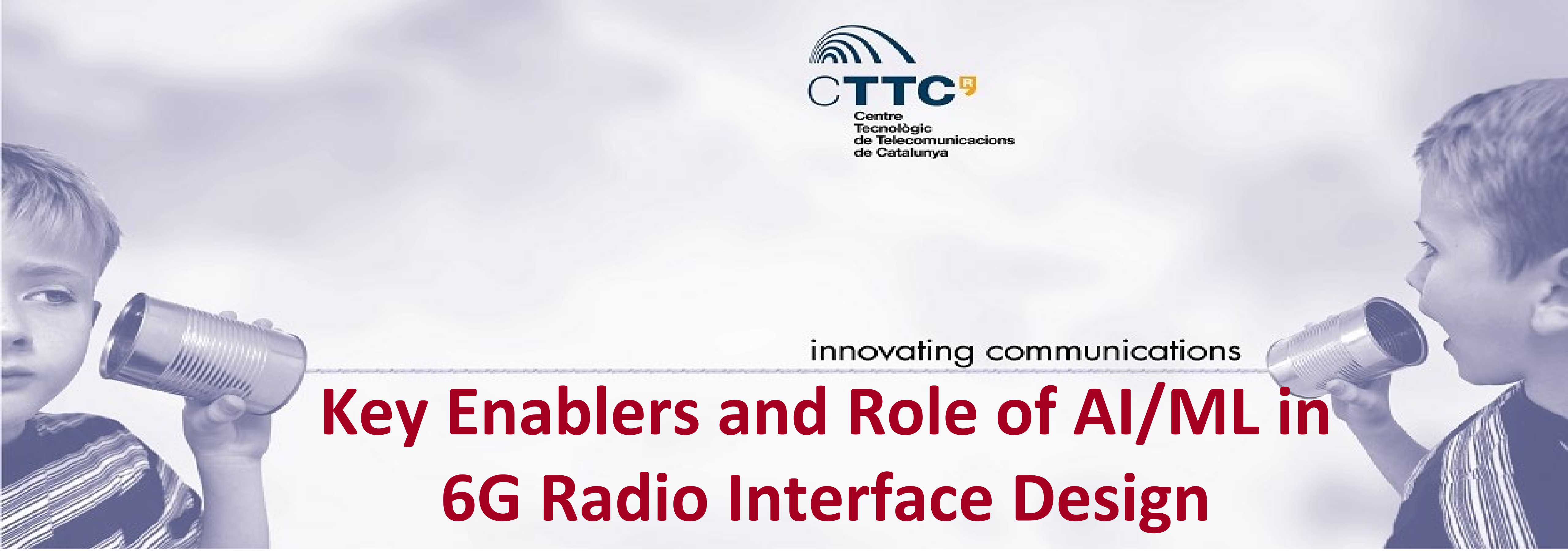


Key Enablers and Role of AI/ML in 6G Radio Interface Design

An academic view

Carles Antón-Haro, PhD, MBA

Director of R&D Programmes, Research Director (R4)

carles.anton@cttc.es

AENOR
ER
Gestión I+D+i
UNE 166002
IDI-0024/2011

tecnio catalonia
ACCIÓ
Generalitat de Catalunya
Fins a 31/12/2019

one6G Summit 2021 - 10 November 2021

AGENDA

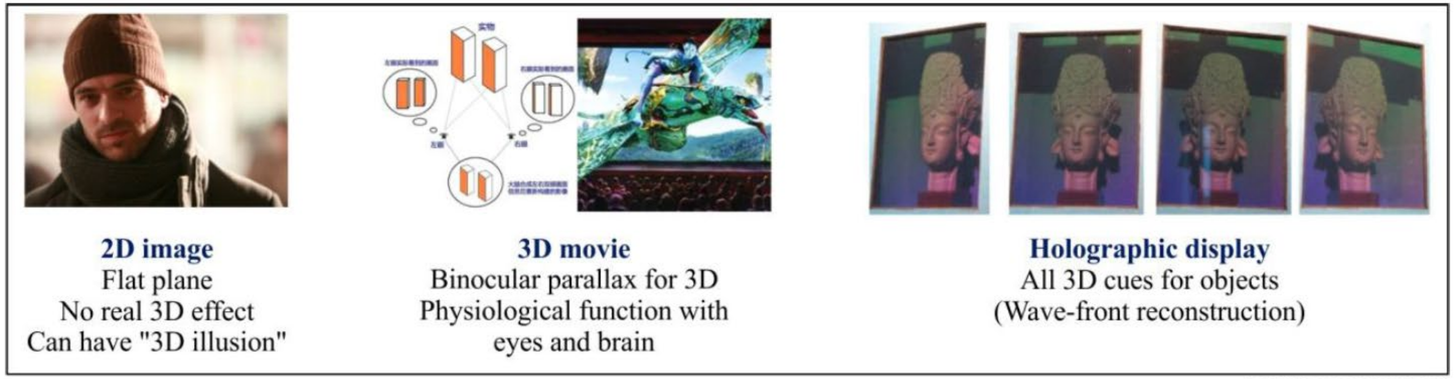
- Overview of new use cases, technical requirements and KPIs for 6G.
- Key enablers for 6G radio interface designs.
- Role of AI/ML in 6G radio interface design, examples.
- Conclusions

AGENDA

- **Overview of new use cases, technical requirements and KPIs for 6G.**
- Key enablers for 6G radio interface designs.
- Role of AI/ML in 6G radio interface design, examples.
- Conclusions

6G NEW USE CASES, A SAMPLE [ITU20]

- **<u>Holographic Communications</u>**:

