THE REVOLUTION OF NEW SPACE TOWARDS NEXT G COMMUNICATION NETWORKS

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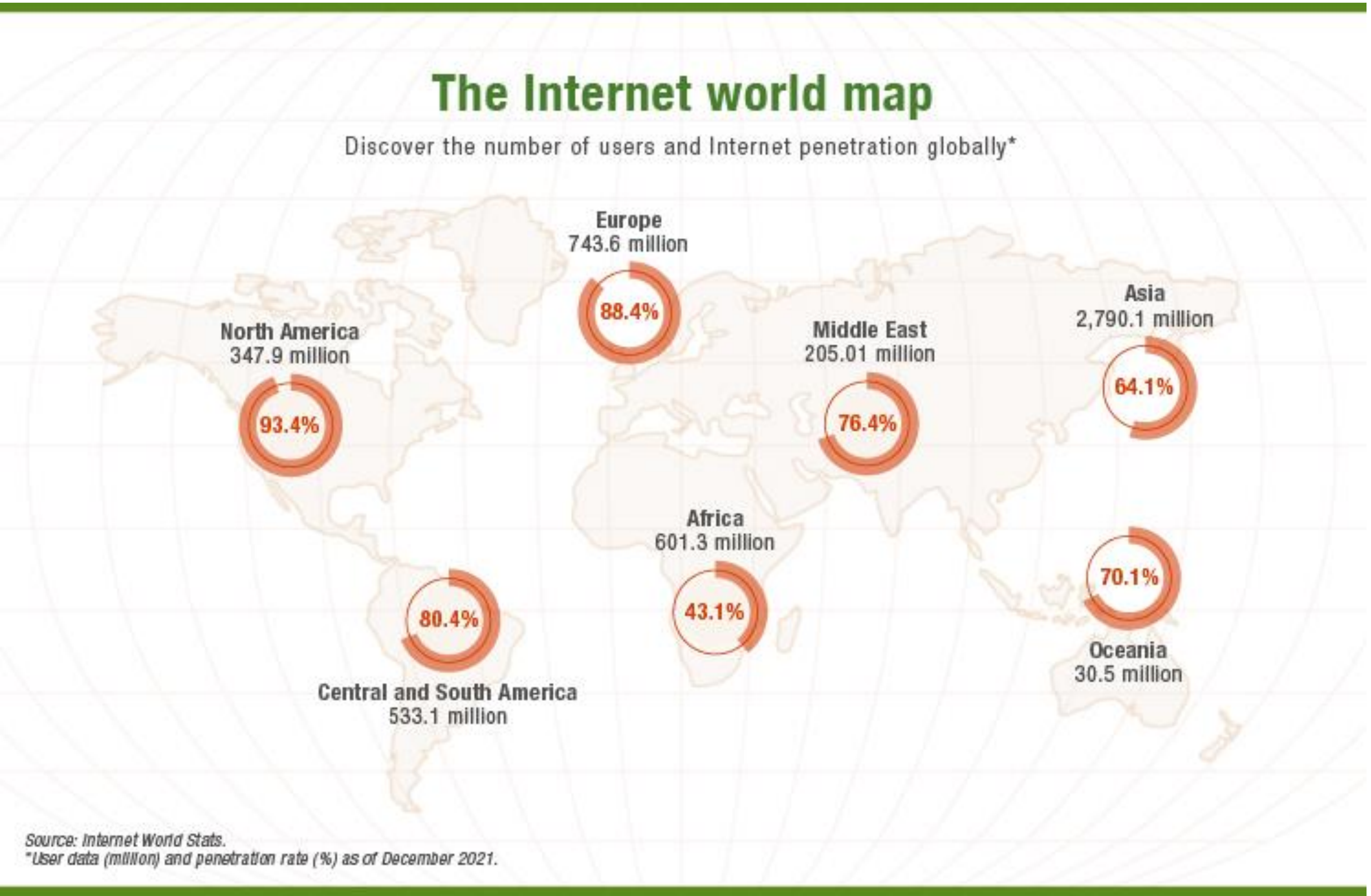
OUTLINE

1. nextG: Why 3D integrated satellite-terrestrial communications?
2. How 3D communications? The current evolution
3. New Space revolution
4. Breakthrough technologies
5. Distributed spatial processing in mega-constellations and swarms

NEXT G: WHY 3D INTEGRATED SATELLITE-TERRESTRIAL COMMUNICATIONS?

- Because of its nature satellites provide the best infrastructure for anywhere, anytime and scalable connection
- There are serious gaps in the global internet connectivity:

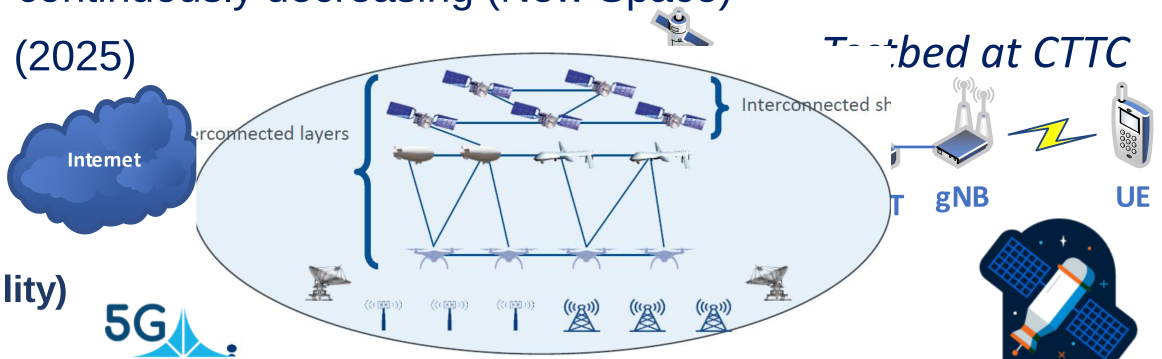


The UN includes the reduction of the digital divide (SDG 9) in its **Sustainable** Development Goals. Among the most relevant technologies New Space and its integration with terrestrial networks can provide high-speed Internet and global coverage at affordable prices.

HOW? THE CURRENT EVOLUTION

5G NEW RADIO: INTEGRATION WITH NTN HAS BEGUN

- Currently, there are **several triggers** that favor the integration of satellite and terrestrial networks (among others):
  - The cash cow of the broadcasting business for SatCom is over
  - The increasing digitization of the communication networks (SDN and NFV)
  - Certain investment stagnation at MNO level and can take advantage of the satellite investment growth
  - The satellite manufacturing and launching costs are continuously decreasing (New Space)
- Standardization activities: 3GPP Rel. 17 (2022)→Rel.20 (2025)
  - **Direct to satellite UE** equipped with GNSS receivers
  - Service continuity between TN and NTN (< 2GHz)
  - Transparent payload architecture
  - NR waveform instead of DVB-S2 **(flexibility, interoperability)**
  - Doppler $> \pm 10\ kHz$
  - Focus on GEO and NGEO satellites



TRANTOR

EXAMPLE: LEO SATELLITE IOT BASED ON 5G STANDARD

Small satellite constellations (5 satellites) connected to a 5G core (single roaming agreement with the MNOs)
LEO nano-satellites based on COTS at 500 km with sat. diversity and a life span of 5 years vs 15 years for GE
Narrow band IoT devices: NB IoT (or 5G IoT) 5$ cost/device
Billions of IoT devices (5-10 device/human)
Applications: 5 – 10 messages/device/day → cattle, agriculture, infrastructures aging, …
1 message/device/hour → logistics (refrigerator containers tracking, wild life tracking, SOS Amazonia, see life jackets, smart grids, SUSTAINABILITY…) **EXTENDING THE COVERAGE OF TN IoT**

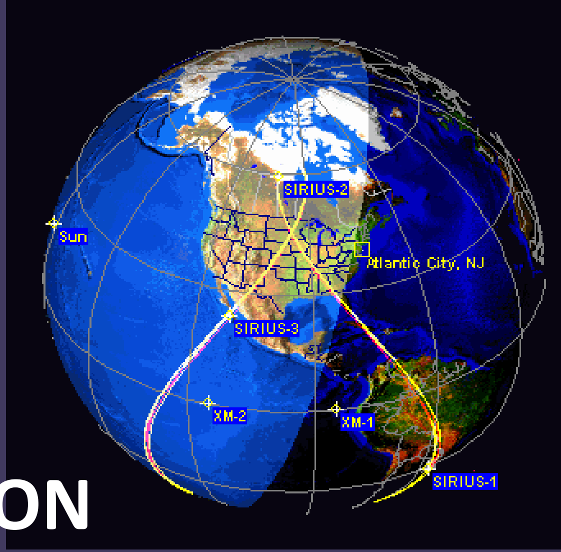
6GNTN

NEW SPACE REVOLUTION VS EVOLUTION

NEW SPACE REVOLUTION: DEMOCRATIZATION OF SPACE

- One of the main differences between the legacy satellite systems and the nextG LEO mega-constellations is the **new architecture and networking complexity → revolution**
  - closer to the Earth
  - shifting from high priced satellites to **massive smaller and cheaper ones** (with redundancy)
  - very high speed interconnecting links (ISL)
  - **in future, also acting as an edge computing device**
  - and very flexible resource allocation, autonomous operation is the goal

- In 2022 more than 2000 objects were launched into space, 28% subscribers growth (BB)
- Forecast of dense LEO networks: Starlink ~42,000 LEO and 1.5+ million subscribers, OneWeb ~6,300, Kuiper ~3,200, Telesat ~1,600 (proprietary and non-standardize systems)
- **Intensive CAPEX and not clear if 5G demand will cover its costs. nextG panorama offers more potential use cases: bigger is not just human use, but machine and devices (hyperconnectivity).**



