6G Enabling Technologies

From system to nano-electronics

Dr Jean-Baptiste Doré & Eric Mercier , CEA-Leti

jean-baptiste.dore@cea.fr

eric.mercier@cea.fr

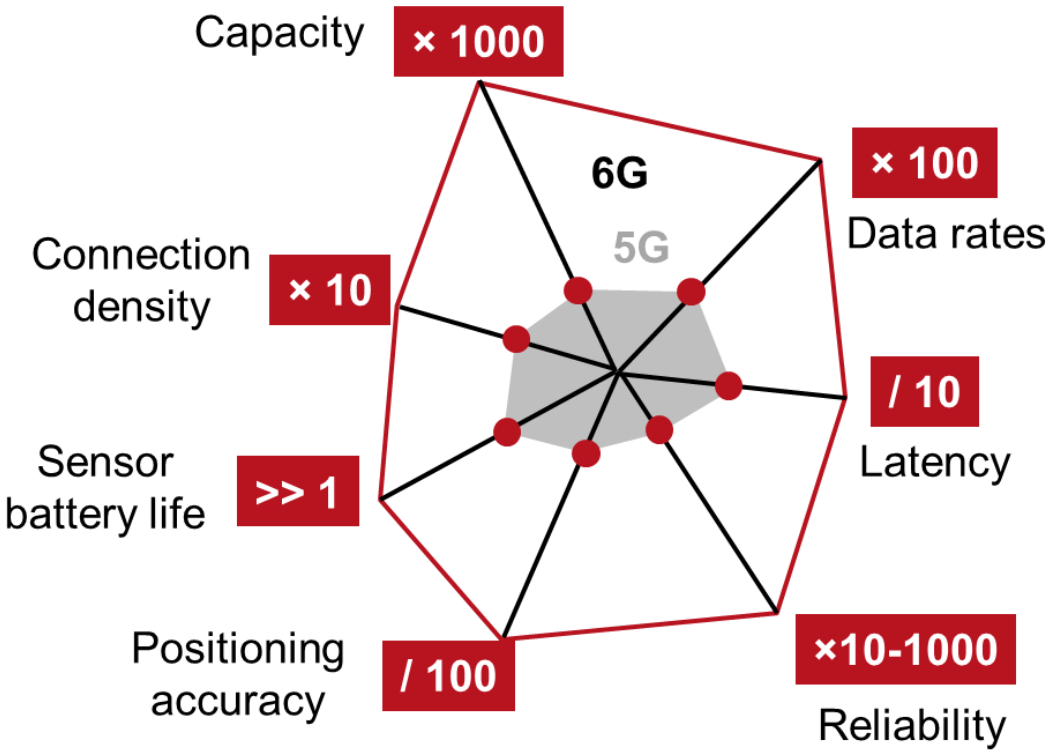
Not just **the X-factor** performance improvement race

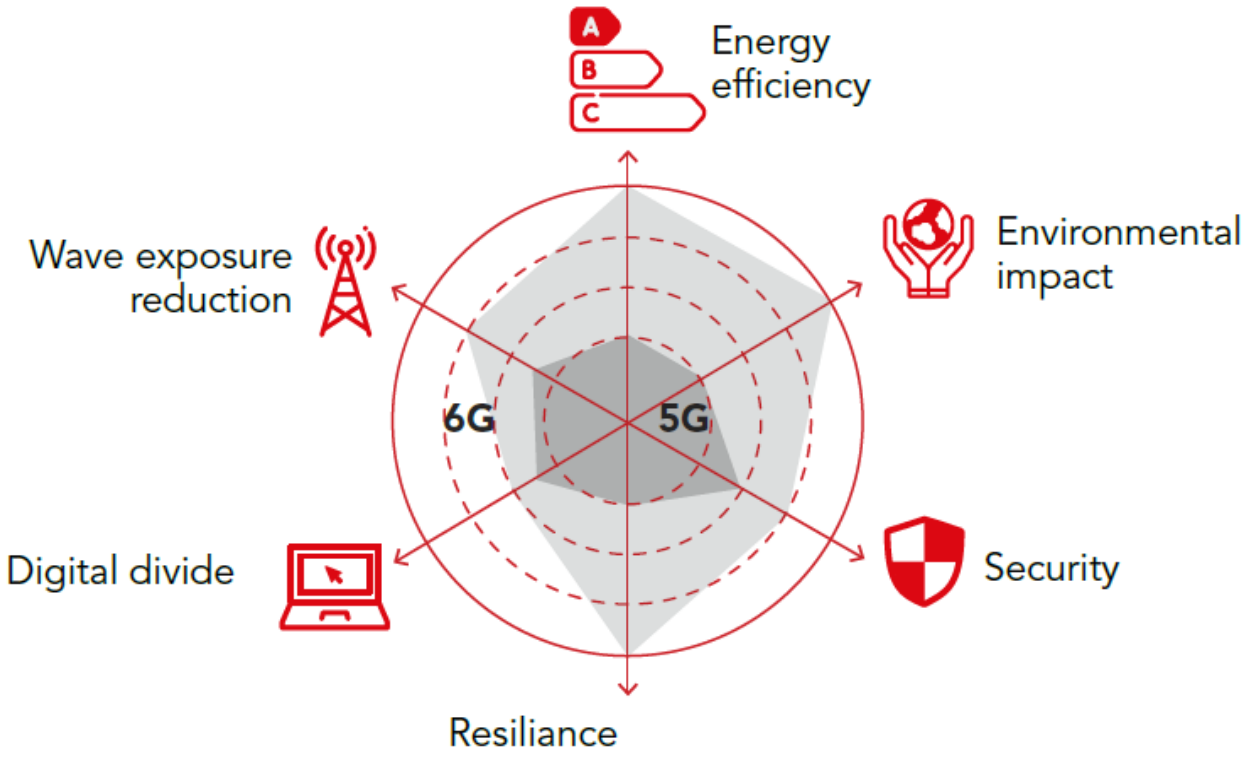
new HW design, AI technologies, network management and operation…

But also **support sustainable evolution of society and economics**

TECHNOLOGY EXPECTATION SHIFT AT 2030 HORIZON

› 6G target performance





Not just **the X-factor** performance improvement race

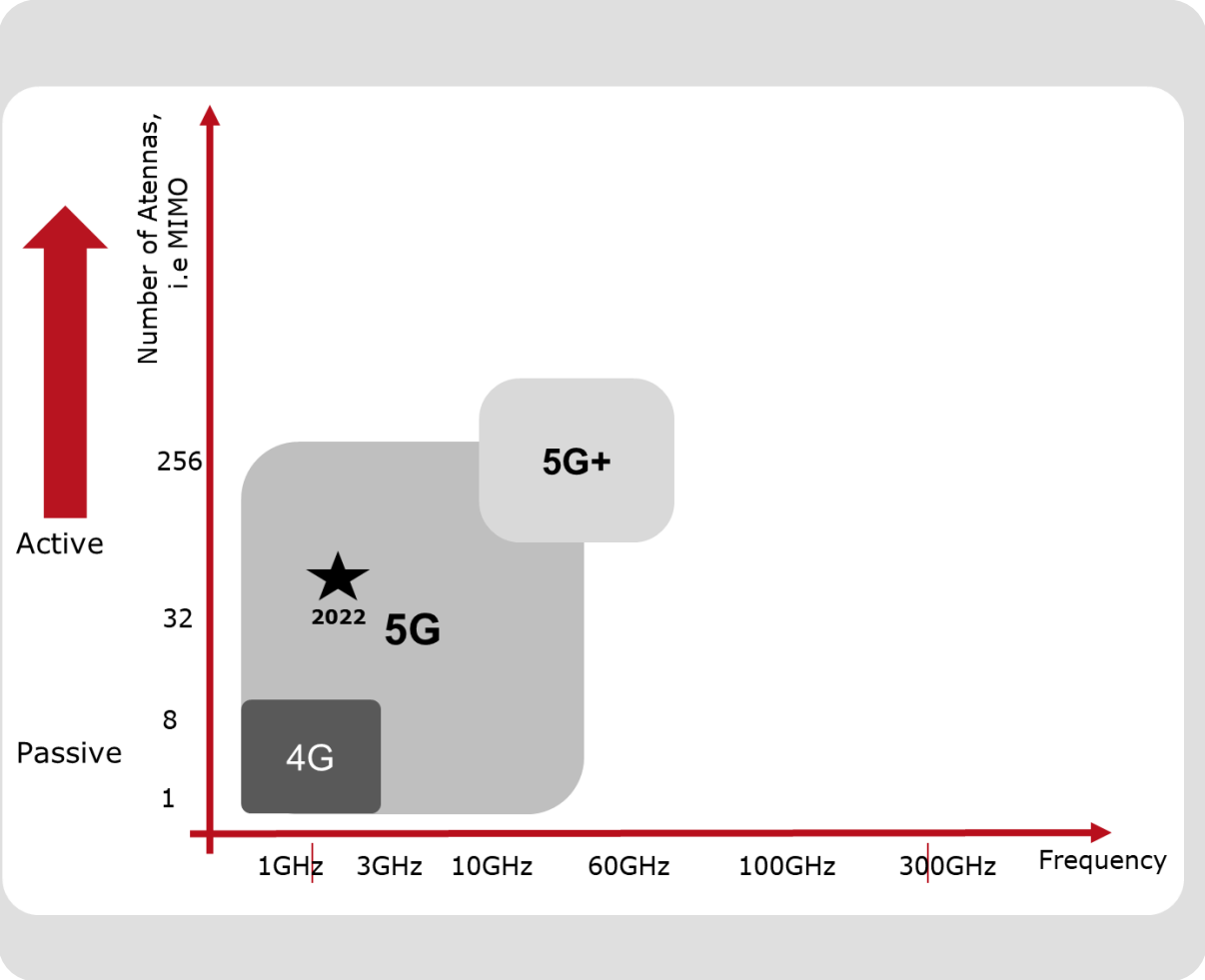
new HW design, AI technologies, network management and operation…

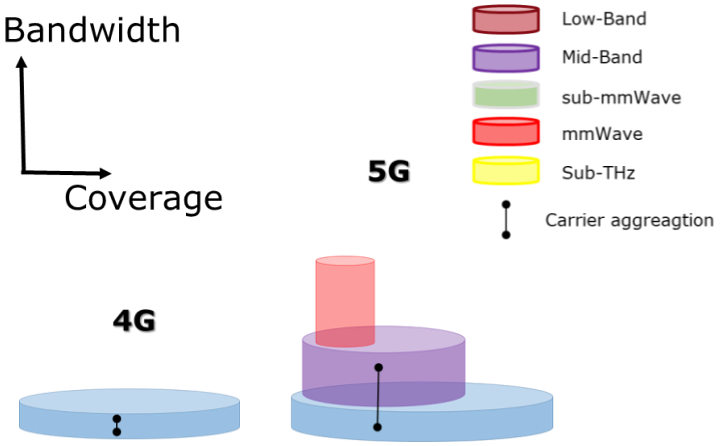
But also **support sustainable evolution of society and economics**


leti
ceatech
What could be
the next technologies
for 6G?

5G OVERVIEW

› Where we are?





New spectrum (3,5GHz and mmWave)

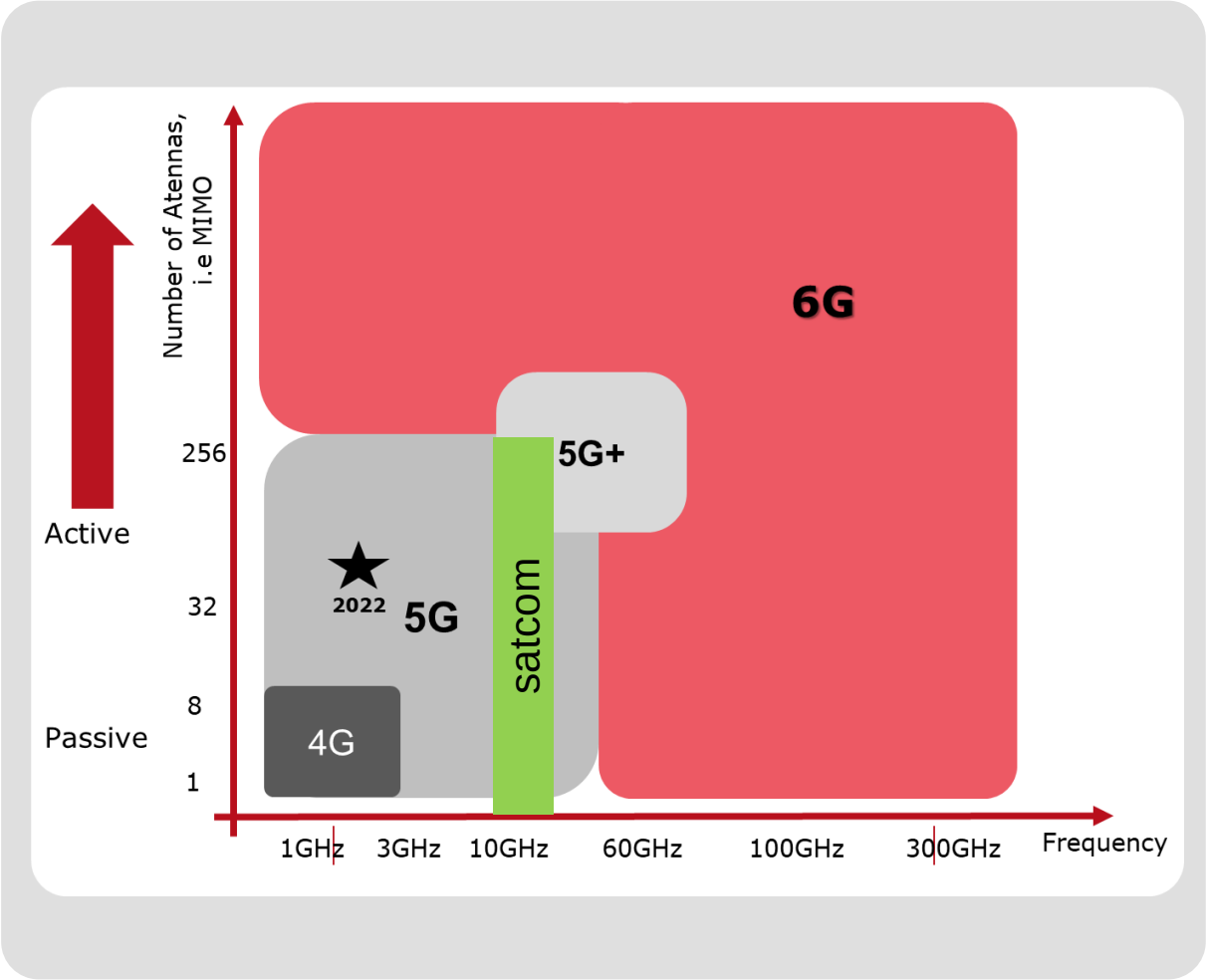
Massive MIMO

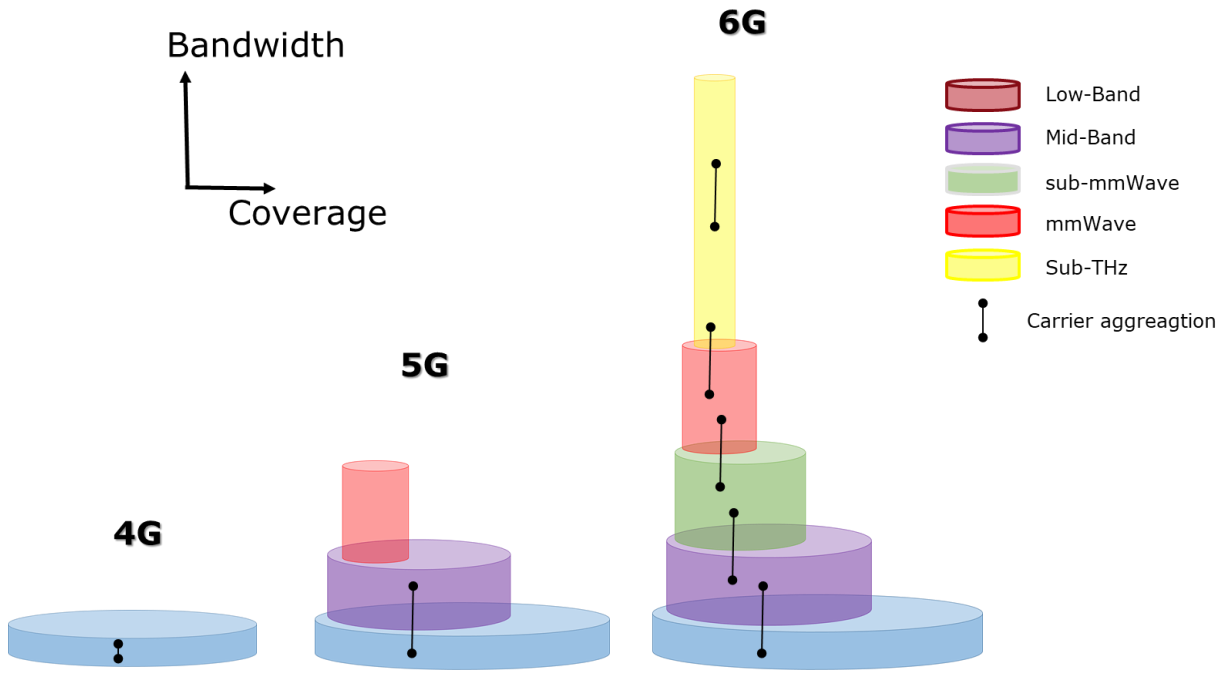
- Today deployment (France – 01/2022)
  - ► 4G: 51.294 sites are in service
  - ► 5G: 9.185 sites are in service (3,5GHz)
    7.433 sites are in service (2,1GHz)
    13.504 sites are in service (700MHz)
    0 site (mmWave)

US, Verizon 14.000 sites mmWave

TOWARD 6G

› Where are we going?

