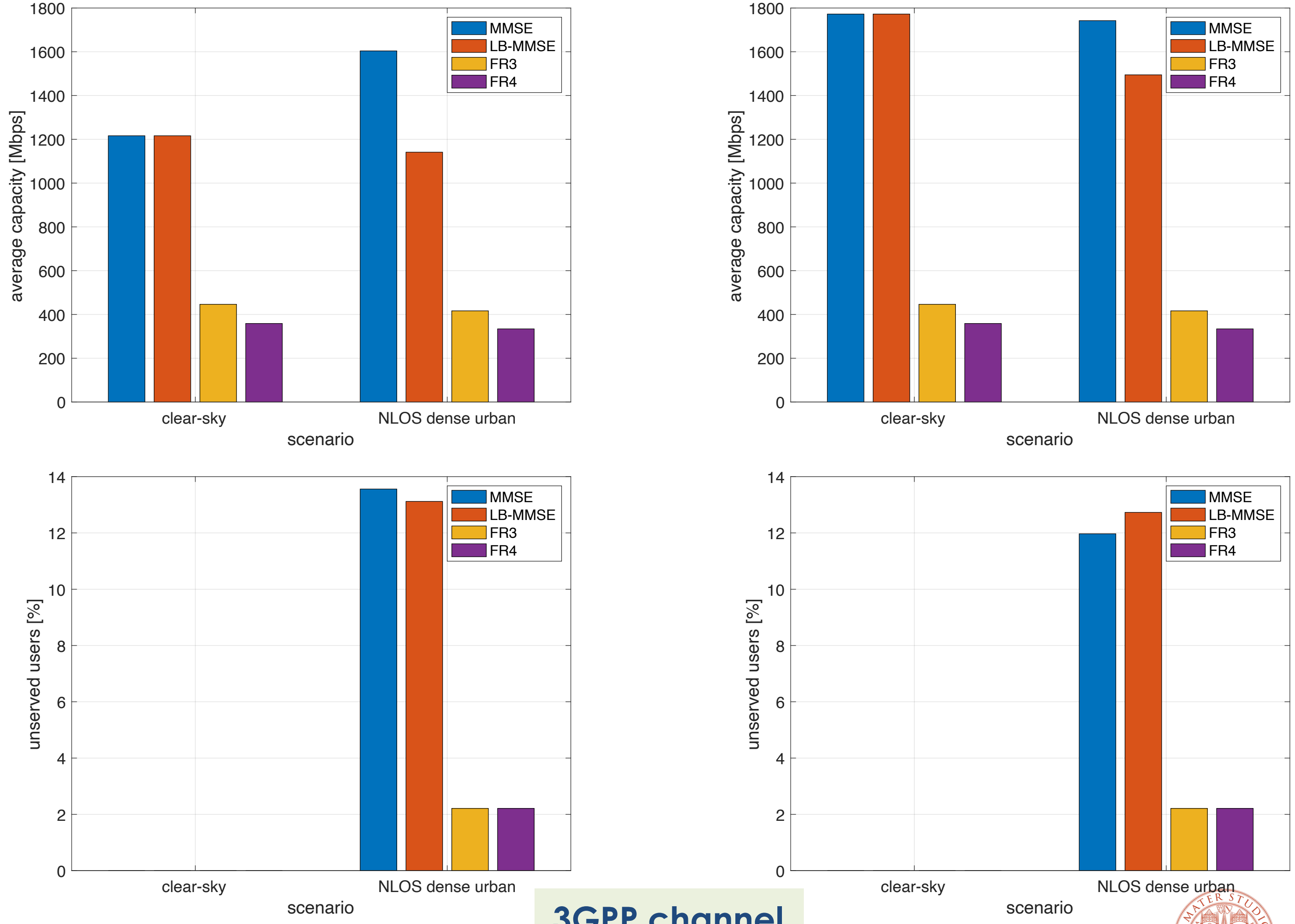
Performance with Earth moving beams and (s)MPC: VSAT

- MMSE and LB-MMSE have the same performance in clear-sky
- Centralised vs Federated
  - significant capacity gain with two satellites per swarm
    - +50% in clear-sky
    - +12.5% in NLOS dense-urban
  - reduction in the number of unserved users thanks to path diversity in NLOS
- FR3/FR4 vs federated
  - massive capacity gain thanks to the exploitation of the full bandwidth
    - up to +350% in both environments
  - increase in the percentage of unserved users
    - ancillary information aging is challenging with multiple satellites



