



6G THE NEXT FRONTIER: VISION, ROADMAPS & TECHNOLOGIES

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In **1926**, the visionary Nikola Tesla stated:

“When wireless is perfectly applied, the whole Earth will be converted into a huge brain.”

By **2030**, responding to fundamental **human and social needs** and based on the **expected progress in ICT** Tesla’s prophecy may become a reality!



4G & 5G HAS STARTED ADDRESSING SUCH CHALLENGES . BUT WE ARE JUST AT THE BEGINNING



- **6G** will provide an ICT infrastructure that **enables end users to perceive themselves as surrounded by a “huge artificial brain”** offering **virtually zero-latency** services, **unlimited storage**, and **immense augmented cognition capabilities**.

6G will not only connect the Earth but also the close proximity sky too...



What we observe today:

- Social issues, coverage
 - 3,5 Billion people without wireless Internet
- Energy, sustainability in hyperconnected society
 - « Energy skyrocketing at the edge ».
- EMF raising concerns
 - What impact of untested spectrum usages? How to decrease exposure?
- Human centricity and trust, data control and governance
- Security and Autonomy

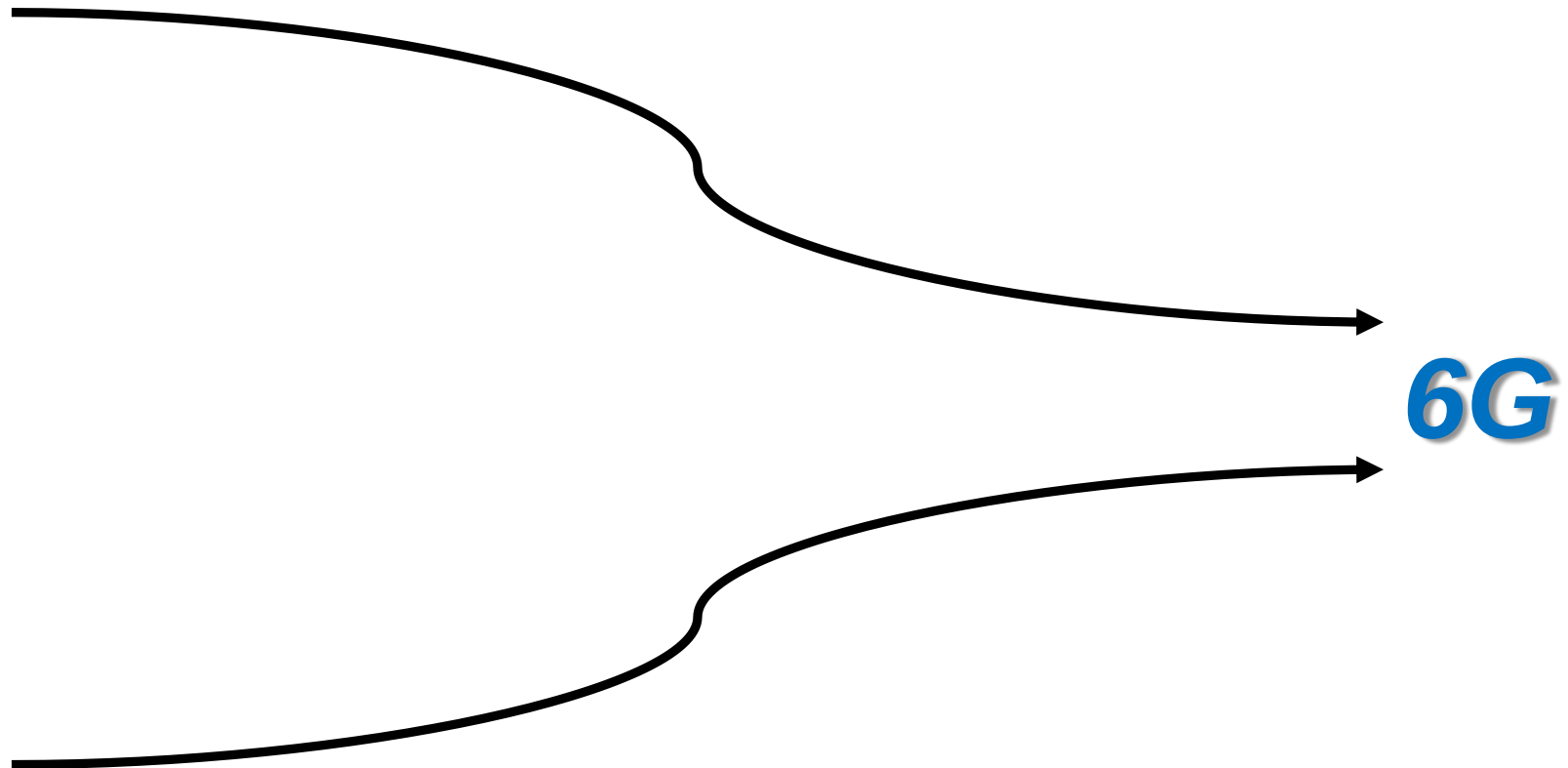
Source:

B. Barani 2/10/2019

Deputy Head of Unit, Future Connectivity Systems
EU commission – DG Connect

WHY WE NEED A NEW 'G'ENERATION ?

Technological breakthrough readiness

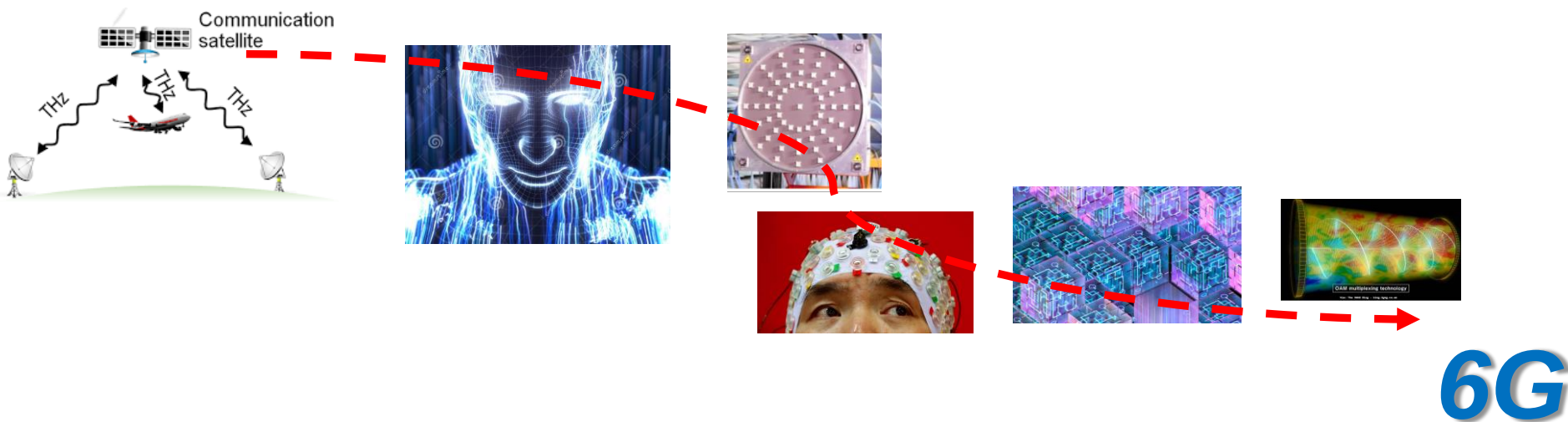


6G

New services, Applications & use cases

WHY WE NEED A NEW 'G'ENERATION ?