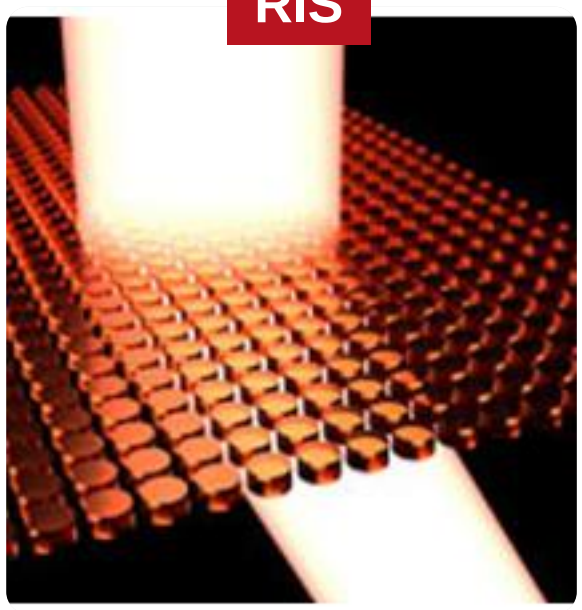




6G HOT TOPICS

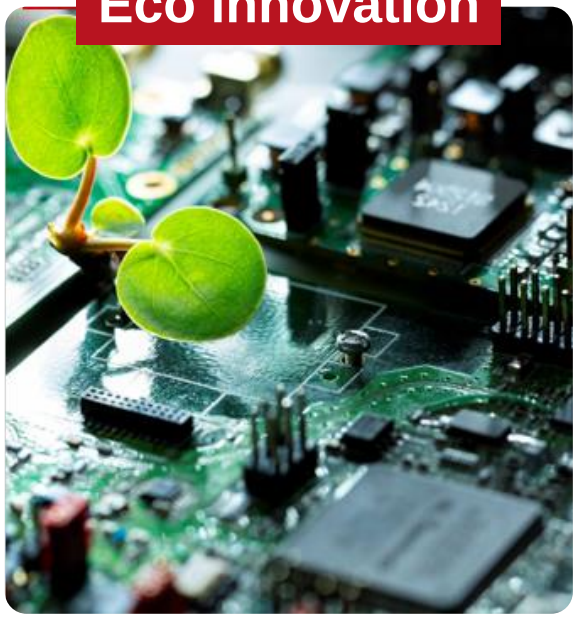
THz frequencies

RIS

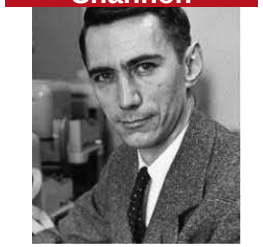


Sub-7GHz MIMO

Eco innovation



Beyond Shannon



NTN

Measure & Metrology

Radio as a service

Security

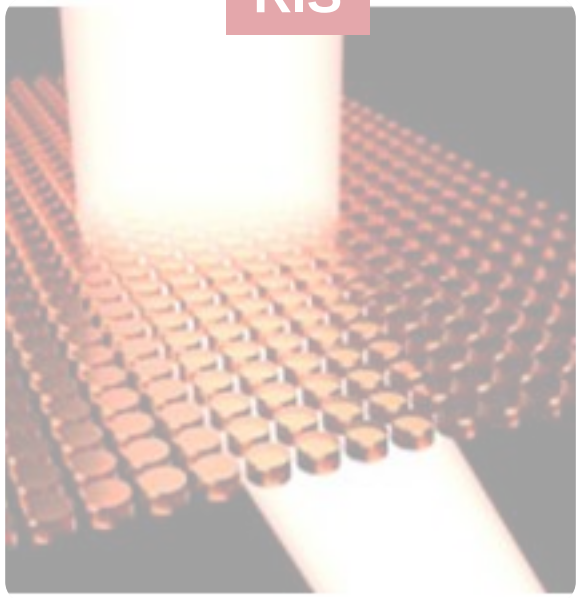
Optical networks

...

6G HOT TOPICS

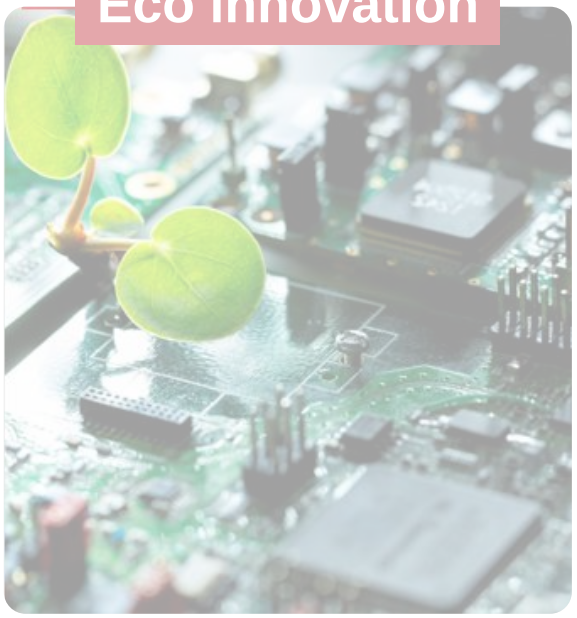
THz frequencies

RIS



Sub-7GHz MIMO

Eco innovation

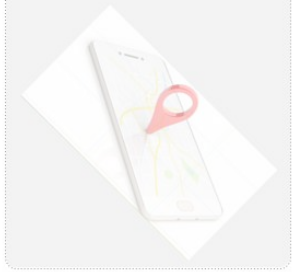


Beyond Shannon

NTN

Measure & Metrology

Radio as a service



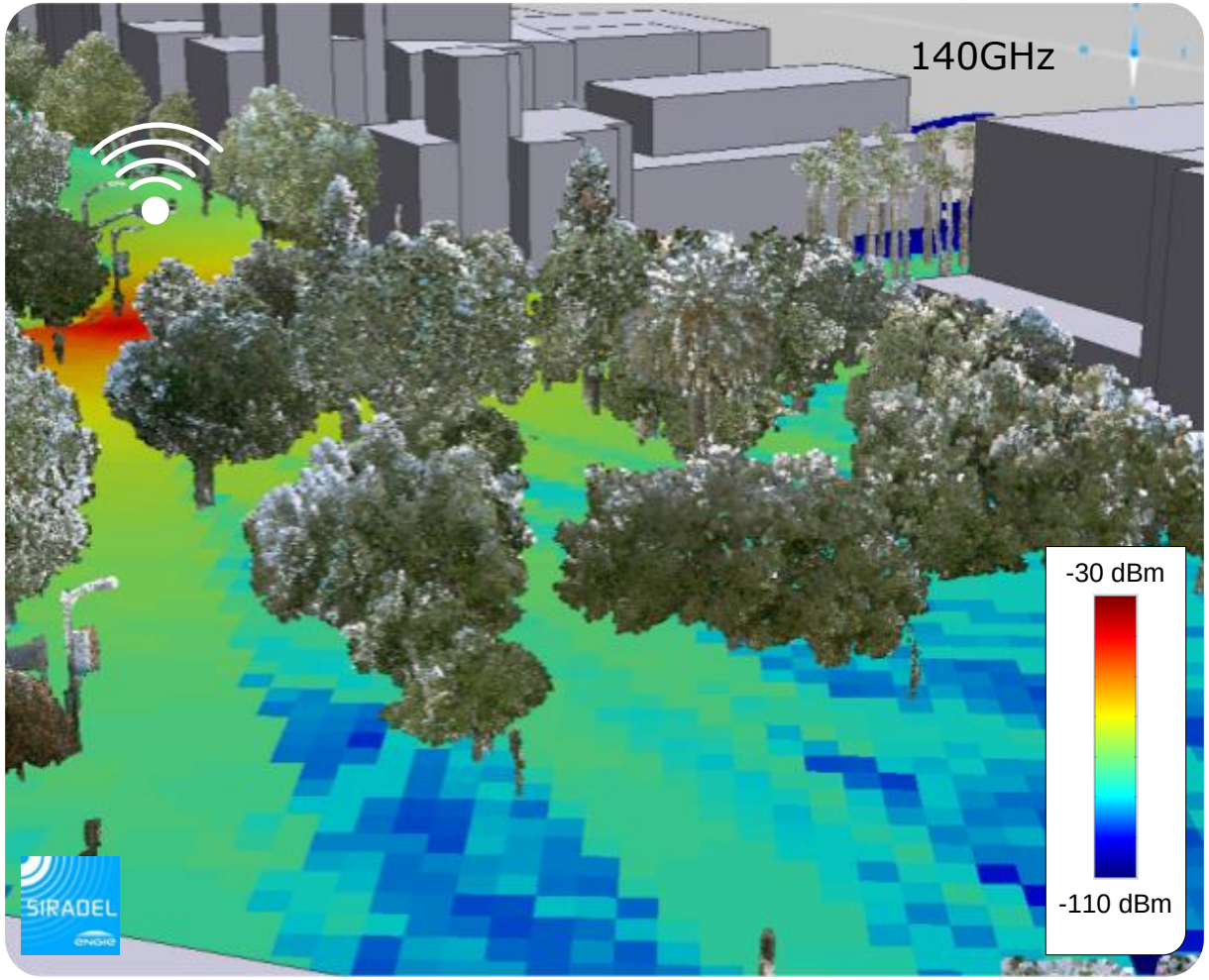
Security

Optical networks

...

INCREASED SPECTRUM AND BANDWIDTH

› Spectrum above 100 GHz



G. Gougeon et al"Assessment of sub-THz Mesh Backhaul Capabilities from Realistic Modelling at the PHY Layer," doi: 10.23919/EuCAP48036.2020.9135258.

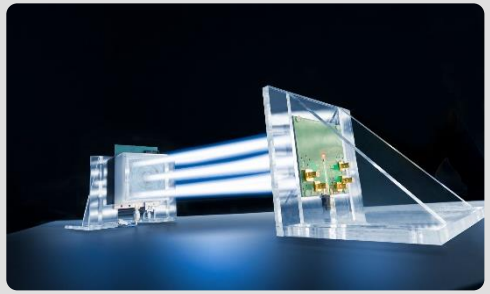
52,6 GHz bandwidth identified for wireless communication

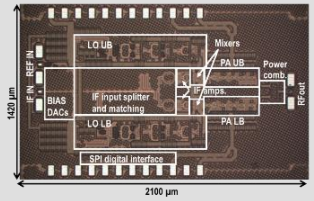
- Strong path loss and blockage
- Need for high gains and steerable antennas
- Strong to medium RF impairments

MANY CHALLENGES TO ADDRESS

Digital signal processing

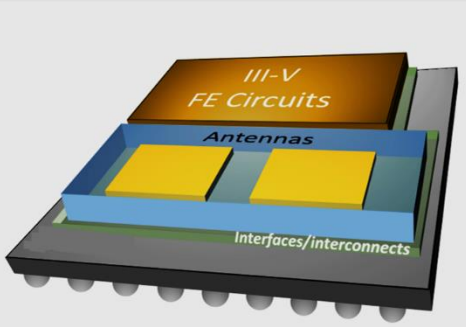
CMOS RF IC design





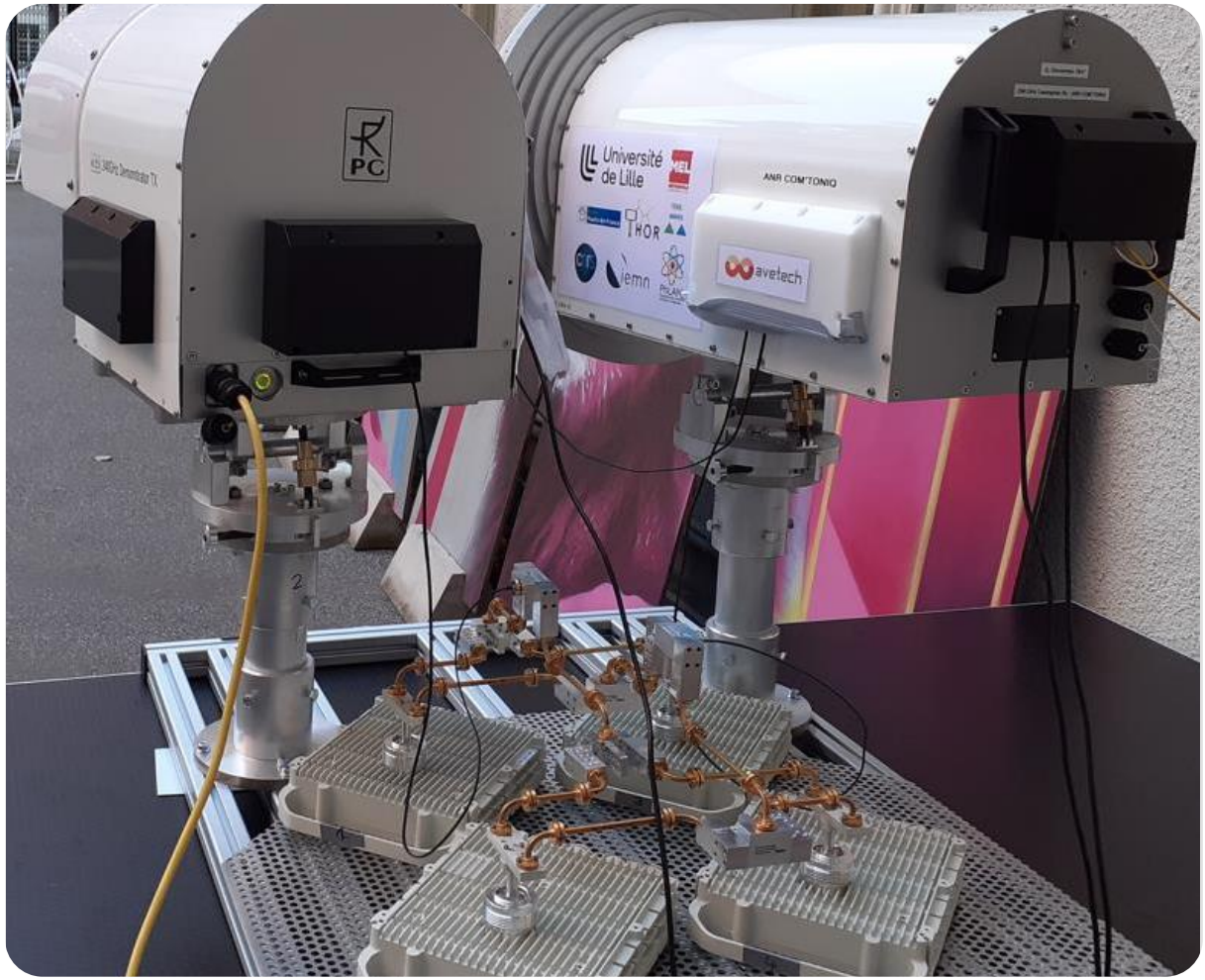
Antenna design integration

Nano electronics & assembly



DOES IT REALLY WORK?

› 300GHz backhaul link

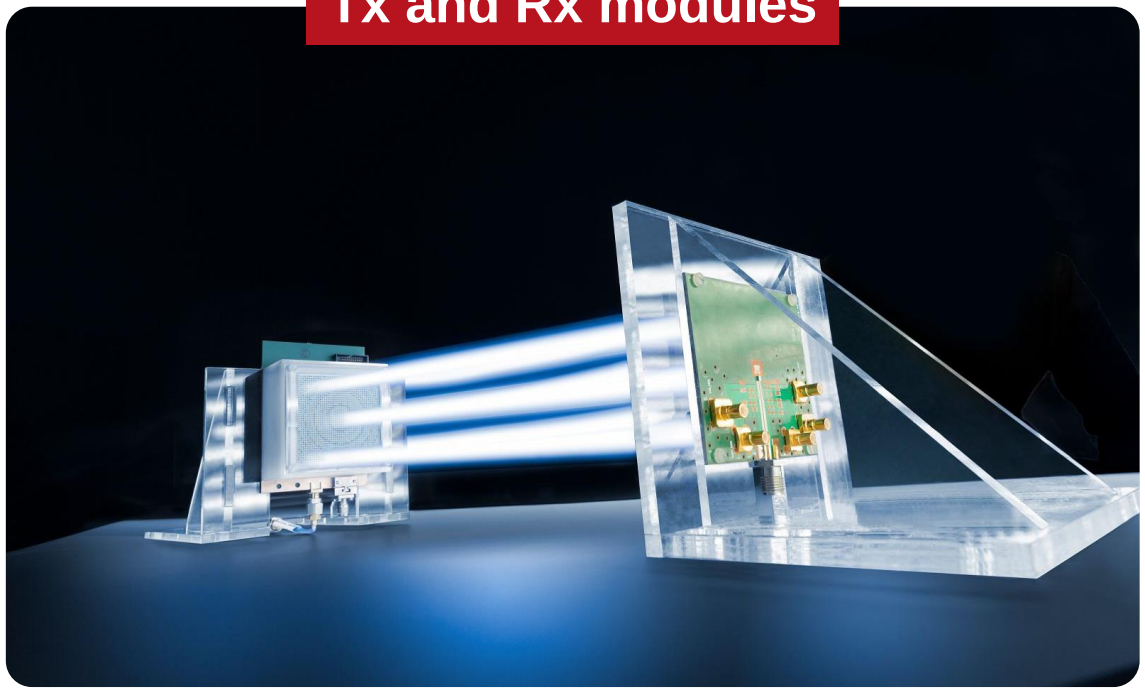


Real time transmission of 4 aggregated channels

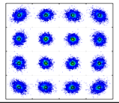
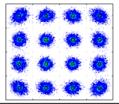
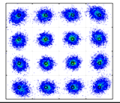
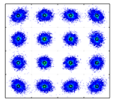
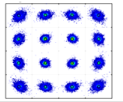
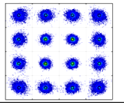
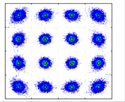
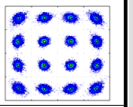
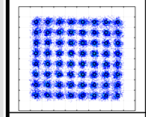
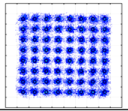
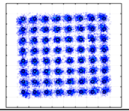
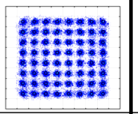
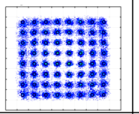
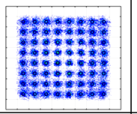
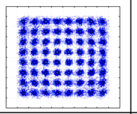
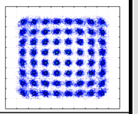
- Aggregation of 4 E-Band channels
- 292, 294, 302, 304 GHz
- Integration is a key point
- … energy consumption also!