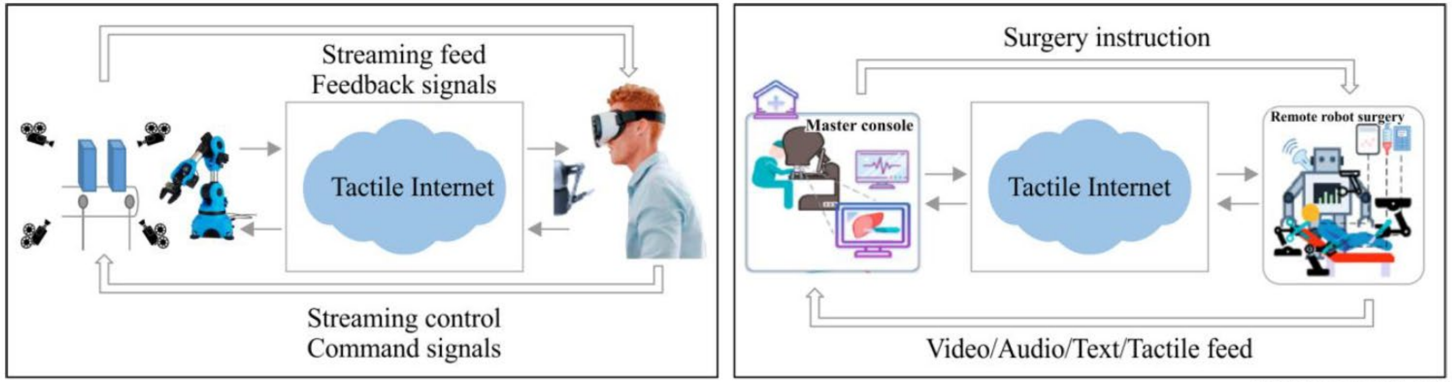


FG-NET2030.3(20)_F01

- Media.
- Improved ehealth/remote education.
- Remote troubleshooting.

  - Combination of very high data rates (Tbps), ultra low latency (sub-ms), synchronization (multi-sense/flow).

- **<u>Tactile Internet for remote operations</u>**: Real-time audio/visual monitoring + haptic/tactile control



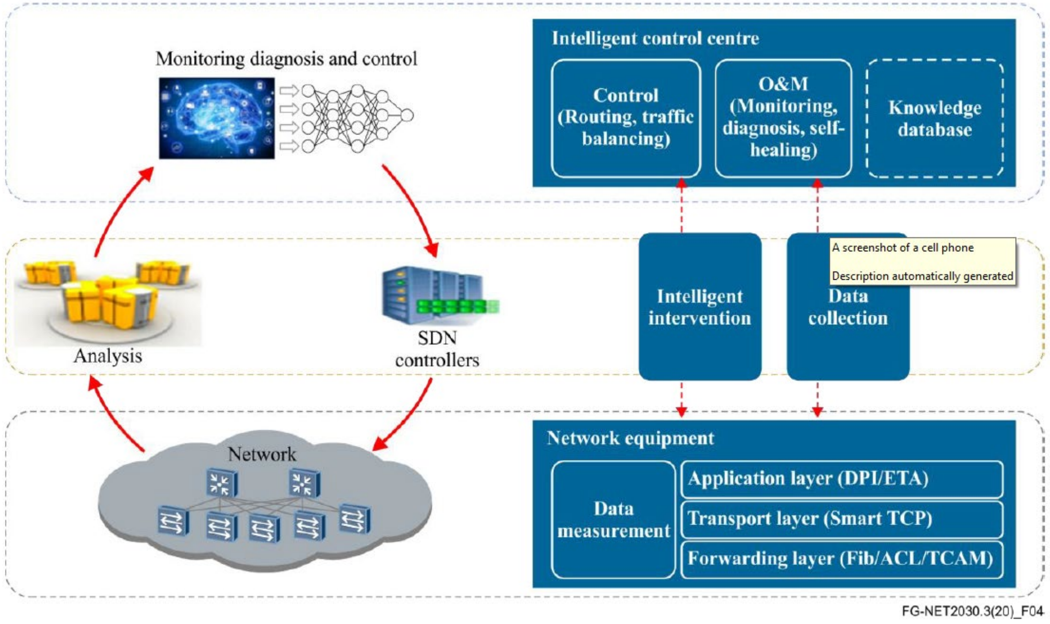
FG-NET2030.3(20)_F03

  - ms-scale e2e latency + sub-ms latency for instantaneous haptic feedback, 99.9999% reliability and higher

6G NEW USE CASES, A SAMPLE [ITU20]

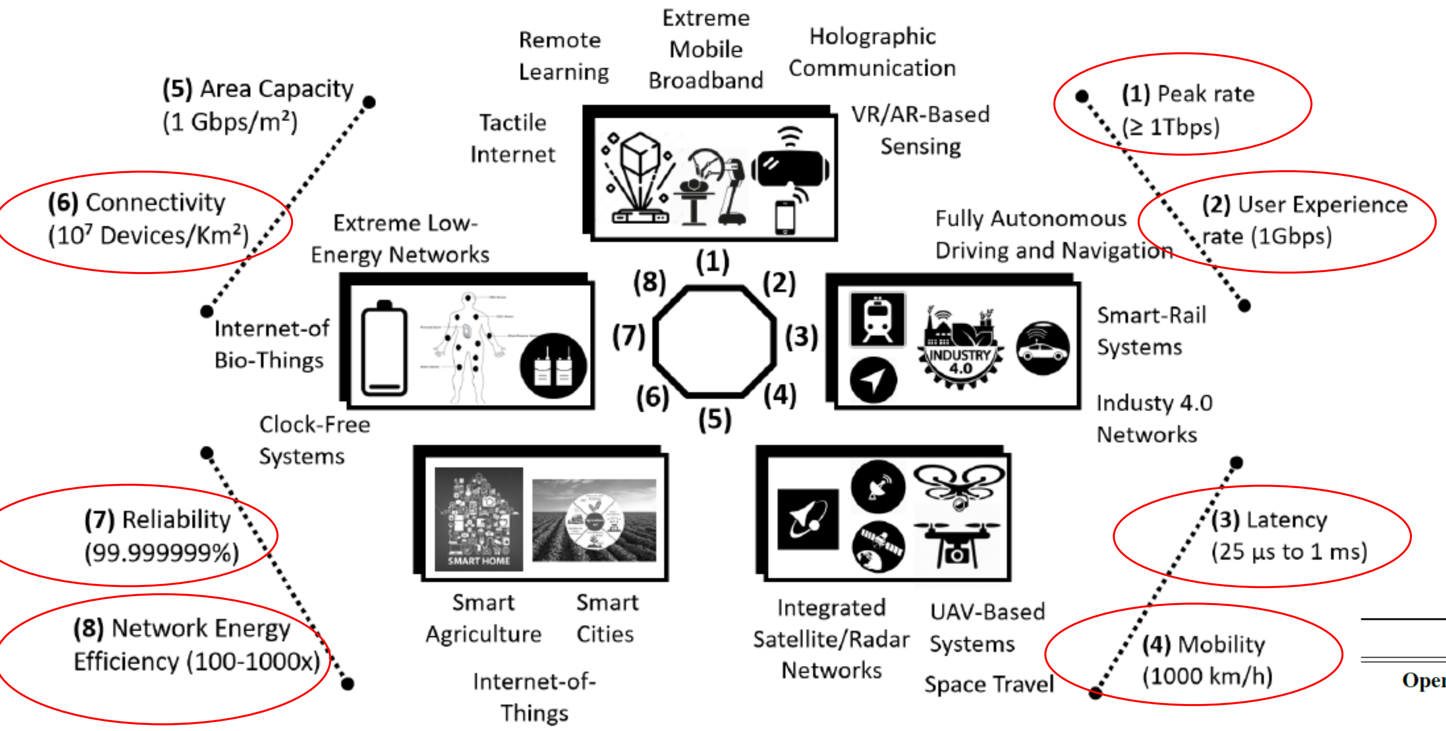
- **<u>Connectivity for everything</u>**: real-time monitoring of buildings, cities, cars, critical infrastructure, wearable devices, intra-body comms, water and power supplies…
  - Increased device density: much beyond mMTC.
  - Large aggregated data rates (#devices), high security and privacy (medical).

