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THE REVOLUTION OF NEW SPACE TOWARDS NEXT G COMMUNICATION NETWORKS

ANA I. PÉREZ-NEIRA

aperez@cttc.es
Prof. UPC
Director of CTTC
ICREA Academia

Centre Tecnològic de Telecomunicacions de Catalunya

MINISTERIO DE CIENCIA E INNOVACIÓN

AGENCIA ESTATAL DE INVESTIGACIÓN

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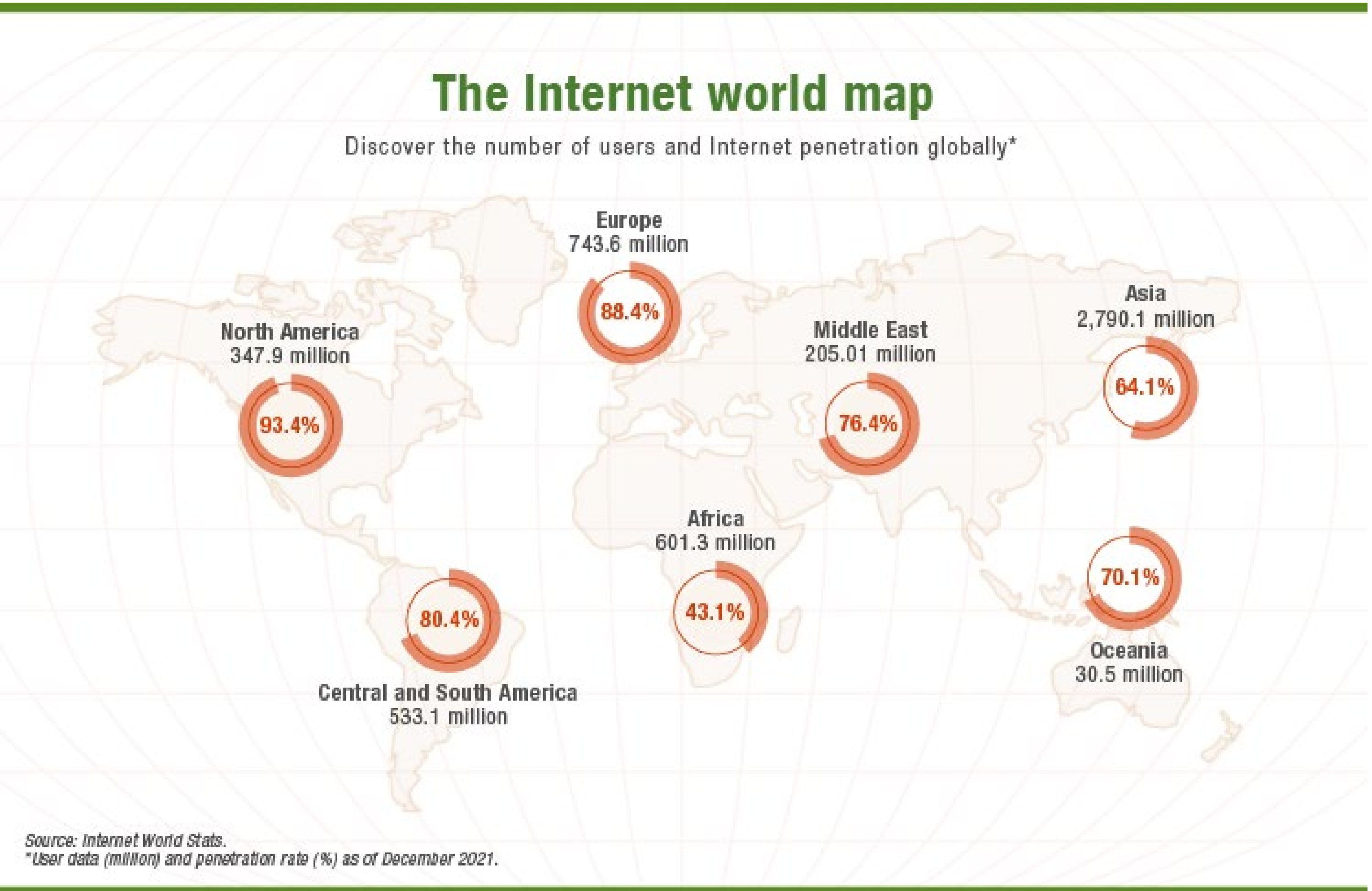
NEXT G: 3D INTEGRATED SATELLITE-TERRESTRIAL COMMUNICATIONS, WHY?

- 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.

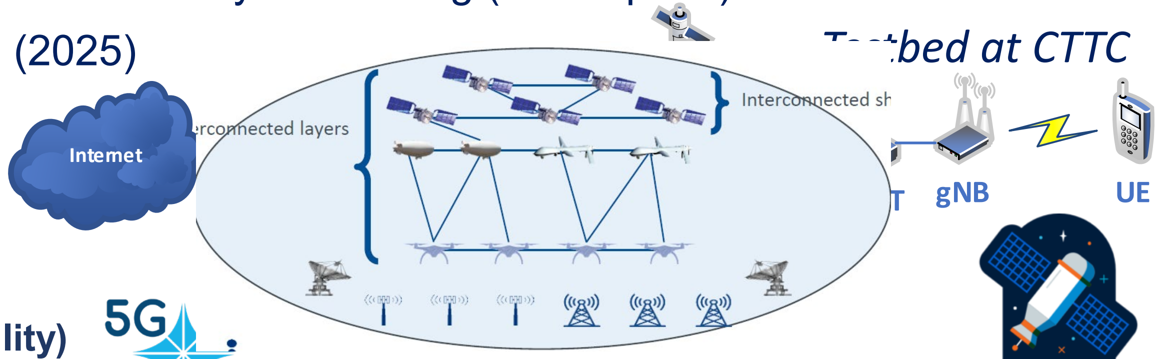
OUTLINE

1. The current evolution of 3D integrated satellite-terrestrial communications.
2. New Space revolution
3. Breakthrough technologies (PHY layer)
4. Joint Communication and computing
    - New waveform
5. Distributed spatial processing
    - In mega-constellations and swarms

HOW 3D? 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 in many countries.
  - The increasing softwarization of the communication networks (SDR, 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)
  - Service continuity between TN and NTN (< 2GHz)
  - Transparent payload architecture
  - Focus on GEO and NGEO satellites
  - Doppler $> \pm 10\ kHz$
  - NR waveform instead of DVB-S2 **(flexibility, interoperability)**
  - **Direct to satellite UE** equipped with GNSS receivers



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 GEO
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**

NEW SPACE REVOLUTION VS EVOLUTION

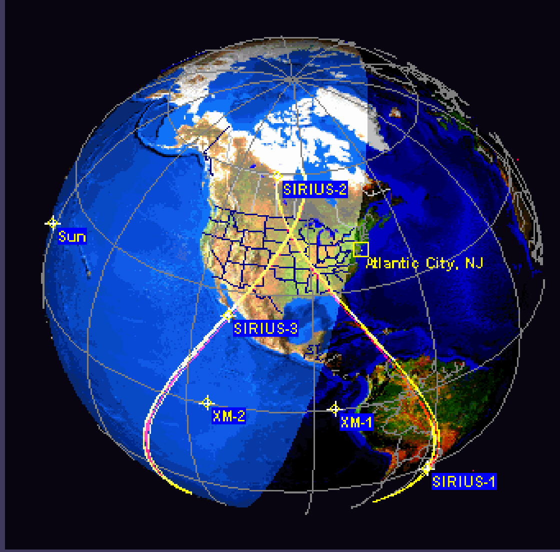
NEW SPACE REVOLUTION: DEMOCRATIZATION OF SPACE

- One of the main differences between the legacy satellite systems and the nextG LEO mega-constellations is the **new architecture and networking complexity → revolution**
  - shifting from high priced satellites to **massive smaller and cheaper ones** (with redundancy)
  - closer to the Earth
  - very high speed interconnecting links (ISL)

- 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)
- **New Space's goals is to reach fast the market, instead of creating customers that are captive of a single vendor/operator technology → NS is more open to incorporate 5G changes and beyond**

(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).