BREAKTHROUGH TECHNOLOGIES IN THIS REVOLUTION

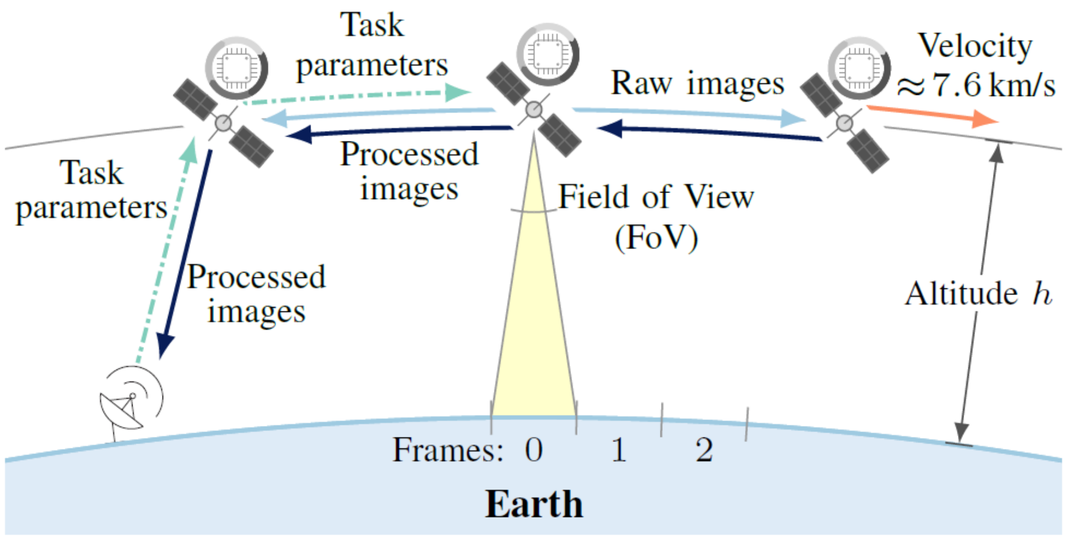
- ONBOARD PROCESSING AND COMPUTING
- ISL
- ADVANCES IN ANTENNA TECHNOLOGY

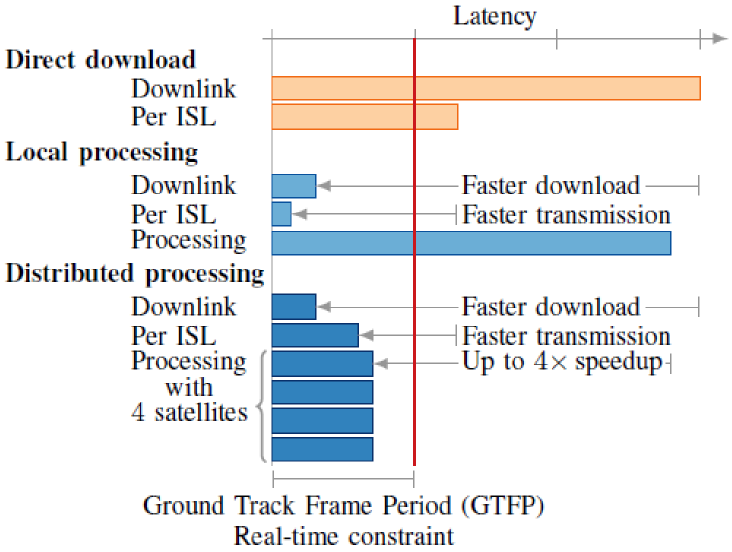
ONBOARD PROCESSING AND COMPUTING

Space is more accessible than ever, and flexible payload architectures, software adaptive, are very attractive:

- For satellite healing and 24x7 autonomous service, reduce the nº gateways
- 5G needs regenerative payloads
- Multiservice satellites software defined: communications, cloud services (ISL capacity is there),…→ Maximize revenue
- To adapt to changing client needs, markets and applications
- Sustainability in Space
- Aligned with IRIS^2 goals in Europe
- There are big efforts to achieve all these with COTS and reduce CAPEX (thanks Elion Mask) and we should now put efforts in reducing OPEX
- **Native Space edge computing:** process the data where it is generated
  - Exponential growth of satellite data from space (e.g., cislunar), Earth Observation, remote sensing, in addition to IoT
  - Store, process and transmit in an intelligent and optimized way
  - Onboard AI: process data and make decisions locally, in real-time, without constant communication with GS
  - New waveforms **(1)** M. M. Gost, A. Pérez-Neira and M. Á. Lagunas, "DCT-Based Air Interface Design for Function Computation," in IEEE Open Journal of Signal Procesing, pp. 44-51, 2023); **(2)** M. M. Gost, A. Pérez-Neira and M. Á. Lagunas, "Lora-based over-the-air computing for Sat IoT", Eusipco23, pp. 1-5, Helsinki (Finland).

EXAMPLE I: REAL-TIME AND HIGH RESOLUTION EO





CRRM Optimization problem on graphs for the segmentation, scatter, processing, and gather phases of our general SMEC framework. Given that the satellites have a limited battery supply, the objective of distributing the tasks across the satellites in the constellation is to minimize the overall energy consumption while fulfilling the limitations of the processing frequency at the satellites' CPU, and the rates at the ISLs and satellite-to-ground link.

Results: capture, process, and download up to **6× more images** than with direct download. Up to **90% of the energy can be saved**.

Next Steps: work on how to obtain the task parameters (semantic communication part)

Israel Leyva-Mayorga, Marc M. Gost, Marco Moretti, Ana Pérez-Neira, Miguel Ángel Vázquez, Petar Popovski, Beatriz Soret, "Satellite edge computing for real-time and very-high resolution Earth observation," submitted to IEEE TC, arxiv: https://arxiv.org/abs/2212.12912. Developed within the Satnex V project.

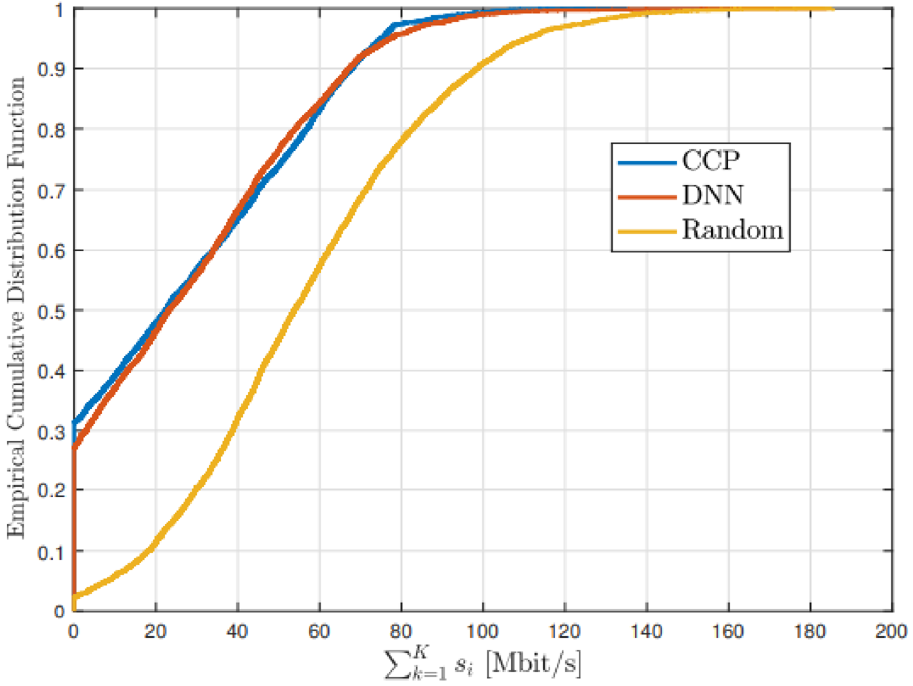
M. Martinez Gost, Israel Leyva, A. Perez-Neira, et al., "Edge Computing and Communication for Energy-Efficient Earth Surveillance with LEO Satellites,"WS18 ICC'22 Workshop - 6GSatComNet, 16-20 Seoul, Corea.

EXAMPLE II: ONBOARD AI – ENABLED MAC CONTROLLER

- From model-based and human-centered operation towards autonomous **data-based functioning**
- Almost mandatory due to the complexity of the future integrated networks in terms of architecture and available data: **RRM for flexible payload**, intelligent Tx/Rx mode adaptation, interference management, gateway switching, traffic allocation, constellation control, spectrum utilization, computing-communication-sensing→ Cross-layer design.
- AI offers faster adaptation than traditional optimization methods, which use to be NP-hard
- Reduce the **time-to-react** from hours to minutes for the NTN.

Limitation: You need a sufficiently large data-set of inputs-outputs.

E.g., Elapsed time gain in flexible payload beam and carrier optimization. **Optimization technique based on sequential convex optimization: 62.1 seconds. DNN python implementation in Tensorflow: 0.041 seconds.**

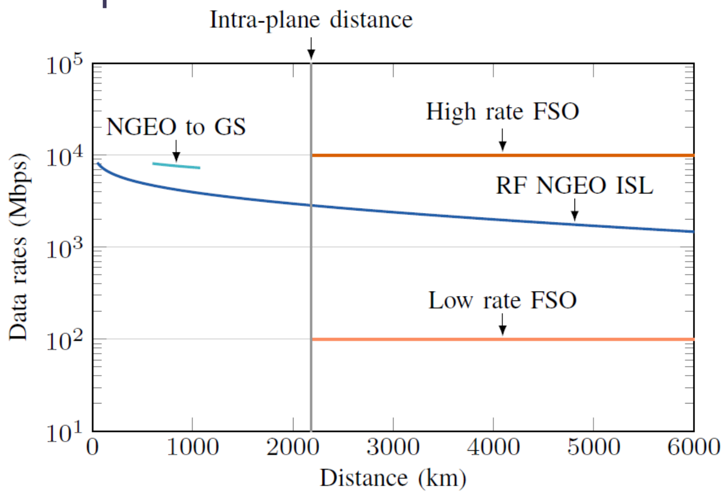


(*)Miguel Á. Vázquez Pol Henarejos, Ana I. Pérez-Neira , "Learning to Optimize Flexible Payloads," *EUSIPCO 2022*.

(**) Machine Learning for Satellite Communications Operations, M.A. Vázquez, P. Henarejos, et al., Communications Magazine, Feb 21

FSO INTER SATELLITE LINKS (ISL)

Optical Wireless Communication is the use of optical carriers to transfer information from one point to another using unguided channel. It is used for ISL and represent a tech. breakthrough.