- **<u>Automated and Intelligent network operation:</u>** To cope with increased flexibility and complexity.



- Low latency (ms/sub-ms) to collect data, real-time analysis and trigger optimization if needed – closed loop control.
- AI for feature and pattern recognition.
- High-bandwidth instantaneous data collection for network status

TECHNICAL REQUIREMENTS AND KPIs FOR 6G



[ITU20] and [Tat21]

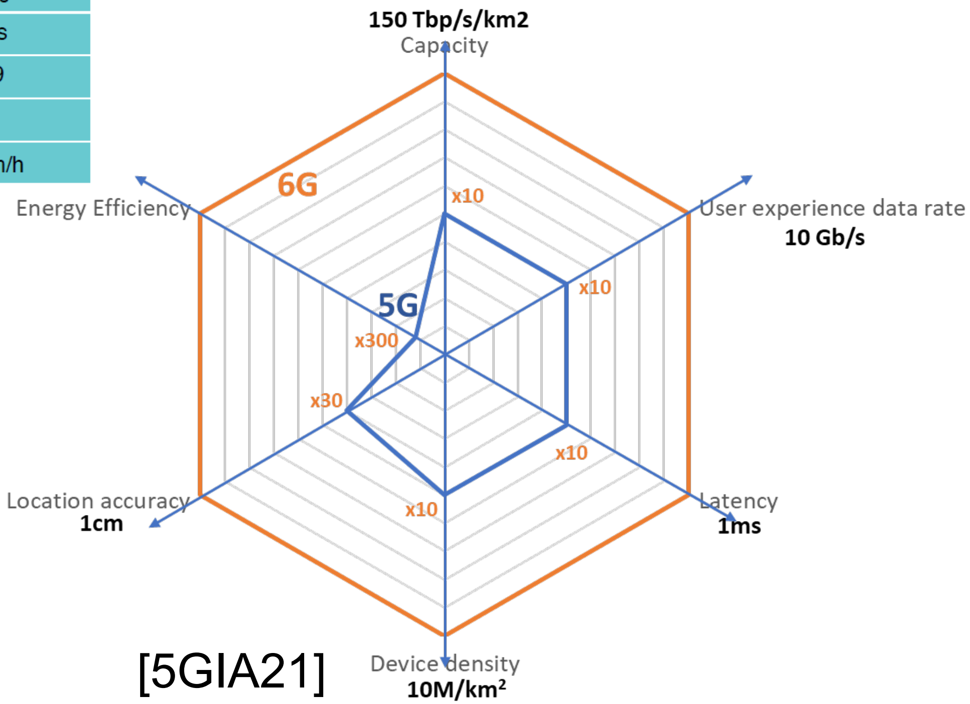
KPI	5G	6G
Operating Bandwidth	Up to 400 MHz for sub-6 GHz bands (band dependent) Up to 3.25 GHz for mmWave bands	Up to 400 MHz for sub-6 GHz bands Up to 3.25 GHz for mmWave bands Indicative value: 10-100 GHz for THz bands
Carrier Bandwidth	400 MHz	To be defined
Peak Data Rate	20 Gbps	≥1 Tbps (Holographic, VR/AR, and tactile applications)
User Experience Rate	100 Mbps	1 Gbps
Average Spectral Efficiency	7.8 bps/Hz (DL) and 5.4 bps/Hz (UL)	1× that of 5G
Connection Density	10^6 devices/km^2	10^7 devices/km^2
User Plane Latency	4 ms (eMBB) and 1 ms (uRLLC)	25 μs to 1 ms (Holographic, VR/AR and tactile applications)
Control Plane Latency	20 ms	20 ms
Mobility	500 km/h	1000 km/h Handling multiple moving platforms
Mobility Interruption Time	0 ms (uRLLC)	0 ms (Holographic, VR/AR and tactile applications)

TECHNICAL REQUIREMENTS AND KPIs FOR 6G (cont'd)

KPI	5G	6G
Peak data rate	20 Gb/s	1 Tb/s
Experienced data rate	0.1 Gb/s	1 Gb/s
Peak spectral efficiency	30 b/s/Hz	60 b/s/Hz
Experienced spectral efficiency	0.3 b/s/Hz	3 b/s/Hz
Maximum bandwidth	1 GHz	100 GHz
Area traffic capacity	10 Mb/s/m^2	1 Gb/s/m^2
Connection density	10^6 devices/km^2	10^7 devices/km^2
Energy efficiency	not specified	1 Tb/J
Latency	1 ms	100 μs
Reliability	1-10^{-5}	1-10^{-9}
Jitter	not specified	1 μs
Mobility	500 km/h	1000 km/h