WILD
WILD WEST

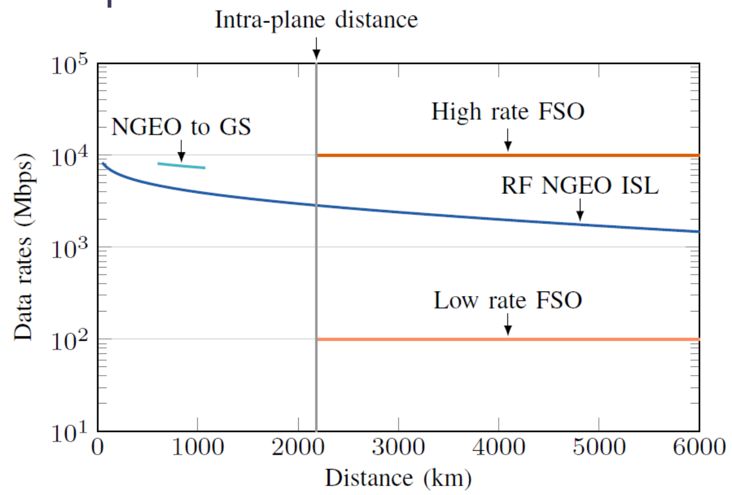


Breakthrough technologies in this revolution

- ISL
- Onboard processing and computing
- Advances in antenna technology

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 represents 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

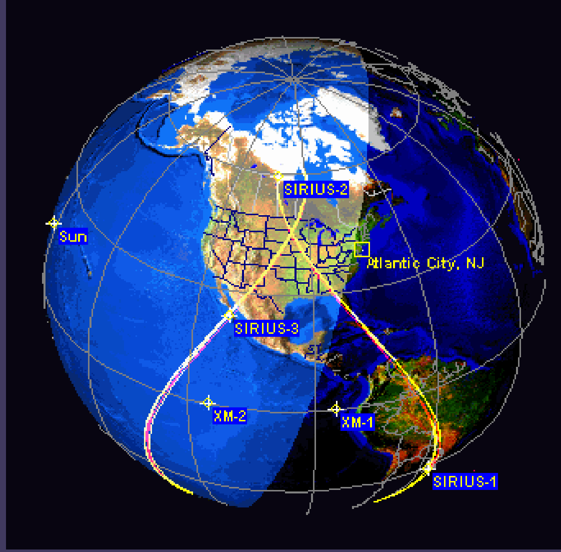
FSO compared to Fiber Optic:

- 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.

Breakthrough technologies in this revolution



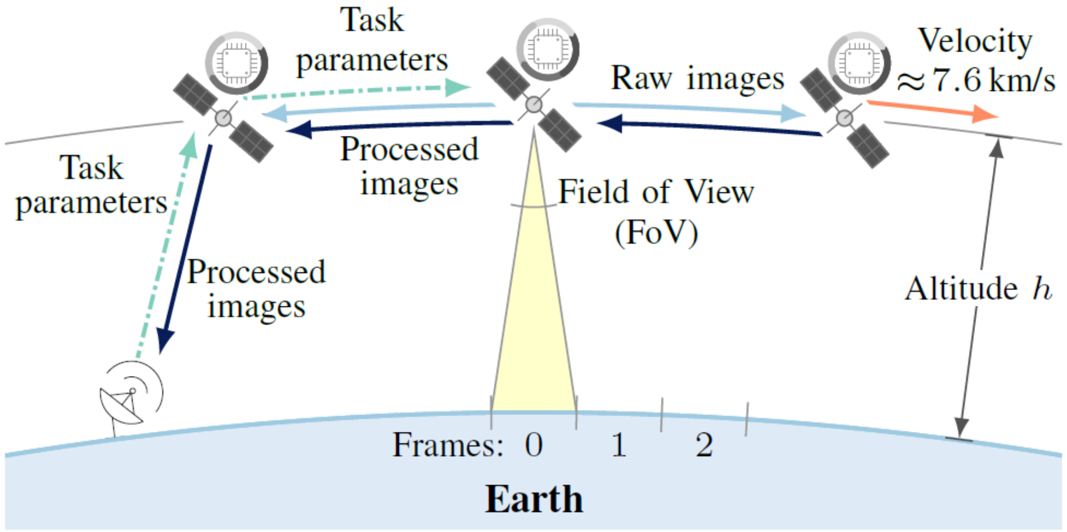
- ISL
- Onboard processing and computing
  New Waveforms: joint Communication and computing
- Advances in antenna technology

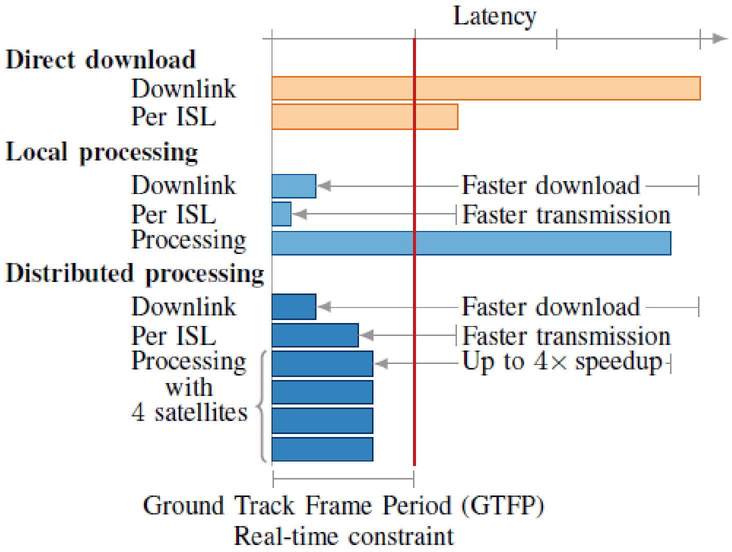
ONBOARD PROCESSING AND COMPUTING

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
- Regenerative payloads for communications
- Multiservice satellites software defined: communications, cloud services (ISL capacity is there),…→ Maximize revenue
- To adapt to changing client needs, markets and applications
- There is a whole **Space economy** that requires processing, processing, …., because it is not so much interested anymore on creating “shiny objects” to be launched but on the service it can provide (**satellite as a service**)
- 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
  - Waveforms for joint computing (distributed) and communicating must be revisited

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)

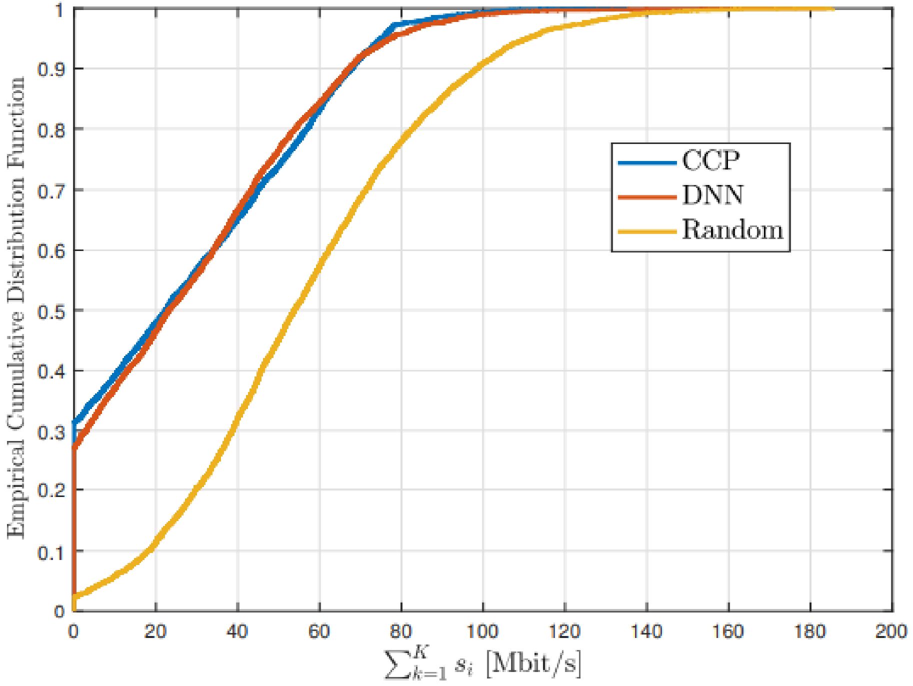
- Israel Leyva-Mayorga, Marc M. Gost, Marco Moretti, Ana Pérez-Neira, Miguel Ángel Vázquez, Petar Popovski, Beatriz Soret, "Satellite edge computing for real-time and very-high resolution Earth observation," IEEE TC, 2023
- M. Martinez Gost, Israel Leyva, A. Perez-Neira, et al., "Edge Computing and Communication 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 where and when resources are needed with 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.