POINT-TO-POINT D-BAND WIRELESS COMMUNICATION DEMONSTRATION

Tx and Rx modules



Main results

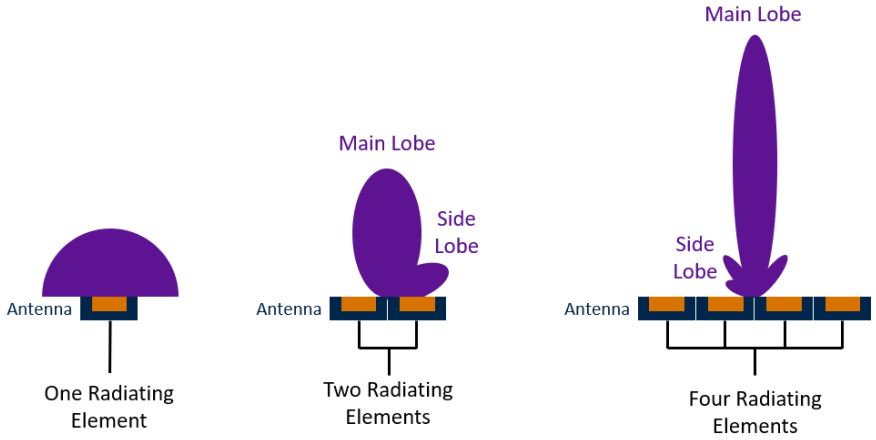
CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
140.40GHz	142.56GHz	144.72GHz	146.88GHz	149.04GHz	151.20GHz	153.36GHz	155.52GHz
1.76Gbauds	1.76Gbauds	1.76Gbauds	1.76Gbauds	1.76Gbauds	1.76Gbauds	1.76Gbauds	1.76Gbauds
							
EVM=9.7%	EVM=10.3dB	EVM=11.2%	EVM=10.7%	EVM=9.0%	EVM=10.1%	EVM=9.8%	EVM=9.5%
7.04Gb/s	7.04Gb/s	7.04Gb/s	7.04Gb/s	7.04Gb/s	7.04Gb/s	7.04Gb/s	7.04Gb/s
							
EVM=9.1%	EVM=9.4%	EVM=9.6%	EVM=9.0%	EVM=9.3%	EVM=9.8%	EVM=9.0%	EVM=8.6%
10.5Gb/s	10.5Gb/s	10.5Gb/s	10.5Gb/s	10.5Gb/s	10.5Gb/s	10.5Gb/s	10.5Gb/s

84 Gb/s for 7.7 pJ/b

High data rate & energy efficiency demonstrated

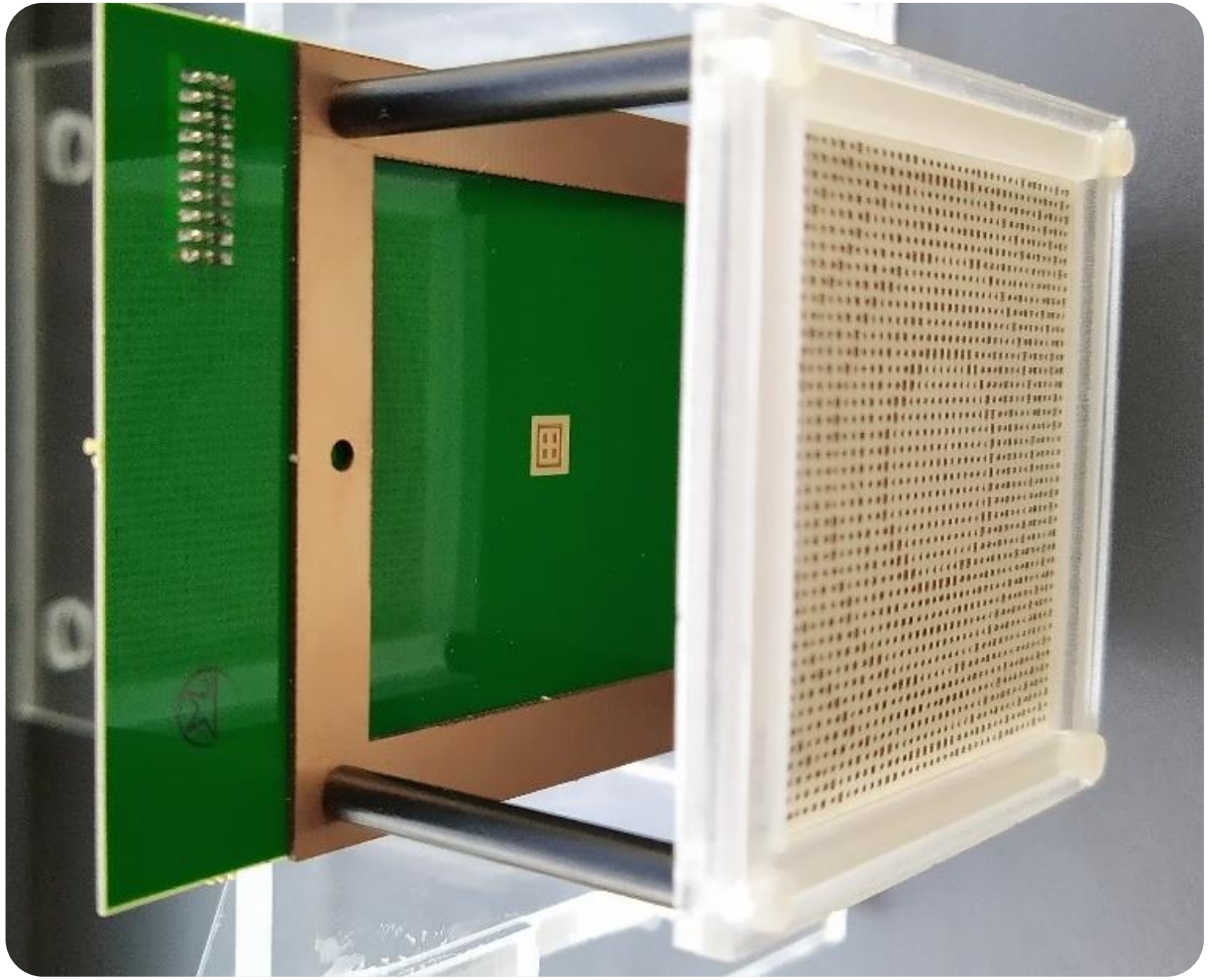
HOW TO DEAL WITH LOSS PROPAGATION AT HIGH FREQUENCY?

› Transmit array antenna at 140 GHz



Increase antenna gain through beamforming

- Beamforming with 1 focal source illuminating a planar array of 1600 antenna elements
- 33 dBi Antenna gain

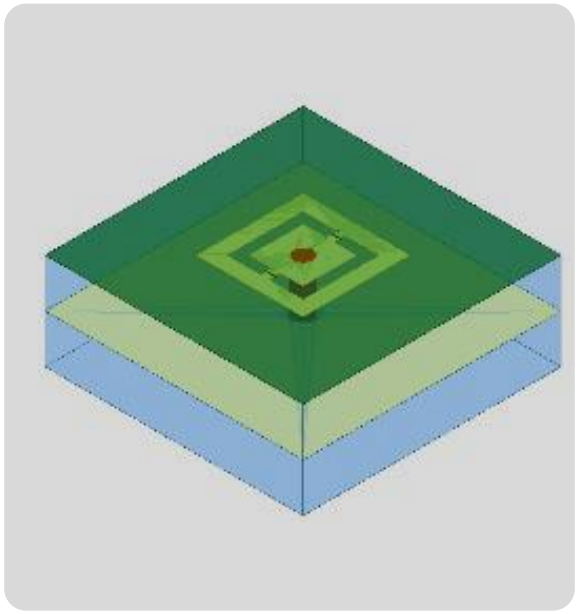


F. Foglia Manzillo et al "High-gain D-band transmitarray in standard PCB technology for beyond-5G communications," IEEE Transaction Antennas and Propag., vol. 68, no. 1, pp. 587-592, Jan. 2020

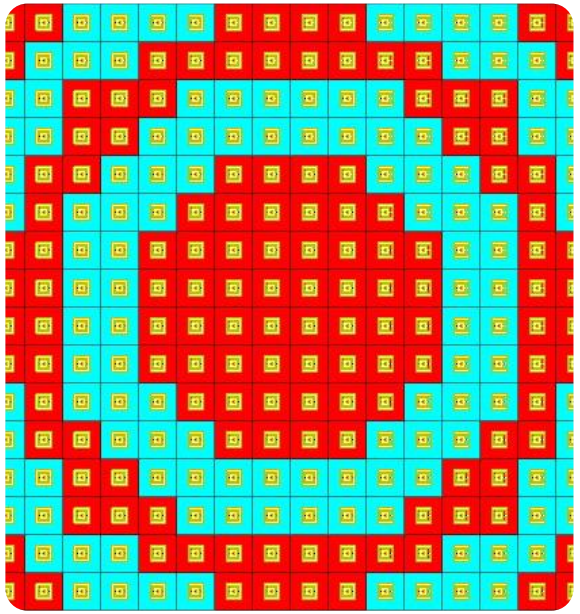
WHICH TECHNOLOGY TO PROVIDE ENERGY EFFICIENT ANTENNA SYSTEM?

› Phase Change Material for antenna unitary cells

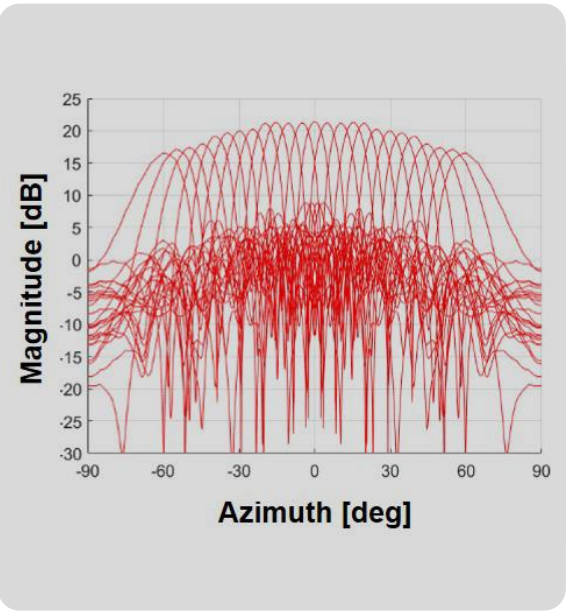
1 antenna panel



1600 unitary antenna cells with GeTe switches



Dynamic Beamsteering configuration

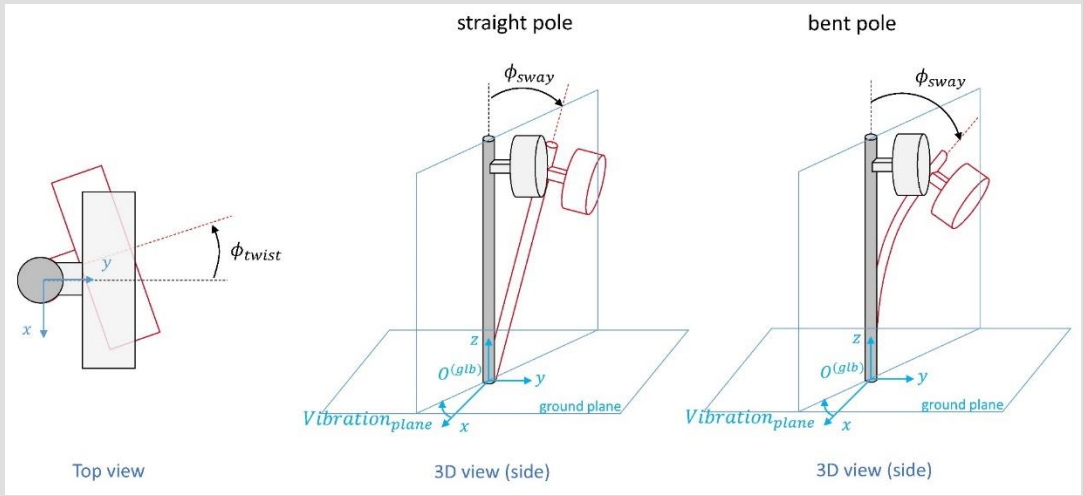


+- 60° beamsteering @140 GHz simulation

[EUCAP2022] S Gharbieh et al, "Phase Change Material Based Reconfigurable Transmitarray: a Feasibility Study"

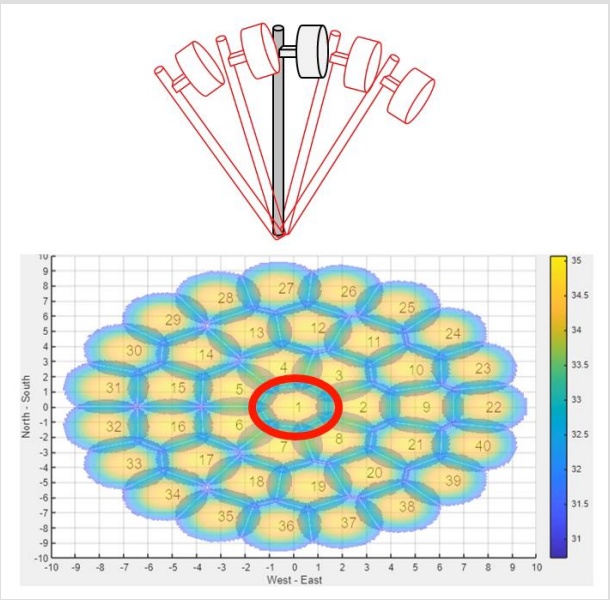
HOW TO TREAT EFFECTIVELY BEAM ALIGNMENT ?

› Beam alignment



Pole vibration – twist and sway – due e.g. to wind and temperature change

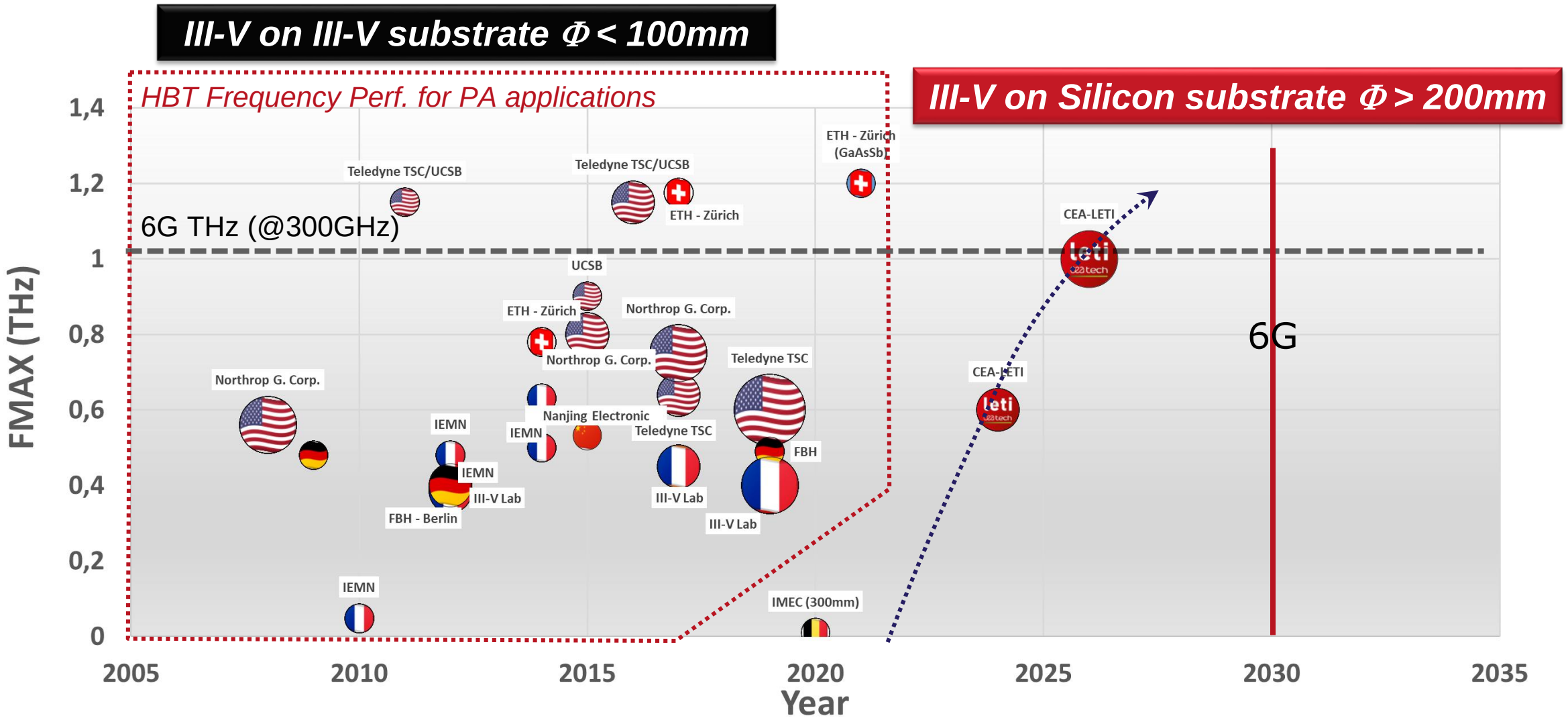
Phased Array Management



1024 radiating elements, grouped by clusters of 4 → 256 phase-shifters to control