[Bjo18] [Gio20] [Zha19]

Improving 5G



[5GIA21]

Key Performance Indicator	5G	6G
System Capacity		
Peak Data Rate (Gbps)	20	1000
Experienced Data Rate (Gbps)	0.1	1
Peak Spectral Efficiency (b/s/Hz)	30	60
Experienced Spectral Efficiency (b/s/Hz)	0.3	3
Maximum Channel Bandwidth (GHz)	1	100
Area Traffic Capacity (Mbps/m^2)	10	1000
Connection Density (devices/km^2)	10^6	10^7
System Latency		
End-to-end Latency (ms)	1	0.1
Delay Jitter (ms)	NA	10^{-3}
System Management		
Energy Efficiency (Tb/J)	NA	1
Reliability (Packet Error Rate)	10^{-5}	10^{-9}
Mobility (km/h)	500	1000

[Raj20]

TECHNOLOGY TRENDS TOWARDS 6G

To summarize, 6G networks are expected to

- Deal with **more challenging applications** (e.g., holographic telepresence)
- Meet **far more stringent requirements**
  - Tbps data throughput, sub-ms latency, extremely high reliability (nine 9's), increased device density, extreme energy efficiency/ultra-low energy consumption, very high security, cm-level accuracy localization, etc.
  - Different use cases will have different sets of KPIs (only, some reach the maximum requirements).

This calls for an **in-depth re-design of the radio interface**/RANs:

- Using higher carrier frequencies: more electromagnetic spectrum available
  - Sub-THz, THz, infrared, and up to visible light comms (high capacity P2P).
- Extreme densification of the network infrastructure, such as APs (e.g., cell-free networks).
- Distributed processing and cache memories.
- Leverage network slicing and multi-access edge computing.
- Increasing integration of terrestrial and satellite wireless networks: UAVs and LEOs.

AGENDA

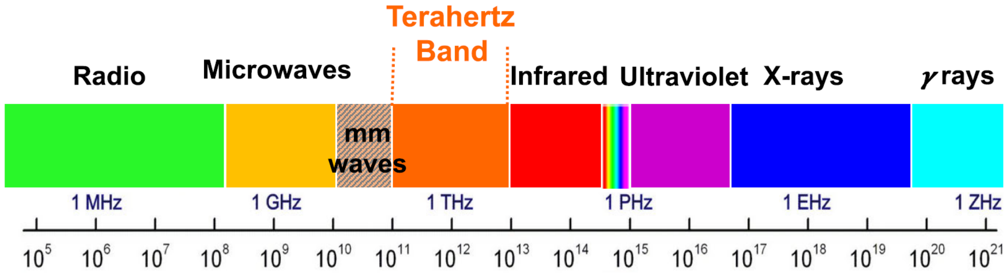
- Overview of new use cases, technical requirements and KPIs for 6G.
- **Key enablers for 6G radio interface designs.**
- Role of AI/ML in 6G radio interface design, examples.
- Conclusions

KEY ENABLERS FOR 6G RADIO INTERFACE DESIGN

A **non-exhaustive** list distilled from [5GIA21] [NOK20] [Raj20] [Tat21]:

- Terahertz communications
- Optical Wireless Communications
- Ultra-Massive MIMO and Holographic Radio
- Cell-free networking
- Intelligent Reflecting Surfaces (IRS)
- Integrated positioning, sensing, and communication
- Enhanced modulation and coding schemes
- Advanced multiple-access schemes: NOMA, Rate Splitting

KEY ENABLERS FOR 6G RADIO INTERFACE DESIGN (cont'd)

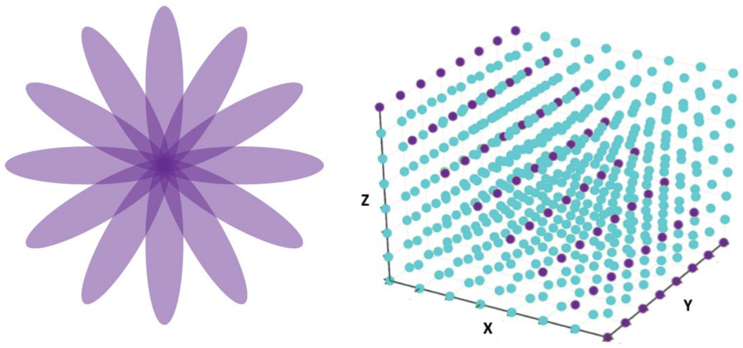


- **Terahertz communications**:
  - Huge amounts of spectrum available
  - HW implementation constraints and mitigation: RF, ADC
  - Channel modelling, new waveforms

- **Optical Wireless Communications**:
  - Infrared (FSO, backhauling) and visible light spectrum (VLC, broadband local connectivity) with LED/LD
  - Extremely high bandwidth, high spatial confinement, inherent security, unlicensed spectrum.
  - Positive-valued amplitude constraint (VLC)…unlike RF.
  - Optical blockage: hybrid RF/OWC
  - Accurate channel modelling with mobility

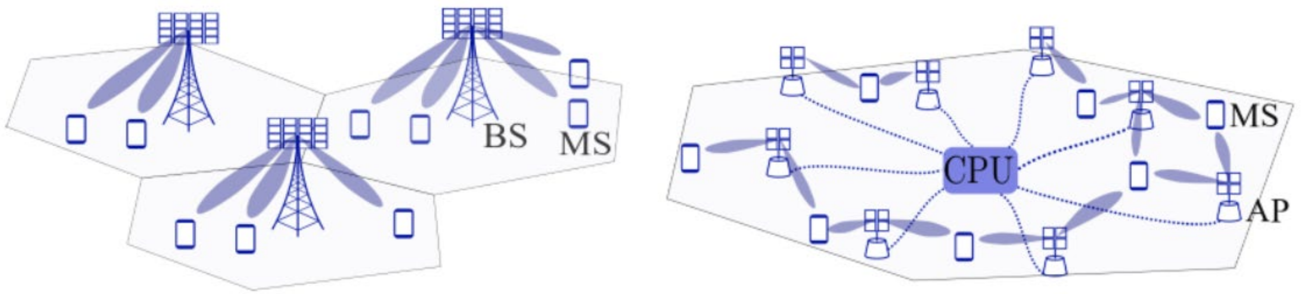
KEY ENABLERS FOR 6G RADIO INTERFACE DESIGN (cont'd)