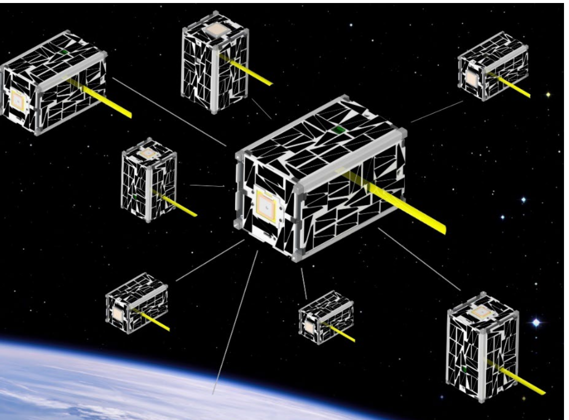
E.g., Elapsed time gain in flexible payload beam and carrier optimization. **Optimization technique based on sequential convex optimization: 62.1 seconds. DNN python implementation in Tensorflow: 0.041 seconds.**



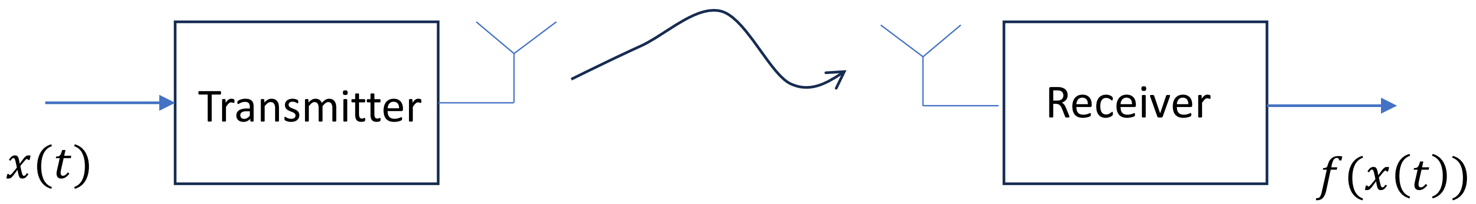
- Miguel Á. Vázquez Pol Henarejos, Ana I. Pérez-Neira , "Learning to Optimize Flexible Payloads," *EUSIPCO 2022*.
- Machine Learning for Satellite Communications Operations, M.A. Vázquez, P. Henarejos, et al., Communications Magazine, Feb 21

NEW WAVEFORM (I): MOTIVATION COMMUNICATION-COMPUTING -SENSING

- **Motivation:** when the observations (e.g., radar, multispectral imagery, altimetric data, or thermal spectroscopy) are generated in more than one satellite, we are facing **distributed sensing architectures** (e.g. due to native space age computing). Then data fusion can be used to enhance the final application results: 1) observation-level fusion, 2) feature-level fusion, and 3) decision-level fusion with prediction capabilities → **computation, in task-oriented communications**



INITIAL ARCHITECTURE



measurement

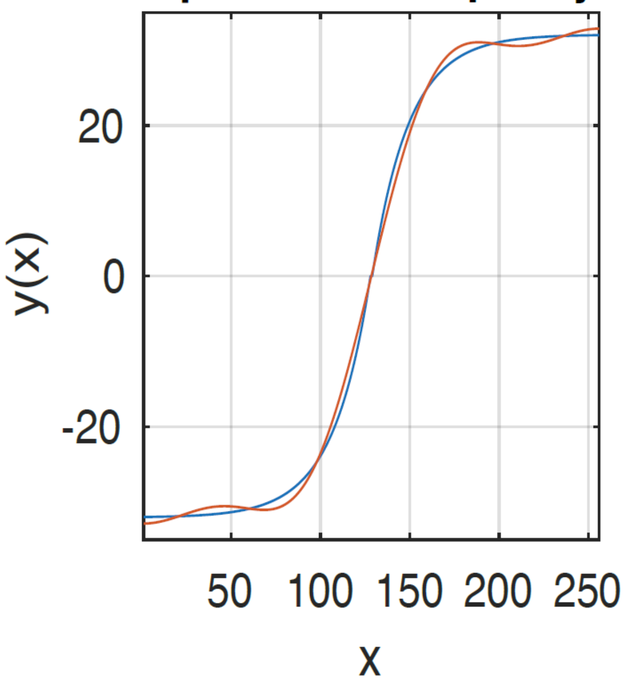
Compute with some fidelity/quality criterion

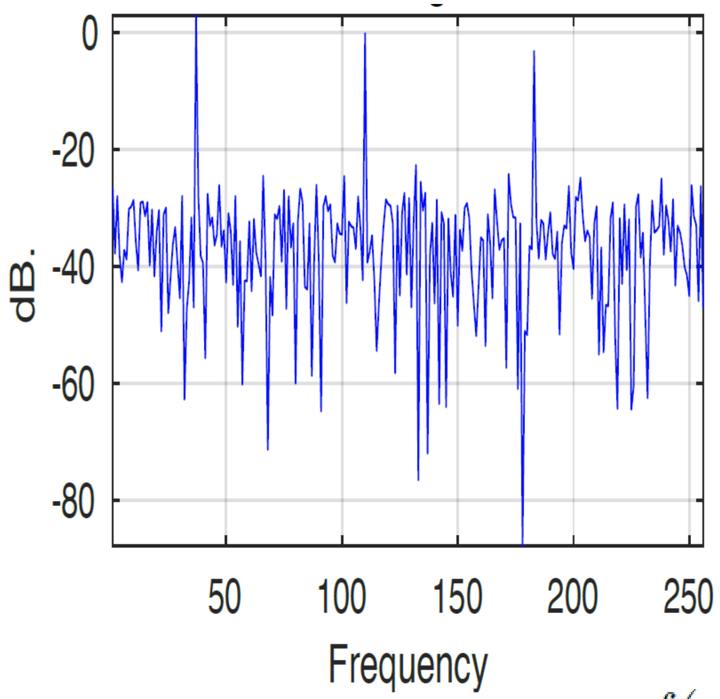
NEW WAVEFORM (2): DCT FOR FUNCTION APPROXIMATION

The DCT (Discret Cosinus Transform) can approximate any function with a minimum number of coefficients

Trade-off between approximation accuracy and bandwidth

Example: Compressor





$$m = 0, \ldots, N-1$$

Compared to other approximations, e.g. Volterra (Taylor expansion):

- Low number of coefficients
- Cte. envelope, orthogonal and real basis functions
- The approximation error distributes uniformly along the range of x
- Good properties for gradient adaptation of the weights

Quantized measurement: m=Q(x)

$$f(m) = \sum_{k=0}^{N-1} g_k F_k \cos\left(\frac{\pi k(2m+1)}{2N}\right)$$

“Adaptive function approximation based on the Discrete Cosine Transform (DCT),” 27th International Conference on Circuits, Systems, Communications and Computers (CSCC), Rhodes Island (Rodos Island), Gree
July 19-22, 2023. Marc Martínez Gost, A. Pérez-Neira, Miguel A. Lagunas

NEW WAVEFORM (3): DCT BASED AIR INTERFACE

Quantized measurement: m=Q(x)

$$f(m) = \sum_{k=0}^{N-1} g_k F_k \cos\left(\frac{\pi k(2m+1)}{2N}\right) \qquad m = 0, \ldots, N-1$$

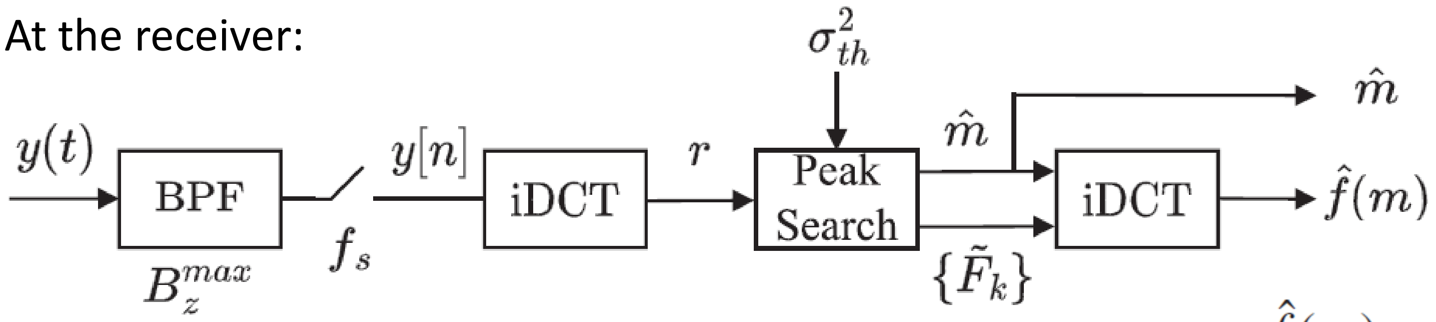
Basic idea: we propose a DCT based waveform for the task of estimation and function approximation.