SoA THz devices

› Leti ambition for 6G



2030 as 6G momentum Towards sub-THz transceiver

› Key Challenges

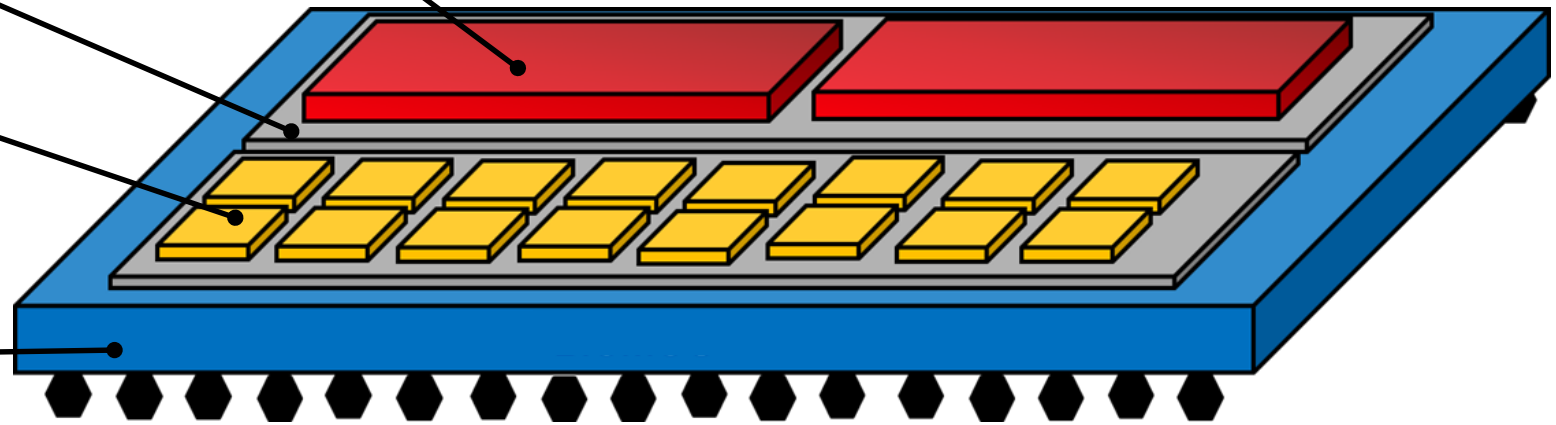
Devices & Functions

III-V THz
Transistors & Circuits

THz
Passive devices & interconnects

Integrated Antennas

Advanced (Bi) CMOS
functions



Architecture & System

- Packaging & 3D assemblies
- Co-optimization for 3D Integration
- Thermal & mechanical issues
- Electromagnetic Coupling & compatibility issues
- Costs VS Performances

FDSOI

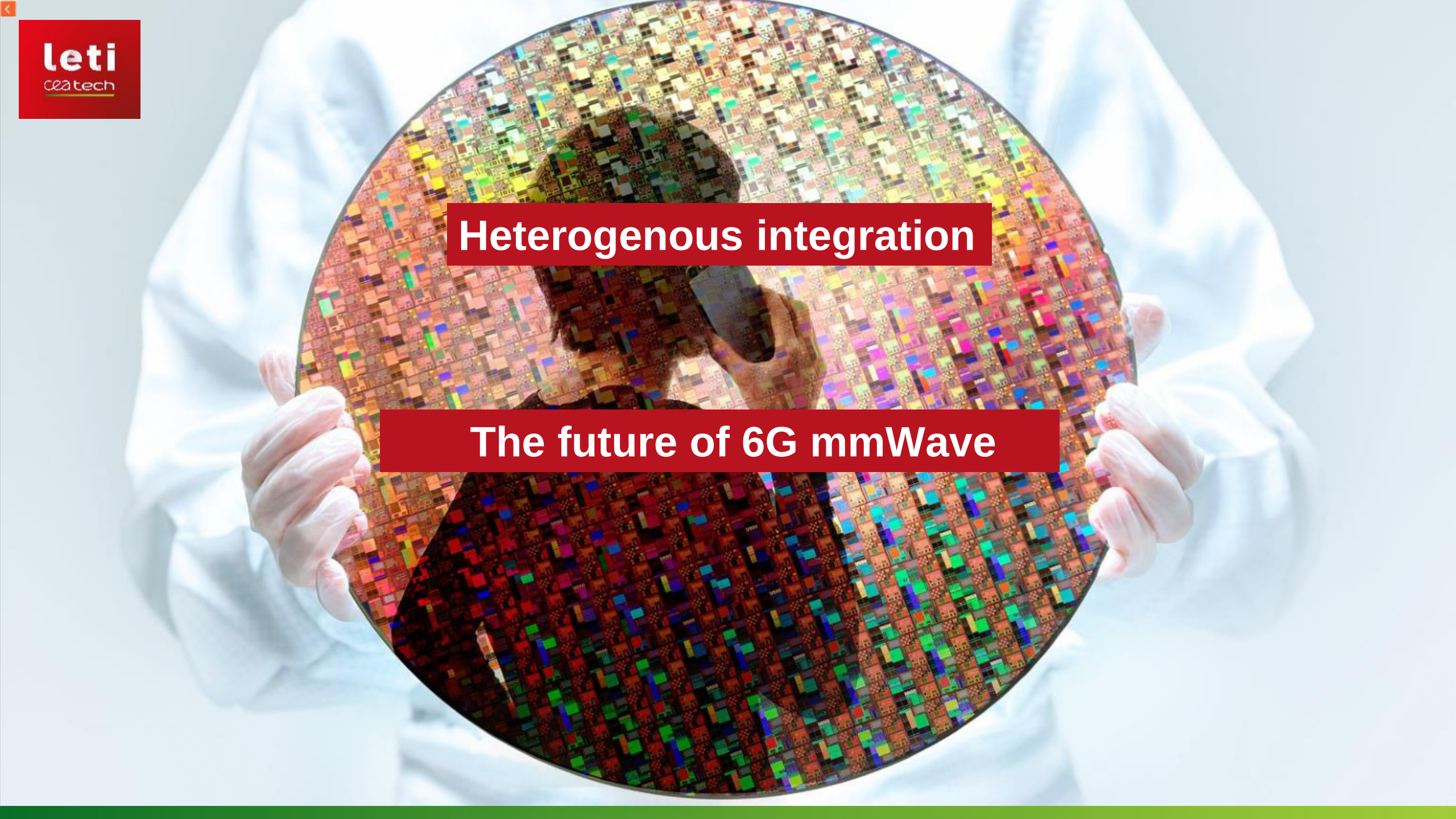
Perfect fit for 5G mmWave

2021

Pixel 6 Pro supports 5G mmWave designed on Samsung's FDSOI 28nm platform

2022

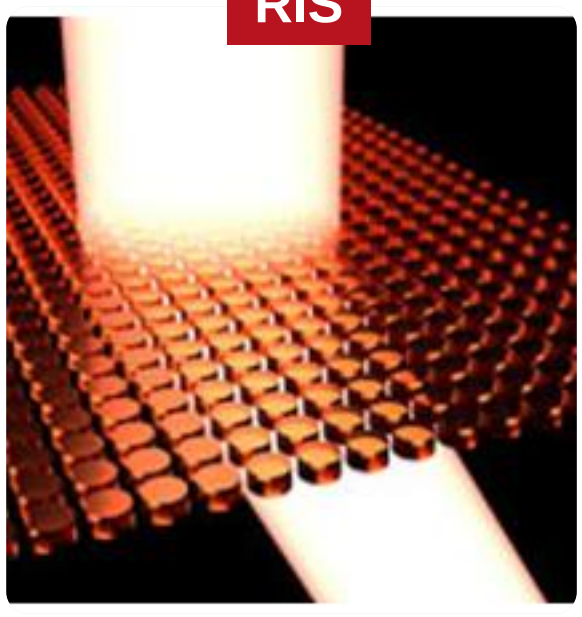
MediaTek Enters 5G mmWave Market […] mmWave antenna-in-package module with mmW RF transceiver fabricated using GF 22FDX (FDSOI).


Heterogenous integration
The future of 6G mmWave

6G HOT TOPICS

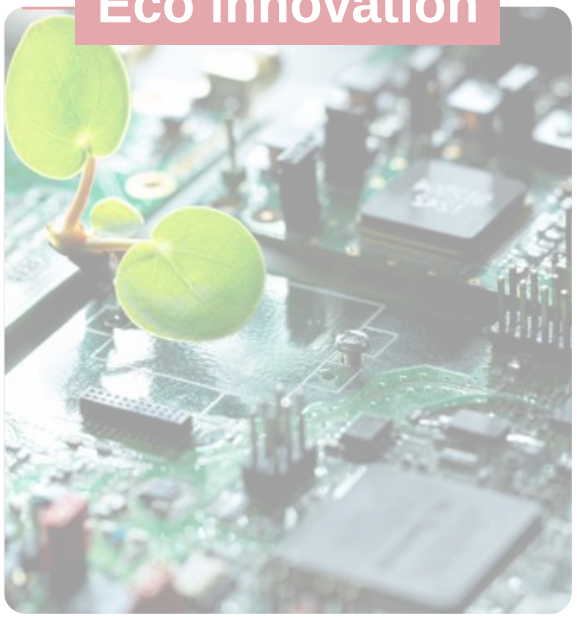
THz frequencies

RIS



Sub-7GHz MIMO

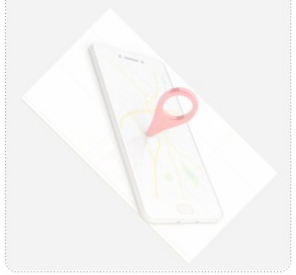
Eco innovation



NTN

Measure & Metrology

Radio as a service



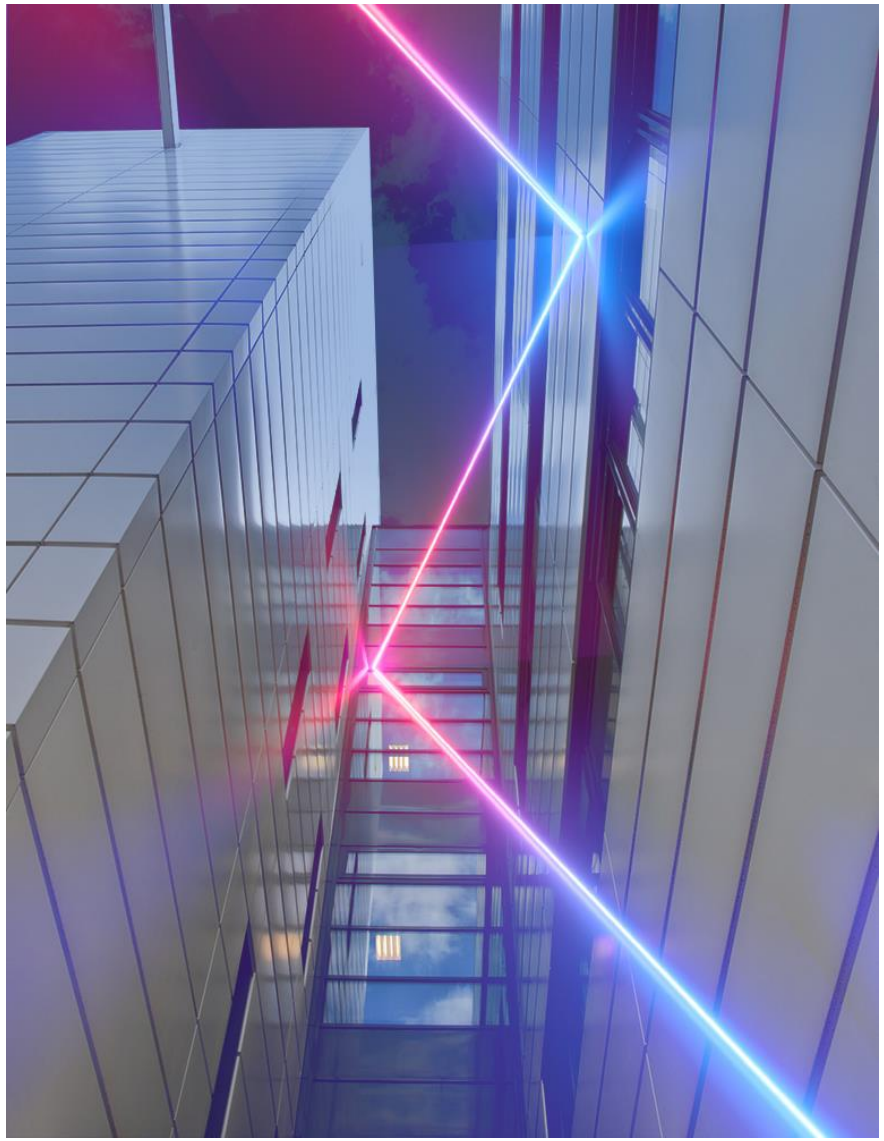
Security

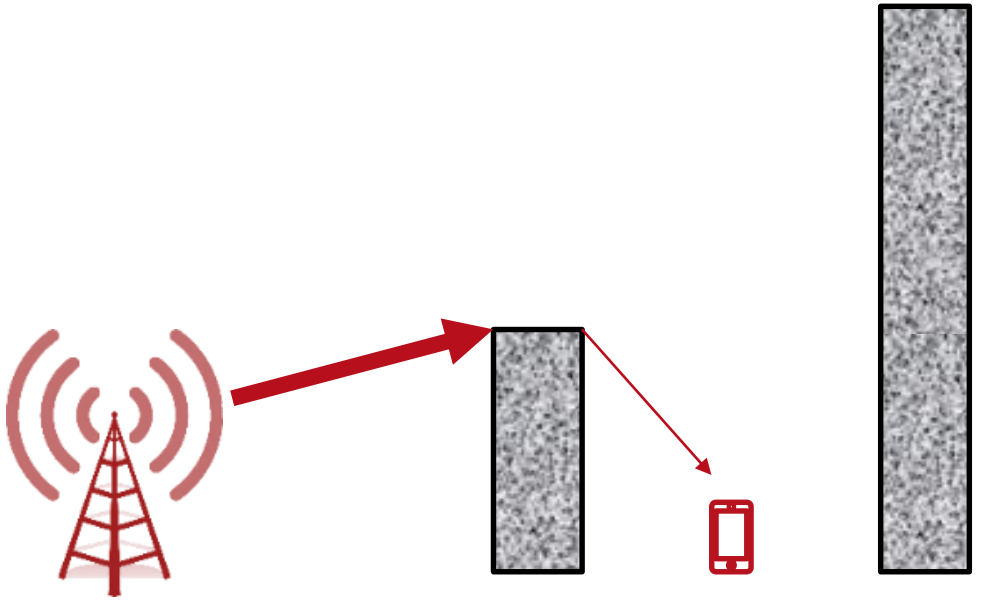
Optical networks

...