Single satellite

3GPP channel TR 38.811

Two satellites

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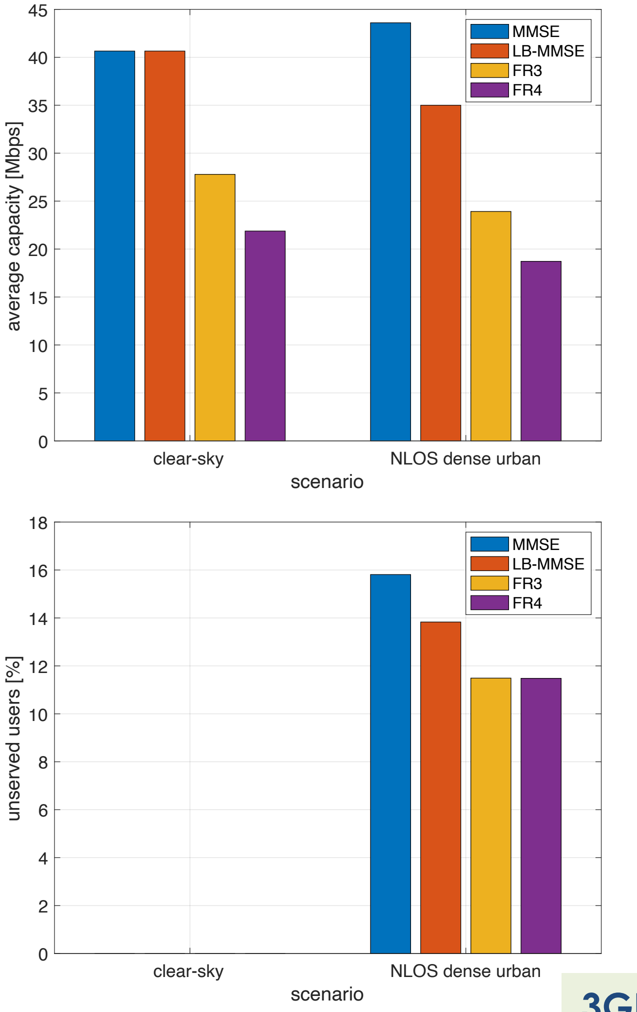
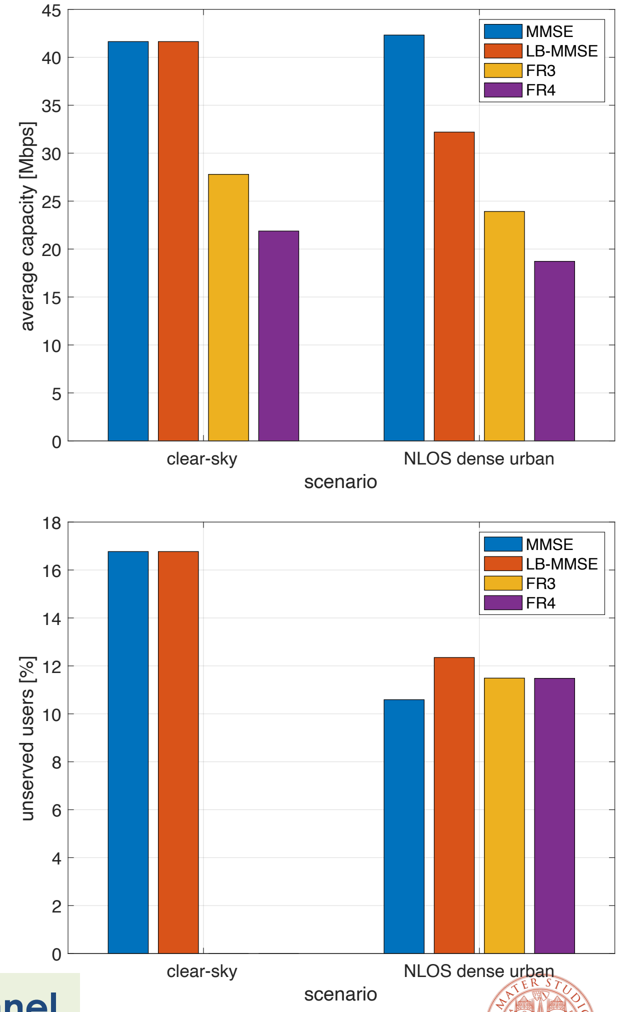
Performance with Earth moving beams and (s)MPC: handheld

- Centralised vs Federated
  - similar capacity performance
  - reduction of the unserved users thanks to path diversity in NLOS
  - massive increase of the unserved users in clear-sky
    - due to ancillary information aging, the improved SNR cannot compensate the loss in the SIR
- FR3/FR4 vs federated
  - massive capacity gain thanks to the exploitation of the full bandwidth
    - up to +80% in both environments
  - reduction in the percentage of unserved users with federated MIMO
    - ancillary information aging is still challenging



Single satellite

3GPP channel TR 38.811



Two satellites

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Challenges

- **Payload** design and constraints
  - array dimension
  - BFN and OBP
  - on-board power consumption
- Tight intra-swarm time and frequency **synchronisation**
- Need for accurate CSI or location **estimates**
  - ancillary information aging
  - potentially low C/I and overhead for CSI-based algorithms
  - privacy and non-GNSS enabled UEs for location-based algorithms
- Inter-swarm **interference**
- **Scheduling**: non-trivial since the beamformed SINR is known a posteriori
  - multiple time-slot based → increased aging interval
  - iterative and integer programming solutions have been recently proposed
  - ML/NN solutions can be considered

Conclusions

- The integration of a NTN component into 5G is a reality since Rel. 17

- However, both **evolutionary and revolutionary technologies** are needed towards a truly **unified 6G NT-T system infrastructure**

- **Federated CF-MIMO** will be one of the **pivotal technologies for 6G NTN**
  - significant gains can be achieved, in particular for VSAT
  - the outage introduced by the ancillary information aging might pose a challenge in some scenarios
  - additional satellites are beneficial when path diversity is more important (NLOS conditions)
  - compared to FR 3 and 4 schemes, the advantage can be impressive, but considering also the outage that can be introduced, it strongly depends on the propagation environment
    - single satellite: significantly better in clear-sky conditions for all terminals
    - multiple satellites: significantly better in NLOS conditions for handheld terminals

Current initiatives…

6GNTN

- https://www.6g-ntn.eu/
- https://www.linkedin.com/company/6g-ntn/
- https://twitter.com/6Gntn

EAGER

- https://www.eagerproject.eu
- https://www.linkedin.com/company/eager-project/
- https://twitter.com/eagersatcom

5GSTARDUST

- https://www.5g-stardust.eu
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