Technological breakthrough readiness



New services, Applications & use cases



TWO EXAPLES OF BEYOND 5G APPLICATIONS

5 Senses Interactive Hologram Technology



Interactive Haptic Communications



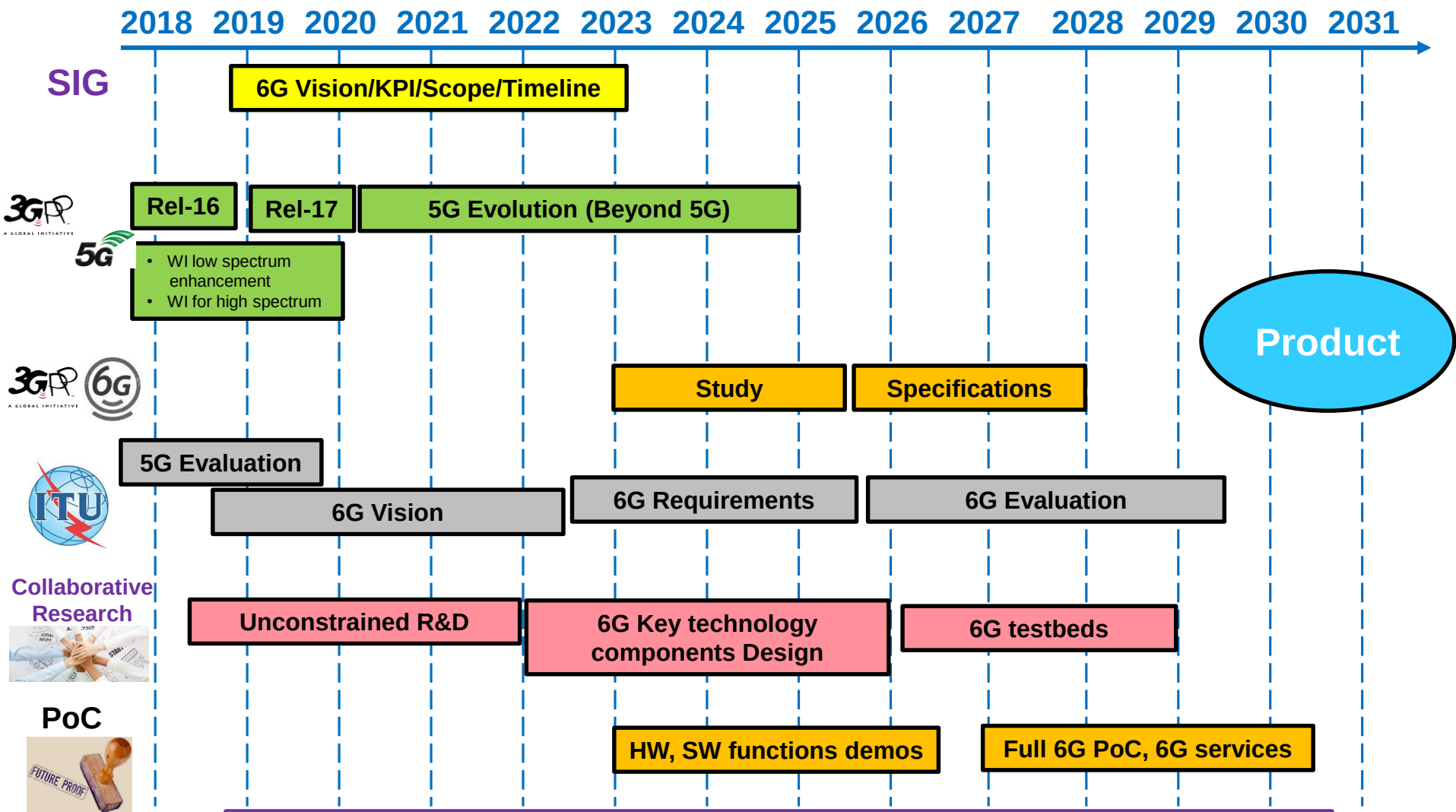
Low Latency (μs -ms)

Self-designing Joint C⁴ : Communication + Computing + Caching + Control

Ultra-high capacity (1-10s Tbps)

Deterministic (~~stochastic~~) network optimization

6G ROADMAP AND TIMELINE



Source: Calvanese et al., "6G: The Next Frontier: From Holographic Messaging to Artificial Intelligence Using Subterahertz and Visible Light Communication", IEEE Vehicular Magazine September 2019.

SOME ASSUMPTIONS ON 6G

Artificial intelligence will dominate in:

- **delivery area** - in the core and at the edges of the network(s)
- **fruition area** - devices like smartphones and things (super IoT)
- **application space**

XR (MR/VR/AR) will become **pervasive**

- The technology support for it is still unclear (visual ambient, super contact lens, holograms, ...)
- Smart materials might allow any surface to display information,
- **Holographic projectors** might become available (even on mobile terminals)

It will be **cheaper to augment humans** to become able **to receive & visualize bits** than **augmenting the any ambient to display** them

Perception of “Infinite” capacity

- Ultra-high data rates
- Massive scalability to millions of devices

3D Intelligence Coverage

- Ubiquitous consistent user experience in time and location (3D)

Zero Latency networks

- Extreme low latency (interactive services, tactile internet, remote surgery)

Extreme low power & Energy Free Connectivity

- Long battery life/ ultra-low energy consumption

COMPARISON OF MAIN 5G & 6G KPIS

KPI	5G	6G
Traffic Capacity	10 Mbps/m2	~ 1-10 Gbps/m3
Data rate DL	20 Gbps	1 Tbps
Data rate UL	10 Gbps	1 Tbps
Uniform user experience	50 Mbps 2D everywhere	10 Gbps 3D everywhere
Latency (radio interface)	Up tp 1 msec	Up to 0.1 ms
Jitter	How can we achieve them? Will this be enough?	
Reliability (frame error rate)		
Energy/bit	NS	pJ/bit
Localization precision	10 cm on 2D	1 cm on 3D

Source: Calvanese et al., "6G: The Next Frontier: From Holographic Messaging to Artificial Intelligence Using Subterahertz and Visible Light Communication", IEEE Vehicular Magazine September 2019.

6G MEGA TRENDS

- **TREND 1:** More bits, more spectrum
 - **TREND 2:** 3D Spatial BW & 3D coverage for intelligence support
 - **TREND 3:** New Technologies (Meta materials, in memory computing, quantum c.)
- **TREND 4:** Ubiquitous Role of Antennas & Reconfigurable Intelligent Surfaces
 - **TREND 5:** New Applications, New Service Classes & new Media
 - **TREND 6:** Energy Free Connectivity (wireless harvesting, Zero energy radio, ...)
- **TREND 7:** C⁴: Convergence of **C**ommunication, **C**omputation, **C**aching & **C**ontrol
 - **TREND 8:** Ubiquitous support of AI & the path to fully distributed Intelligence
- **TREND 9:** Breaking Big Data with Massive Small Data
 - **TREND 10:** Network Personnalisation

Scenario for Sub-THz Spectrum Use

Ultra-high capacity xHaul

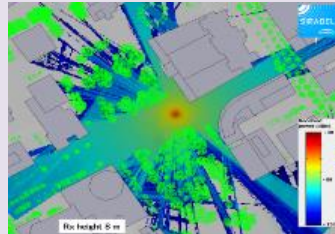
- 100+ Gbps transport, for
- Dense massive MIMO networks
 - Cell-free network architecture
 - Massive cloud & edge computing
 - Enhanced broadband fixed access
 - Casual drone-based xHaul
 - ...



bit/s/Hz/J

Enhanced hotspot

- 100+ Gbps per cell,
Multi-user access
Few meters range,
Low mobility, for
- Kiosk (high speed download)
 - Enhanced immersive experience
 - ...



D2D

- 100+ Gbps P2P or P2MP, for
- Server farm
 - Inter-chip
 - Intra-chip
 - ...



bit/s/Hz/J

Frequency of interest:

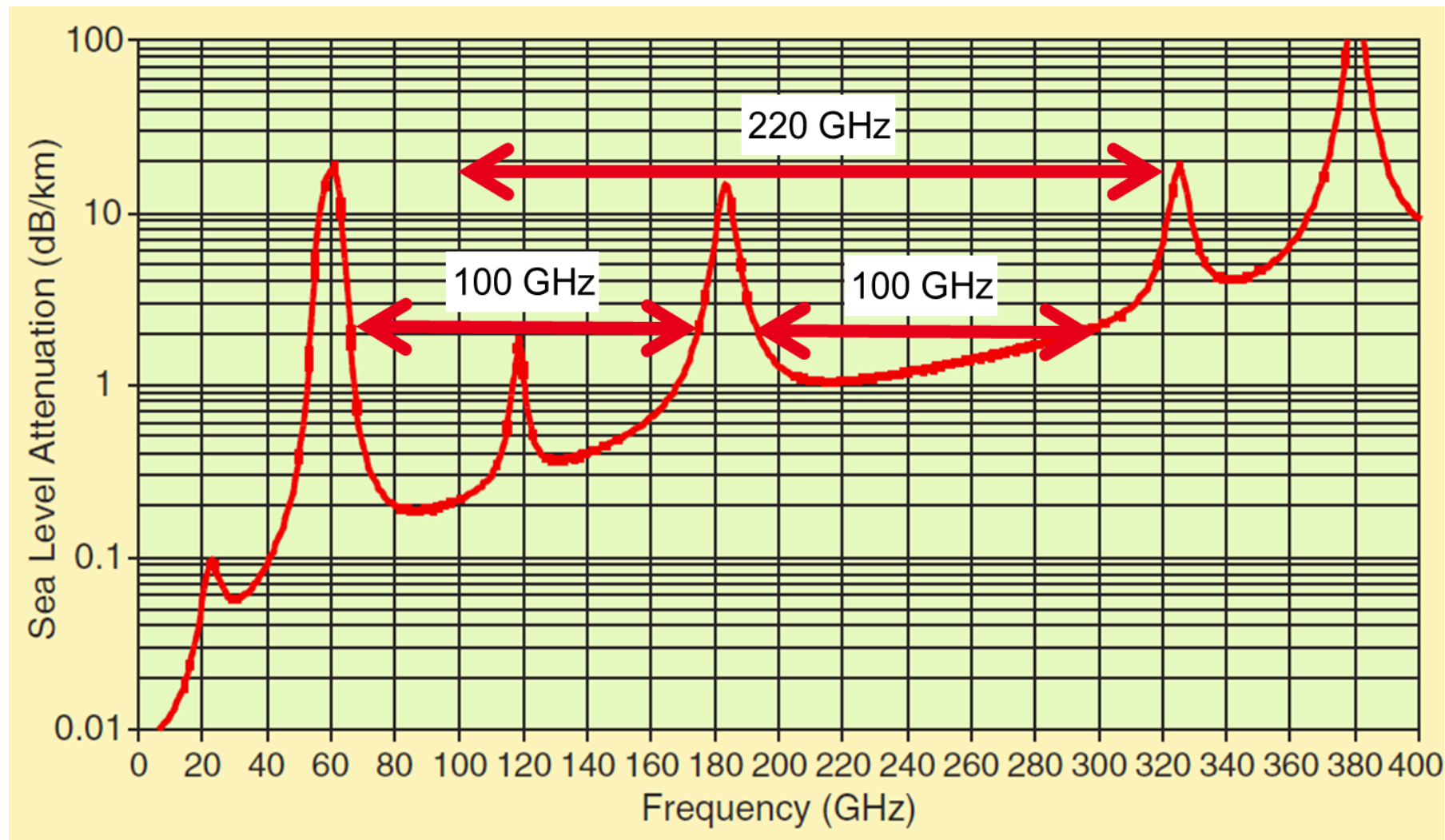
92- 94 GHz,
94.1-100 GHz,
102-109.5 GHz,
111.8-114.25 GHz,
122.25-123 GHz,
130-134 GHz,
141-148.5 GHz,
151.5-164 GHz,
167-174.5 GHz,
174.5-174.8 GHz,
191.8-200 GHz