FSO (Free Space Optics) compared to RF:

- Unlicenced spectrum
- Less power consumption (~1/2 of RF). In terms of power, 10, 20, and 50 W for FSO, mmwave, and Ka links.
- Reduced size (~1/10 of the RF antenna diameter)
- ATP (Acquisition, Tracking and Pointing) systems allow to use FSO as ISL

FSO compared to Fiber Optic:

- Zero refractive index in space (vs ~1.5 index of fiber)→ LEO as the only way to offer long distance, low-latency service
- Varying in atmosphere

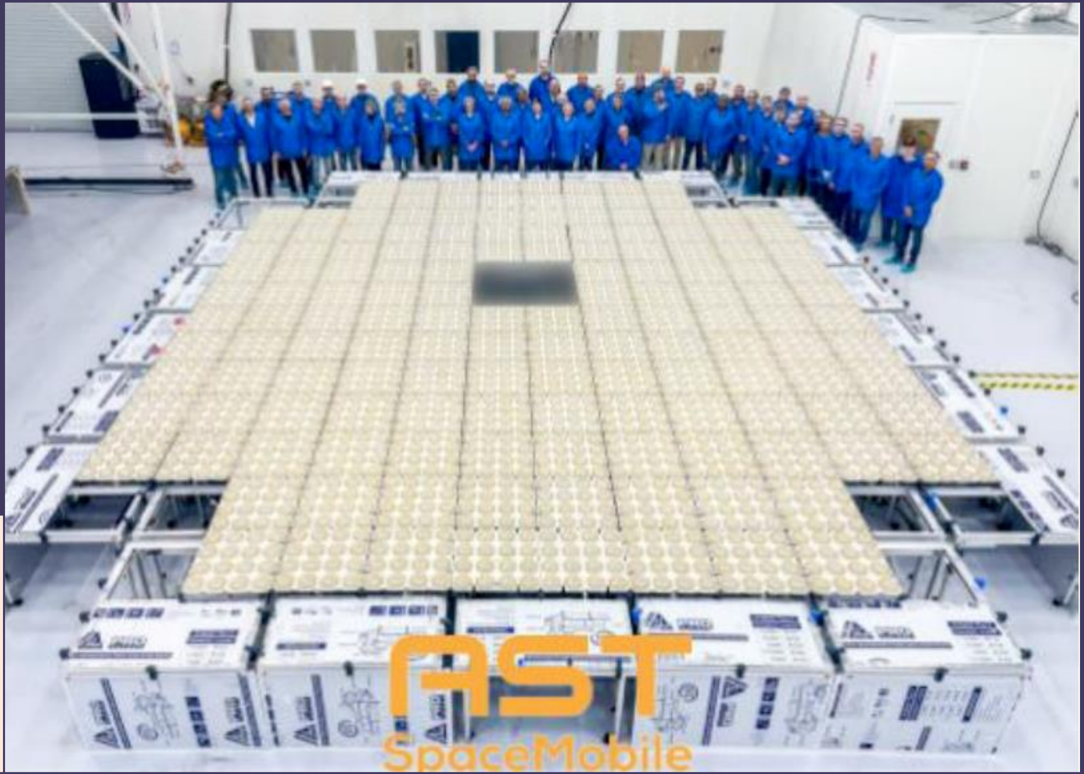
Starlink of SpaceX is planning to incorporate 4 laser ISL for their 2nd gen LEO sat.

Marc Amay, J. Bas, “On Hybrid Radio Frequency - Free-Space Optic (RF-FSO) Systems as Enablers of 6G Services over Non-Terrestrial Networks,” ICASSP 2023.

Advances in antenna technologies: PHASED ARRAY (PA)

To close the link budget for **direct to UE 5G** connectivity at L/S band: large phased antenna arrays can be used on NGEO (with higher practicality than in GEO)

Also, due to the NGEO movement, advances in phased array antenna technologies are interesting for electronic tracking



FROM "CLASSICAL" CO-LOCATED PA

Lynk Global (5110 satellites of 4 m^2),
AST SpaceMobile (170 satellites of 128 m^2),
T-Mobile/SpaceX (2,000 Gen2 satellites in 2024?), …

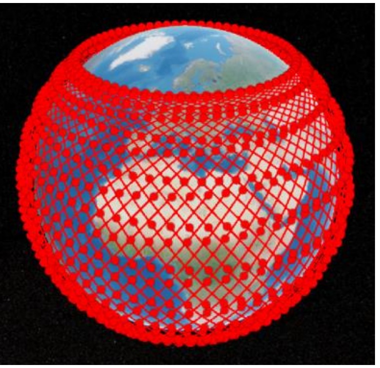
TO LESS "CLASSICAL" DISTRIBUTED BEAMFORMING FOR 6G DIRECT UE CONNECTIVITY

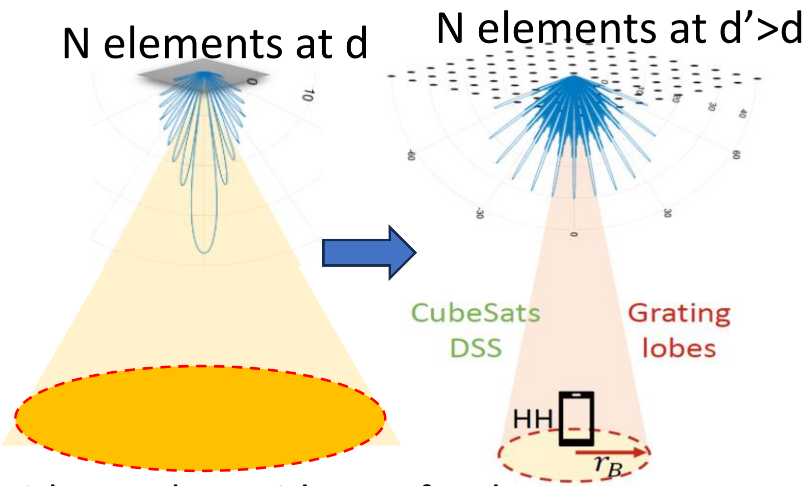
- SATELLITE SWARM
- TWO SATELLITES

SATELLITE SWARMS: INTRODUCTION

- Satellite swarms (e.g., 100s to 1000s of femtosats, sub-100gram, or sub-1kg cubesats) are emerging as a technology enabler to deploy large and reconfigurable apertures at a fraction of cost of a monolithic satellites
- Compared to collocated phased arrays, satellite swarms can have:
  - Lower building and launching costs
  - Larger number of cost efficient PA, fault tolerant, scalable
  - Negligible antenna losses (e.g., impedance mismatch caused by mutual coupling)
  - Larger number of beams with smaller spot beam diameter: bps/m^2 increases thanks to aggressive spatial frequency reuse factor more close to what is done in TN cellular networks
- Beamforming in such large scale N-swarm array systems **create larger apertures** than those practicable for an array of N-elements collocated in one satellite (with the same number of antennas)

Xavier Artiga, Màrius Caus, Mathini Sellathurai, Heriot-Watt U.,Ankit Gupta, Heriot-Watt U., “WI Y2.2B-Distributed Beamforming of Satellite Swarms,” Satnex V, ESA project, May 1st, 2023.





GOALS:

1- Scenario modelling: Swarm geometry

2- Design parameters

3- KPIs

4- Identify future research directions

A PLACEHOLDER FOR SUBSEQUENT STUDIES

The FoV is larger with LEO than with GEO for the same coverage area → UT can be resolved with higher angular differences.

1. SCENARIO MODELING: SWARM GEOMETRY

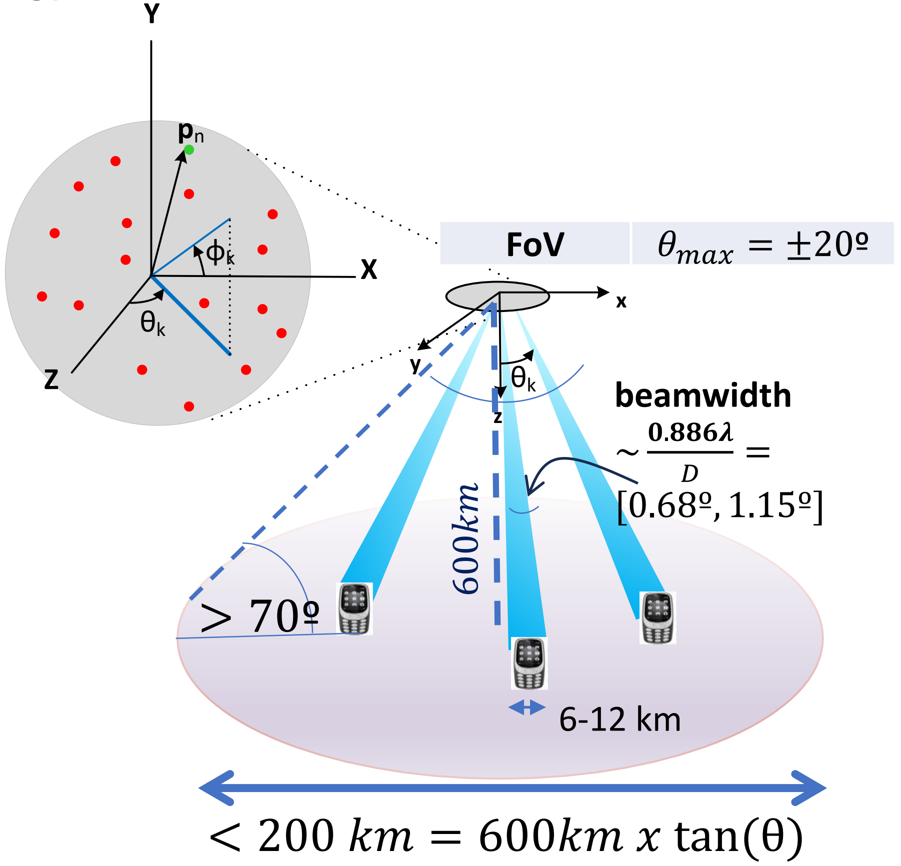
- There are N_R radiating elements confined within a circle of diameter D that generate K beams
- The position of the antennas/satellites are defined by (d_n, φ_n)
- The angle of departure related is defined by (ϕ_k, θ_k)
- Determine the FoV and the beamwidth
- Channel impulse response in LoS:

$$h_{n,k}(t,\tau) = a_{n,k}\delta(\tau - \tau_{n,k})e^{j2\pi f_k t}$$

- Received signal after synchronization $(1 \leq k \leq K)$:

$$y_k(t) = \sum_{n=0}^{N_R-1} a_{n,k} x_n\left(t - \tau_{n,k} + \tau_{min,k}\right) + z_k(t)$$

$$a_{n,k} = \sqrt{\frac{G(\theta_k, \phi_k)G_R}{L_k K_B T B_W}}\, e^{\frac{j2\pi}{\lambda} d_n \sin\theta_k \cos(\phi_k - \varphi_n)}$$



1. SCENARIO MODELLING: TIMING REQUIREMENTS AND SPATIAL PROCESSING

Narrow band array condition: If the differential delays $\{\tau_{n,k} - \tau_{min,k}\}$ do not exceed $\pm$7.5% of the symbol period, ISI can be neglected

$$\frac{D}{\lambda} \ll \frac{f_k}{B} \rightarrow \{\tau_{n,k} - \tau_{min,k}\} \ll T_s$$

- If condition 1 is satisfied, the narrowband system model can be considered

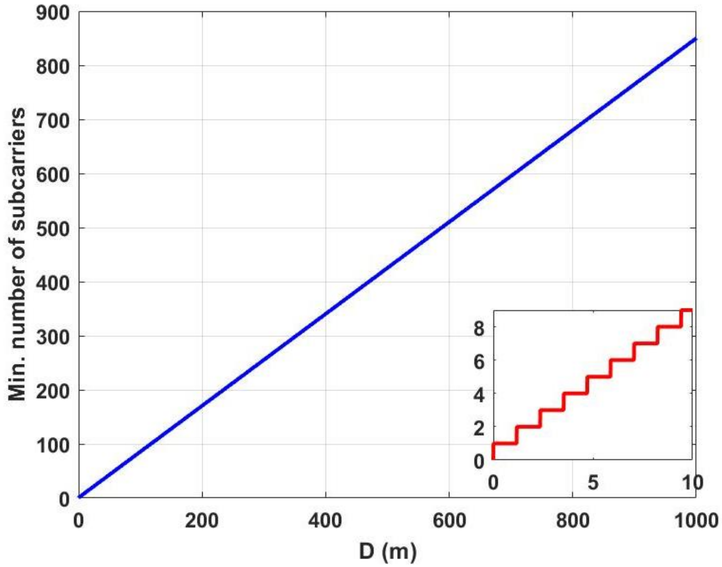
$$y_k(t) = \boldsymbol{a}_k^H \boldsymbol{w}_k s_k(t) + \sum_{j\neq k} \boldsymbol{a}_k^H \boldsymbol{w}_j s_j(t) + z_k(t)$$