Time index

$$z[n] = A_c \sqrt{\frac{2}{N}} \sum_{k \in \mathcal{K}} F_k \cos\left(\frac{\pi k(2m+1)}{2N} n\right)$$

N-FSK

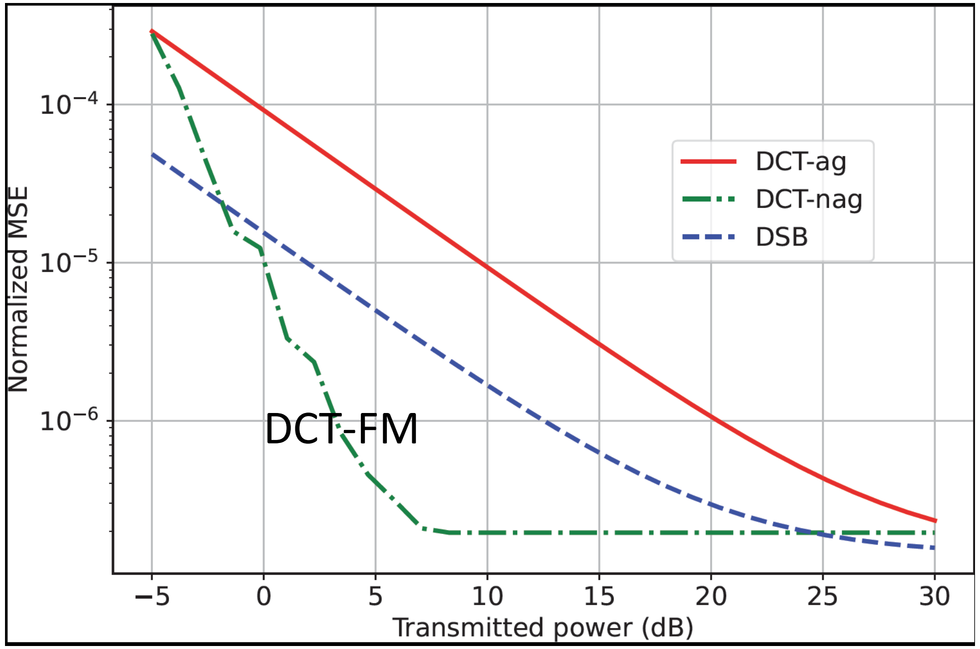
At the receiver:



$$\hat{f}(m) = \sqrt{\frac{2}{N}} \sum_{k \in \mathcal{K}'} \tilde{F}[k] \cos\left(\frac{\pi k(2m+1)}{2N}\right)$$

"DCT-Based Air Interface Design for Function Computation," IEEE Open Journal for Signal Processing, 2023, M. Martínez, A. Perez-Neira, M.A.Lagunas.

NEW WAVEFORM (4): DCT-FM



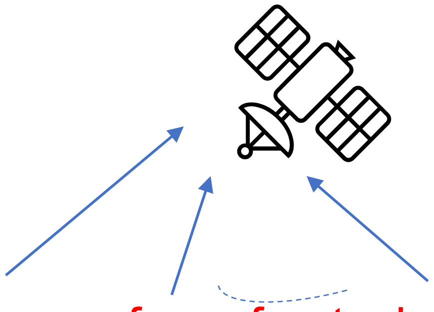
Average error, *MSE*(*f, K*), for the sigmoid function with *K* = 3 coefficient.

Next, we simplify the transmitted DCT waveform as:

$$z_{an}[n] = A_c\sqrt{\frac{2}{N}}\exp\left(j\frac{\pi(2m+1)}{2N}n\right)$$ Narrow band FM

$$MSE(f,K) = \frac{1}{N}\sum_{k\notin\mathcal{K}} F_k^2 + P_e\sum_{m=0}^{N-1}|f(m)-f(\hat{m})|^2$$

$$P_e \approx (N-1)Q\left(\sqrt{\frac{A_c^2|h|^2}{N_o}}\right)$$



In fact, **the LoRa waveform, used for Sat-IoT, reads as**:

$$z_{LoRa}[n] = z_{an}[n]\exp\left(j\frac{\pi f_{mod}}{N}n^2\right)$$

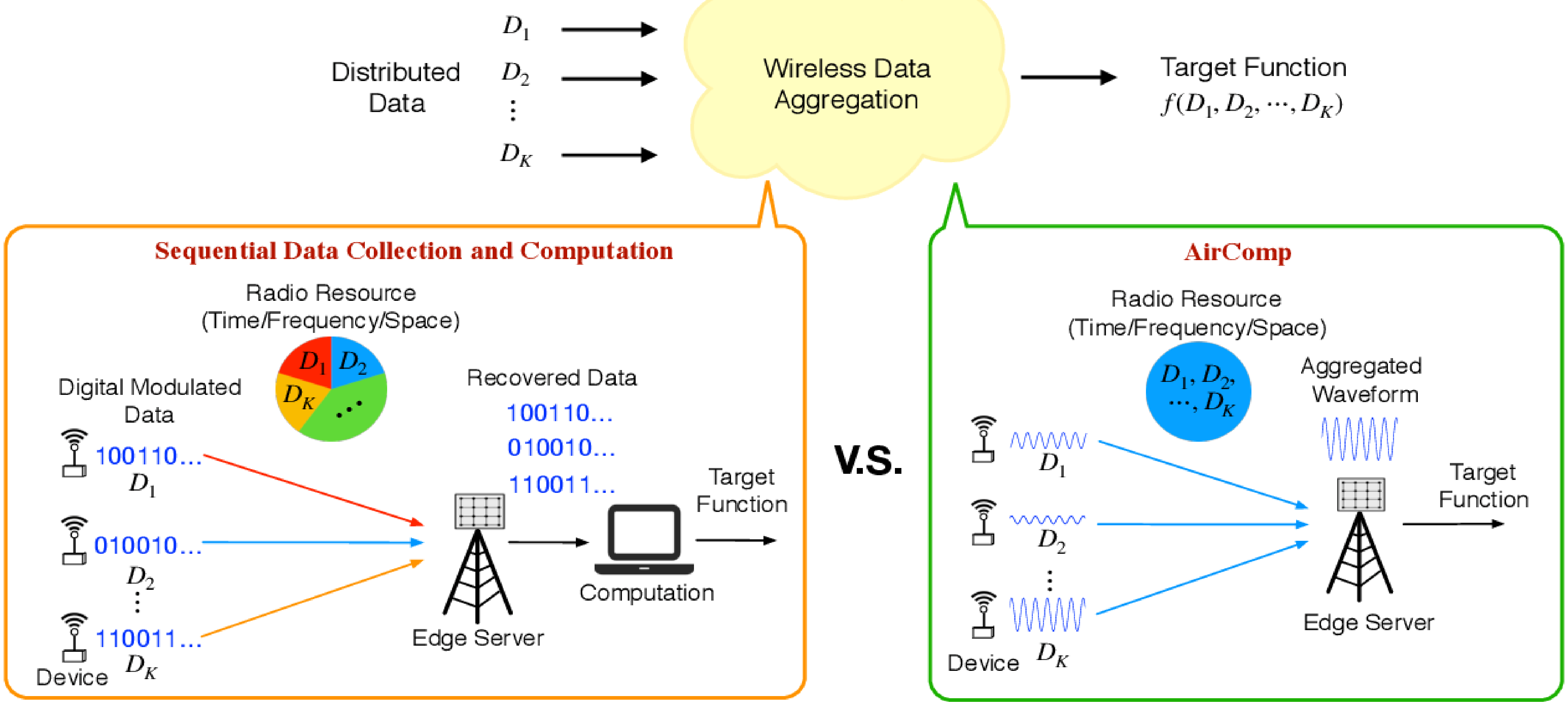
with the proposed DCT-FM focus for function approximation

LoRa provides a suitable waveform for task-oriented purposes

We extend its use for Over-the-Air computing access

SECOND ARCHITECTURE: MANY TO ONE

Over-the-air-computing:



B. Nazer and M. Gastpar, "Computation Over Multiple-Access Channels," in IEEE Transactions on Information Theory, vol. 53, no. 10, pp. 3498-3516, Oct. 2007, doi: 10.1109/TIT.2007.904785.

AM: $y(t) = x_1(t) + x_2(t) + \cdots + x_K(t)$

NEW WAVEFORM (5): DCT-FM FOR OTA ACCESS

$$\exp(jw_1) + \exp(jw_2) \neq \exp(j(w_1+w_2))$$

The received waveform with simultaneous L transmissions (from **L** different sensors), each conveying a different realization of the same measurement, reads as:

$$y[n] = \sum_{l=1}^{L} A_c h_l z_l[n] + w[n],$$

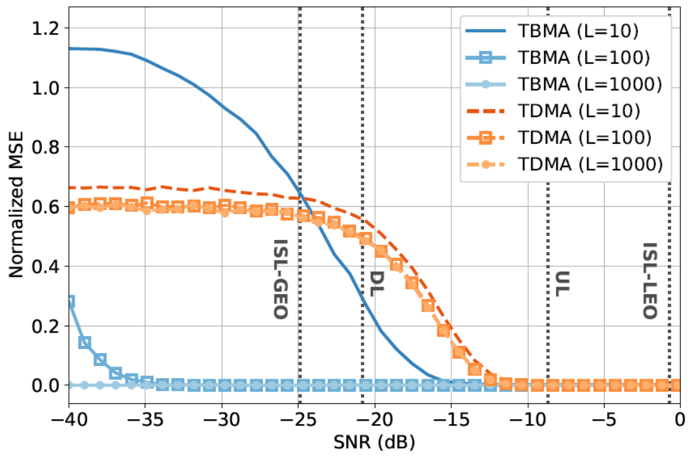
$$z_l[n] = A_c \sqrt{\frac{2}{N}} \cos\left(\frac{\pi(2m_l+1)}{2N} n\right)$$

After DCT at the receiver (if **L>N** freq. bins)

$$\mathbf{r} = \frac{1}{L}[L_0, \ldots, L_{N-1}]^T + [\tilde{w}_0, \ldots, \tilde{w}_{N-1}]^T = \tilde{\mathbf{p}}_\theta + \tilde{\mathbf{w}}$$

pdf

DCT-FM can also benefit from the aggregation property of OTA, good for even low SNR



Normalized MSE in estimating the mean of a random Gaussian process with TBMA and TDMA for $L = \{10, 100, 1000\}$ users for the different scenarios. In vertical dotted lines the working SNR for the different scenarios are indicated.