Source ANFR

Source: <http://www.brave-beyond5g.com/> - Siradel, CEA Leti, CentraleSupélec, ANFR

MORE SPECTRUM ABOVE 90 GHZ

TREND 1: More bits, more spectrum

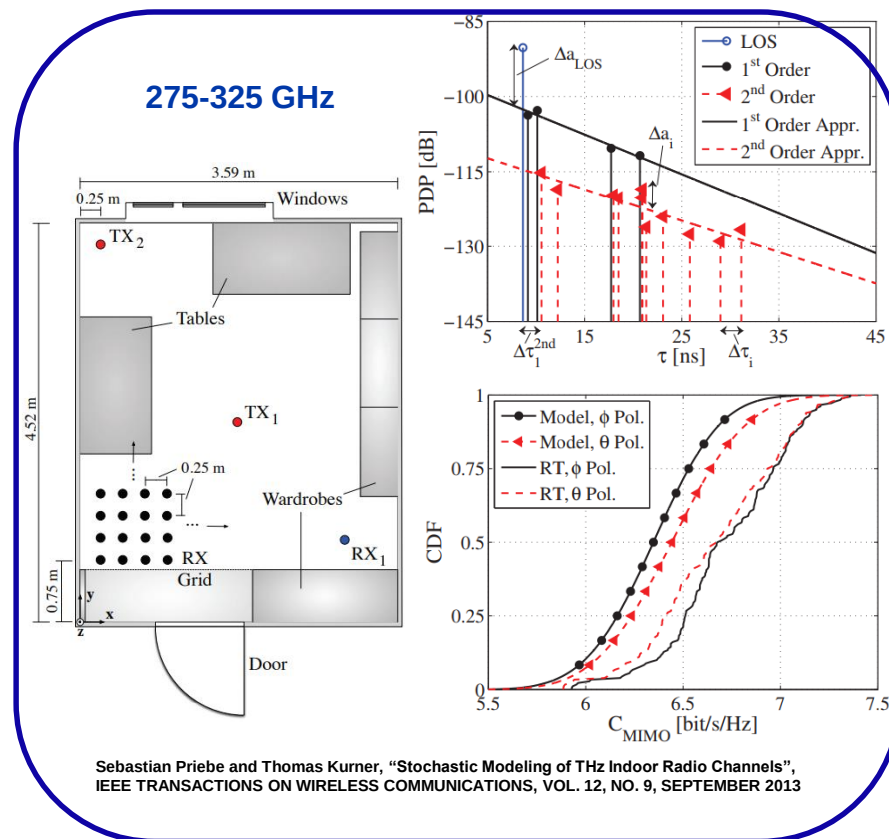
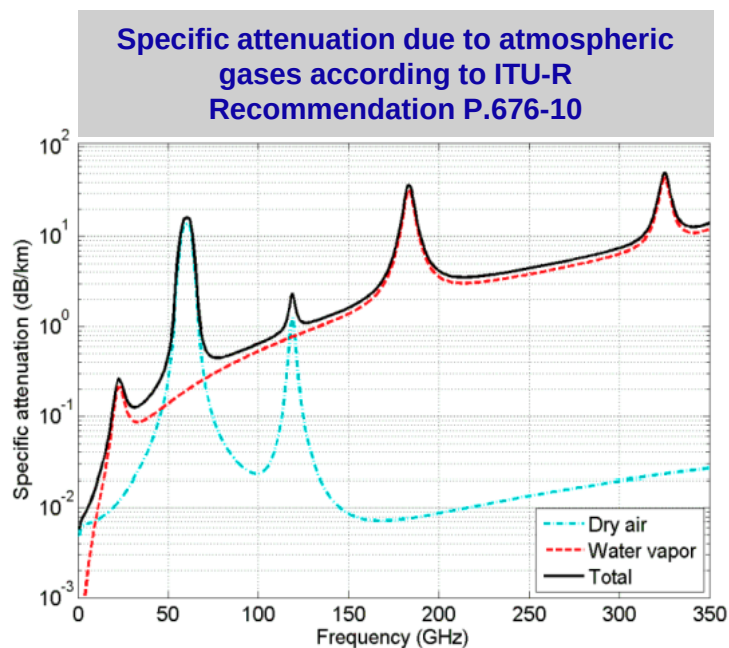


THE SUB-THZ COMMUNICATION CHALLENGE

PROPAGATION ISSUES

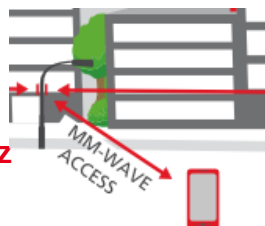
TREND 1: More bits, more spectrum

- An extensive research has been done for frequencies below 100 GHz but not for frequencies above 100 GHz.
- The attenuation for frequencies above 100 GHz reaches tens of dB/km ► **for short ranges though the attenuation is negligible.**

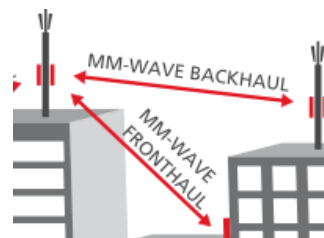


5G & BEYOND RESEARCH AT CEA-LETI: BEAMFORMING/BEAM STEERING APPROACHES

20.8 dBi @ 28 GHz
beam-steering



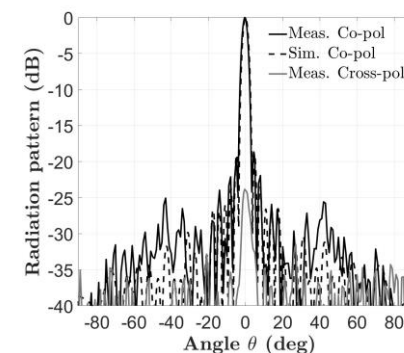
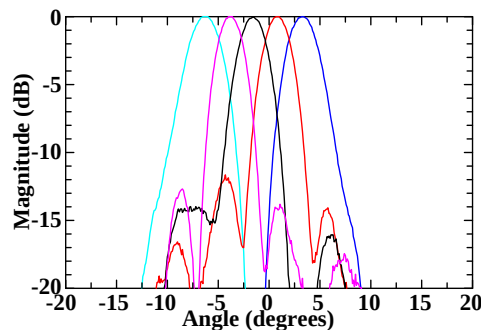
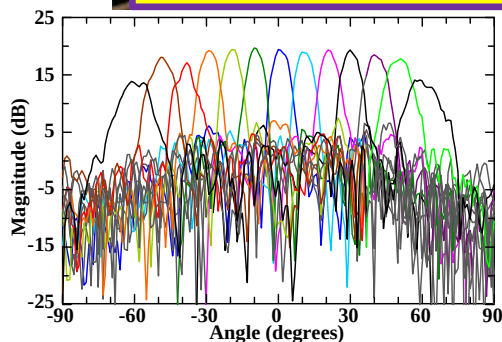
32 dBi @ 60 GHz
beam-switching



33 dBi @ 140 GHz
fixed beam

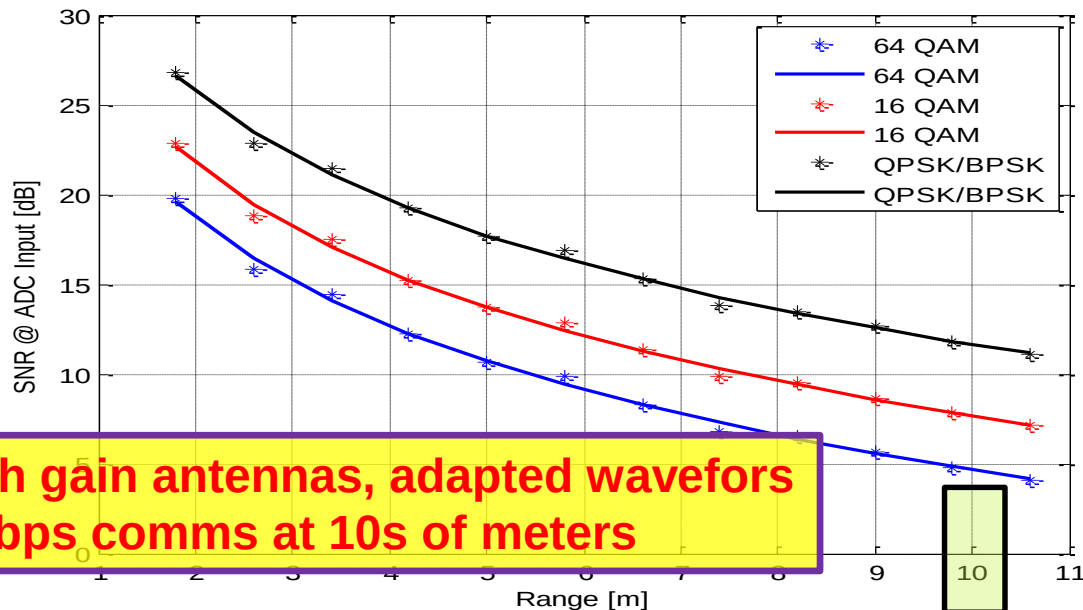
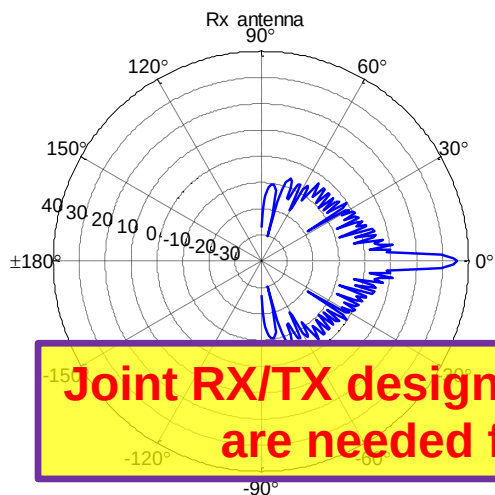