- **Ultra-Massive MIMO and Holographic Radio**:
  - From mMIMO (5G, 10s) to umMIMO (6G, 1000s)
  - From beamspace approach (far-field) to interaction with devices and scattering (near-field).
  - Ultra-high spatial resolution (e.g., orbital angular momentum).
  - Implementation complexity grows with carrier frequency.
  - Continuous aperture arrays (TCA) for holographic radio: interference patters, not beams.



Massive MIMO Beam Space (Channels) Holographic Radio Space

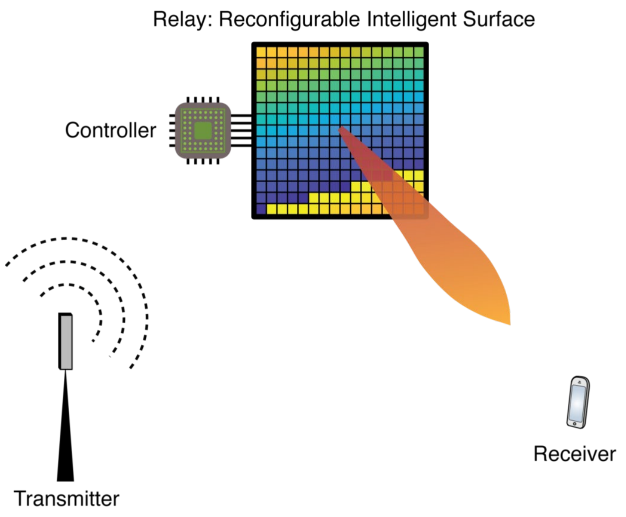
- **Cell-free networking**:
  - From large co-located arrays in APs to large number of lower cost APs with few antennas each.
  - APs cooperate via CPUs + fronthaul network.
  - Each UE served by few "good" antennas (nearby APs): increase data rate for majority of users (not peak)
  - Lower latency: content caching nearby and spatial diversity (THz).
  - Re-design of initial and random access (multiple APs)



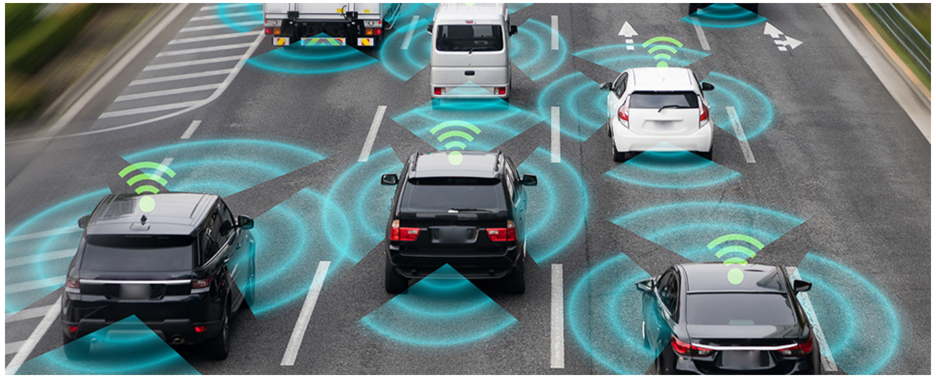
(a) Massive MIMO cellular network (b) Cell-free massive MIMO network

KEY ENABLERS FOR 6G RADIO INTERFACE DESIGN (cont'd)

- **Intelligent Reflecting Surfaces (IRS)**:
  - 2D thin surface, metamaterials with EM properties controllable without RF chains.
  - Improve propagation: additional scattering (THz, LOS with blocking) / passive beamforming toward Rx.
  - Low cost (no RF), complexity, energy consumption…potentially.
  - Transparent to wireless network / jointly optimized with Tx/Rx, reconfigurable.
  - Challenges: implementation, experimental validation, real-time control.



- **Integrated positioning, sensing, and communication**:
  - Avoid additional system for localization or sensing.
  - 6G: cm-accuracy or below and object sensing (radar-like).
  - Novel waveform designs or multiplexing with communication signals (e.g., chirp).
  - Leverage large arrays (mMIMO) for sensing tasks (sweeping).
  - Key enabler in CCAM, industrial automation.

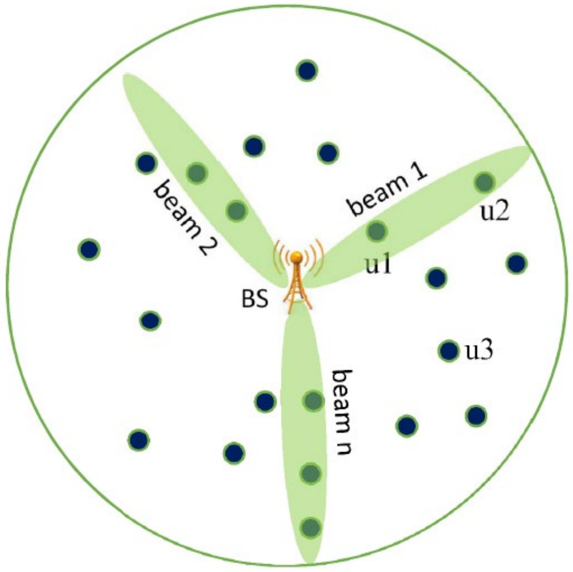


KEY ENABLERS FOR 6G RADIO INTERFACE DESIGN (cont'd)