- It is considered that each antenna has its own power budget (per antenna power constraints)
- The metric that is considered to measure the quality of the links is the SINR, namely

$$SINR_k = \frac{|\boldsymbol{a}_k^H \boldsymbol{w}_k|^2}{\sum_{j\neq k} |\boldsymbol{a}_k^H \boldsymbol{w}_j|^2 + 1}$$

- From the SINR we can readily obtain the maximum achievable sum rate under the Gaussian signaling

$$R = \sum_{k=1}^{K} R_s \log_2(1 + SINR_k)$$



The higher D the higher Ts must be→ narrower subcarriers → more subcarriers as BW is fixed

2. SYSTEM PARAMETERS AND BENCHMARK (I)

-**Benchmark:** Collocated Uniform planar array (**UPA**): antennas are uniformly spaced in a square of side 1/2/4 m with a minimum **inter-antenna spacing of $\lambda_c/2$=75mm (2 GHz)**

-Swarm Random array (**RA**): antenna elements are randomly located in a circle of diameter D=50/100/200 m with a minimum **inter-sat spacing of 2.5 m** (constant density= $\frac{1}{\pi}(13/25)^2 = 0{,}086$ antennas/ square m)

- Swarm Uniform array (**UA**): antenna elements uniformly located in a circle of diameter D=50/100/200 m with a minimum **inter-sat spacing of 2.5 m** (constant density= $\frac{1}{\pi}(13/25)^2$=0,086 antennas/ square m)

Variable nº antennas/satellites:
13x13: UPA of 1 m2
RA/UA of Diameter=50m
26x26: UPA of 2 m2
RA/UA of Diameter=100m
52x52: UPA of 4 m2 (Bluewalker3)
RA/UA of Diameter=200m

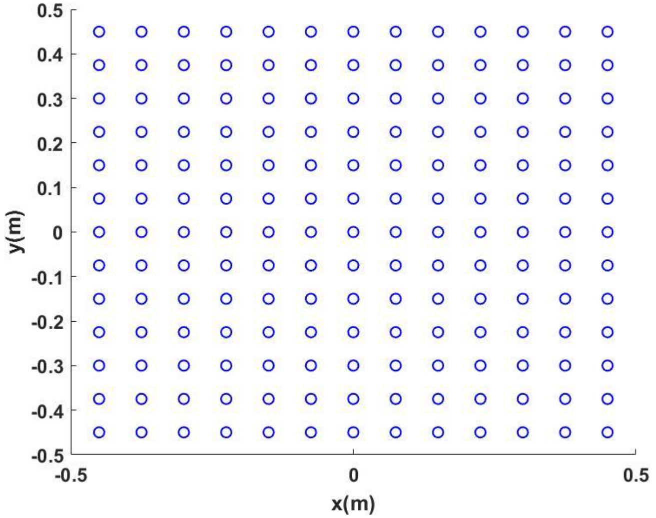
Swarm altitude	600 km
Bandwidth	30 MHz
Frequency	2 GHz (S band), λ=0.15 m
EIPR density/beam	34 dBW/MHz
Antenna temperature	290 K
Noise figure	7 dB
Ambient temperature	290 K
Tx antenna gain	0 dBi per element
Rx Antenna gain	0 dBi per element
Min over the horizon angle	70º
Rx sensitivity power level	-90 dBm (QPSK)

3GPPP for handheld UT (rx SNR $[0, 15]$) dB

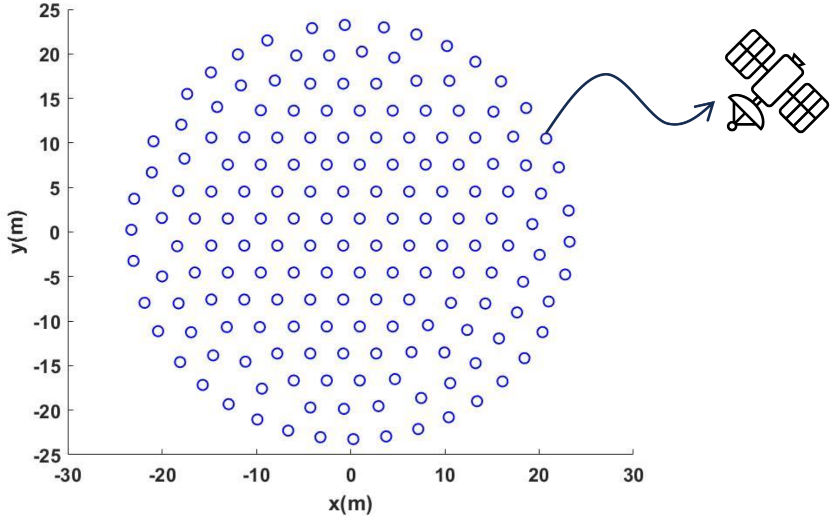
NOTE: for higher D increases then the UE is not in the far field anymore ($d_F \geq \frac{2D^2}{\lambda}$)

2. SYSTEM PARAMETERS AND BENCHMARK (II): ANTENNA TOPOLOGY

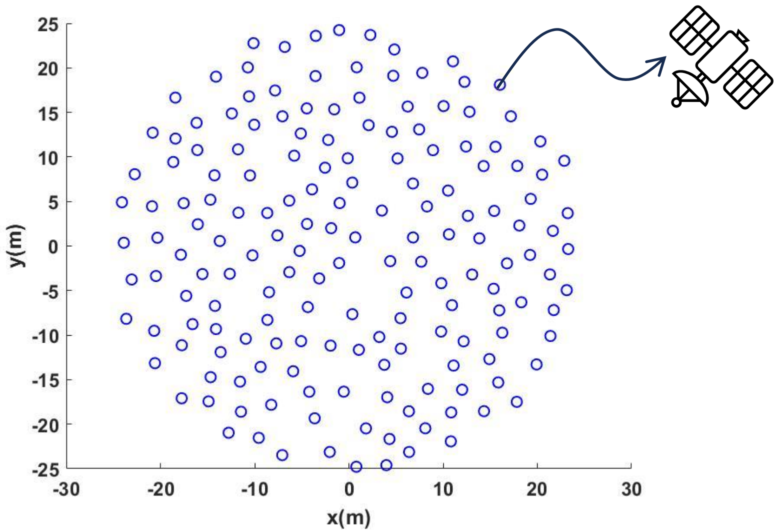
BENCHMARK: Array of col-located antennas



Uniform **Swarm** of satellites



Random **Swarm** of satellites



3. KPI: BEAMPATTERN OF MF IN A FOV OF $\pm 20^{o}$, CTE Nº ELEMENTS

Collocated antennas in UPA at λ/2=0.075m

3dB-beamwidth is 7.81º (81 km)

max. SLL is -13dB

Swarm of satellites uniform (UA) at 2.5m

3dB-beamwidth is 0.18º (1.89 km)

max. SLL is -3dB

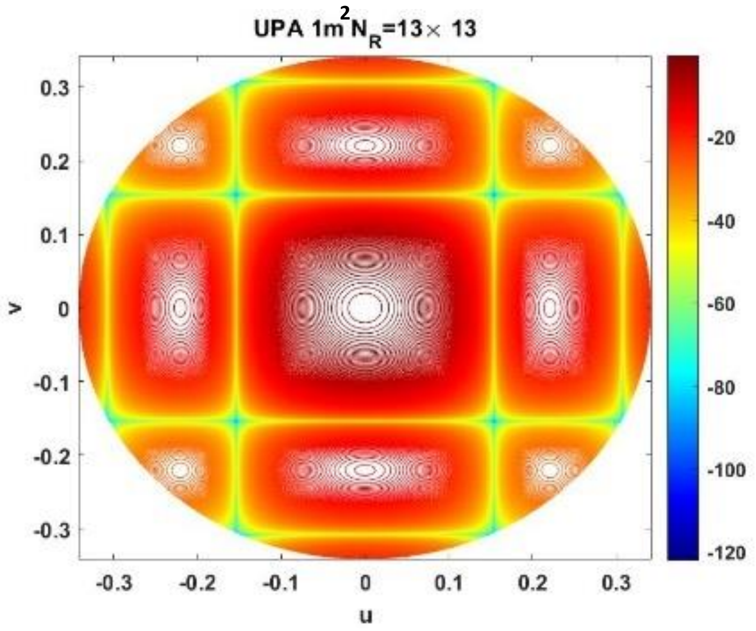
Problem: grating lobes within the FoV

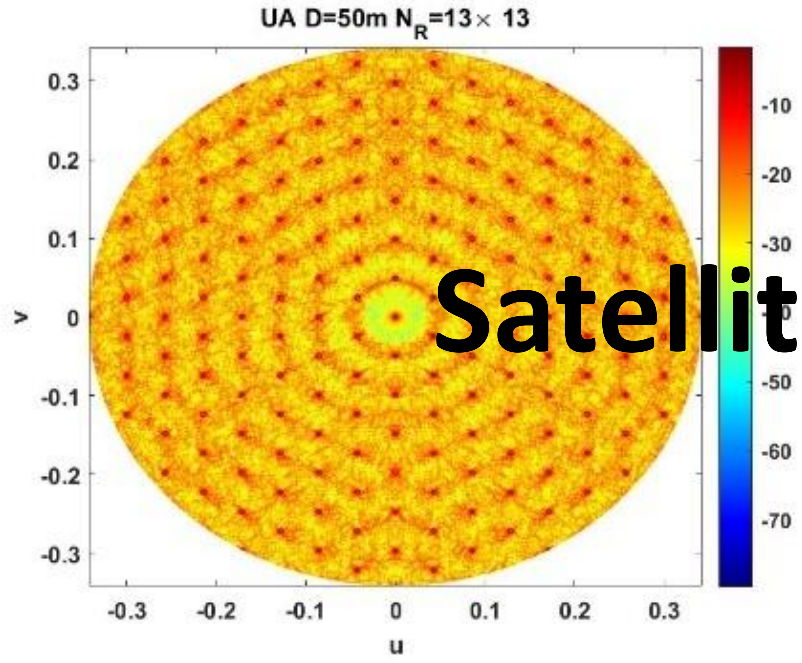
Swarm of satellites random (RA) at 2.5 m