**Issues with high directive antennas:
Resilience to blockage, mobility management, beam alignment, ...**



APPLICATION OF 5G CHANNEL MODEL FOR 6G SYSTEM PERFORMANCE EVALUATION

Directive antenna
(32 dBi, 20x20 elements, 3° beam)



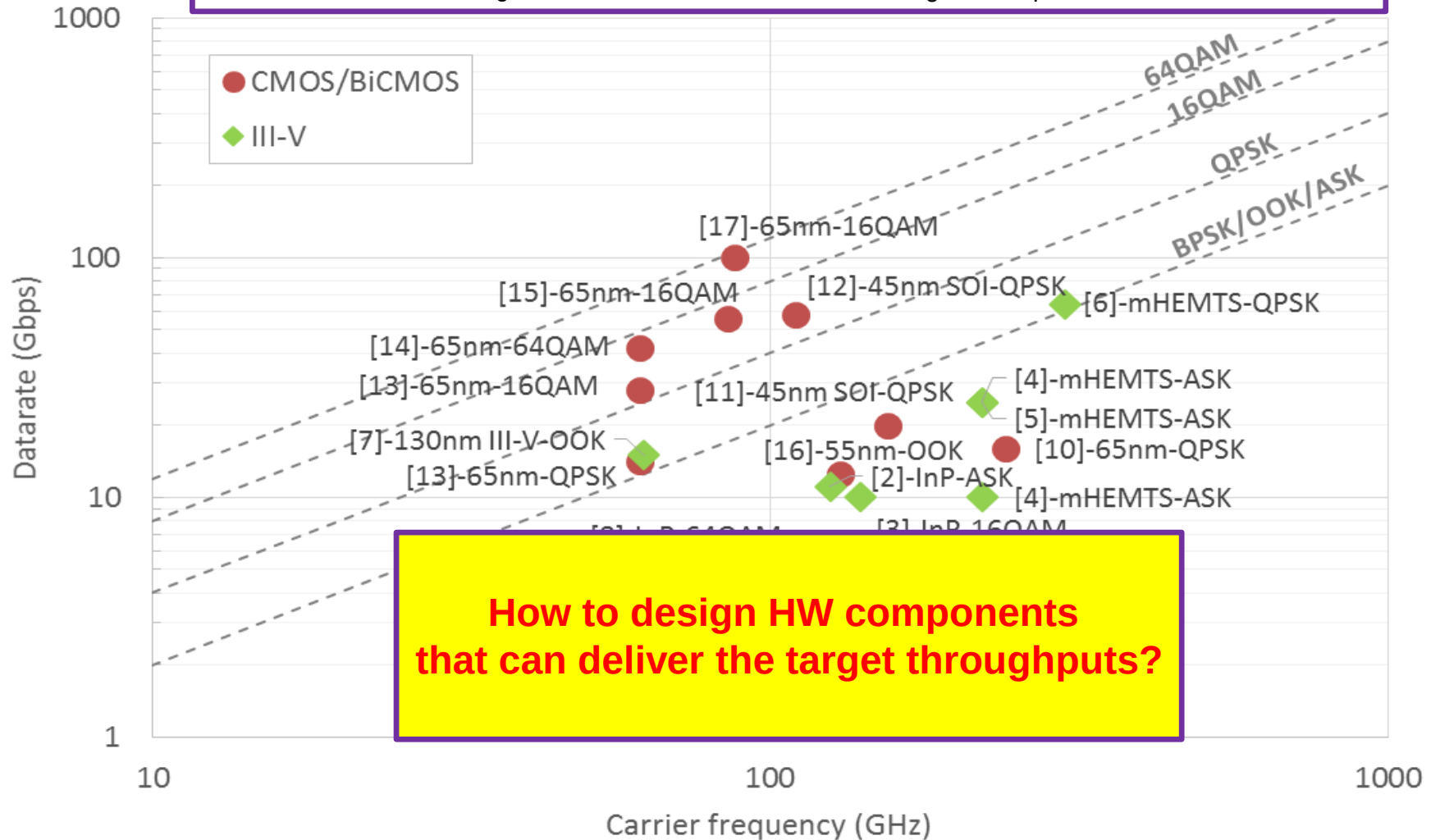
Joint RX/TX design, high gain antennas, adapted waveforms are needed for Tbps comms at 10s of meters

	64QAM	16QAM	QPSK	BPSK
Emitter				
RF bandwidth (GHz)	30	30	30	30
Number of subbands	16	16	16	16
Bandwidth (GHz)	1,6	1,6	1,6	1,6
Power Amplifier OCP1dB (dBm)	4,5	4,5	4,5	4,5
Output Back Off (dB)	7	5	3	3
Mean power at Tx output (dBm)	-2,5	-0,5	1,5	1,5
Tx-antenna interconnexion loss (dB)	2	2	2	2
Mean Power at antenna input (dBm)	-4,5	-2,5	-0,5	-0,5
Receiver				
LNA-antenna interconnexion loss (dB)	2	2	2	2
Sensitivity (dBm)	-31	-35	-43	-46
Signal to Noise Ratio				
Thermal noise (dBm)	-81,94	-81,94	-81,94	-81,94
Implementation loss (dB)	5	4	2	2
Noise figure (dB)	25	25	25	25
Signal processing				
Required SNR for BER=1e-5 (dB)	21	18	11,5	8,5

THE SUB-THZ COMMUNICATION CHALLENGE: HW PERSPECTIVE & ITS LIMITATIONS

TREND 1: More bits, more spectrum

Source: Calvanese et al., "6G: The Next Frontier: From Holographic Messaging to Artificial Intelligence Using Subterahertz and Visible Light Communication", IEEE Vehicular Magazine September 2019.



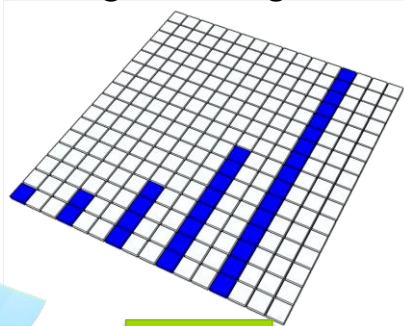
CEA-LETI VISION: Visible light Communication Roadmap

... the other way to exploit the spectrum ...

TREND 1: More bits, more spectrum



Digital to Light



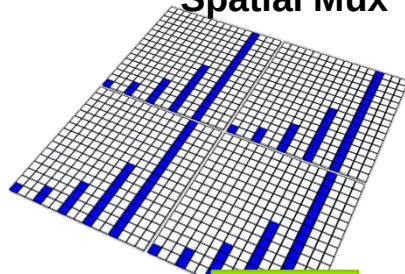
2022

- $\mu\text{Led } 60\mu\text{m } 2^{10} \text{ pixels (x4)}$
 - Digital OFDM
 - ASIC design
 - 5 bps/Hz
- 1 Gbps**

2020

- Multiusers
- 100 Mbps**

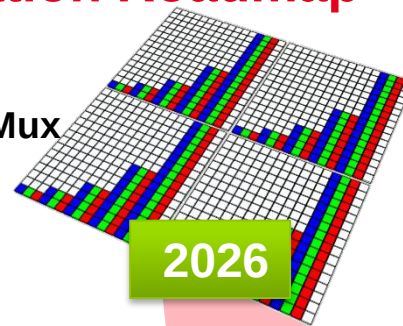
Spatial Mux



2024

- $\mu\text{Led } 30\mu\text{m } 16 \times 2^{10} \text{ pixels}$
 - $16 \times \text{Spatial Division}$
 - ASIC fab
 - 10 bps/Hz
- 20 Gbps**

Wavelength Mux



2026

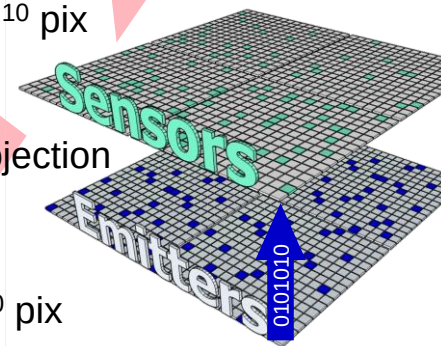
- $\mu\text{Led } 30\mu\text{m } 4 \times 16 \times 2^{10} \text{ pix}$
 - RGB multiplexing
 - ASIC demo
 - 15 bps/Hz
- 100 Gbps**