- **Enhanced modulation & coding schemes**:
  - Reduce PAPR for e.g., IoT with low cost devices, THz at the edges.
  - Modulation: One size does not fit all:
    - Single-carrier for larger phase noise in higher frequencies.
    - Multi-carrier for spectral containment and scheduling.
    - Orthogonal Time-Frequency Space (OTFS, QAM in delay-Doppler).
  - Coding:
    - Cope with Gbps throughput: reduce iterations, parallelism
    - Reasonable energy efficiency (consumption) and cost.
    - Low error floor and sharp waterfall regions (reliability)

Modulation Technique	Complex Orthogonality	Critically Sampled Sampled Lattice	Well-Localized Localized Filters
OFDM	Yes	Yes	No
NS-OFDM	Yes	No	No
FMT	Depends	No	Yes
Lattice OFDM	No	No	Yes
Staggered Multi-tone	No	Yes	Yes
CP-OFDM	Yes	No	No
Windowed OFDM	Depends	No	Depends
Bi-Orthogonal OFDM	Yes	No	Yes
GFDM	No	No	Yes

- **Advanced multiple-access techniques:**
  - NOMA for massive access and short packets (grant-free)
  - Rate splitting (common/private): dynamically manage interference (SIC, noise)



AGENDA

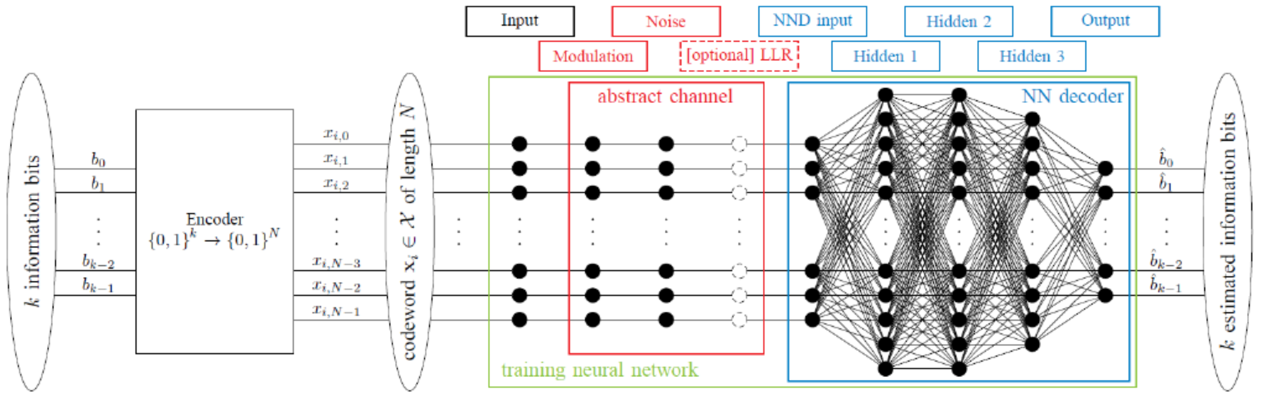
- Overview of new use cases, technical requirements and KPIs for 6G.
- Key enablers for 6G radio interface designs.
- **Role of AI/ML in 6G radio interface design, examples.**
- Conclusions

AI/ML-ENABLED RADIO INTERFACE DESIGN

- Progressive introduction of **sophisticated technologies for 6G networks**:
    - uMassive and cell-free MIMO, NOMA, massive random access, Terahertz communications, or network virtualization and disaggregation.
- Fundamental performance advantages in terms of **enhanced user experience**, but also require **complex management** solutions.
- Complexity can only be addressed by introducing **increasing levels of network automation** to facilitate **efficient resource exploitation** and **reduced operating expenses**.
- **AI/ML** (Artificial Intelligence/Machine Learning) called to play a **pivotal role**:
    - *Model* deficit: model behind the optimization problem not tractable or unknown
    - *Algorithm* deficit: problem cannot be efficiently or reliably solved
- 6G radio interface design: advocate for ***hybrid* AI-driven/model-based** approach.
    - Leverage on decades of signal processing and engineering know-how @PHY and LINK
    - Capable of providing QoS performance guarantees.

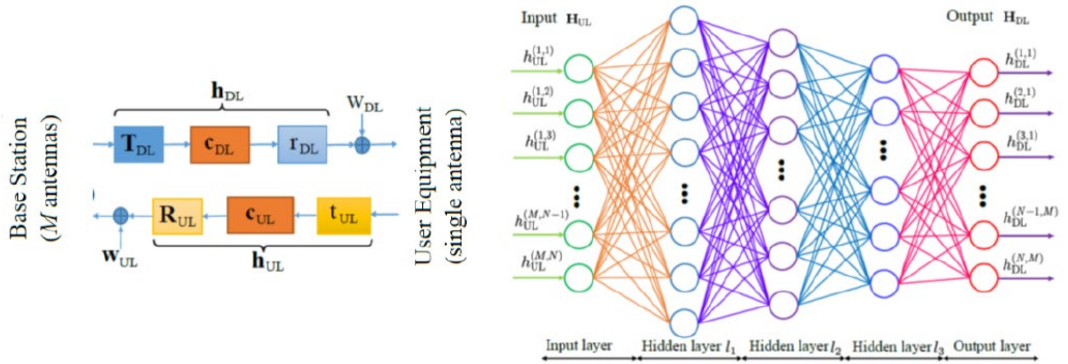
AI/ML-ENABLED RADIO INTERFACE DESIGN: EXAMPLES

- **Advanced channel decoding or data detection schemes based on deep-unfolding strategies**