ENHANCED COVERAGE

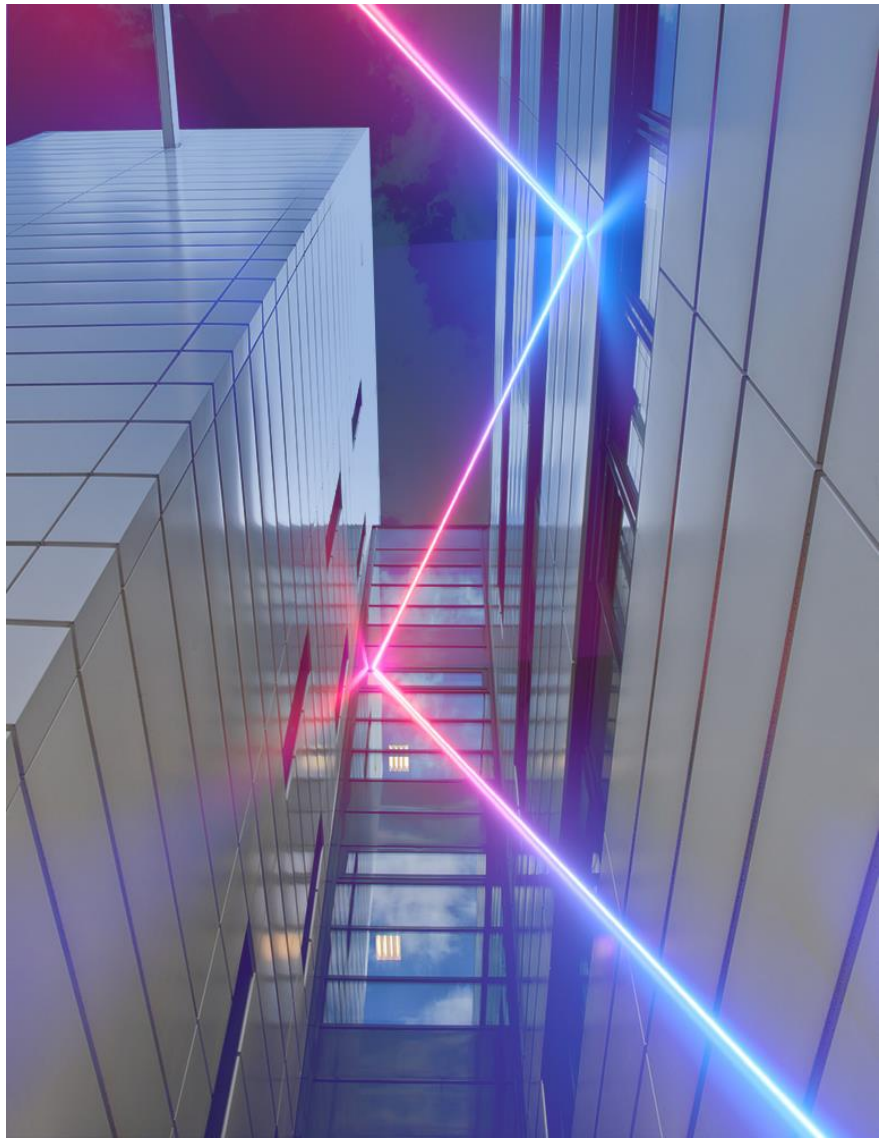
› Using Reconfigurable Intelligent Surfaces (RIS)





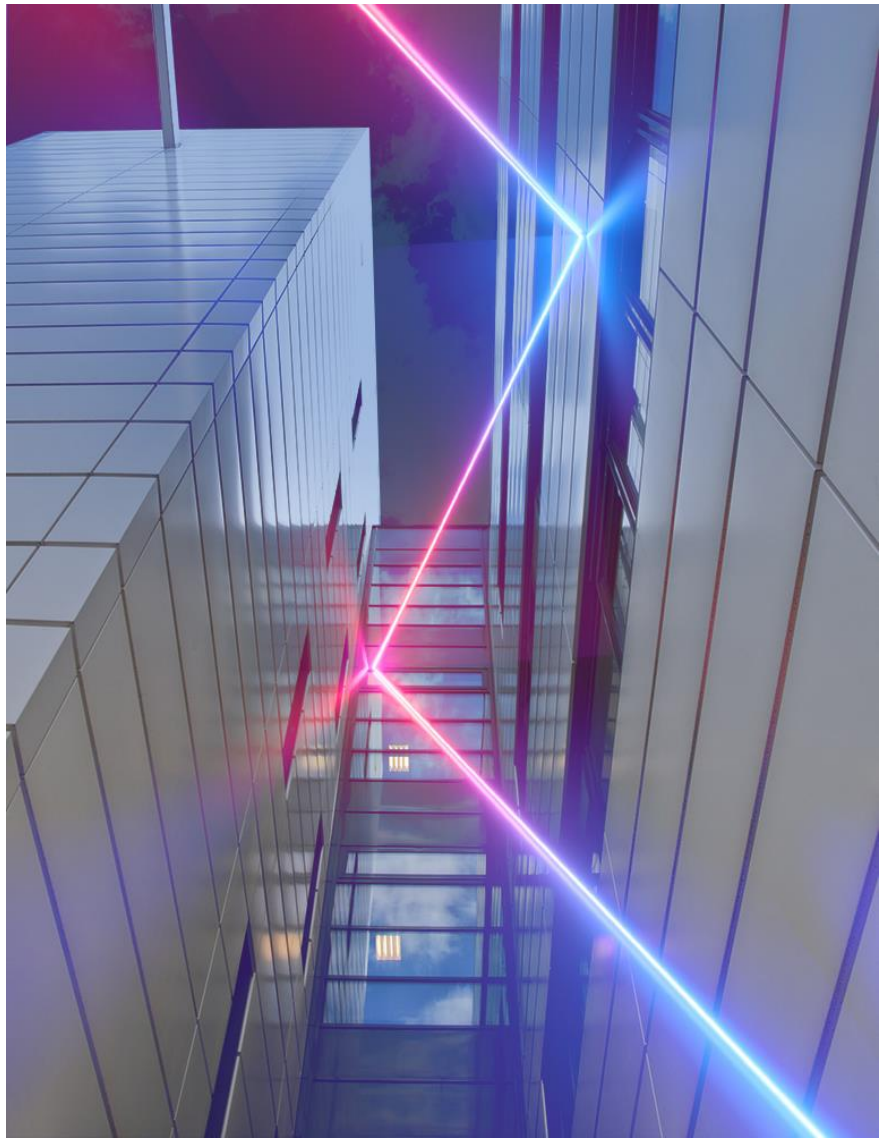
ENHANCED COVERAGE

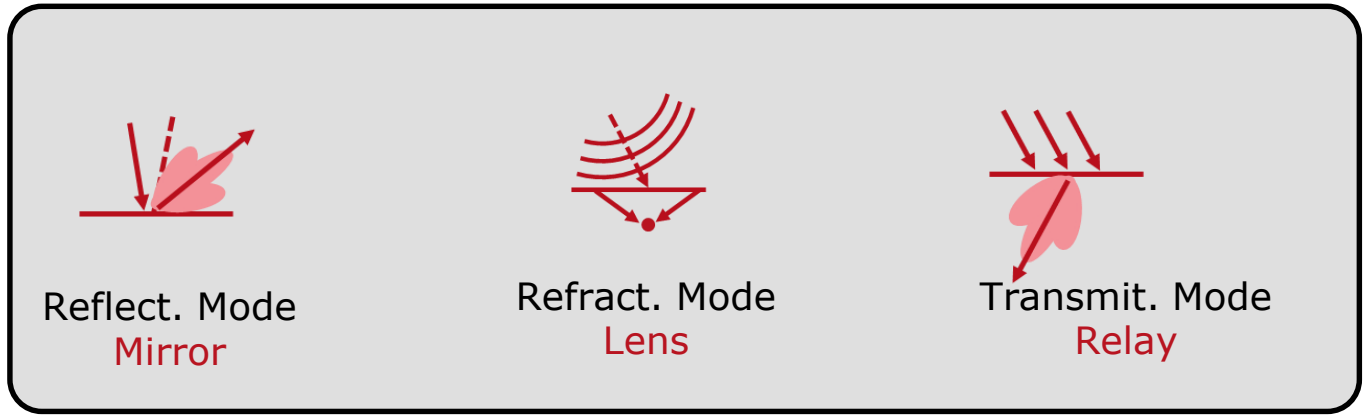
› Using Reconfigurable Intelligent Surfaces (RIS)



ENHANCED COVERAGE

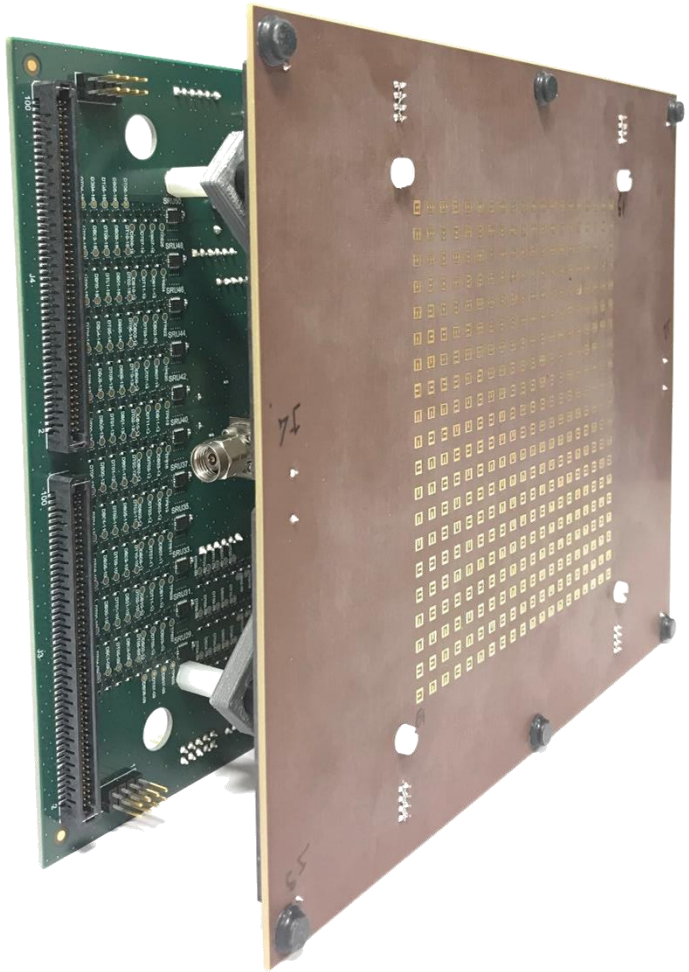
› Using Reconfigurable Intelligent Surfaces (RIS)

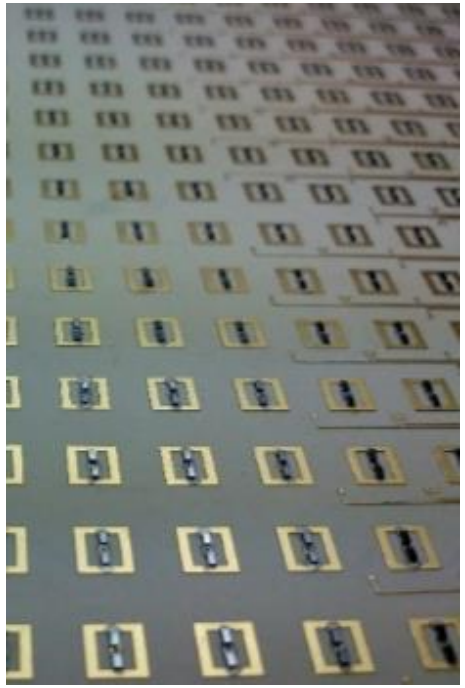




HOW TO DESIGN RIS?

› CEA-Leti prototype based on transmit array antenna





Space-fed arrays with RF-switch-based holographic beam-forming

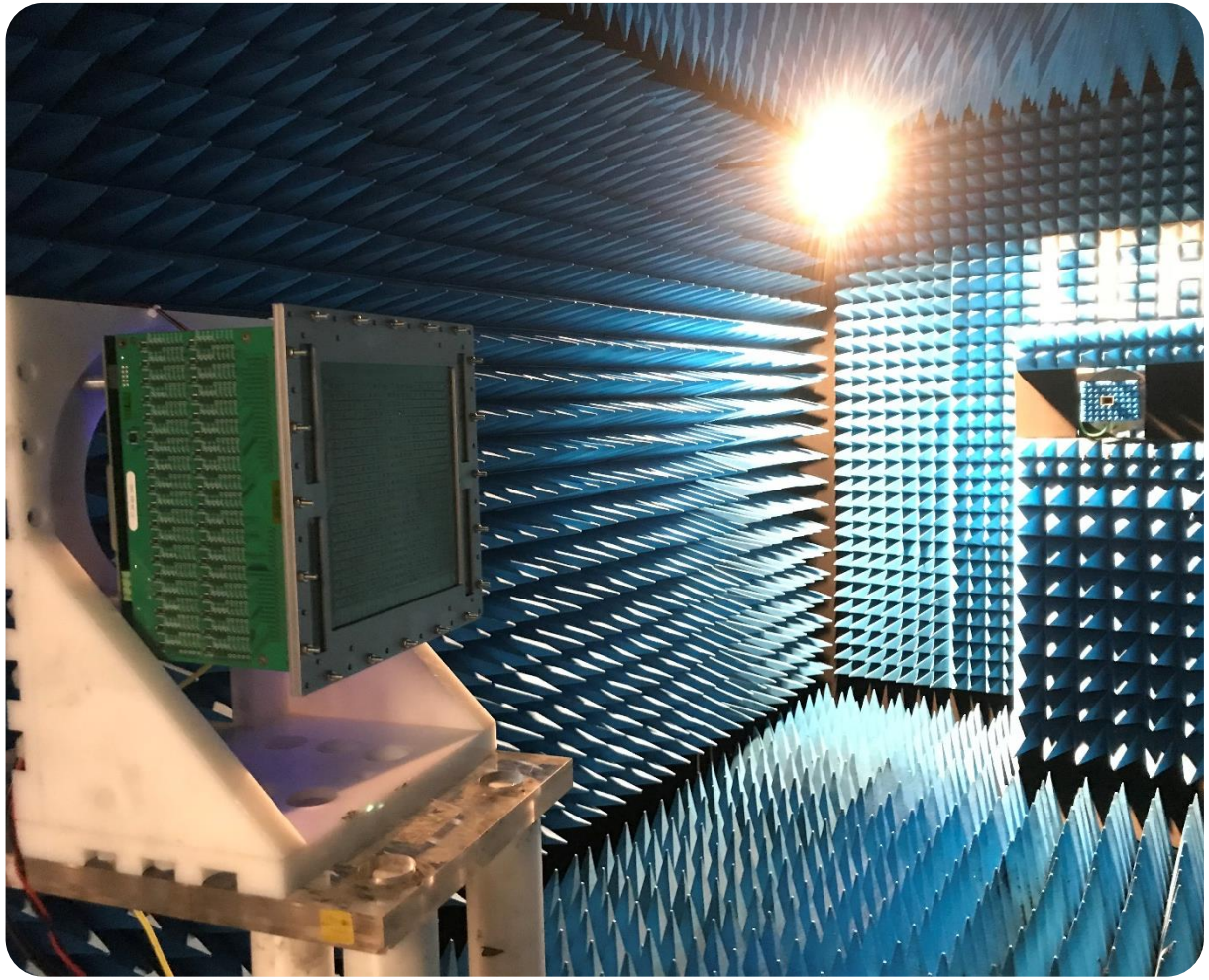
- No phase shifters or power amplifiers
- No loss or parasitic radiation of the feed network
- Phase-control devices integrated into the radiating element

OUR LASTEST DEMONSTRATION AT KA-BAND

› Electronically reconfigurable transmitarray with CP polarization manipulation

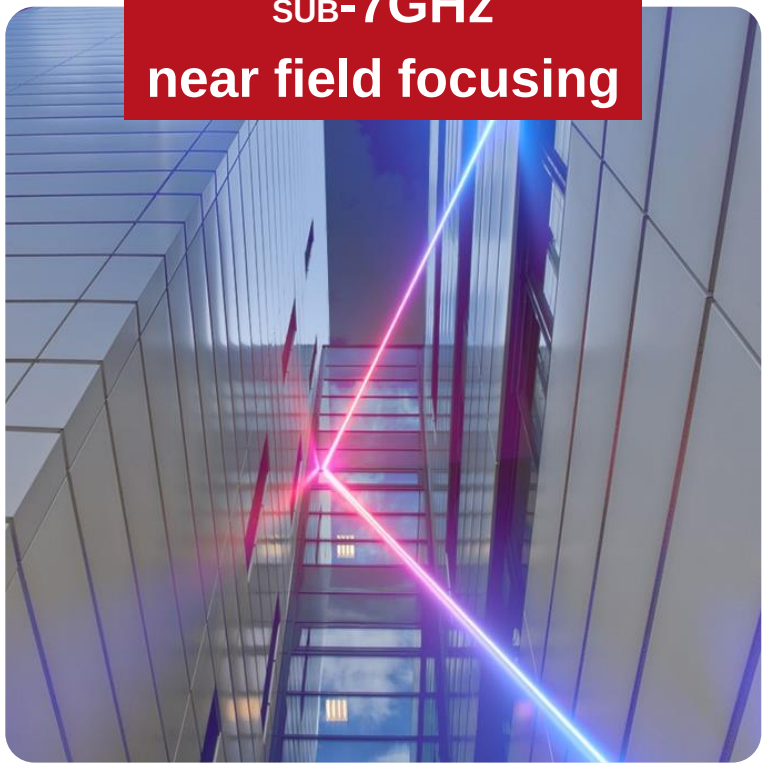
576-element transmitarray with 2304 p-i-n diodes

- 2-bit phase resolution
- RHCP/LHCP switchable polarization
- ±60° 2-dimensional beam-steering
- Frequency selective