20 Gbps

- Sensor array 2^{10} pix

- One to one projection

- $\mu\text{Led } 30\mu\text{m } 2^{10} \text{ pix}$



1 Tbps

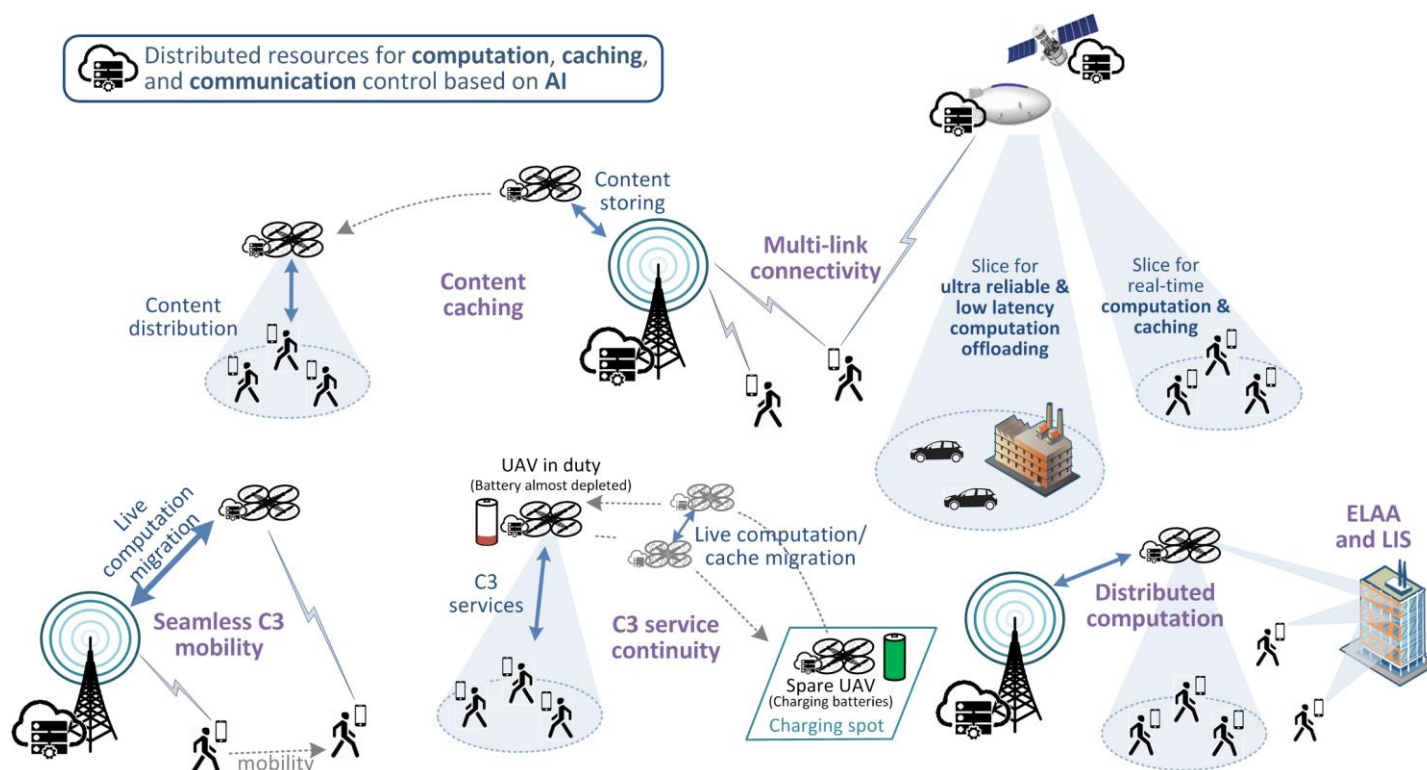
2027

Massive parallelization

Source: Calvanese et al., "6G: The Next Frontier: From Holographic Messaging to Artificial Intelligence Using Subterahertz and Visible Light Communication", IEEE Vehicular Magazine September 2019.

FROM 2D CENTRALIZED CONNECTIVITY TO 3D DISTRIBUTED INTELLIGENCE COVERAGE

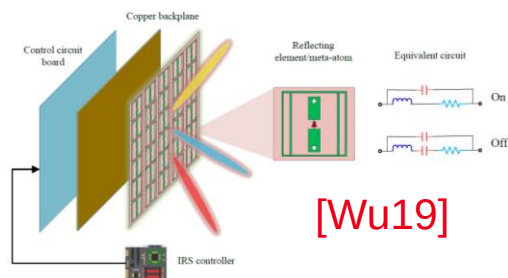
- 6G networks will integrated terrestrial non terrestrial components in a EE and scalable framework
- E2E resources will be dynamically orchestrate to deal with heterogeneous service requirements, and new connectivity & intelligence paradigms



THE POTENTIAL OF METAMATERIALS & RIS

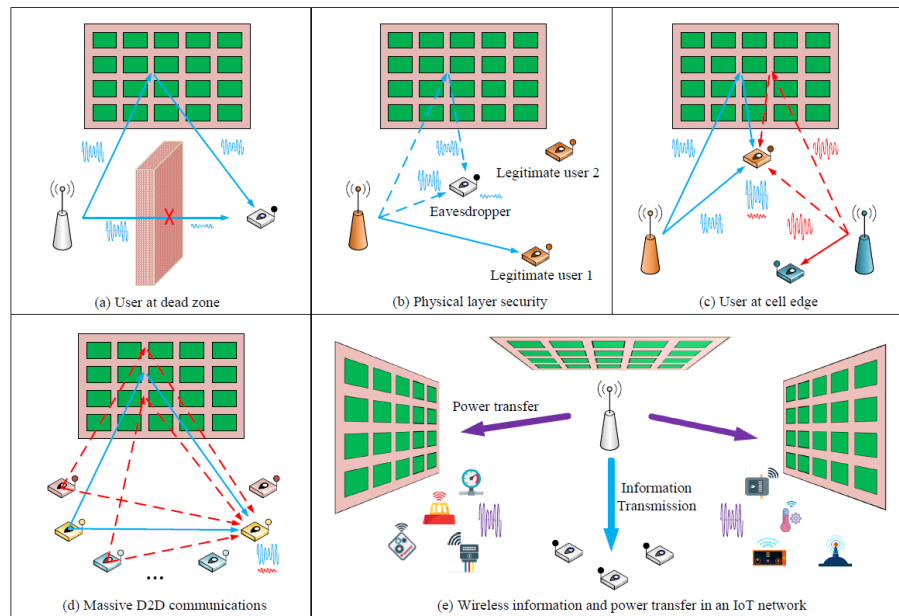
- Growing interest for intelligent surfaces and reconfigurable radio environments

- Mostly intended for communication so far



[Wu19]

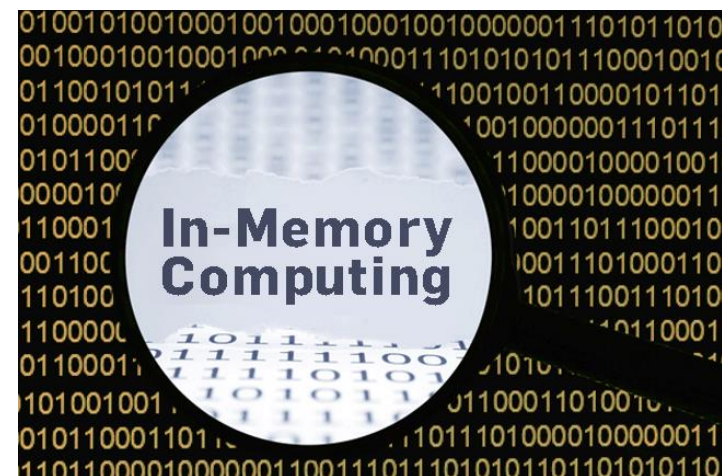
Ex. of Reconfigurable Intelligent Surface (RIS)



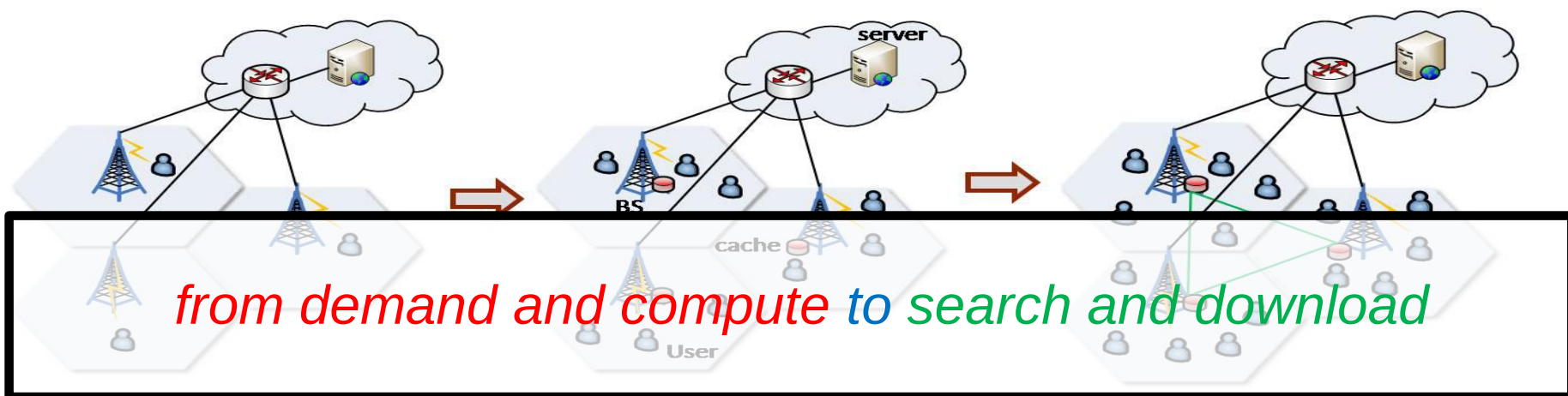
- ... But also possible trend in 6G localization
 - Surface-aided reconfigurable radio channels to improve localization and environment sensing (i.e., besides communication)
 - Proactively control multipath channel (today seen as a nuisance to localization)
 - Alleviated synchronization issues inherent to conventional massive MIMO-based and/or to active cooperative localization
 - Ultra low power low complexity devices (still a claim at this stage though)