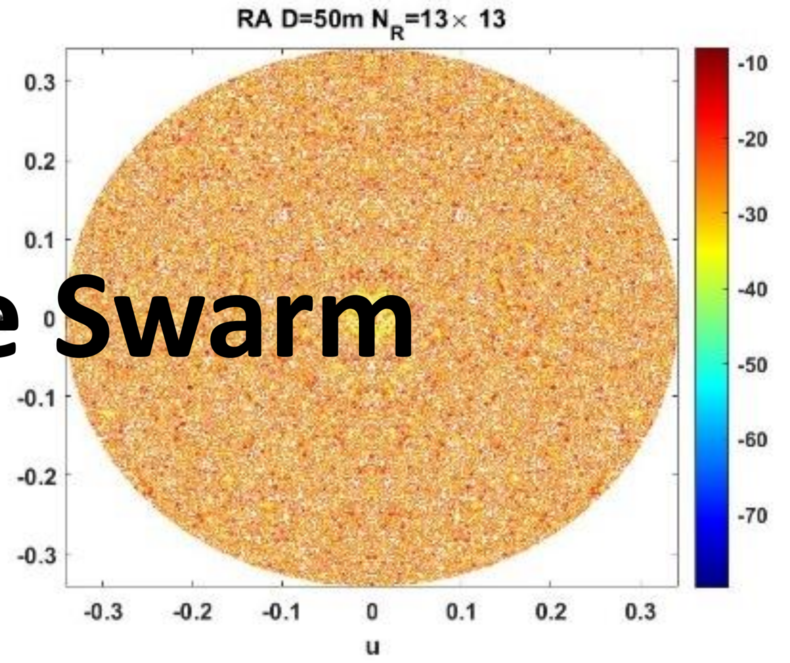
3dB-beamwidth is 0.18º (1.89 km)

max. SLL is -11.5dB

No grating lobes







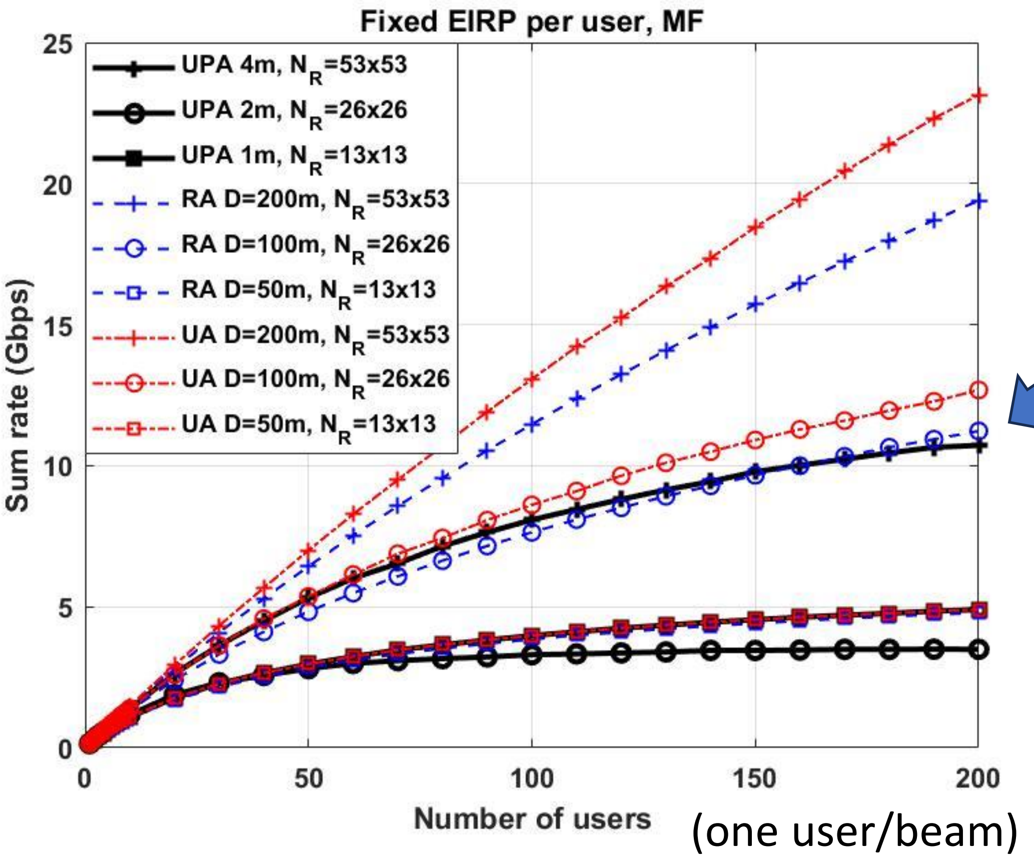
Satellite Swarm

Same number of antennas but lower antenna density in the swarms

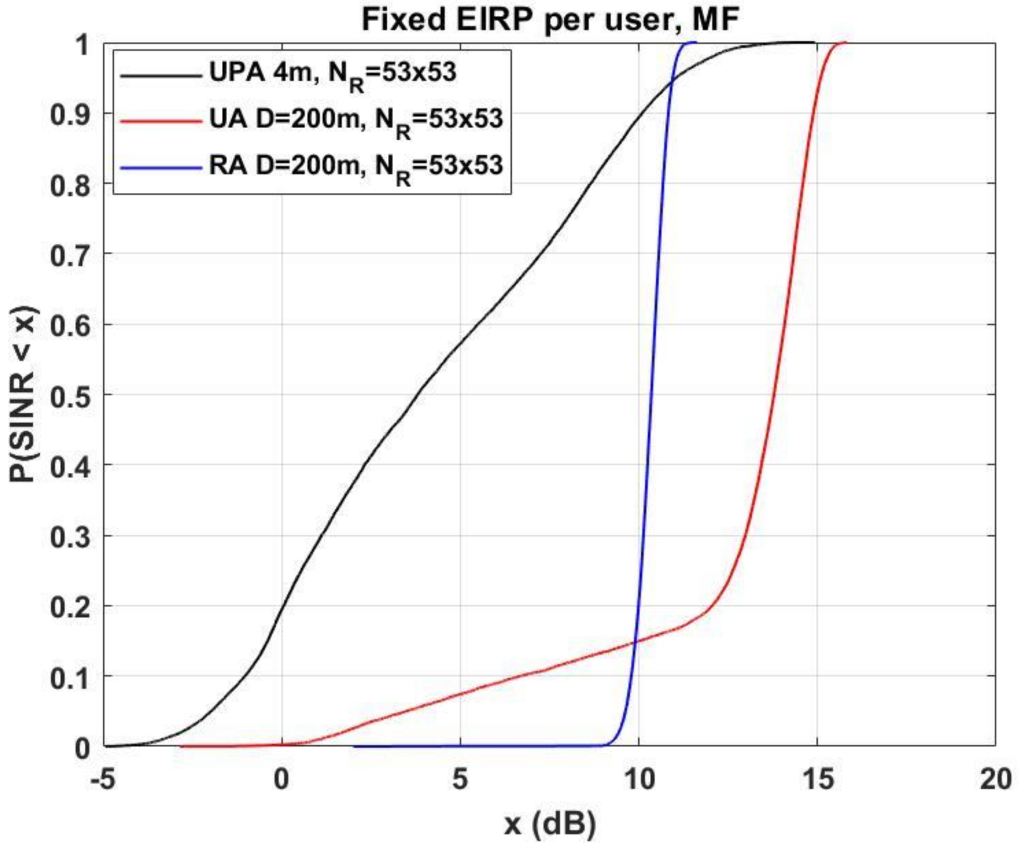
- The highest side lobe suppression is provided by UPA
- UA and RA achieve higher angular resolution at the expenses of increasing the side lobe level

3. KPI: SUM RATE AND CDF MF PRECODER (FIXED EIRP PER USER)

- RA and UA achieve similar results as UPA using 4 times less antennas
- The gain of RA and UA results from increasing the element spacing (significant improvement from $1.5\lambda_c \longrightarrow \mathrm{D} = 1\mathrm{m}$
- UA outperforms RA in sum rate but providing a more unbalanced SINR among users



(one user/beam)



Larger apertures with lower nº satellites (cost and launching are relevant system KPIs)

4. FUTURE DIRECTIONS: PRACTICAL CHALLENGES

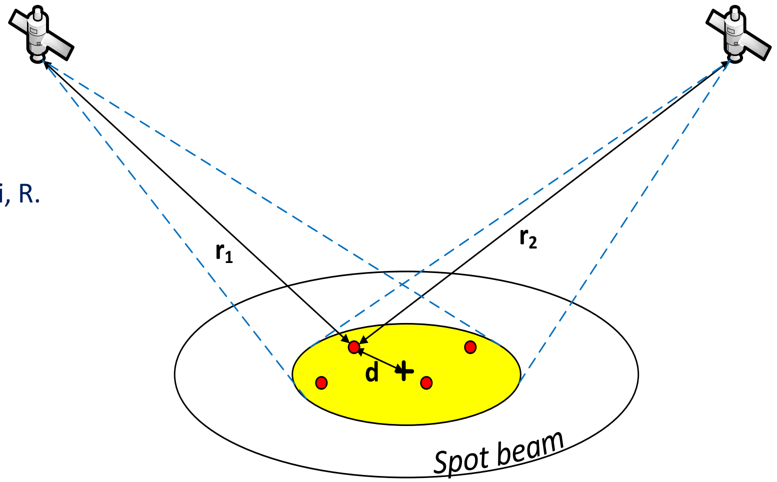
- **Hierarchical structure: signaling between leader and follower satellites**
  - All require centralized CSI estimation
  - MF RA swarm is a good trade off performance vs complexity
  - Harmonic mean beamformer (max. Directivity)(*) provides significant gains at the expense of large matrix inversions

- **System operation with extremely narrow beamwidth**
  - Initial attach procedure requires covering the whole FoV (thousands of beams): due to the large beam resolution, the proposed beamforming is suitable for user-centric rather than fix spot beam
  - Fast refreshing rate requirement of beamforming weights

- **Pilot based CSI acquisition (in progress)**
- **Time/frequency and phase synchronization**
- **Stability of the flying formation (current technology makes I challenging, but realizable)**

Work in progress

(*) Formation-of-Arrays Atnenna Technology for High Throughput mobile non-terrestrial networkds, G. Bacci, R. de Gaudenzi, . Luise, OL. Sanguinetti, E. Sebastia," submitted to IEEE Trans. AES, Feb 2023



Next, we present a different focus/work line:

- No CSIT is needed

- Diversity combining is done at rx

(*) A. Perez-Neira, M. A. Vazquez and M. A. Lagunas, "Why do we call it Mean Square Error beamformer? Study in the unicast and multicast satellite scenarios," WSA 2021; 25th International ITG Workshop on Smart Antennas, French Riviera, France, 2021, pp. 1-6.