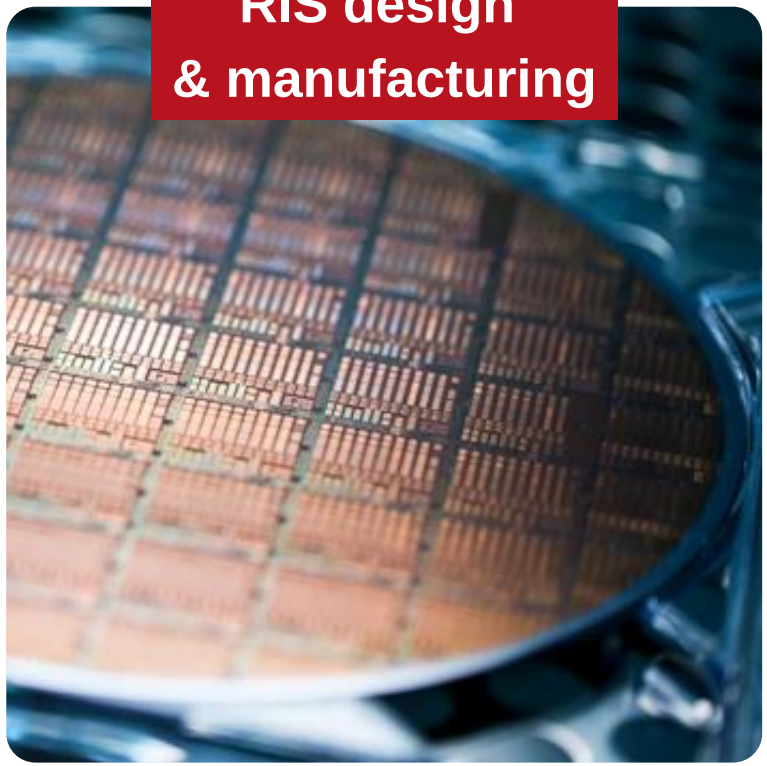


RIS CHALLENGES

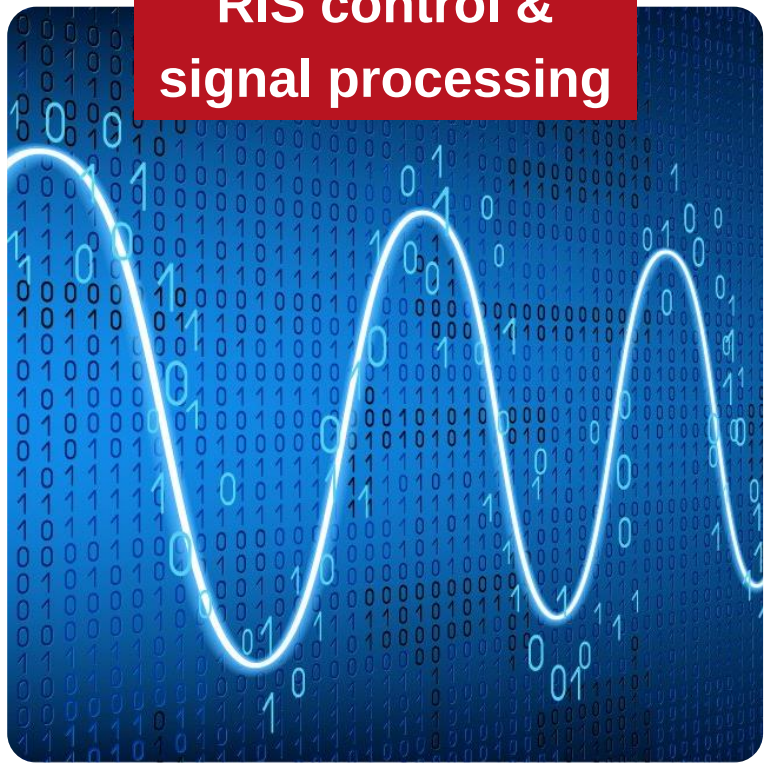
sub-7GHz near field focusing



RIS design & manufacturing



RIS control & signal processing

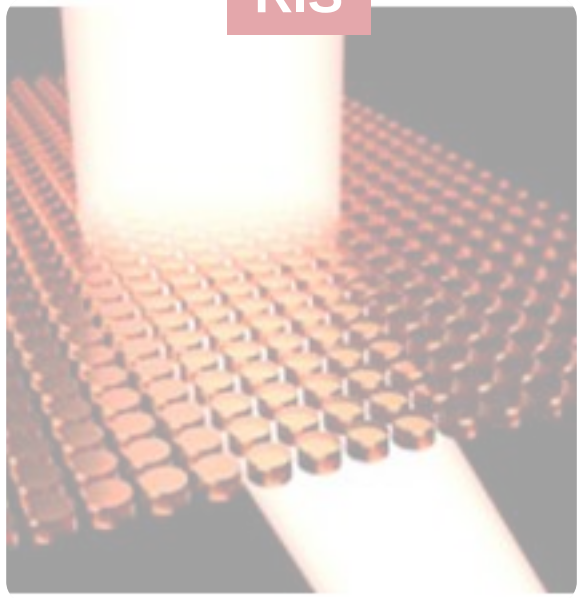


and many others to make this technology a success…

6G HOT TOPICS

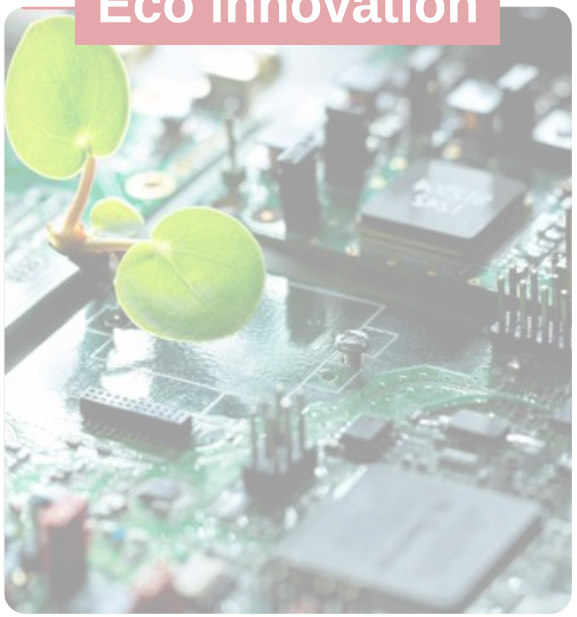
THz frequencies

RIS



Sub-7GHz MIMO

Eco innovation



Beyond Shannon

NTN

Measure & Metrology

Radio as a service

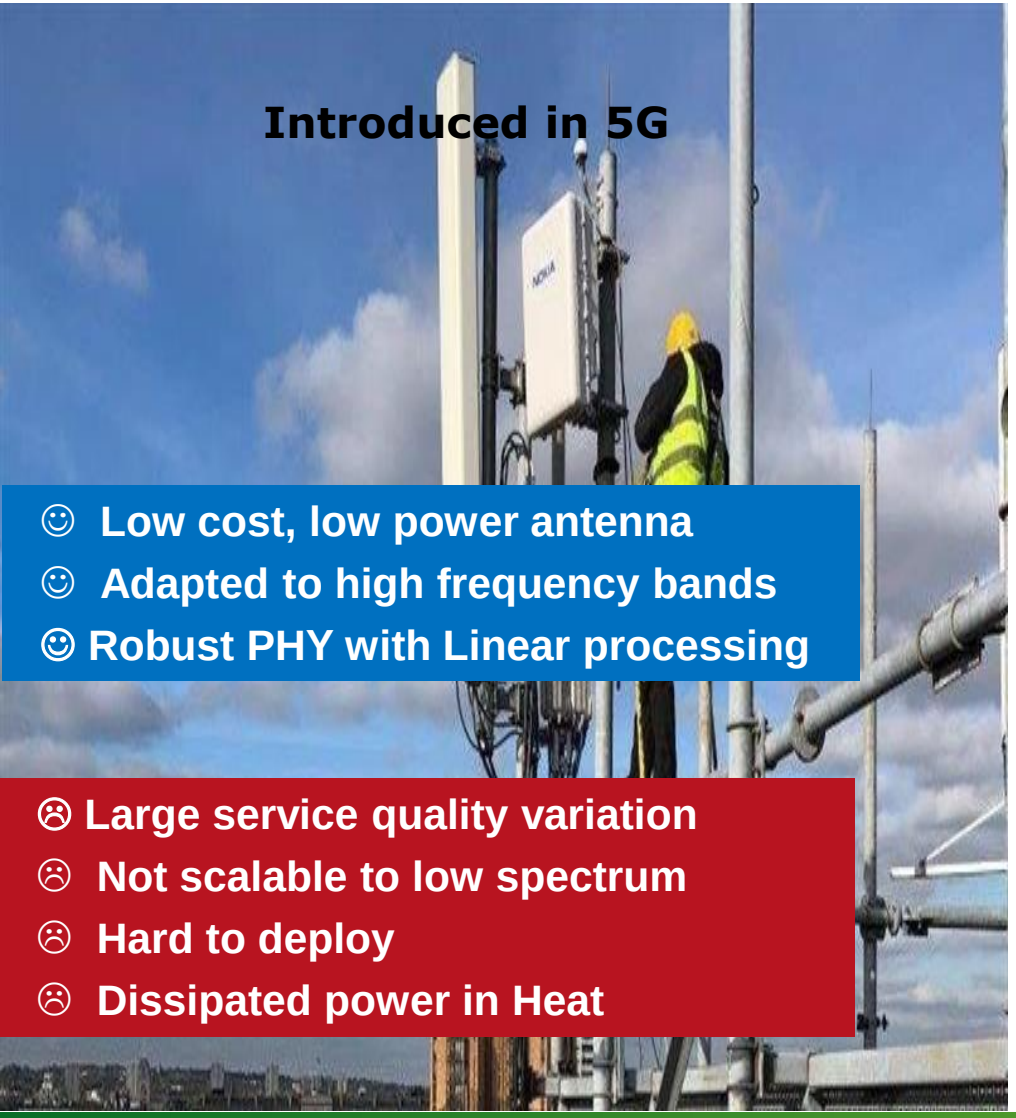
Security

Optical networks

...

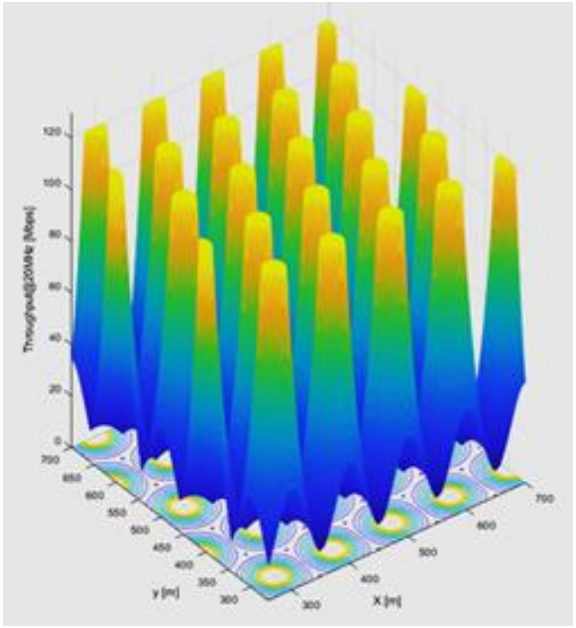
IMPROVING CELLULAR NETWORKS

› 4G/5G Attempts

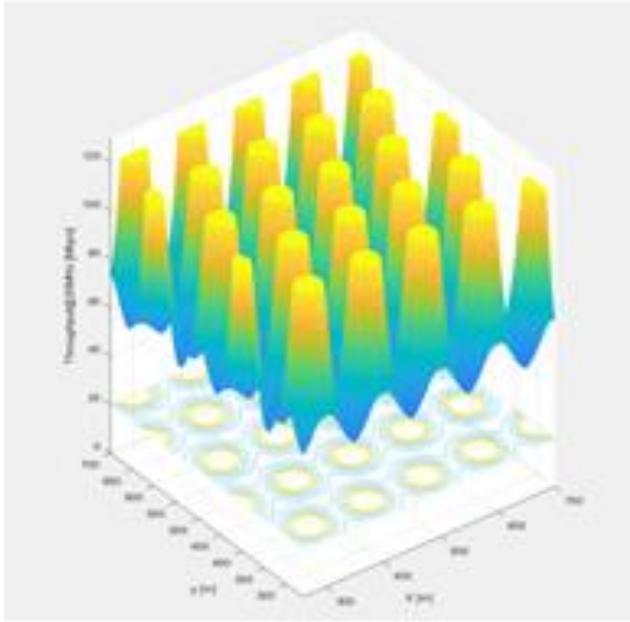


Is massive MIMO the solution ?

partially



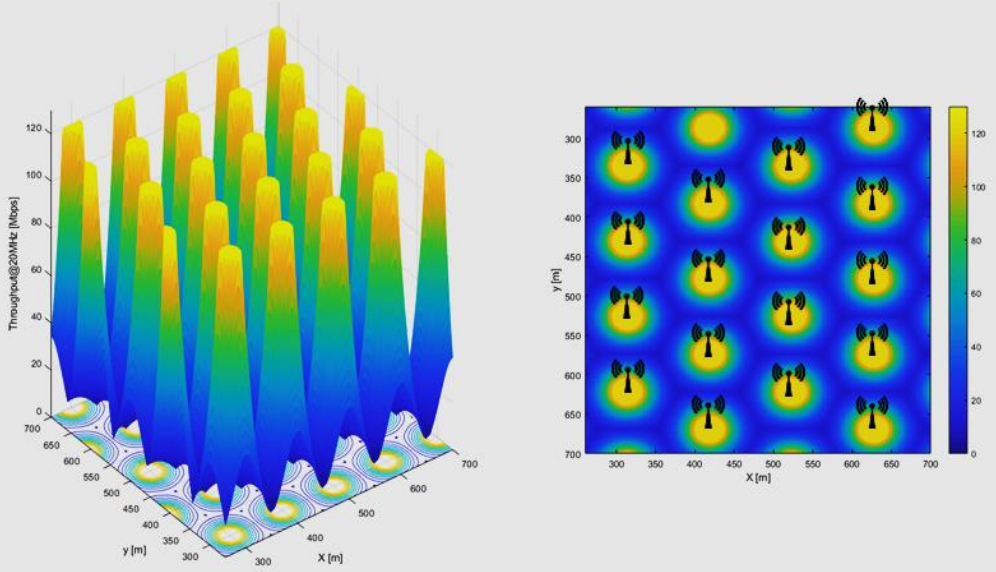
Traditional 4G



Massive MIMO $M = 64$

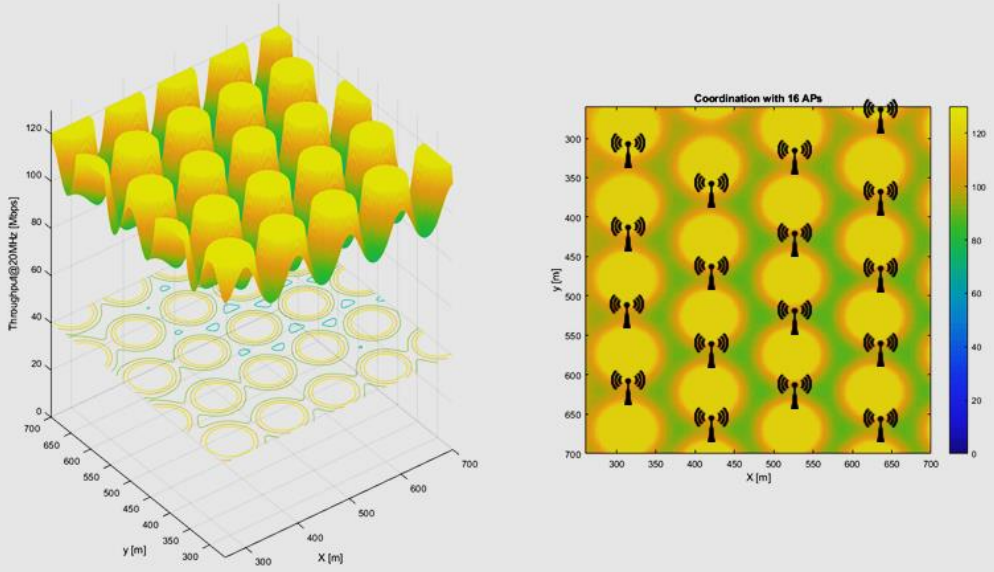
TOWARD DISTRIBUTED MIMO

Traditionnal



Capacity **limited**
by inter cell interference

Cell free MIMO



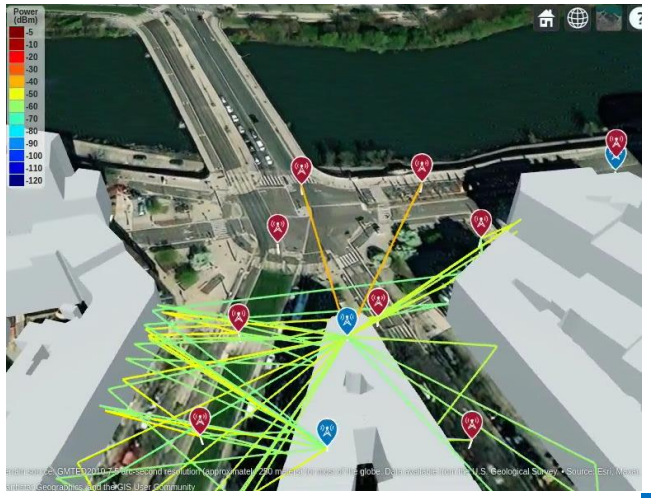
Capacity **increases**
with the use of distributed MIMO