In memory computing

- Less data travelling time
- In memory database, in memory applications
- New programming models



• Computational caching



Communication

Communication + Caching

Communication* + Caching* + Computation*

CONCLUSIONS: NEW SPECTRUM & (DISTRIBUTED) COOPERATION SCHEMES

- A new **physical** layer incorporating **sub-THz** bands and **VLC**
- **Exploitation of ambient backscattering**, which enables **tiny devices** to operate with **no battery** by redirecting ambient radio-frequency (RF) signals
- Exploitation of **Reconfigurable Intelligent Surfaces** for both **connectivity** & **localization**
- A new **(distributed) architecture supporting** nearly **deterministic services** (latency, energy,...)
- **Distributed security mechanisms**
- **Decentralized authentication** (especially for the IoT scenario) exploiting **distributed ledger** technologies & exploiting **blockchain** like mechanisms
- **Innovative cryptographic techniques** will be used to **achieve** an **effective accommodation between AI and privacy**.

CONCLUSIONS: THE EDGE EATING THE CLOUD & UBIQUITOUS 3D INTELLIGENCE SUPPORT

- A pervasive introduction of AI at the network edge & *Holistic Management of C4 Resources* : *Communication, Computation, Caching, and Control*
 - Incorporating new incorporating **self-configuration** and **self-optimization** capabilities
 - **Distributed AI algorithms**, possibly running under **severe delay constraints**
 - **Proactive strategies** (based on network learning and prediction) for **self-optimization of network resource allocation**
- **Computation caching**: computation-offloading mechanisms, that learn from user behavior to save energy and reduce UL traffic
- **Intelligent memories & storage** (In memory computing)
- Development of **semantic inference** algorithms and **semantic communication** strategies to go **beyond Shannon's** classical information theory
- **3D coverage**: The design of a 3D communication infrastructure incorporating **terrestrial** and **aerial support of C4 services**

Most of beyond 6G will happen locally or in 3D

CONCLUSIONS: BENEFIT OF JOINT KR & EU COLLABORATION



- **Standardisation rush to deliver early 'evolutionary' standards**
- **(vertical) Industry & society are expecting revolutionary solutions and services**
- It is time now for **unconstraint research.... Collaborative and explorative research!**

The Benefit of EU-KR cooperation is on the **development and commercialization of new technology** while ensuring their long term **Rol**

- This comes to the **cost of ambition** and **target innovation of technology rather than 'just' faster efficient radio interface**
- **Korea is a key technologic and innovation partner to EU**
 - Together we will enforce **'revolution' of 6G** to reach the ambition industrial revolution that digitalization will bring.

***It is time to investigate together the path to
6G Self-Defined (Artificial) Intelligent Networks & their
applications***



leti

cea tech

담당자님

5G ALLSTAR

Thank you!

고맙습니다

Emilio Calvanese Strinati,
Sergio Barbarossa,
José Luis Gonzalez-Jimenez,
Dimitri Kténas,
Nicolas Cassiau,
Luc Maret, and Cédric Dehos

With its ability to provide a single platform enabling a variety of services, such as enhanced mobile broadband communications, virtual reality, automated driving, and the Internet of Things, 5G represents a breakthrough in the design of communication networks. Nevertheless, considering the increasing requests for new services and predicting the development of new technologies within a decade, it is already possible to envision the need to move beyond 5G and design a new architecture incorporating innovative technologies to satisfy new needs at both the individual and societal levels.

The goal of this article is to motivate researchers to move to a sixth generation (6G) of mobile communication networks, starting from a gap analysis of 5G and predicting a new synthesis of near-future services like holographic communications, high-precision manufacturing, a pervasive introduction of artificial intelligence (AI), and the integration of new technologies, such as subterahertz or visible light communication (VLC), in a truly 3D coverage scenario. Such a framework will incorporate terrestrial and aerial radio access points to bring cloud functionalities *where and when needed on demand*.



The Road to a Global "Brain"

In 1926, the visionary Nikola Tesla stated, "When wireless is perfectly applied, the whole Earth will be converted into a huge brain." By 2030, responding to fundamental human and social needs and based on the expected progress in information and communication technologies

6G: THE NEXT FRONTIER

From Holographic Messaging to Artificial Intelligence Using Subterahertz and Visible Light Communication

Leti, technology research institute

Commissariat à l'énergie atomique et aux énergies alternatives

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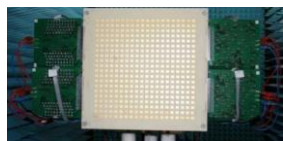
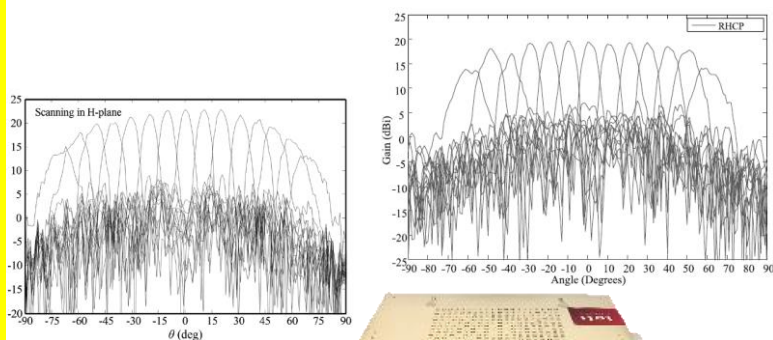


THE SUB-THZ COMMUNICATION CHALLENGE: ANTENNAS DESIGN PERSPECTIVE - CURRENT STATE-OF-THE-ART @ CEA-LETI

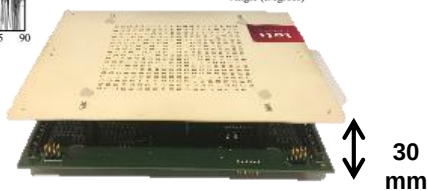
TREND 1: More bits, more spectrum

Electronically-steerable transmitarrays

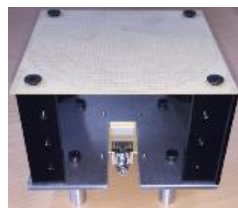
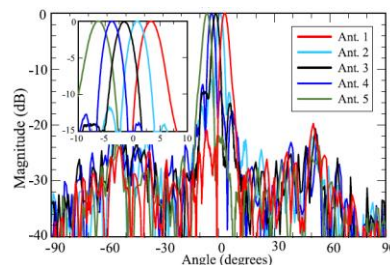
- Spatial feeding mechanism to limit the splitting loss,
- Analogue or hybrid beam-forming based architectures,
- P-i-n diodes on the flat-lens array to limit the complexity and phase-shifting loss.