(**) Reliability oriented OTFS-based LEO satellites joint transmission scheme," Globecom' 22, M. Caus, A. Pérez-Neira, et al."

CONCLUSIONS

- 3GPPP standardization evolves 5G NR NTN to gain interoperability (with the same UT)
- New Space revolution helps in this evolution
- OPEX must also help to reduce costs. The main **breakthrough** technologies have been addressed and discussed at PHY level:
  - On board processing and computing
  - FSO Inter Satellite Links
  - Active Antennas and distributed swarm beamforming that enable user-centric beamforming

Thank you!

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HR EXCELLENCE IN RESEARCH

NEW SPACE REVOLUTION: DEMOCRATIZATION OF SPACE

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  - very high speed interconnecting links (ISL)
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- In 2022 more than 2000 objects were launched into space, 28% subscribers growth (BB)
- Forecast of dense LEO networks: Starlink ~42,000 LEO and 1.5+ million subscribers, OneWeb ~6,300, Kuiper ~3,200, Telesat ~1,600 (proprietary and non-standardize systems)
- When orbital period decreases as satellites move from GEO to LEO and VLEO, there are several consequences:
  - reduced signal delay
  - mega-constellations are needed to avoid gaps in the BB coverage
  - big extensions covered by oceans
  - observation time per satellite decreases significantly
  - depending on the application complex earth terminal antennas are needed

- **Intensive CAPEX and not clear if 5G demand will cover its costs. nextG panorama offers more potential use cases: bigger is not just human use, but machine and devices (hyperconnectivity).**

ADVANCES IN ANTENNA TECHNOLOGIES: PHASED ARRAY (PA)

To close the link budget for **direct to UE** connectivity at L/S band: large phased antenna arrays can be used on NGEO

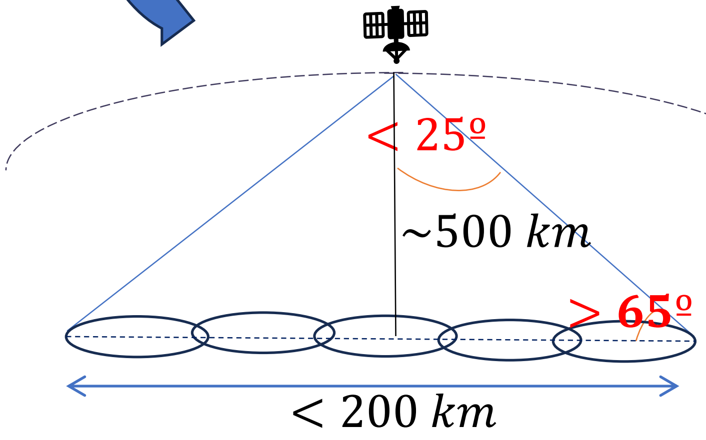
Also, due to the NGEO movement, advances in phased array antenna technologies are interesting for electronic tracking

1.-As in legacy GEO satellite communications, the capacity can be allocated based on a geographic beam-centric approach (Signal Processing for High-Throughput Satellites: Challenges in New Interference-Limited Scenarios, in IEEE Signal Processing Magazine, vol. 36, no. 4, pp. 112-131, July 2019, A. I. Perez-Neira, et al.)

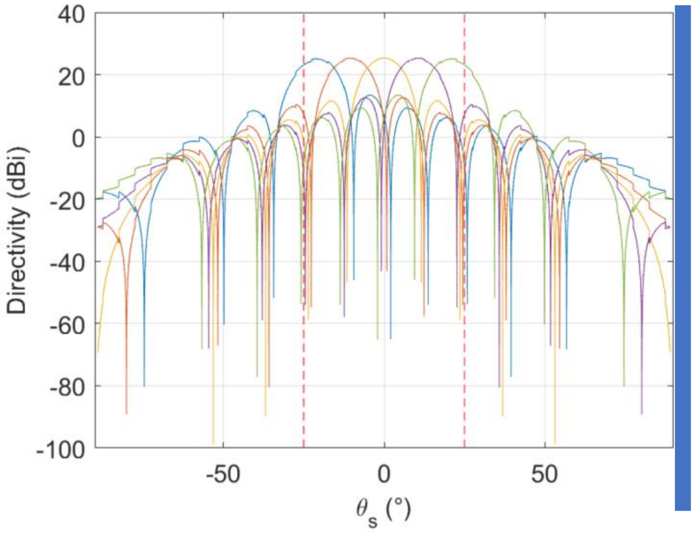
OR

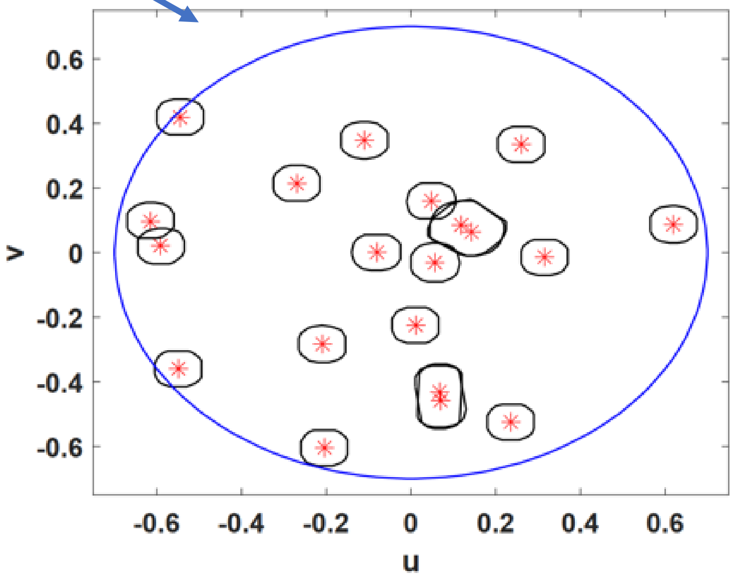
2.-The field of view in LEO is wider than in GEO satellites. This facilitates to create dynamic spot beams, putting signal power and capacity exactly where it is needed on the ground: user centric approach. Flexible payloads are required. (“Smart Beamforming for Direct LEO Satellite Access of future IoT” Special Issue "Satellite Networks for Massive IoT Communication", Sensors (ISSN 1424-8220; CODEN: SENSC9), July 2021, Marius Caus, Ana Perez-Neira, Eduard Mendez)

Beamforming for simultaneous channelization of the different satellite services



100 URA
0.5λ
10.7º
47km

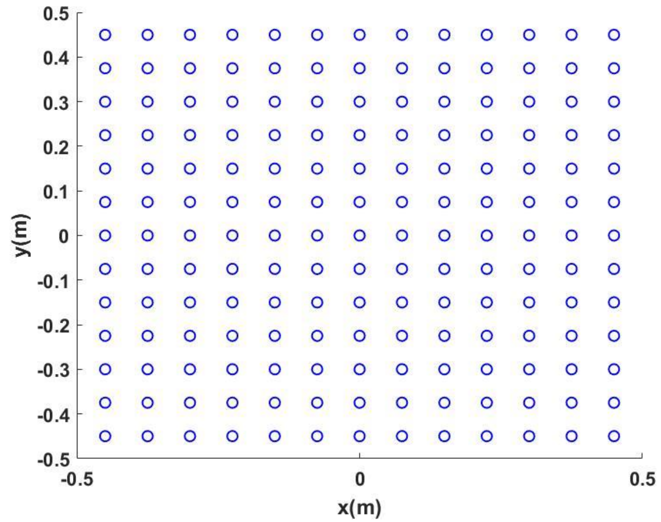




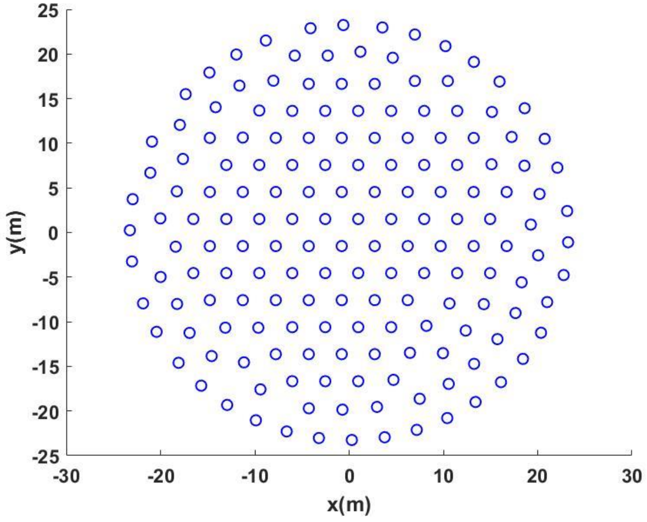
1. SCENARIO MODELING: SWARM GEOMETRY

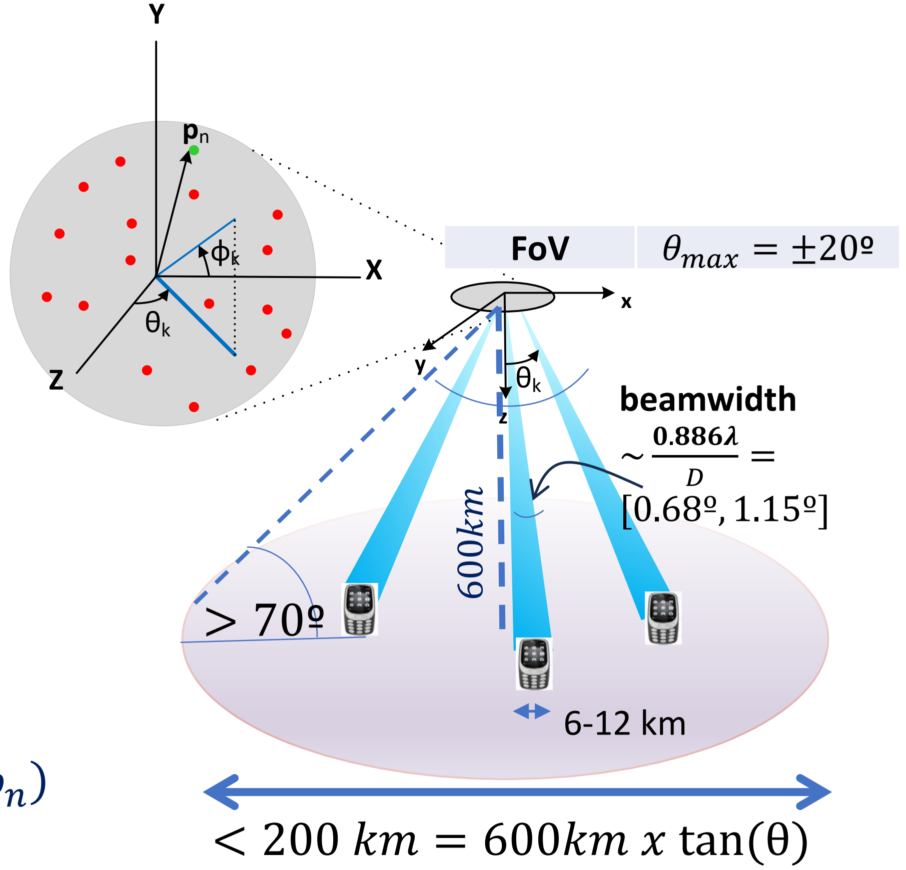
- There are N_R radiating elements confined within a circle of diameter D that generate K beams