N=512

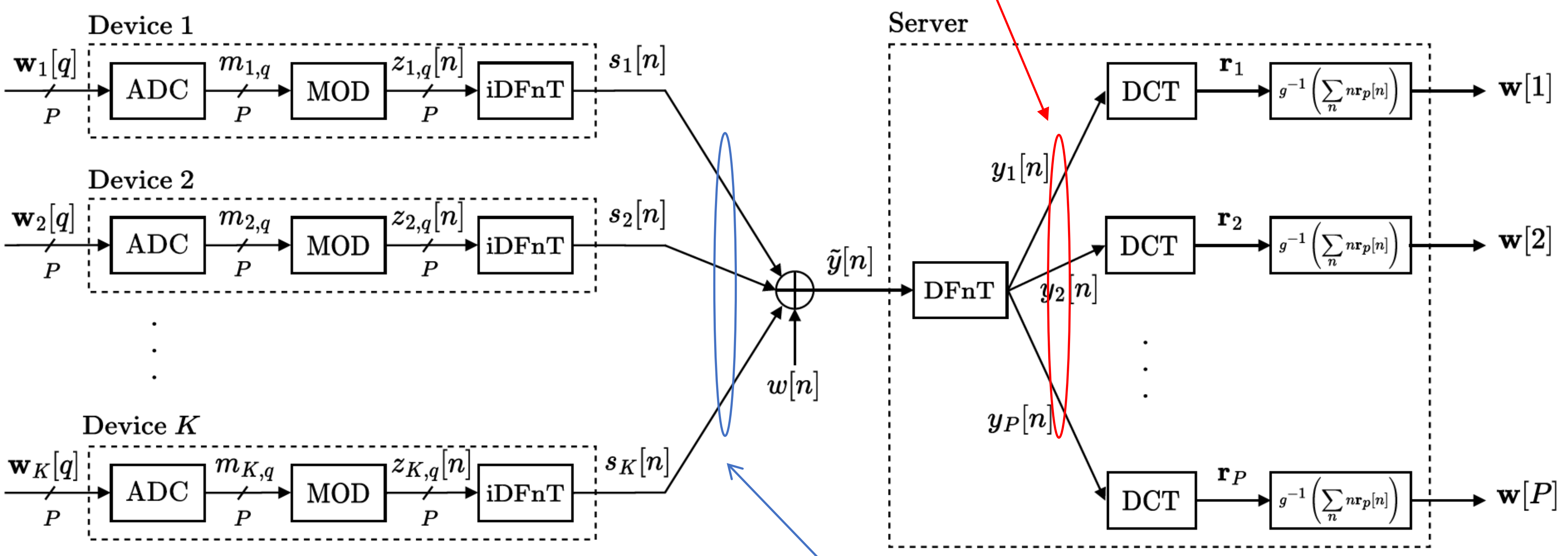
"LORA-BASED OVER-THE-AIR COMPUTING FOR SAT IOT," EUSIPCO 2023. Marc Martínez Gost, A. Pérez-Neira, Miguel A. Lagunas

NEW WAVEFORM (6): DCT-FM FOR OTA ACCESS

Now we use it for distributed computing: federated learning.

Assign orthogonal resources to different parameters, in LoRa (DCT-FM) Multiple access is carried out thanks to Orthogonal Chirp Division Multiplexing (OCDM).

Each device senses P different parameters, each one on a different chirp.



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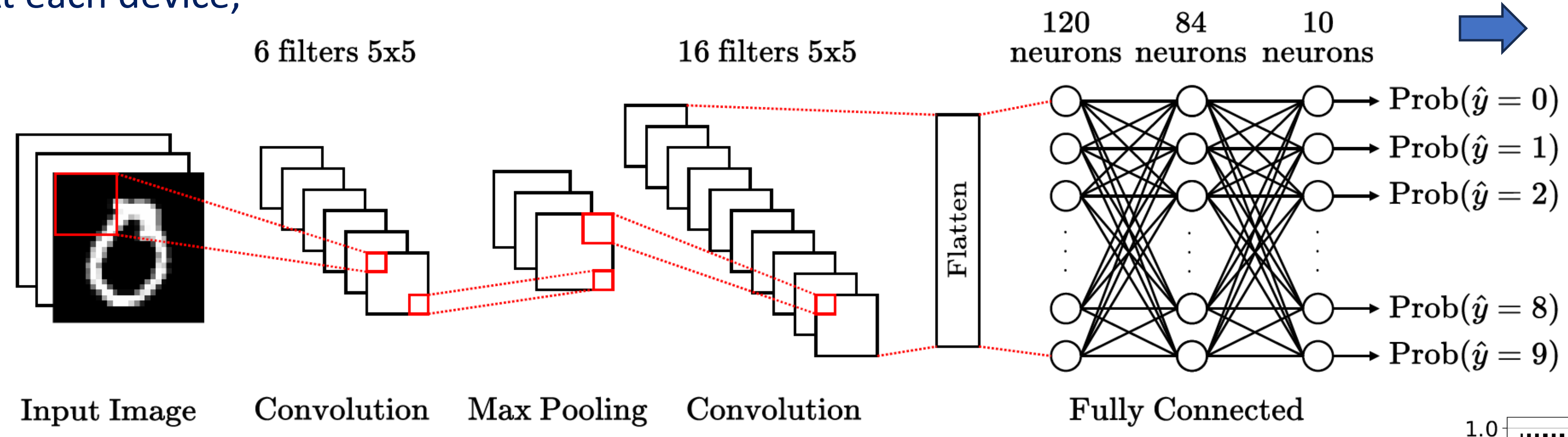
exing

The same parameter is sent with OTA by all the sensors

“Frequency Modulation Aggregation for Federated Learning,” Globecom 2023. Marc Martínez Gost, A. Pérez-Neira, Miguel A. Lagunas

NEW WAVEFORM (7): DCT-FM FOR FEDERATED

At each device,

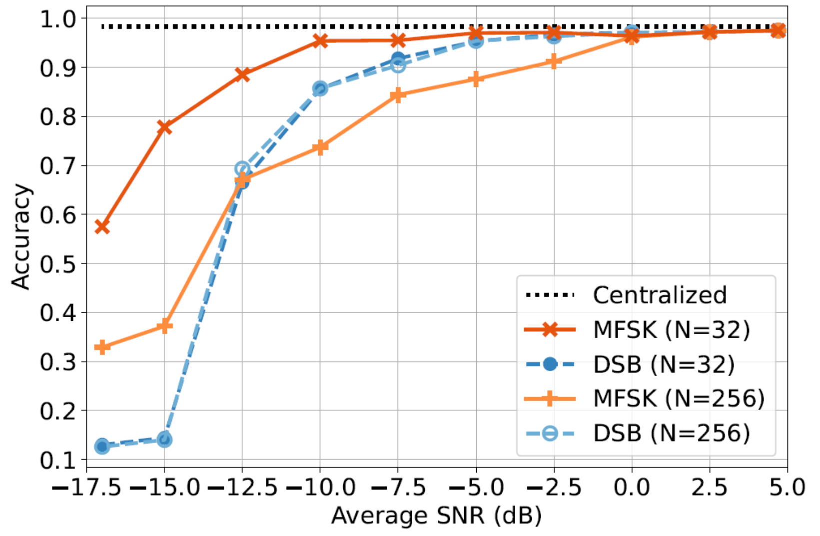


many parameters

50 devices
P= 50.000 parameters

Cross-entropy

DCT-FM OTA much better than simply aggregation

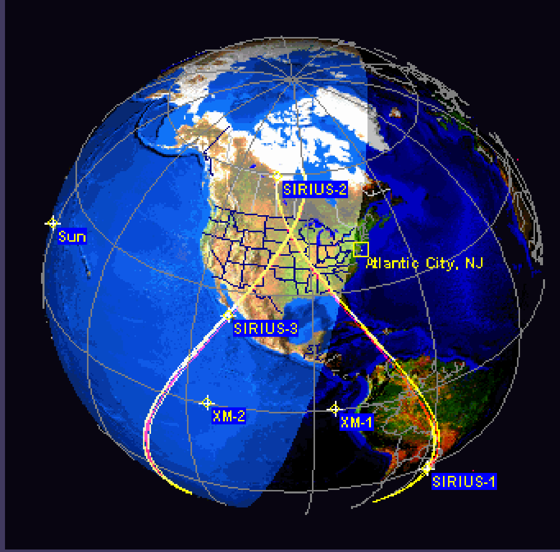


Accuracy of the FEEL system for the digital frequency modulation (MFSK) and the linear analog modulation (DSB) for $N = \{32, 256\}$, along with the upper bound of a centralized trained model.