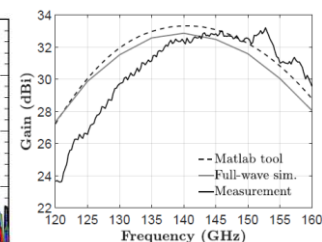
1-bit transmitarray



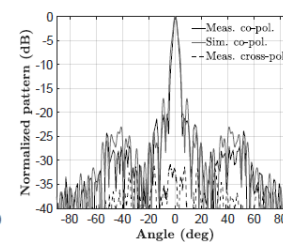
Low-profile transmitarray



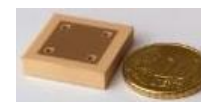
Switched-beam



High-data-rate module



Monolithic TA

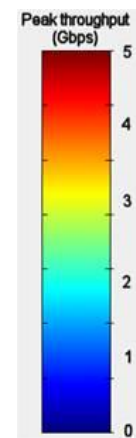
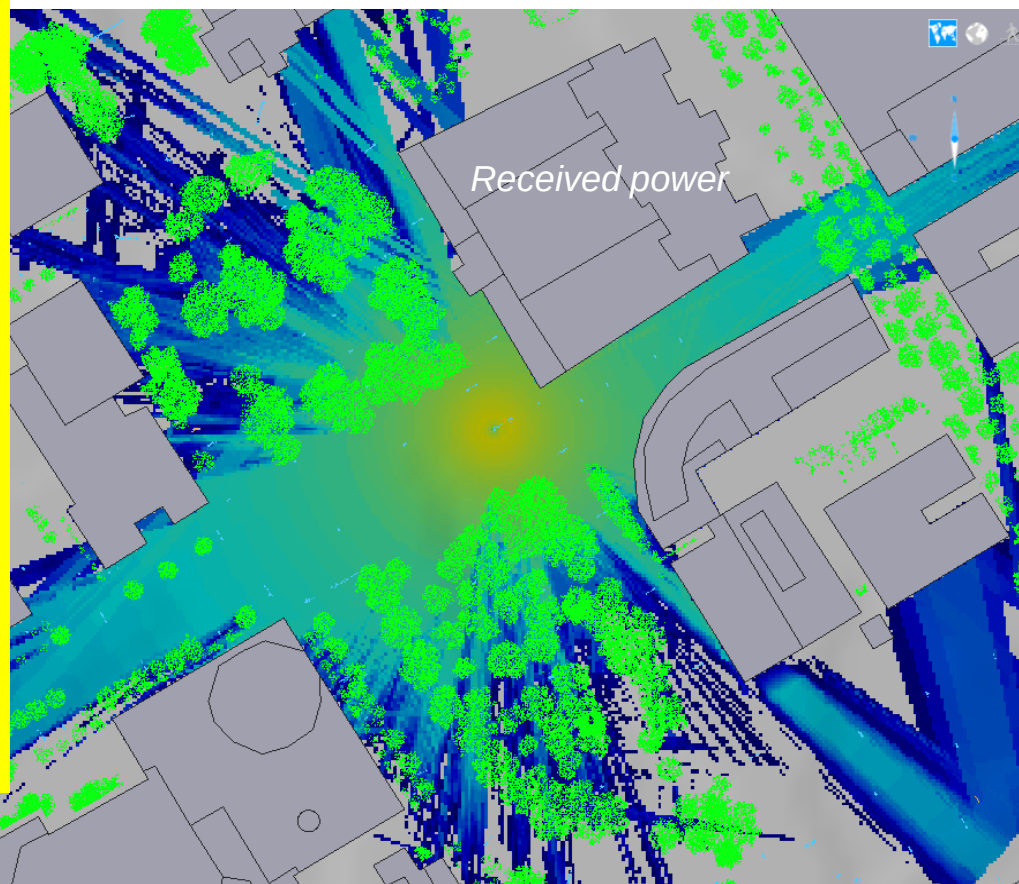


10 GHz 20 GHz 30 GHz 60 GHz 80 GHz ... 140 GHz ... 300 GHz



PATH TO THZ SPECTRUM: NEW MODULATION AND WAVE FORMS DESIGN

TREND 1: More bits, more spectrum



PHY layer

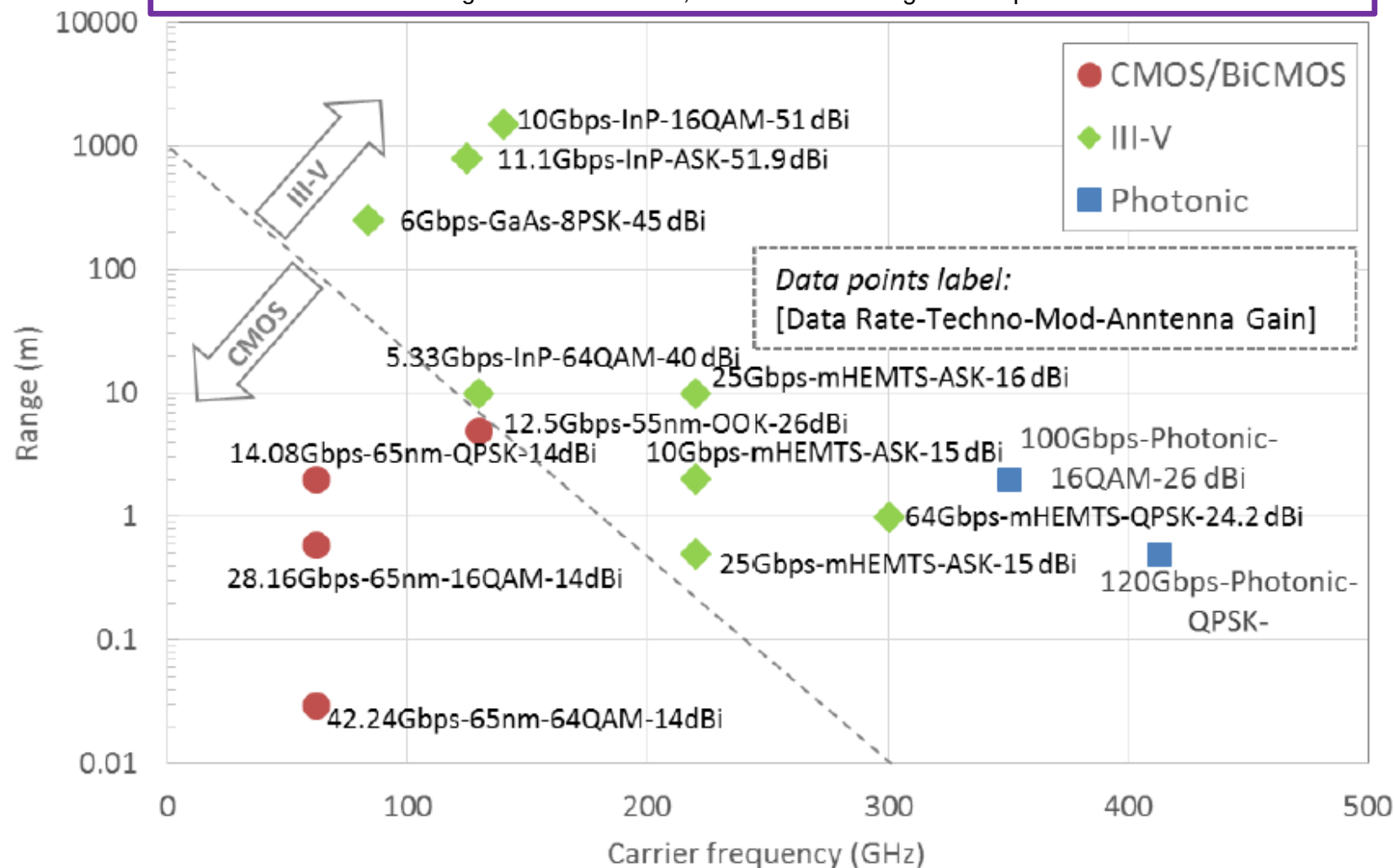
- Single Carrier
- BW 800MHz
- Carrier frequency 125GHz
- 5GNR LDPC FEC
 - Rate 0,3 to 0,9

Link budget

- 150 GHz
- EIRP 44dBm
- Antenna gain (Tx/Rx) 25dBi
- RX NF 10 dB

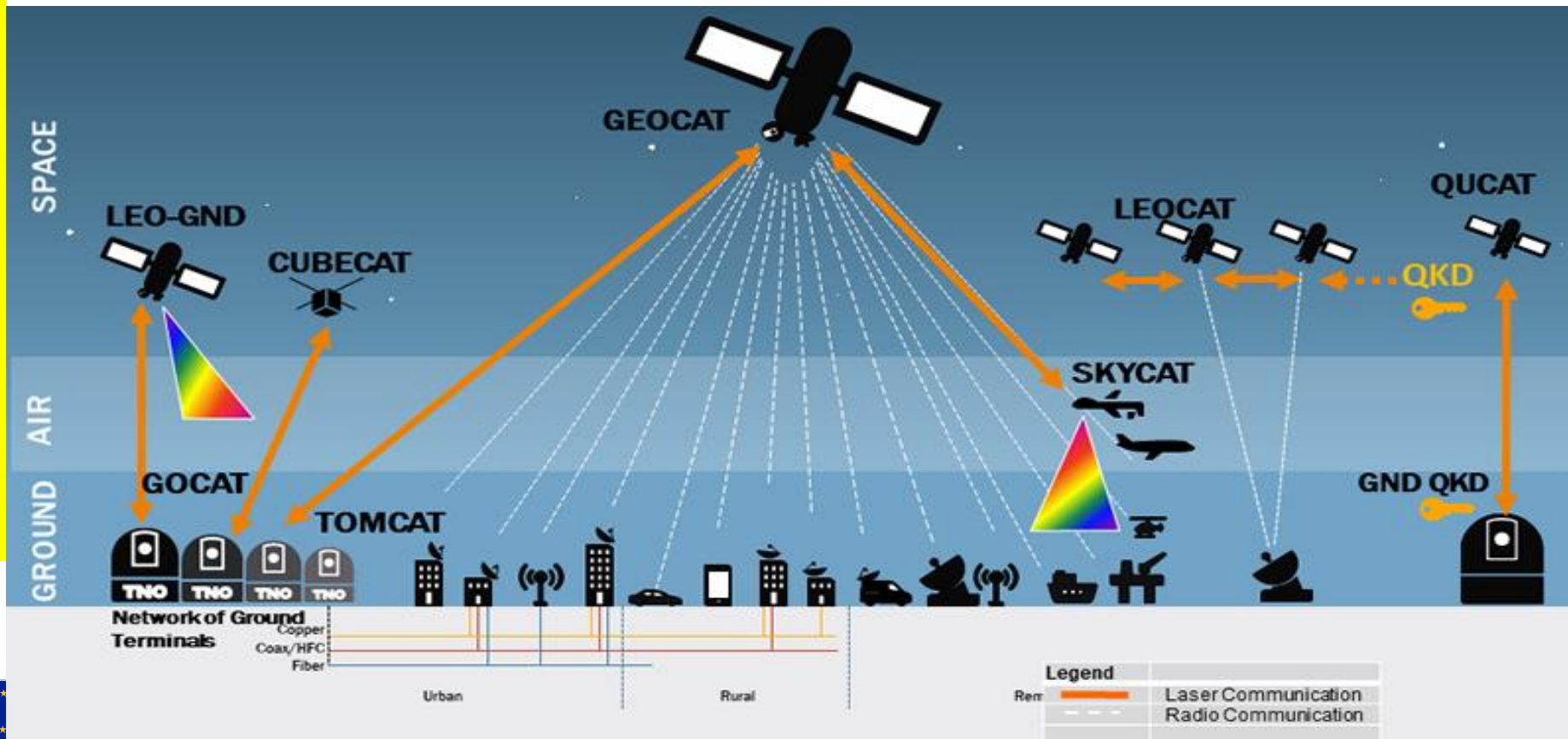
THE SUB-THZ COMMUNICATION CHALLENGE: HW PERSPECTIVE AND LIMITATIONS

Source: Calvanese et al., "6G: The Next Frontier: From Holographic Messaging to Artificial Intelligence Using Subterahertz and Visible Light Communication", IEEE Vehicular Magazine September 2019.