CONCLUSION

› Benefits of cell-free massive MIMO

Good Uniform service Quality

Flexibility: all frequency bands



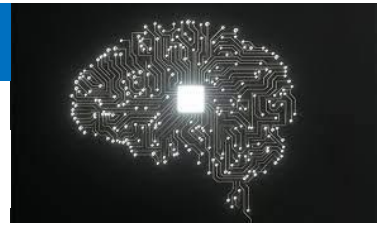
Designed for low cost components

High energy efficiency

Acceptability

Low EMF

Favorable environment for AI

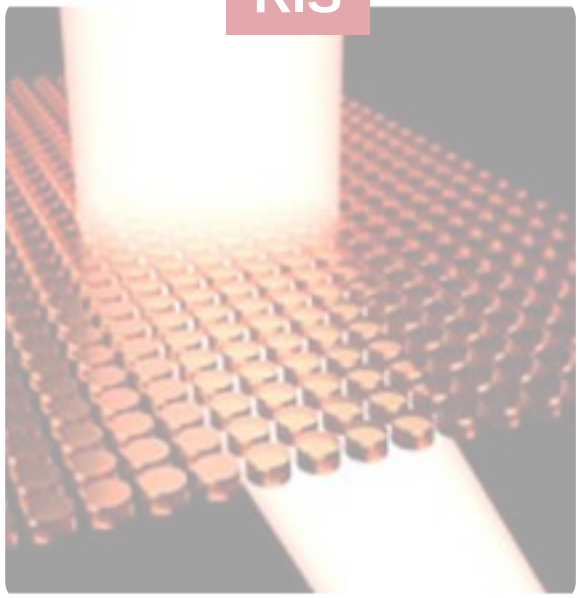


Designed to be smart

6G HOT TOPICS

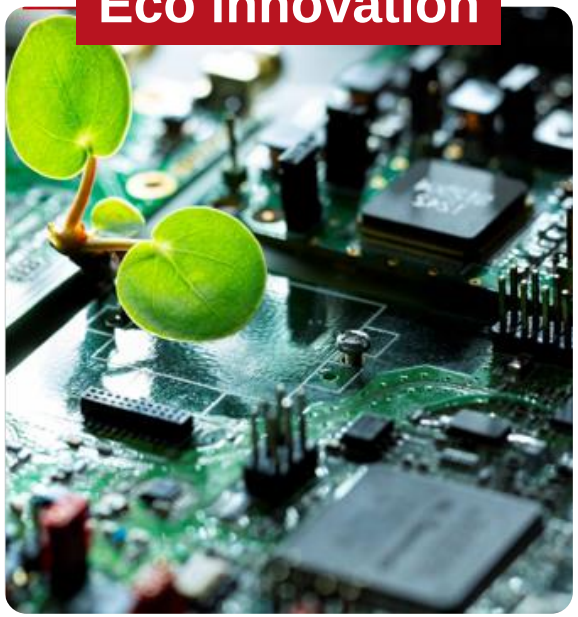
THz frequencies

RIS



Sub-7GHz MIMO

Eco innovation

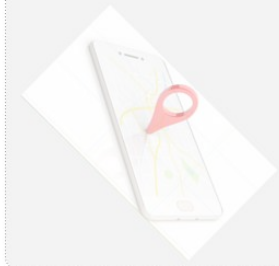


Beyond Shannon

NTN

Measure & Metrology

Radio as a service



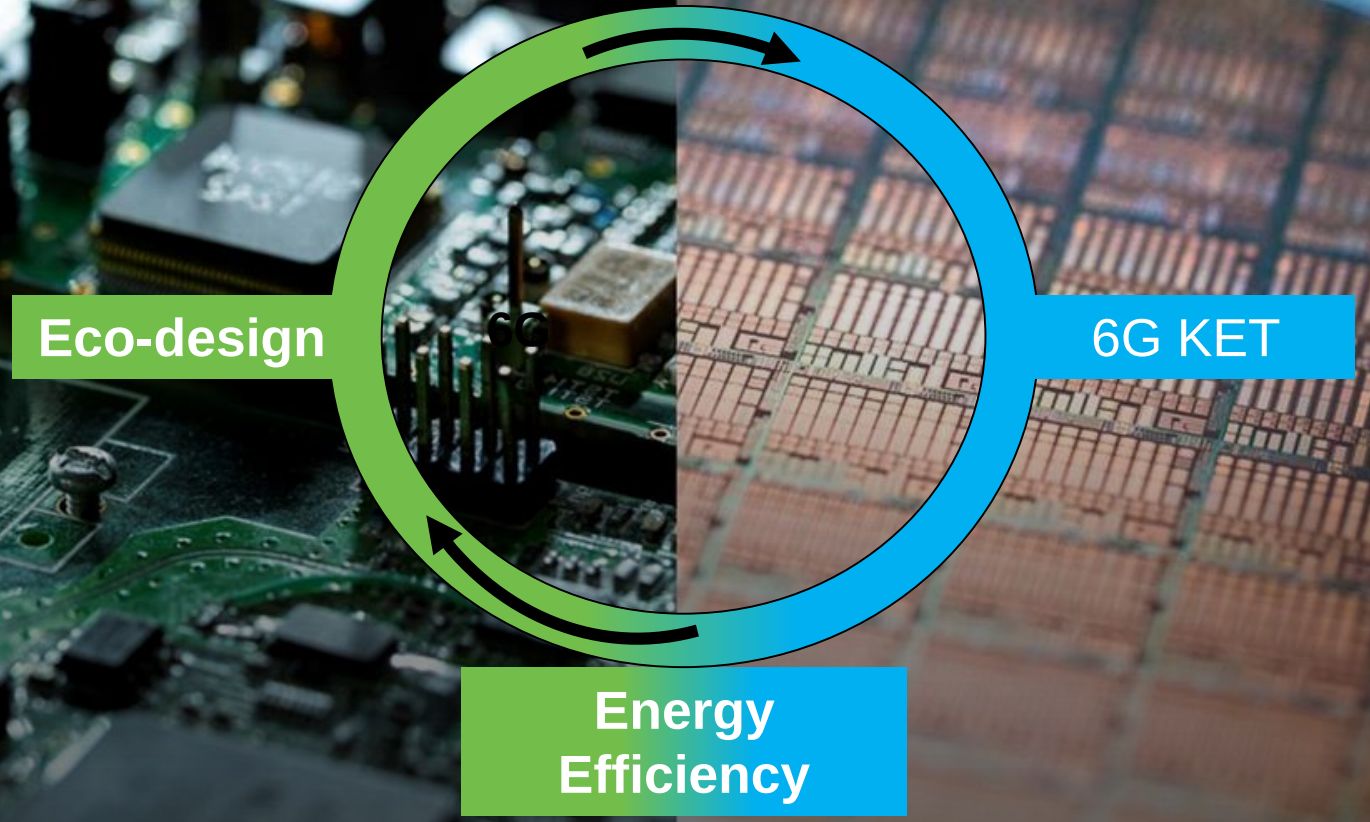
Security

Optical networks

...

Our visions

› Requirements on 6G hardware



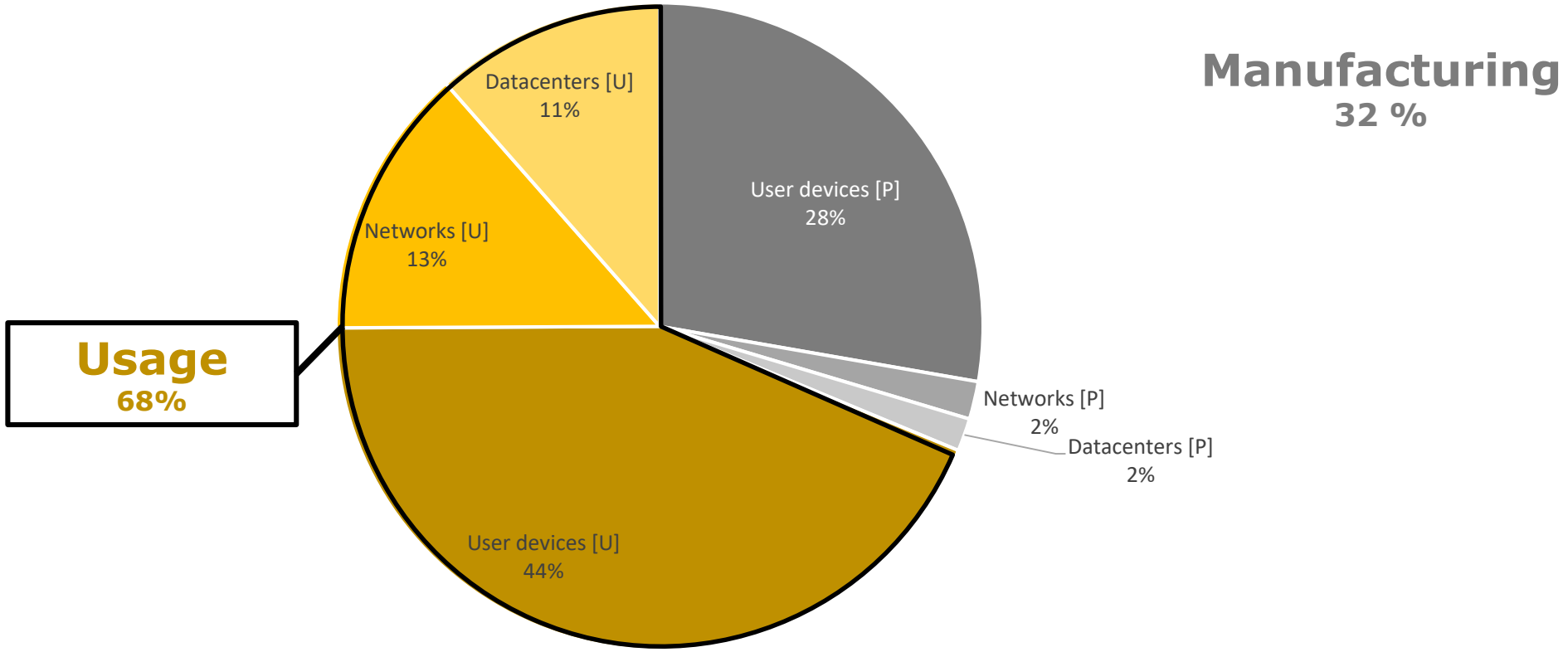
Hardware for Sustainability

Hardware for Performance

ICT carbon footprint breakdown

› Where we are?

Digital World carbon footprint 2020



Source : Malmodin 2020 data from C. Freitag, M. Berners-Lee, K. Widdicks, B. Knowles, G. S. Blair, and A. Friday, 'The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations', *Patterns*, vol. 2, no. 9, p. 100340, Sep. 2021, doi: 10.1016/j.patter.2021.100340.

ICT carbon footprint breakdown

› The CO_2 equation[1]

population, technology affluence, energy intensity and carbon intensity

$$CO_2e = Users \times \frac{GB}{User} \times \frac{kWh}{GB} \times \frac{CO_2e}{kWh}$$

Moore's Law and ICT Innovation in the Anthropocene

David Bol, Thibault Pirson and Rémi Dekimpe
Electronic Circuits and Systems group, ICTEAM Institute
Université catholique de Louvain, Louvain-la-Neuve, Belgium
{david.bol, thibault.pirson, remi.dekimpe}@uclouvain.be

Abstract In information and communication technologies (ICTs), innovation is intrinsically linked to empirical laws of exponential efficiency improvement such as Moore's law. By following these laws, the industry achieved an amazing relative decoupling between the improvement of key performance indicators (KPIs), such as the number of transistors, from physical resource usage such as silicon wafers. Concurrently, digital ICTs came from almost zero greenhouse gas emission (GHG) in the middle of the twentieth century to direct annual carbon footprint of approximately 1400 MT CO2e today. Given the fact that we have to strongly reduce global GHG emissions to limit global warming below 2°C, it is not clear if the simple follow-up of these trends can decrease the direct GHG emissions of the ICT sector on a trajectory compatible with Paris agreement.

Source : D. Bol, T. Pirson, and R. Dekimpe, 'Moore's Law and ICT Innovation in the Anthropocene', in *2021 Design, Automation Test in Europe Conference Exhibition (DATE)*, Feb. 2021, pp. 19–24.

ICT carbon footprint breakdown

› The CO_2 equation[1]

$$CO_2e = Users \times \frac{GB}{User} \times \frac{kWh}{GB} \times \frac{CO_2e}{kWh}$$

Paris agreement

-7,6% year on carbon footprint

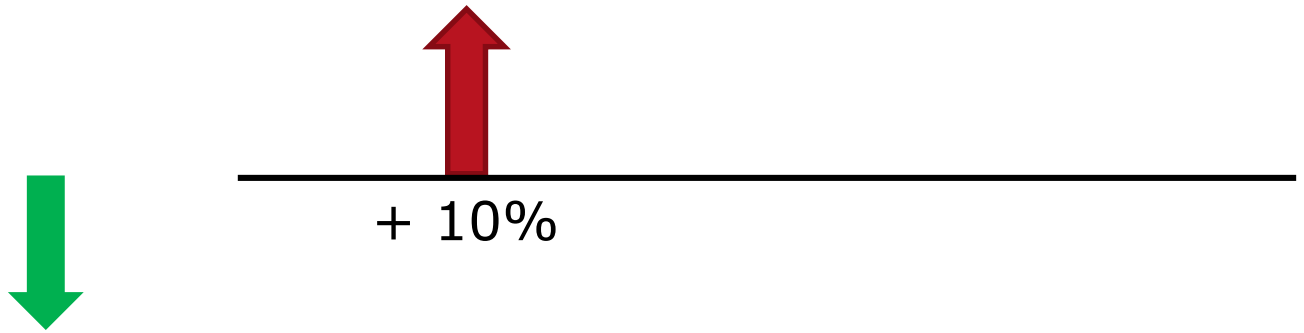
2040: 75% reduction

Source : D. Bol, T. Pirson, and R. Dekimpe, 'Moore's Law and ICT Innovation in the Anthropocene', in *2021 Design, Automation Test in Europe Conference Exhibition (DATE)*, Feb. 2021, pp. 19–24.

ICT carbon footprint breakdown

› The CO_2 equation[1]

$$CO_2e = Users \times \frac{GB}{User} \times \frac{kWh}{GB} \times \frac{CO_2e}{kWh}$$



Paris agreement

-7,6% year on carbon footprint

2040: 75% reduction

Source : D. Bol, T. Pirson, and R. Dekimpe, 'Moore's Law and ICT Innovation in the Anthropocene', in *2021 Design, Automation Test in Europe Conference Exhibition (DATE)*, Feb. 2021, pp. 19–24.

ICT carbon footprint breakdown

› The CO_2 equation[1]

$$CO_2e = Users \times \frac{GB}{User} \times \frac{kWh}{GB} \times \frac{CO_2e}{kWh}$$

+ 10%

Paris agreement

-7,6% year on carbon footprint

2040: 75% reduction

Energy mix

Source : D. Bol, T. Pirson, and R. Dekimpe, 'Moore's Law and ICT Innovation in the Anthropocene', in *2021 Design, Automation Test in Europe Conference Exhibition (DATE)*, Feb. 2021, pp. 19–24.

ICT carbon footprint breakdown

› The CO_2 equation[1]

$$CO_2e = Users \times \frac{GB}{User} \times \frac{kWh}{GB} \times \frac{CO_2e}{kWh}$$