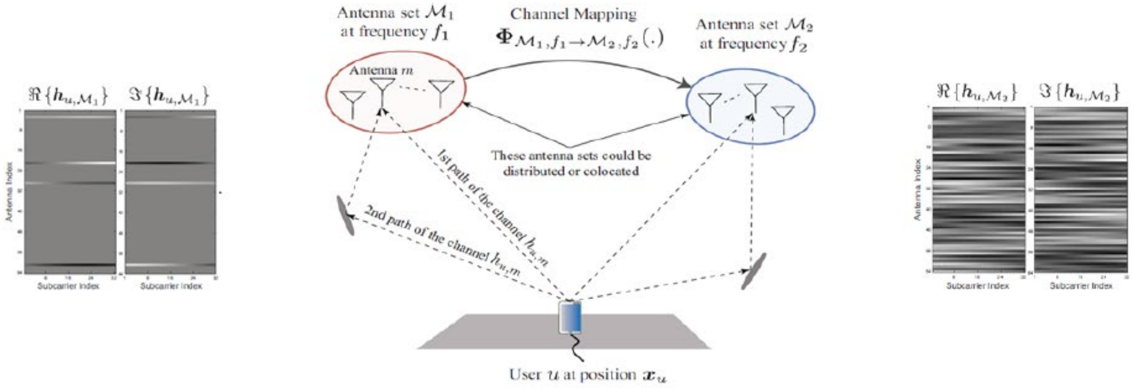


T. Gruber, S. Cammerer, J. Hoydis, S. ten Brink, "On deep-learning based channel decoding", Annual Conf. on Information Sciences and Systems (CISS), 2017

- **Bandwidth-saving/pilot-less channel estimation strategies for mMIMO, cell-free/distributed**



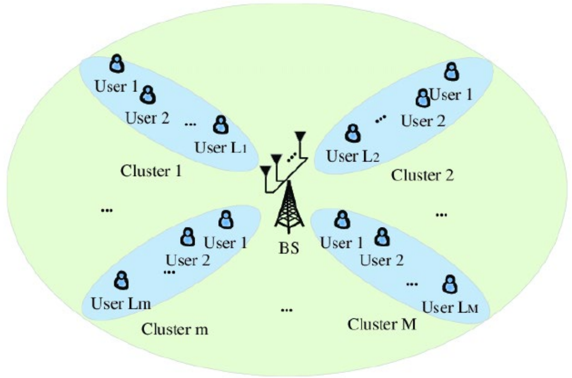
"Deep Learning for UL/DL Channel Calibration in Generic Massive MIMO Systems", C. Huang, G. Alexandropoulos, A. Zappone, C. Yuen, M. Debbah, IEEE Int'l Conference on Communications (ICC), 2019.



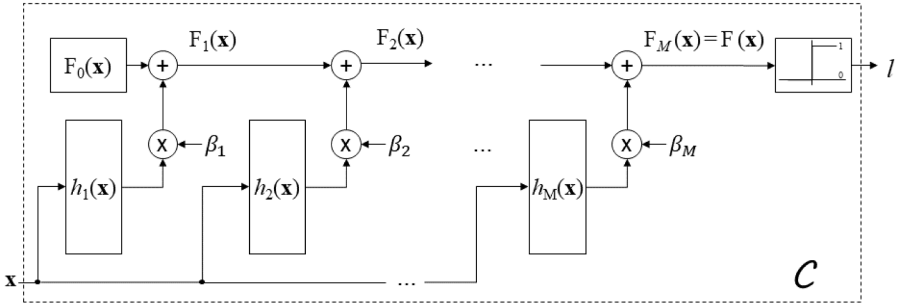
"Deep Learning for TDD and FDD Massive MIMO: Mapping Channels in Space and Frequency", M. Alrabeiah, A. Alkhateeb, ArXiV 2019.

AI/ML-ENABLED RADIO INTERFACE DESIGN: EXAMPLES

- **(Un)supervised user clustering for MIMO-NOMA**

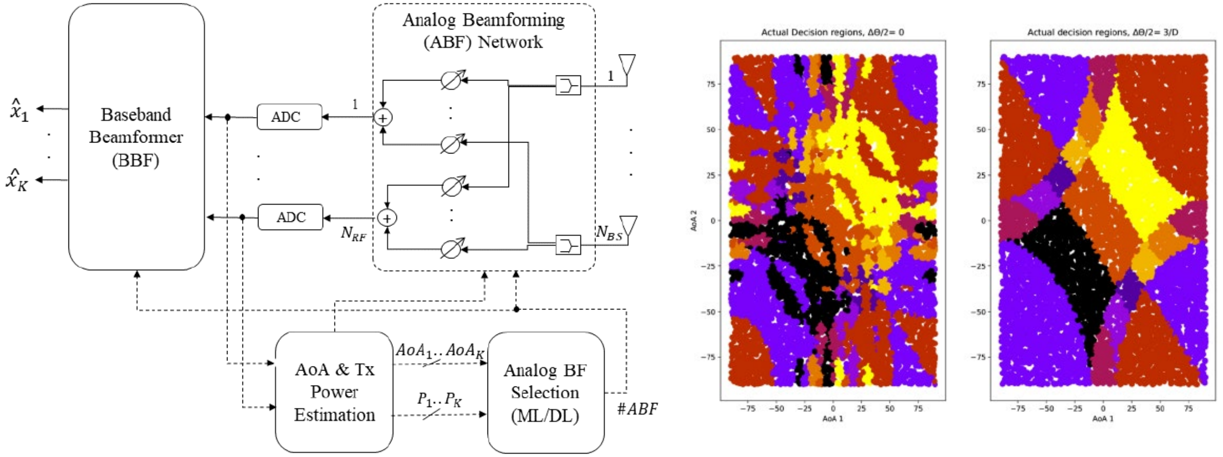


"Unsupervised Machine Learning-Based User Clustering in Millimeter-Wave-NOMA Systems", J. Cui, Fan, N. Al-Dhahir, IEEE Trans. Wireless Communications, Vol. 17, No. 11, Nov. 2018.