& SPLIT LEARNING

"LoRa modulation for split Learning," IEEE Campsap 2023. Marc Martínez Gost, A. Pérez-Neira, Miguel A. Lagunas

The goodness of FM



Breakthrough technologies in this revolution

- ISL
- Onboard processing and computing
- Advances in antenna technology:

  Distributed beamforming with a swarm of satellites

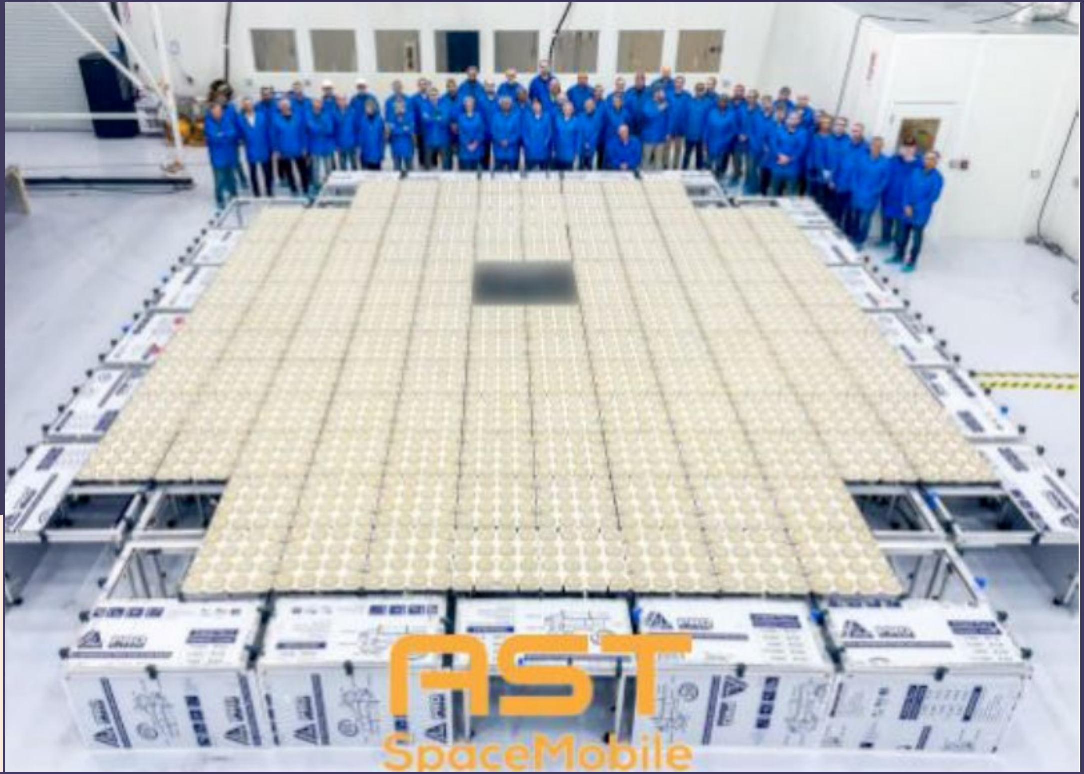
Advances in antenna technologies: PHASED ARRAY (PA)

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?), …

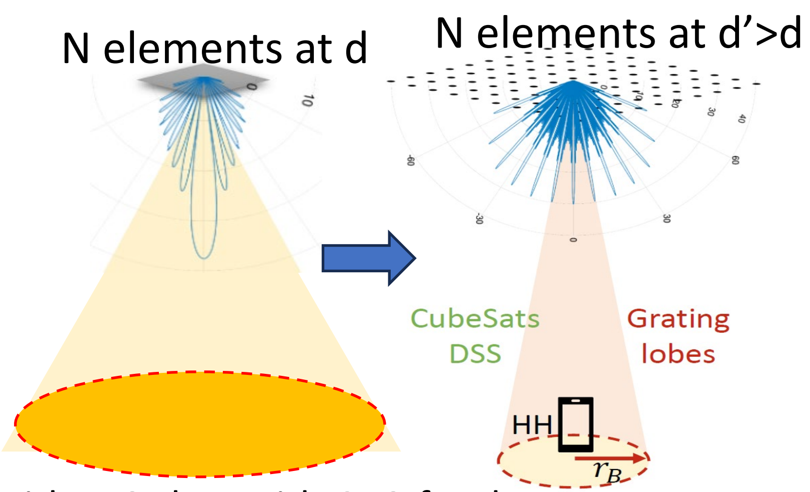


TO LESS "CLASSICAL" DISTRIBUTED BEAMFORMING FOR 6G DIRECT UE CONNECTIVITY

- 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 closer 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.

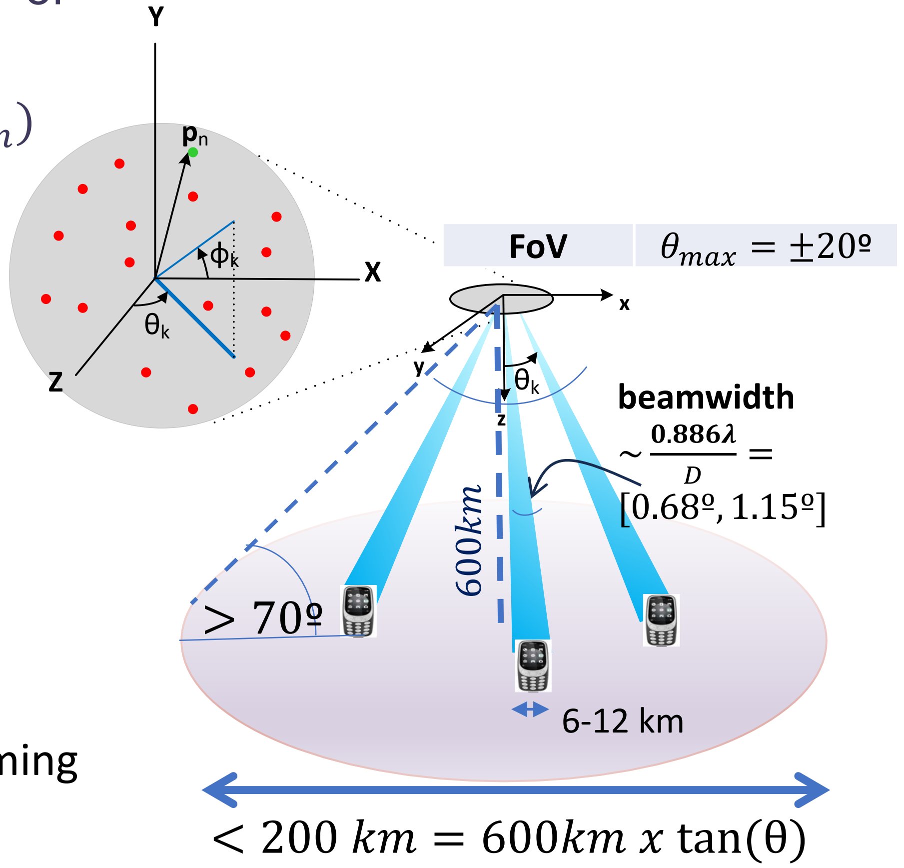
1. SCENARIO MODELING: SWARM GEOMETRY

- 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

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

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

To be shaped with the transmit beamforming



With LoS:

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

1. SCENARIO MODELLING: TIMING REQUIREMENTS AND SPATIAL PROCESSING

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

$$\frac{D}{c} \ll \frac{1}{B} \rightarrow \{\tau_{n,k} - \tau_{min,k}\} \ll T_s$$

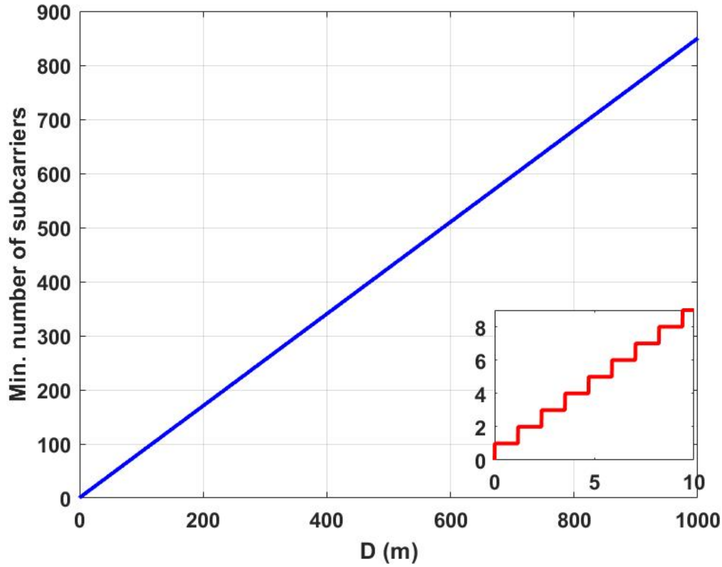
- **Narrow band array condition**: If the differential delays $\{\tau_{n,k} - \tau_{min,k}\}$ do not exceed $\pm$7.5% of the symbol period, ISI can be neglected