Array of col-located antennas



Uniform Swarm of satellites





- The position of the antennas/satellites are defined by (d_n, φ_n)
- The angle of departure related is defined by (ϕ_k, θ_k)
- Determine the FoV and the beamwidth

1. SCENARIO MODELLING: TIMING REQUIREMENTS AND SPATIAL PROCESSING

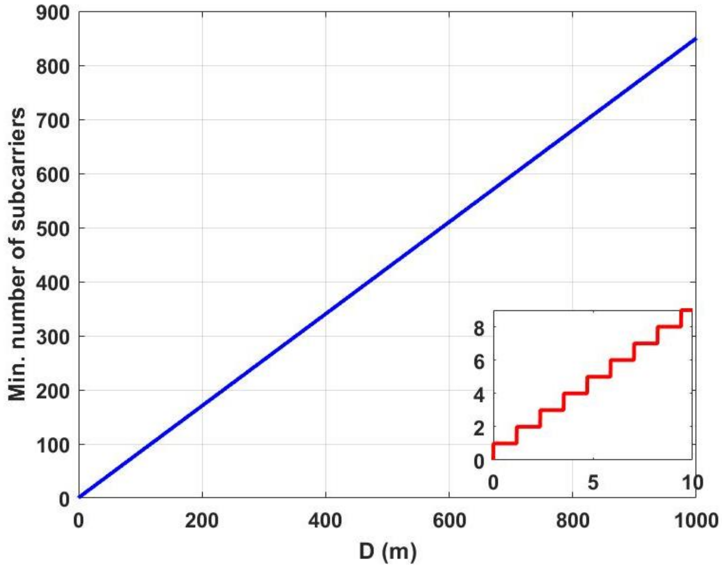
Channel impulse response is in LoS:

$$h_{n,k}(t,\tau) = a_{n,k}\delta(\tau - \tau_{n,k})e^{j2\pi f_k t}$$

$$\frac{D}{\lambda} \ll \frac{f_k}{B} \rightarrow \{\tau_{n,k} - \tau_{min,k}\} \ll T_s$$

- Received signal after synchronization ($1 \leq k \leq K$):

$$y_k(t) = \sum_{n=0}^{N_R-1} a_{n,k}x_n(t - \tau_{n,k} + \tau_{min,k}) + z_k(t) \text{ with } a_{n,k} = \sqrt{\frac{G(\theta_k,\phi_k)G_R}{L_k K_B T B_W}}\, e^{\frac{j2\pi}{\lambda} \mathrm{d_n} \sin\theta_k \cos(\phi_k - \varphi_n)}$$



Condition: If the differential delays $\{\tau_{n,k} - \tau_{min,k}\}$ do not exceed $\pm$7.5% of the symbol period, ISI can be neglected

- If condition 1 is satisfied, the narrowband system model can be considered

$$y_k(t) = \boldsymbol{a}_k^H \boldsymbol{w}_k s_k(t) + \sum_{j \neq k} \boldsymbol{a}_k^H \boldsymbol{w}_j s_j(t) + z_k(t)$$

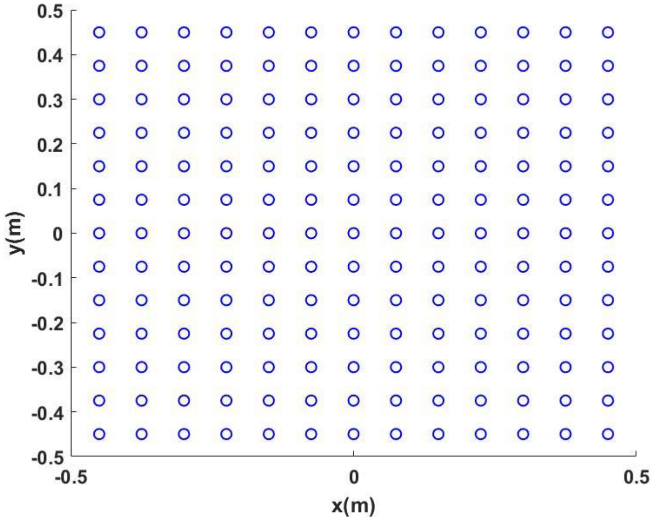
- It is considered that each antenna has its own power budget (per antenna power constraints)
- The metric that is considered to measure the quality of the links is the SINR, and the maximum achievable sum rate under the Gaussian signaling

$$SINR_k = \frac{|\boldsymbol{a}_k^H \boldsymbol{w}_k|^2}{\sum_{j \neq k} |\boldsymbol{a}_k^H \boldsymbol{w}_j|^2 + 1}; \qquad R = \sum_{k=1}^{K} R_s \log_2(1 + SINR_k)$$

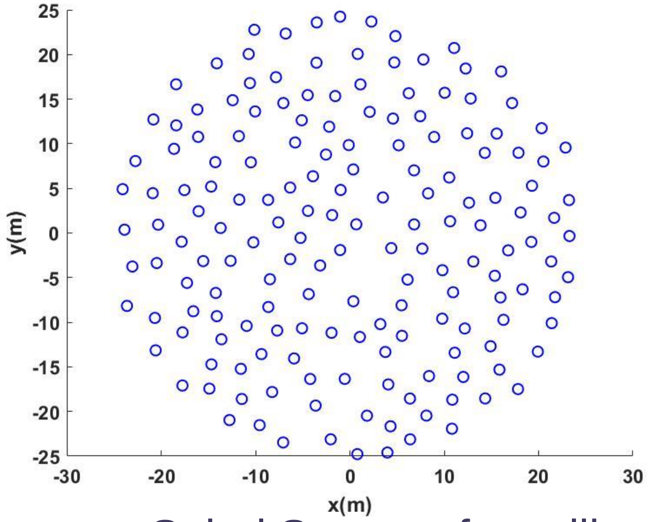
The higher D the higher Ts must be→ narrower subcarriers → more subcarriers as BW is fixed