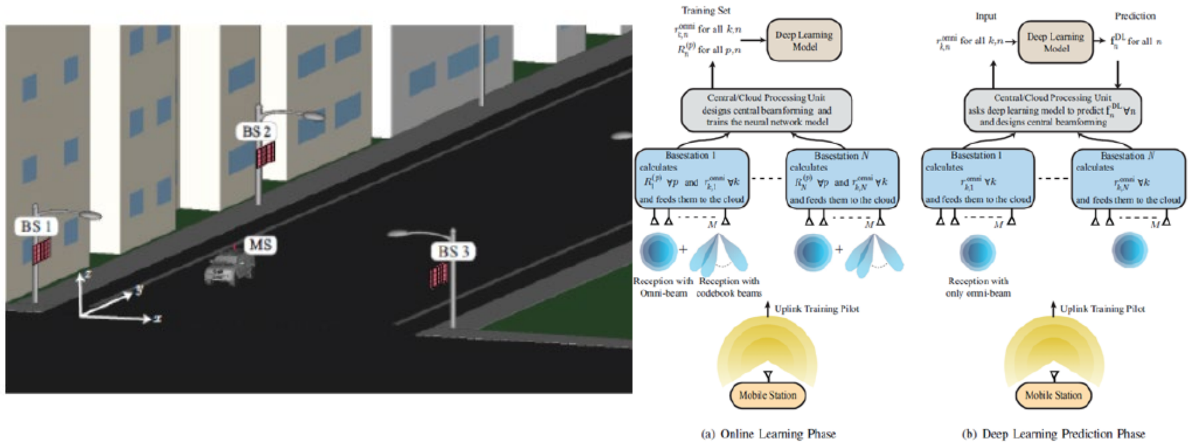


C. Ben Issaid, C. Antón-Haro, X. Mestre and M. -S. Alouini, "User Clustering for MIMO NOMA via Classifier Chains and Gradient-Boosting Decision Trees," in *IEEE Access*, vol. 8, pp. 211411-211421, 2020

- **Beam prediction/selection for coordinated or hybrid beamforming:**



C. Antón-Haro and X. Mestre, "Advanced Learning Architectures and Sufficient Statistics for Beam Selection in mmWave Bands with Multi-Path Propagation", IEEE GLOBECOM, Taipei (Taiwan), Dec. 2020.



"Deep Learning Coordinated Beamforming for Highly-Mobile Millimeter Wave Systems", A. Alkhateeb, Varkey, Y. Li, Q. Qu, D. Tujkovic IEEE Access, Vol. 6, 2018.

AGENDA

- Overview of new use cases, technical requirements and KPIs for 6G.
- Key enablers for 6G radio interface designs.
- Role of AI/ML in 6G radio interface design, examples.
- **Conclusions**

CONCLUSIONS AND KEY TAKEAWAYS

- **New use cases** (holographic, tactile, intelligent network operation) pushing 6G technical requirements and **KPIs to the limit**.
- This calls for an **in-depth re-design of the radio interface**/RANs.
- **Identified some key enablers** for 6G radio interface designs.
  - Terahertz communications
  - Optical Wireless Communications
  - Ultra-Massive MIMO and Holographic Radio
  - Cell-free networking
  - Intelligent Reflecting Surfaces (IRS)
  - Integrated positioning, sensing, and communication
  - Enhanced modulation and coding schemes
  - Advanced multiple-access schemes: NOMA, RS
- **AI/ML expected to play a pivotal role** in 6G radio interface design:
  - Deal with increased complexity, automation levels, model or algorithm deficit.
  - Advocate for hybrid approaches for PHY, LINK
- Several **examples of ML/AI-enabled radio interface design identified**:
  - Advanced channel decoding, bandwidth-saving/pilot-less channel estimation strategies for mMIMO, user clustering for MIMO-NOMA, beam prediction/selection for coordinated/hybrid beamforming,…

REFERENCES

- [5GIA21] White Paper “European Vision for the 6G Network Ecosystem,” Vision and Societal Challenges Working Group, The 5GIA Association, June 2021.
- [Aky20] I. F. Akyildiz, A. Kak and S. Nie, "6G and Beyond: The Future of Wireless Communications Systems," in IEEE Access, vol. 8, pp. 133995-134030, 2020.
- [Ant21] A. Dejonghe, C. Antón-Haro, X. Mestre, L. Cardoso and C. Goursaud, "Deep Learning-Based User Clustering For Mimo-Noma Networks," 2021 IEEE Wireless Communications and Networking Conf. (WCNC), 2021, pp. 1-6.
- [Bjo18] E. Bj▯ornson and E. G. Larsson, \How energy-e▯cient can a wireless communication system become?" in Proc. Asilomar Conf. Signals, Syst., and Comput. (ASILOMAR), 2018.
- [Gio20] M. Giordani, M. Polese, M. Mezzavilla, S. Rangan, and M. Zorzi, \Toward 6G networks: Use cases and technologies," IEEE Commun. Mag., vol. 58, no. 3, pp. 55{61, Mar. 2020.
- [ITU19] ITU-T, “Network 2030: A blueprint of technology, applications, and market drivers toward the year 2030,” Nov. 2019.
- [ITU20] ITU-T, “Focus group on technologies for network 2030: Representative use cases and key network requirements,” Feb. 2020.
- [NOK20] H. Viswanathan and P. E. Mogensen, "Communications in the 6G Era," in IEEE Access, vol. 8, pp. 57063-57074, 2020 // Nokia Bell-Labs White Paper.
- [Raj20] N. Rajatheva, E. Bjornson, A. Bourdoux, *et al*, “White Paper on Broadband Connectivity in 6G,”, arXiv 2004.14247 , 2020.
- [Tat21] H. Tataria, M. Shafi, A. F. Molisch, M. Dohler, H. Sjöland and F. Tufvesson, "6G Wireless Systems: Vision, Requirements, Challenges, Insights, and Opportunities," in Proceedings of the IEEE, vol. 109, no. 7, pp. 1166-1199, July 2021.
- [Zha19] Z. Zhang, Y. Xiao, Z. Ma, M. Xiao, Z. Ding, X. Lei, G. K. Karagiannidis, and P. Fan, “6G wireless networks: Vision, requirements, architecture, and key technologies," IEEE Veh. Technol. Mag., vol. 14, no. 3, pp. 28-41, Sept. 2019.

THANKS FOR YOUR KIND ATTENTION !

QUESTIONS ?

Carles Antón-Haro, PhD, MBA

Director of R&D Programmes, Senior Research Associate

Centre Tecnològic de Telecomunicacions de Catalunya

Parc Mediterrani de la Tecnologia, Av. Carl Friedrich Gauss 7

08860 Castelldefels (Barcelona) - SPAIN

carles.anton@cttc.es Tel: +34.93.645.29.23