- 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

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 (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)

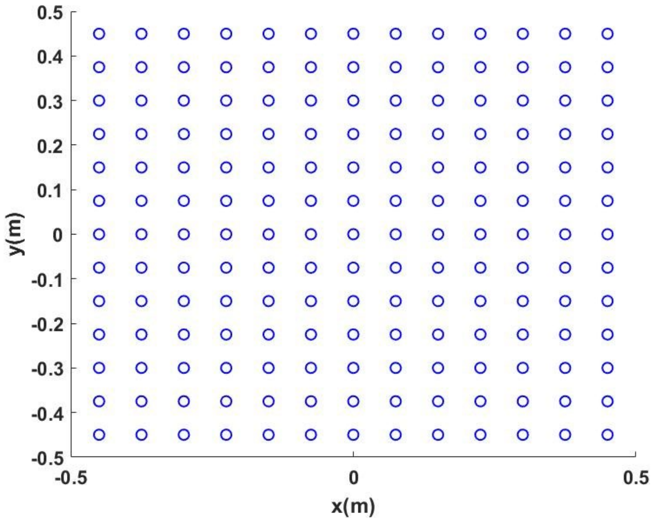
Variable nº antennas/satellites:
13x13: UPA of 1 m2
RA/UA of Diameter=50m
26x26: UPA of 2 m2
RA/UA of Diameter=100m
52x52: UPA of 4 m2 (Bluewalker3)
RA/UA of Diameter=200m

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)

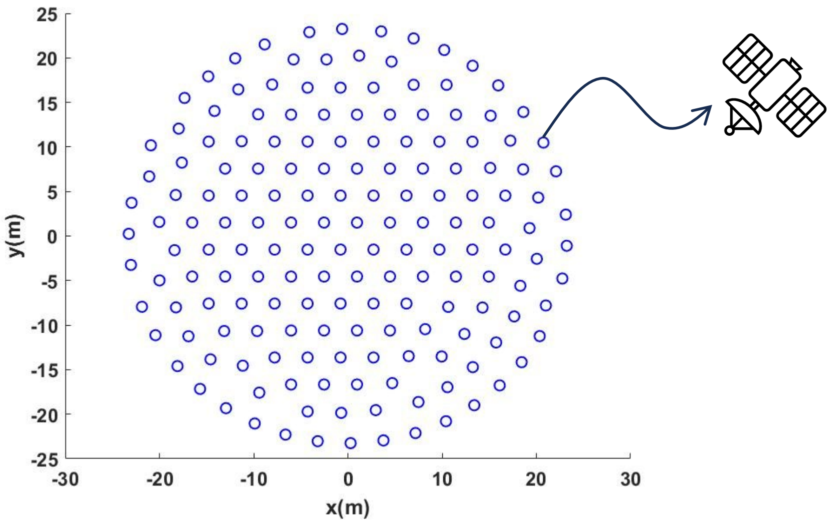
3GPPP for handheld UT (rx SNR $[0, 15]$) dB

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

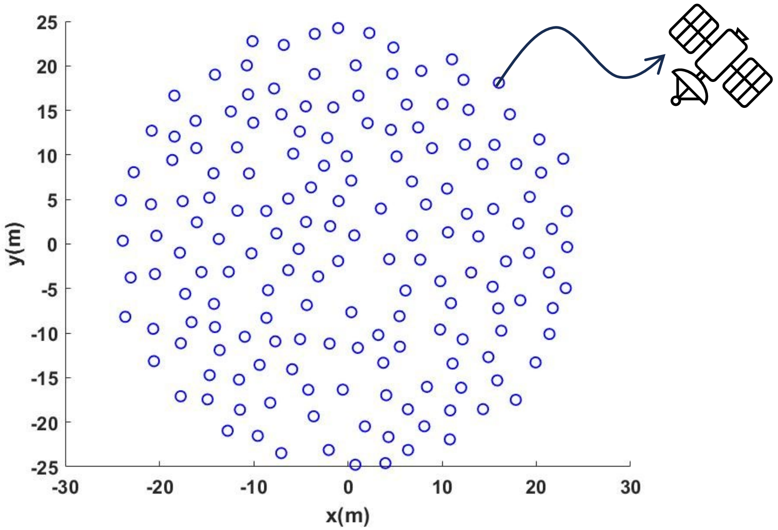
BENCHMARK: Array of col-located antennas



Uniform **Swarm** of satellites



Random **Swarm** of satellites



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

Collocated antennas in UPA at $\lambda/2$=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

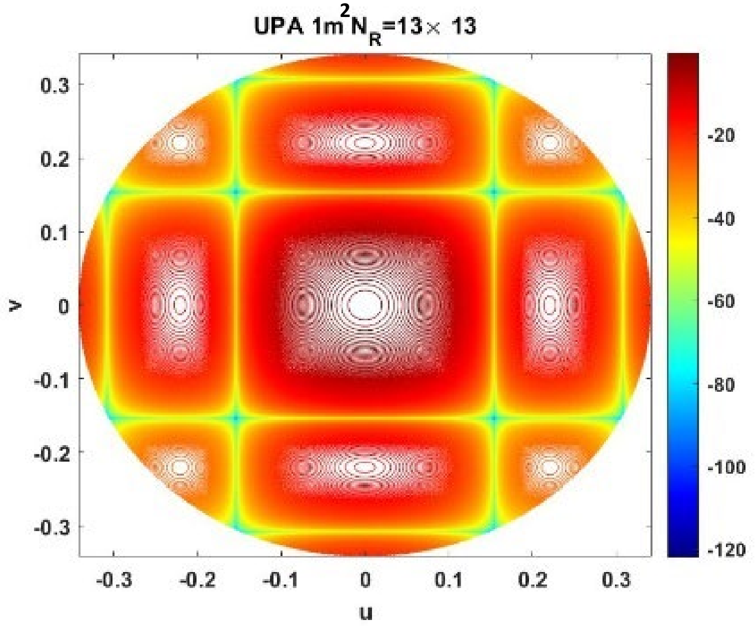
Problem: grating lobes within the FoV

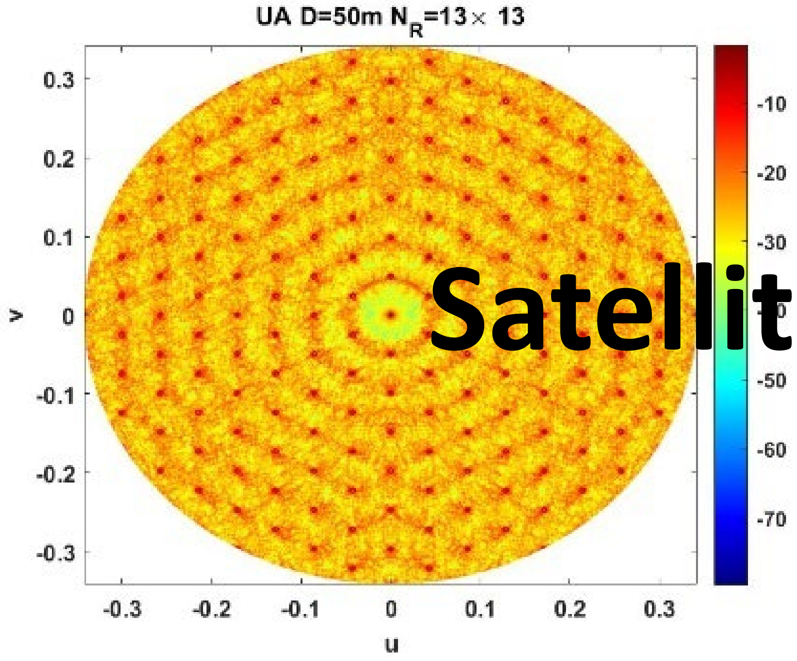
Swarm of satellites random (RA) at 2.5 m