2. SYSTEM PARAMETERS AND BENCHMARK (II): ANTENNA TOPOLOGY

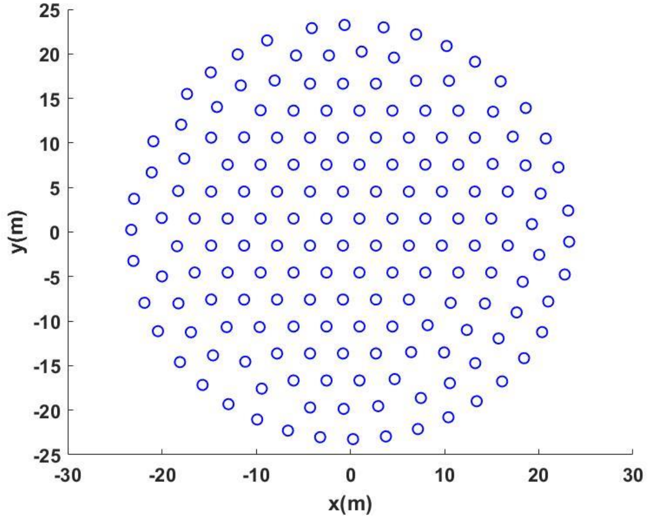
Array of col-located antennas



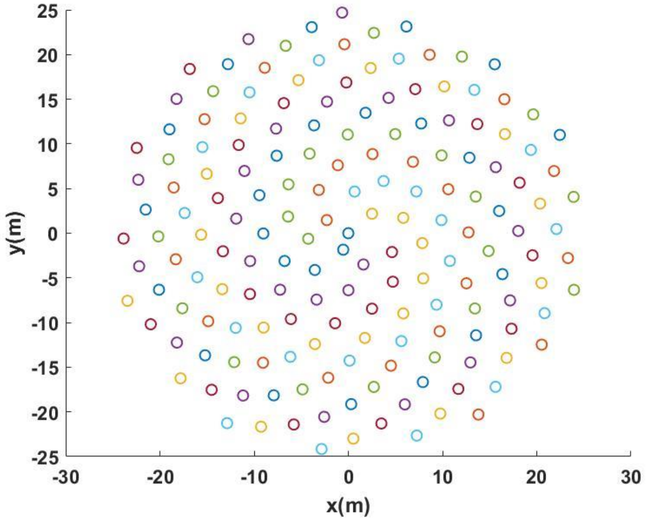
Random Swarm of satellites



Uniform Swarm of satellites



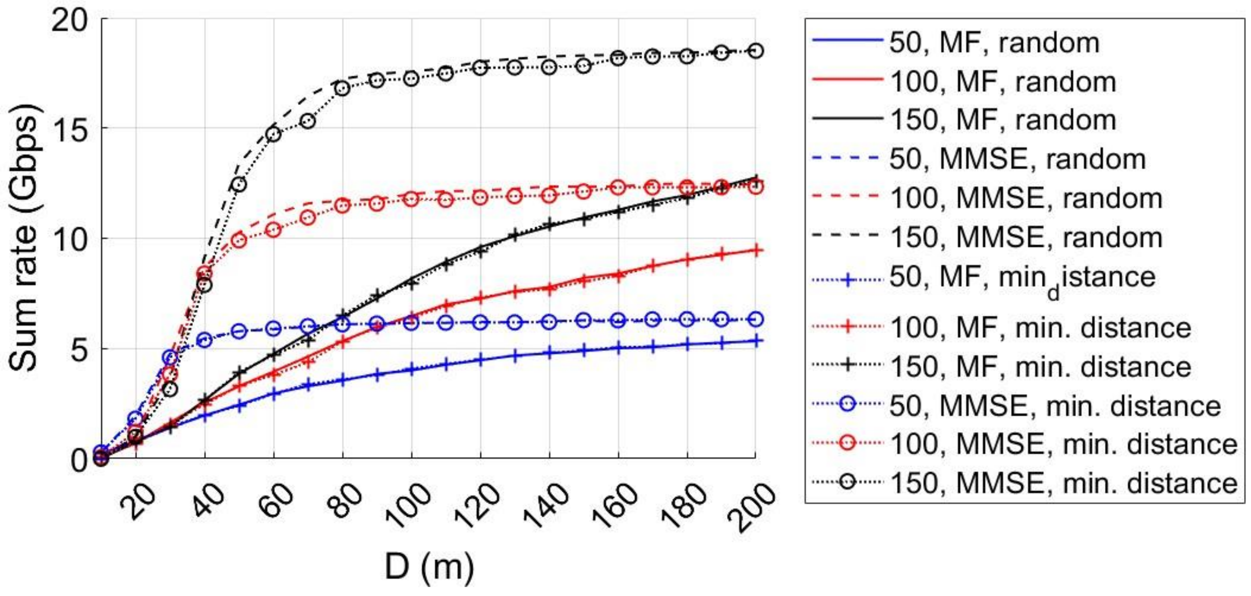
Spiral Swarm of satellites



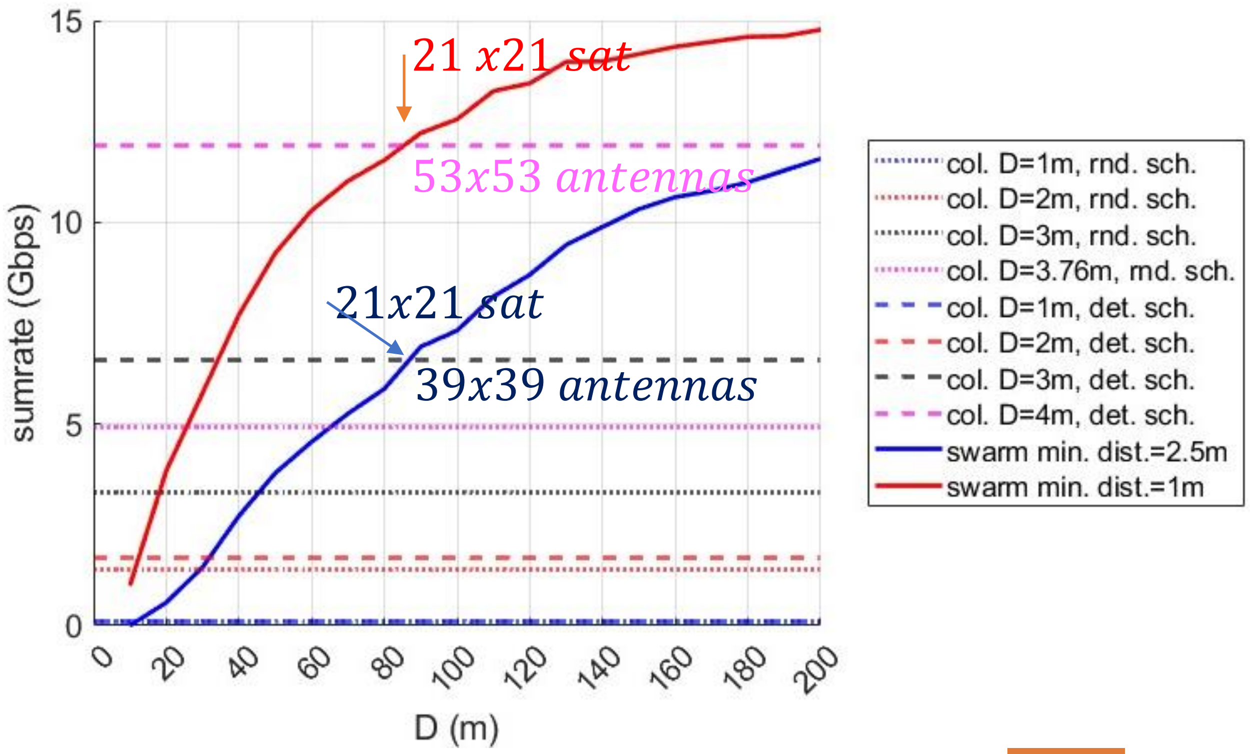
3. KPI: SUM RATE VS SWARM DIAMETER (RA, FIXED EIRP PER USER)

- MMSE clearly outperforms MF even with a drastic swarm diameter reduction
- Minimum distance user scheduling does not provide gains in the swarm case (interference coming from SLL)
- Increased satellite densities (reduced minimum distance between satellites) provide significant improvement
- If the user density is increased enough, there will be always a given swarm aperture outperforming a given collocated benchmark

MMSE beamforming



150 users, MF beamforming **Constant density**



$$n^{o}\ sat = \left(\frac{13D}{2x25}\right)^2 \quad (as\ density\ is\ cte)$$

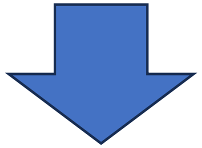
4. FUTURE DIRECTIONS: PRACTICAL CHALLENGES

- **System operation with extremely narrow beamwidth**
  - Initial attach procedure requires covering the whole FoV (thousands of beams): due to the large beam resolution, the proposed beamforming is suitable for user-centric rather than fix spot beam
  - Fast refreshing rate requirement of beamforming weights
  - Swarm diameter reduction yields to reduced gain and large SLL (see plot)

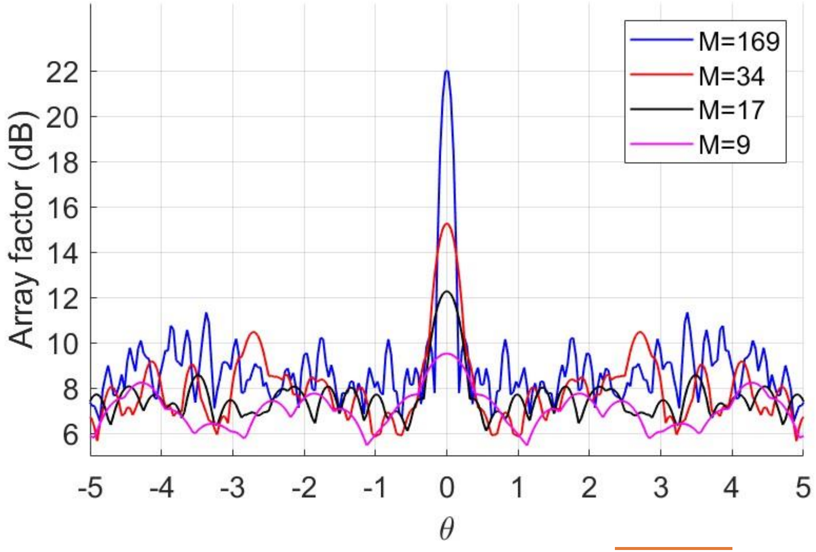
- **Hierarchical structure: signaling between leader and follower sats**
  - MF RA provides a distributed solution (e.g. for IoT terminals) but requires centralized CSI estimation.
  - Centralized MMSE provides significant gains at the expense of large matrix inversions
  - Distributed beamforming schemes based on clustering elements within the swarm evaluated without success

- **Pilot based CSI acquisition (in progress)**
- **Time/frequency and phase synchronization**
- **Stability of the flying formation**

Work in progress

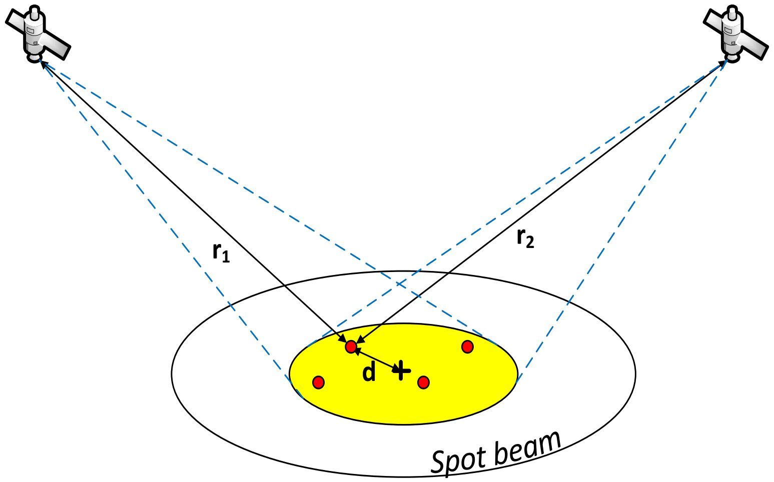


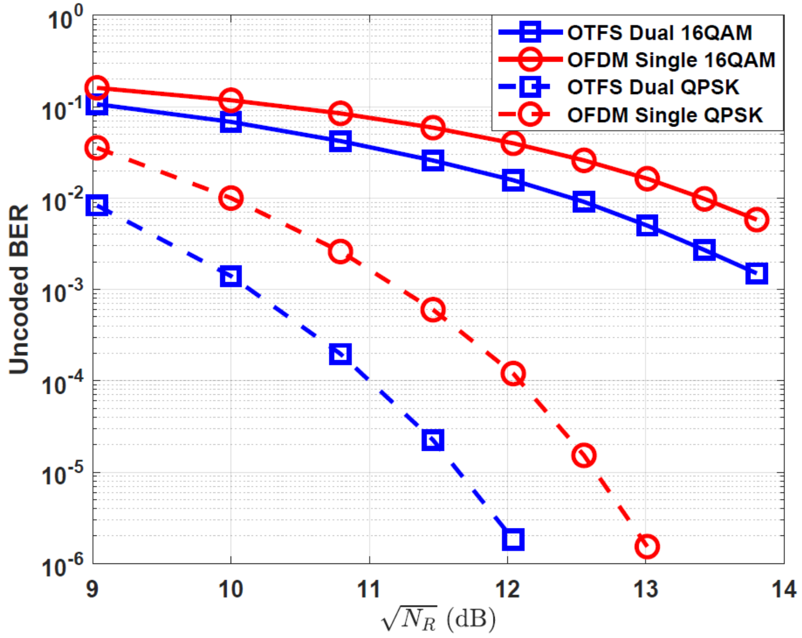
Next, we present a different focus/work line:
- No CSIT is needed
- Diversity combining is done at rx



TWO LEO SATELLITES MULTICONNECTIVITY: BER

- The presence of multiple satellites in the field of view of the users can be exploited to enhance transmission reliability.
- THE SATELLITES DO NOT EXCHANGE CSIT
- For example: combine the received signals coherently, which entails achieving a synchronized reception in time, frequency and phase
- A cooperation area can be constructed so that the UEs inside this area can receive the signals from the different satellites (part of them advance their transmission) at the same time without any frequency misalignment.
- In (*) **OTFS** is adopted to reduce CP and provide more robustness against the Doppler.
- At the same time, the users' transmissions can be allocated different blocks in the delay Doppler domain.





(*) Reliability oriented OTFS-based LEO satellites joint transmission scheme," Globecom' 22, M. Caus, A. Pérez-Neira, et al."

CONCLUSIONS

- Because of their nature satellites provide the best infrastructure for anywhere, anytime and scalable connection
- Satellites are foreseen as key for Earth sustainability services
- 3GPPP standardization evolves 5G NR NTN to gain interoperability (with the same UT)
- Although satellites and launching is much cheaper, New Space requires intensive CAPEX and not clear if 5G demand will cover its costs. nextG panorama offers more potential use cases that require hyperconnectivity.
- OPEX must also help to reduce costs. The main **breakthrough** technologies have been addressed and discussed at PHY level:
  - On board processing and computing
  - FSO Inter Satellite Links
  - Active Antennas and distributed swarm beamforming that enable user-centric beamforming