INCREASED EMPHASIS ON SPATIAL BW

- Integration of satellite communications to enhance bandwidth and also the spatial acuity of the 6G system
- 3D Hyper-connectivity with the ability to deliver bits per second per m^3 rather than simply bits per second



INTEGRATED TERRESTRIAL/NON-TERRESTRIAL 6G NETWORKS FOR UBIQUITOUS 3D SUPER-CONNECTIVITY AND COVERAGE OF C³

- In **6G handoff and roaming** will be **the** big issue because these satellite systems are different networks and 6G has potentially several different standards
 - Handover will be for the C³ architecture
 - Communication
 - Computing (Virtual machines and containers)
 - Caching
- 3D Coverage
- Terrestrial HetNets with macro-, micro-, and pico-BSs
- Flying-BSs (aerial-/UAV-/drone-BSs); altitude: up to several 100 m
- High Altitude Platforms (HAPs) (floating-BSs); altitude: 20 km
- Very Low Earth Orbit (VLEO) satellites; altitude: 200-1,000 km
- Geostationary Orbit (GEO) satellites; altitude: 35,786 km

$$C^3 =$$



COMMUNICATION



COMPUTATION



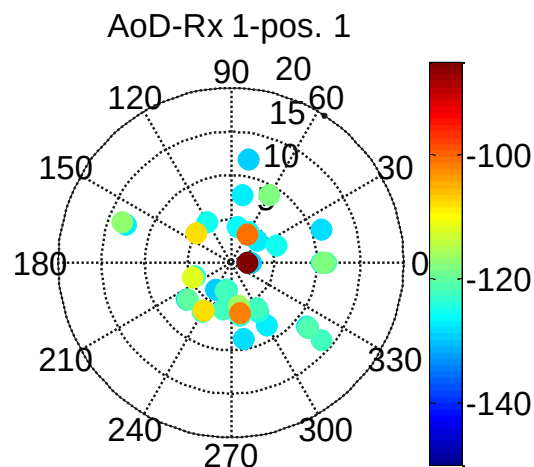
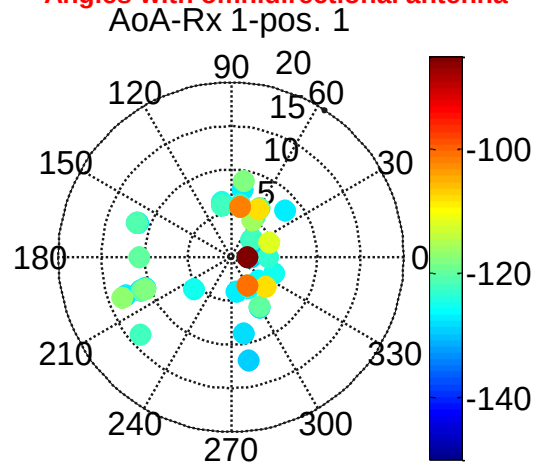
CACHING

APPLICATION OF 5G CHANNEL MODEL FOR 6G SYSTEM PERFORMANCE EVALUATION

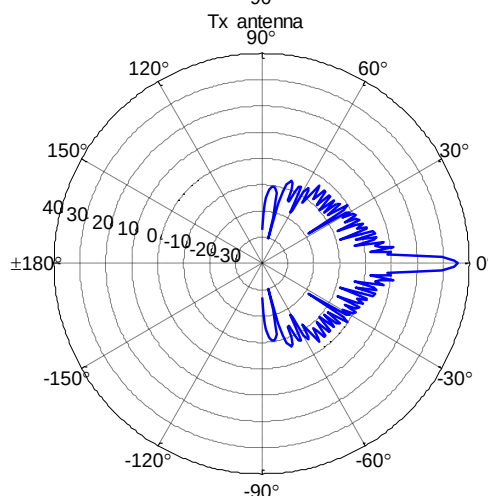
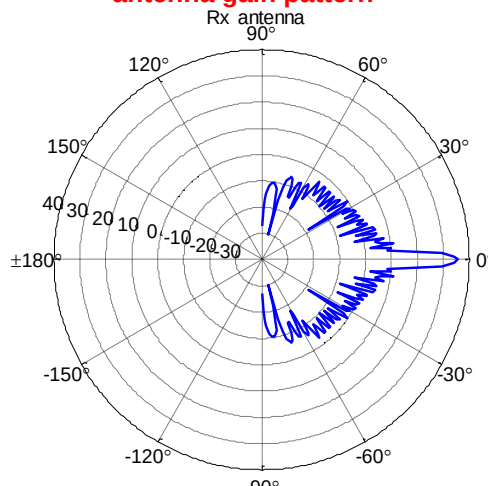
TREND 1: More bits, more spectrum

Transmit array technology:

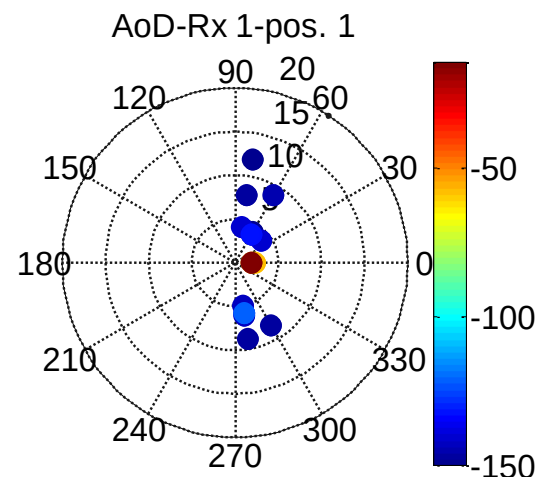
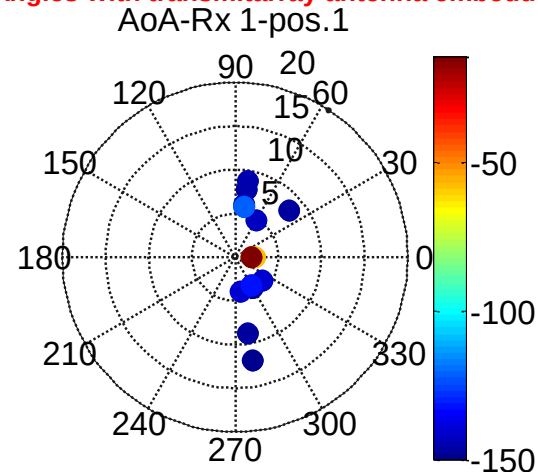
Angles with omnidirectional antenna



antenna gain pattern



Angles with transmitarray antenna embedded



AoD with transmitarray antenna embedded

HOW CRAZY ARE WE?

Band	fo (GHz)	BW (GHz)	Antenna Gain (dBi)	Antenna Size (mmxmm)	Nb Antenna Elements	Beam angle (°)
24 - 27,5	25,5	3	30	118x118	20x20	6
57-66	61,5	9	38	110x110	45x45	2,5
71-76	73,5	5	38	110x110	45x45	2,5
81-86	83,5	5	38	110x110	45x45	2,5
120-170	140	30	40	65x65	60x60	2
200-300	250	100	40	65x65	60x60	2
200-300	250	100	46	30x30	120x120	0,9

Source: CEA-LETI

- Challenge on HW processing for large BW
- New materials (flexible) for antennas patch
- Beam tracking, steering, blocking, ...
-

SOCIETAL STAKES AT THE 2030 HORIZON

- Energy efficiency and environmental responsibility
- Efficient industry and agriculture
- Efficient public services, cities and communities
- Privacy, security and sovereignty
- More quality time for individuals
- **Others that cannot be predicted now**

**4G and 5G has started addressing such challenges ..
But we are just at the beginning**



The edge eating the cloud: Distributed AI at the Edge

- Efficient local data acquisition, knowledge discovery, planning, and operation & management
- Intelligent memories & storage (In memory computing, Computational caching [[Calvanese2017](#)])
- Distributed intelligence
- **Joint C⁴** : Communication + Computing + Caching + Control
- Robustness against devices fails and attacks

Ubiquitous 3D Super-Connectivity & Intelligence support: multi layered –Integrated Terrestrial/Non-Terrestrial communications

- Terrestrial
- Aerial (UAV)
- Satellite
- ...

New spectrum:

Ultra high capacity Sub-THz communications

- Multi-Tbps communications at the cost of
 - coverage, HW complexity and system fragility to blockage, mobility, energy consumption,...
- Many open issues including how to extend and validate 5G propagation and antenna design to sub-THz communications

Visible Light Communications

- Enabling massive parallelization: 1000 simultaneous VLC connections

New Cooperation schemes

- Exploitation of cooperative intelligent surfaces and meta materials
- Multi-link communications to fight blocking at mmw and sub-THz
- ...

Most of beyond 6G will happen *locally* or in 3D