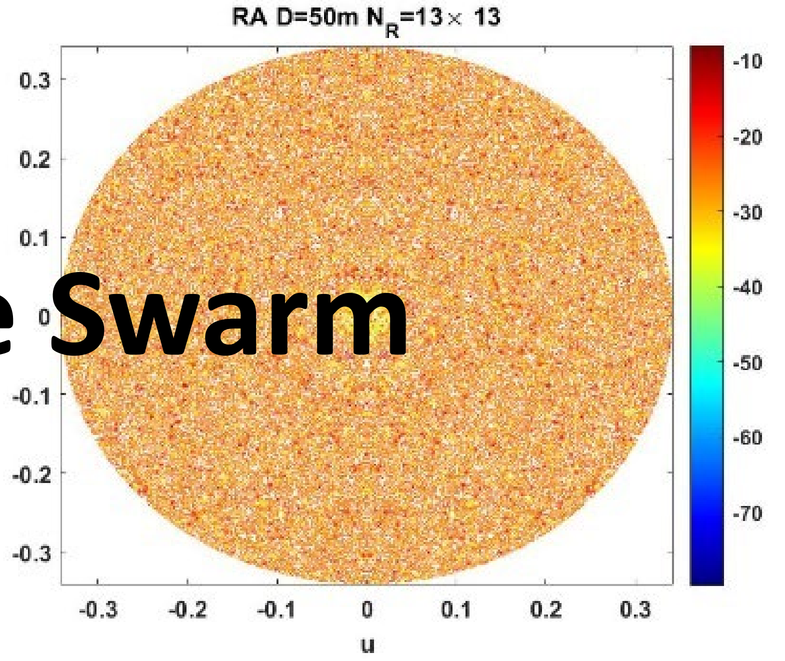
3dB-beamwidth is 0.18º (1.89 km)

max. SLL is -11.5dB

No grating lobes







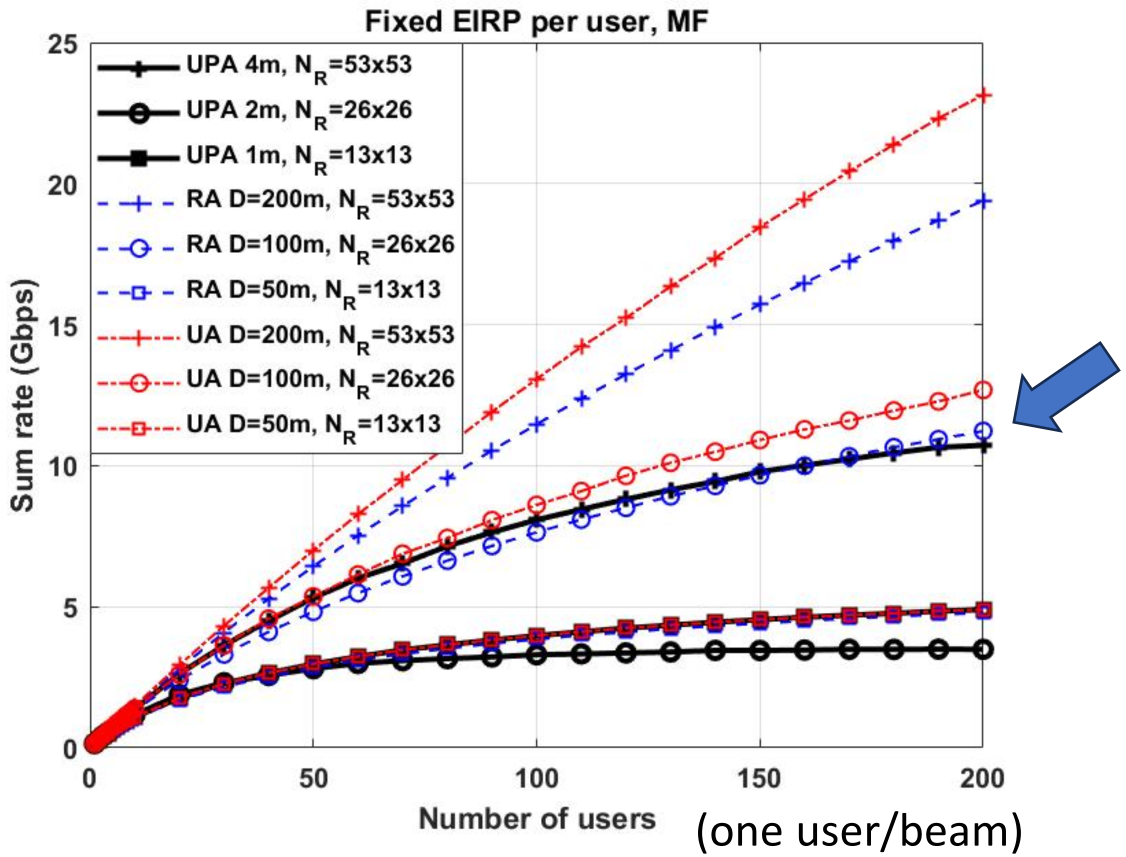
Satellite Swarm

Same number of antennas but lower antenna density in the swarms

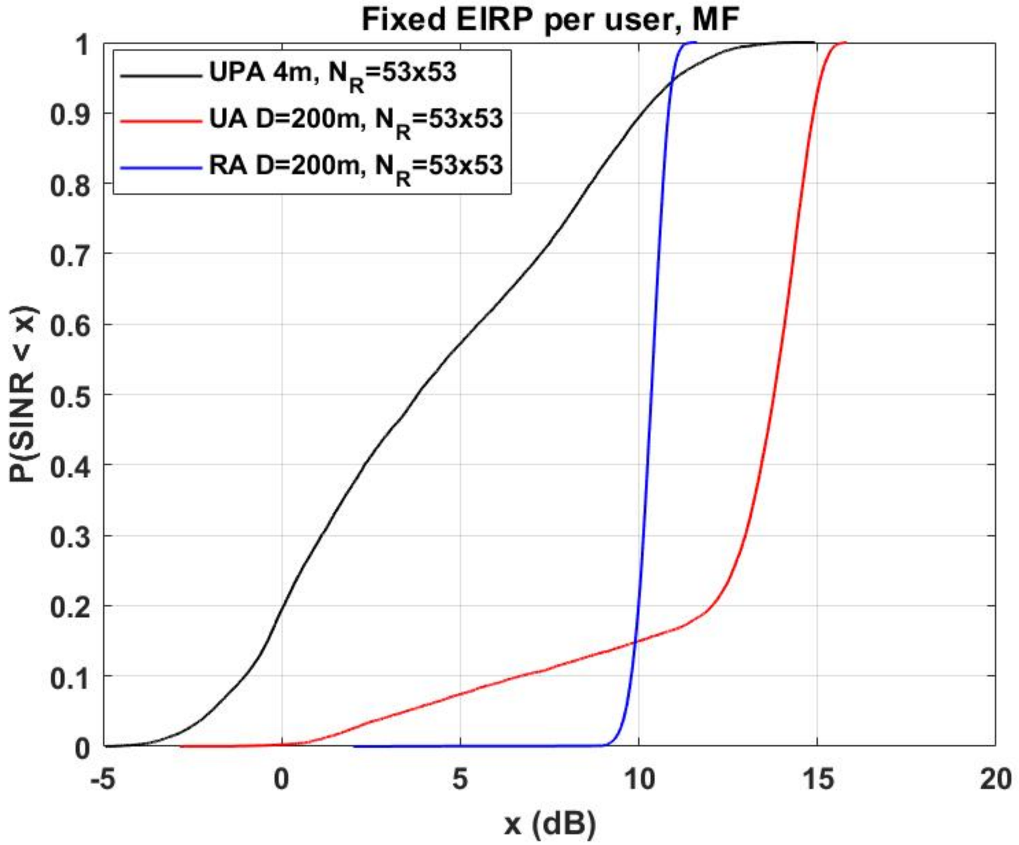
- The highest side lobe suppression is provided by UPA
- UA and RA achieve higher angular resolution at the expenses of increasing the side lobe level

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 $1.5\lambda_c \longrightarrow D = 1m$
- UA outperforms RA in sum rate but providing a more unbalanced SINR among users



(one user/beam)



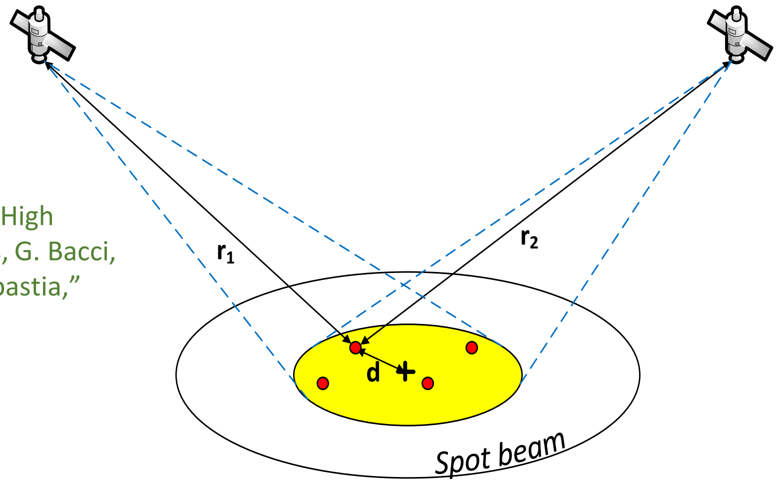
Larger apertures with lower nº satellites (cost and launching are relevant system KPIs)

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
    - 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.
- **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



A different focus/work line:

- No CSIT is needed
- Diversity combining is done at rx

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

CONCLUSION

- 3GPPP standardization evolves 5G NR NTN to gain interoperability (with the same UT)

- New Space revolution helps in the evolution towards 3D networks

- OPEX must also help to reduce costs. Main **breakthrough** technologies have been addressed and discussed at PHY level:
  - FSO Inter Satellite Links
  - On board processing and computing: waveform DCT-FM
  - Active Antennas and distributed beamforming: swarm satellites that enable user-centric beamforming

Thank you!

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ana.perez@cttc.es

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