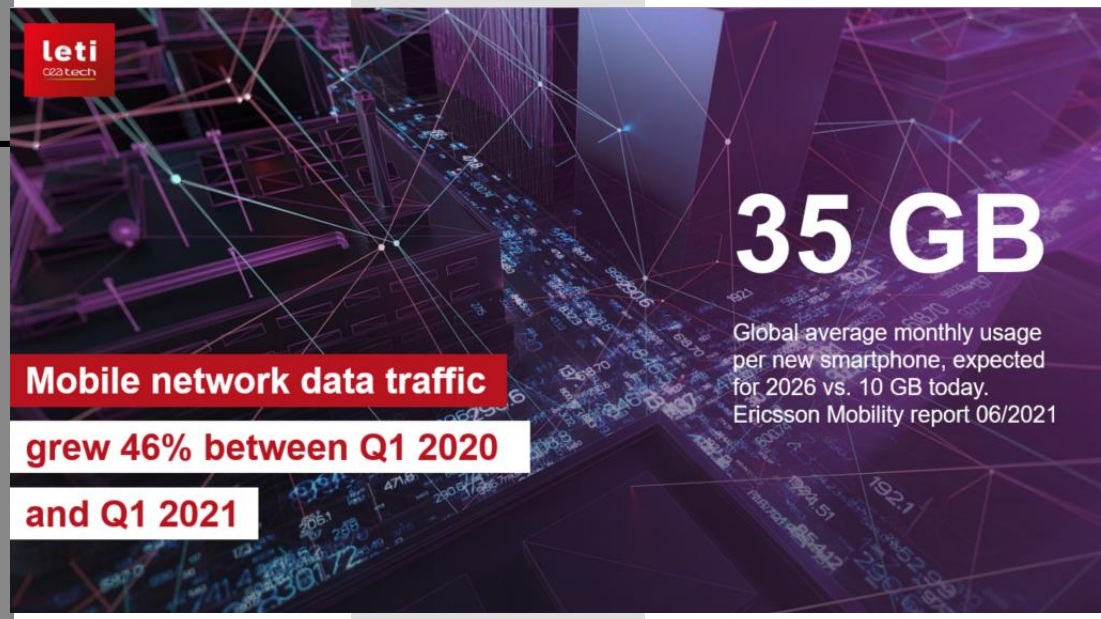
+ 10%

Mobile Traffic +35%

Paris agreement

-7,6% year on carbon footprint

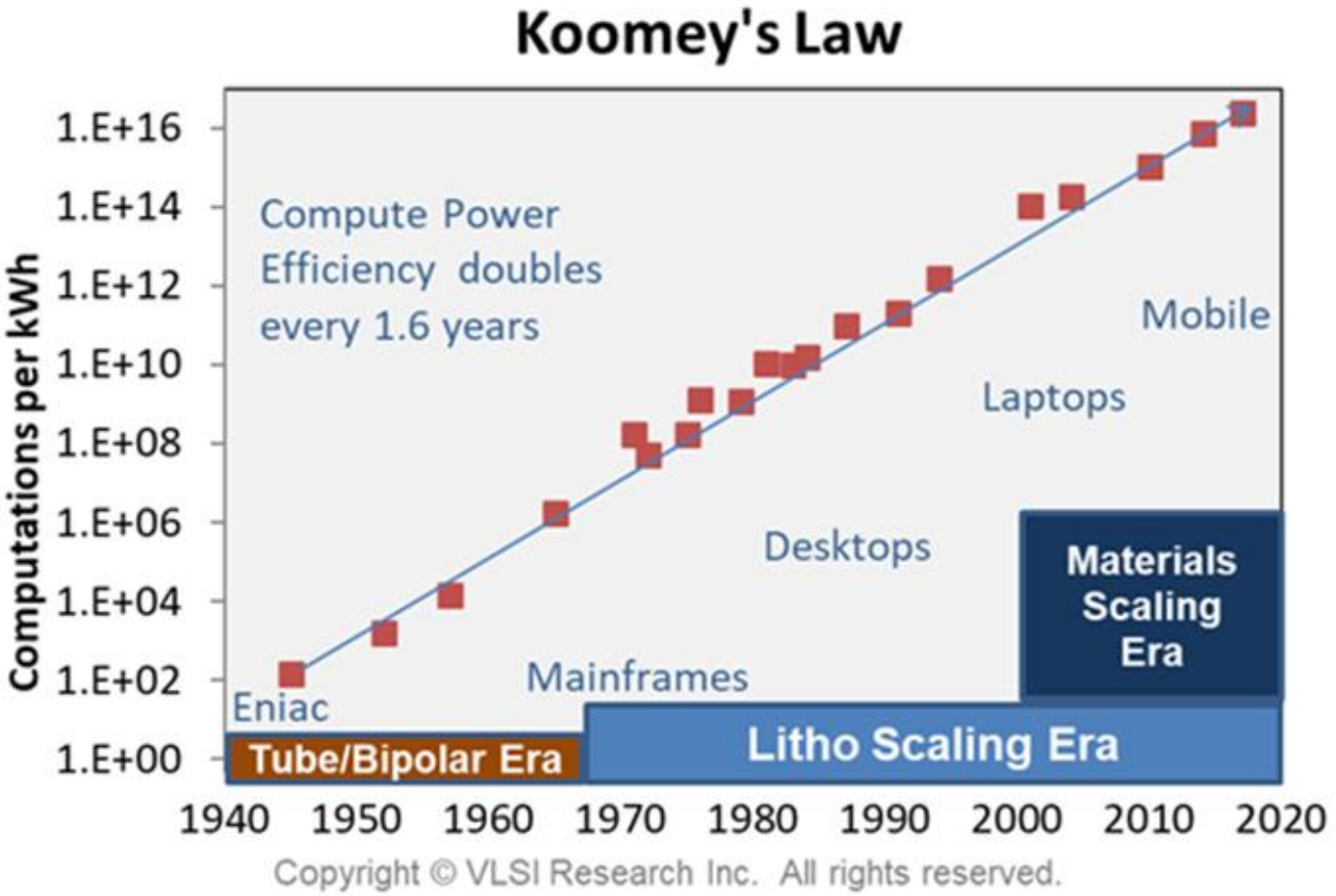
2040: 75% reduction



Source : D. Bol, T. Pirson, and R. Dekimpe, 'Moore's Law and ICT Innovation in the Anthropocene', in *2021 Design, Automation Test in Europe Conference Exhibition (DATE)*, Feb. 2021, pp. 19–24.

ICT carbon footprint breakdown

› The CO_2 equation[1]



$$\times \frac{kWh}{GB} \times \frac{CO_2e}{kWh}$$

Moore & Koomey Law

Energy mix

Source : D. Bol, T. Pirson, and R. Dekimpe, 'Moore's Law and ICT Innovation in the Anthropocene', in *2021 Design, Automation Test in Europe Conference Exhibition (DATE)*, Feb. 2021, pp. 19–24.

ICT carbon footprint breakdown

› The CO_2 equation[1]

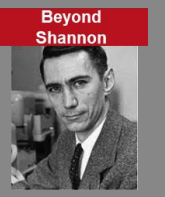
$$CO_2e = Users \times \frac{GB}{User} \times \frac{kWh}{GB} \times \frac{CO_2e}{kWh}$$

effort to be made in the design of 6G

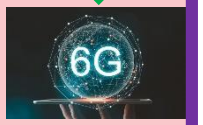
+ 10%

Mobile Traffic +35%

Beyond Shannon



Moore & Koomey Law



Energy mix

bouncing effect

Paris agreement

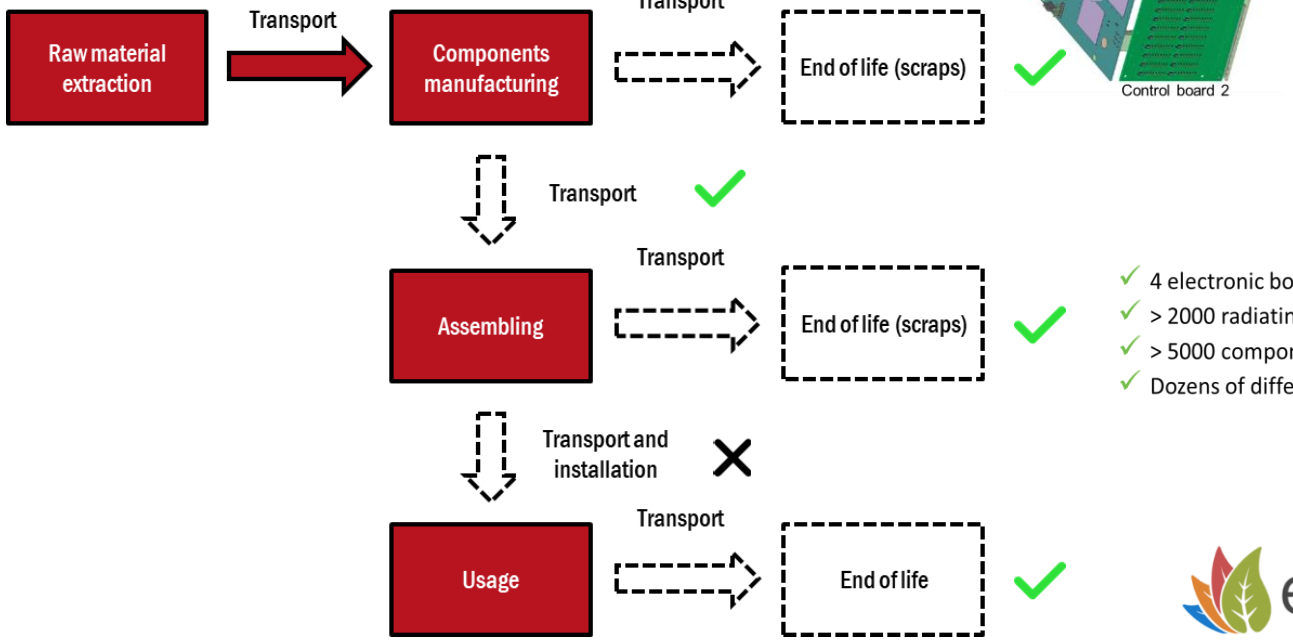
-7,6% year on carbon footprint

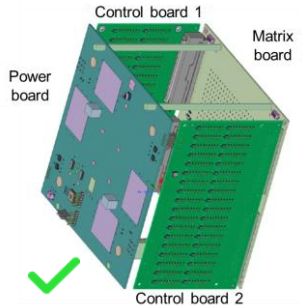
2040: 75% reduction

Source : D. Bol, T. Pirson, and R. Dekimpe, 'Moore's Law and ICT Innovation in the Anthropocene', in *2021 Design, Automation Test in Europe Conference Exhibition (DATE)*, Feb. 2021, pp. 19–24.

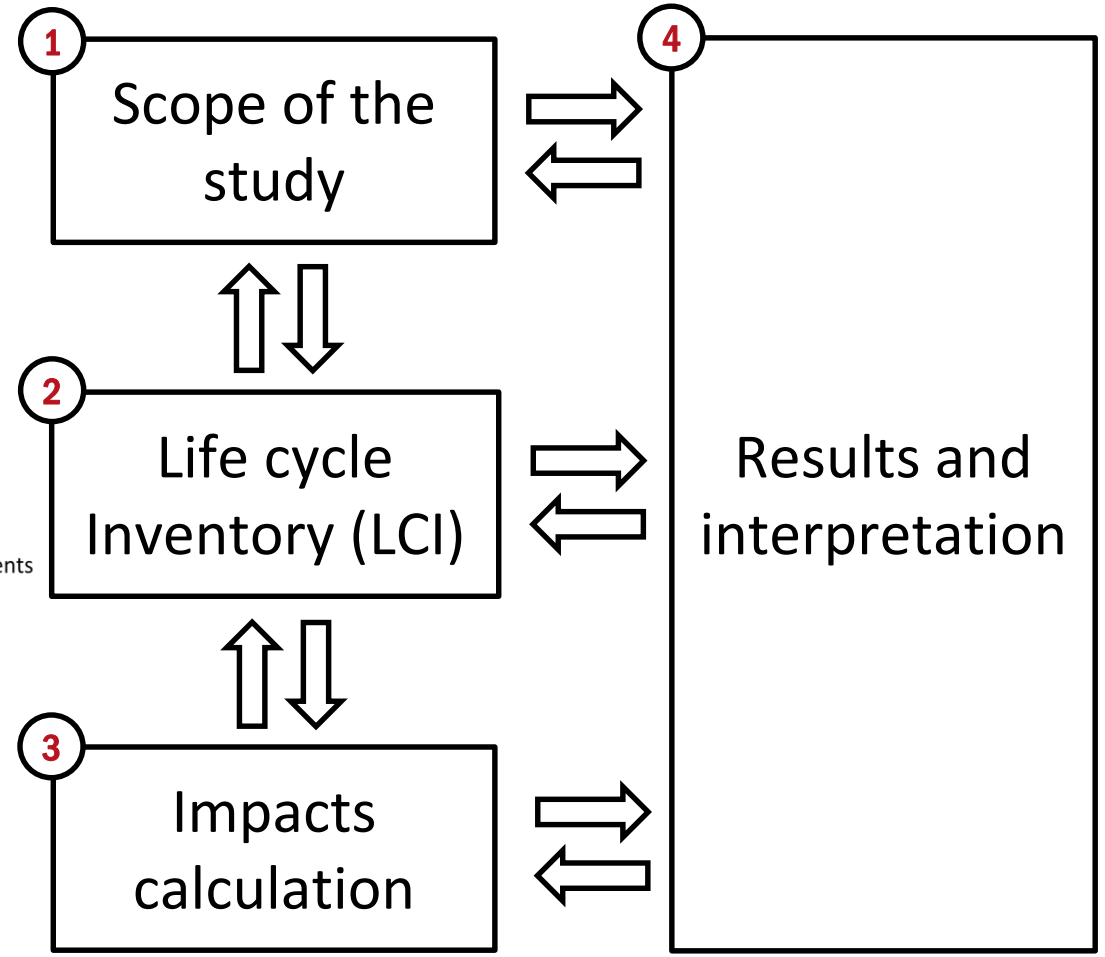
Life Cycle Assessment

› A concrete example





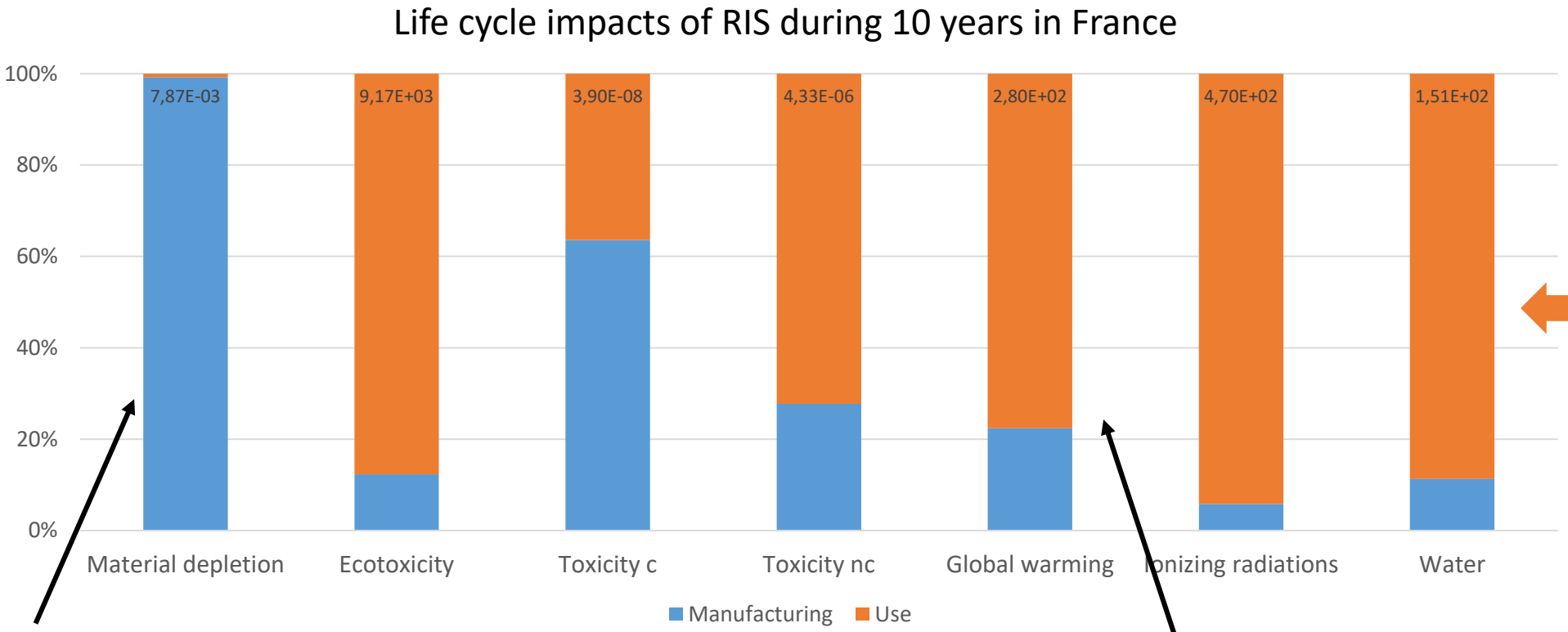
- ✓ 4 electronic boards
- ✓ > 2000 radiating elements
- ✓ > 5000 components
- ✓ Dozens of different components



ISO 14040 & 44

Life Cycle Assessment

› A concrete example



Energy consumption (use phase)

French mix

Use of non-renewable materials

280kg CO2 eq. ≈ 1500-2000 km drive

Usage is the major contributor, but has not effect on material depletion

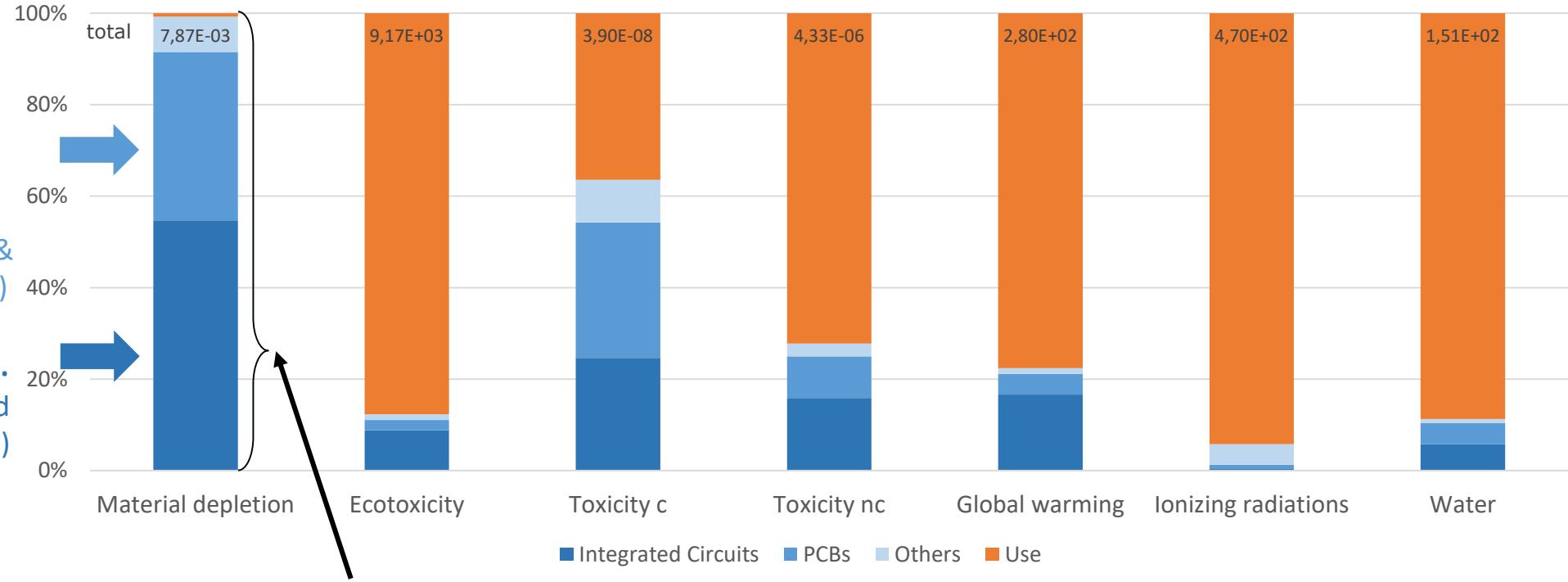
Both **energy reduction and material depletion** has to be taken into account for ecodesign.

Toward Eco-design of a 5G mmWave Transmitarray Antenna Based on Life Cycle Assessment, Guerid et al, EUCNC2022

Life Cycle Assessment

› A concrete example

Manufacturing impacts of the RIS



Circuit Boards (NiAu finishing & etching process)

Integrated C. (Matrix diodes and Serial Shift Registers)

Gold (84%)

ICs and **PCBs** are the major contributors.
Circuit design can directly reduce manufacturing impact.

Avoid **gold** whenever possible.

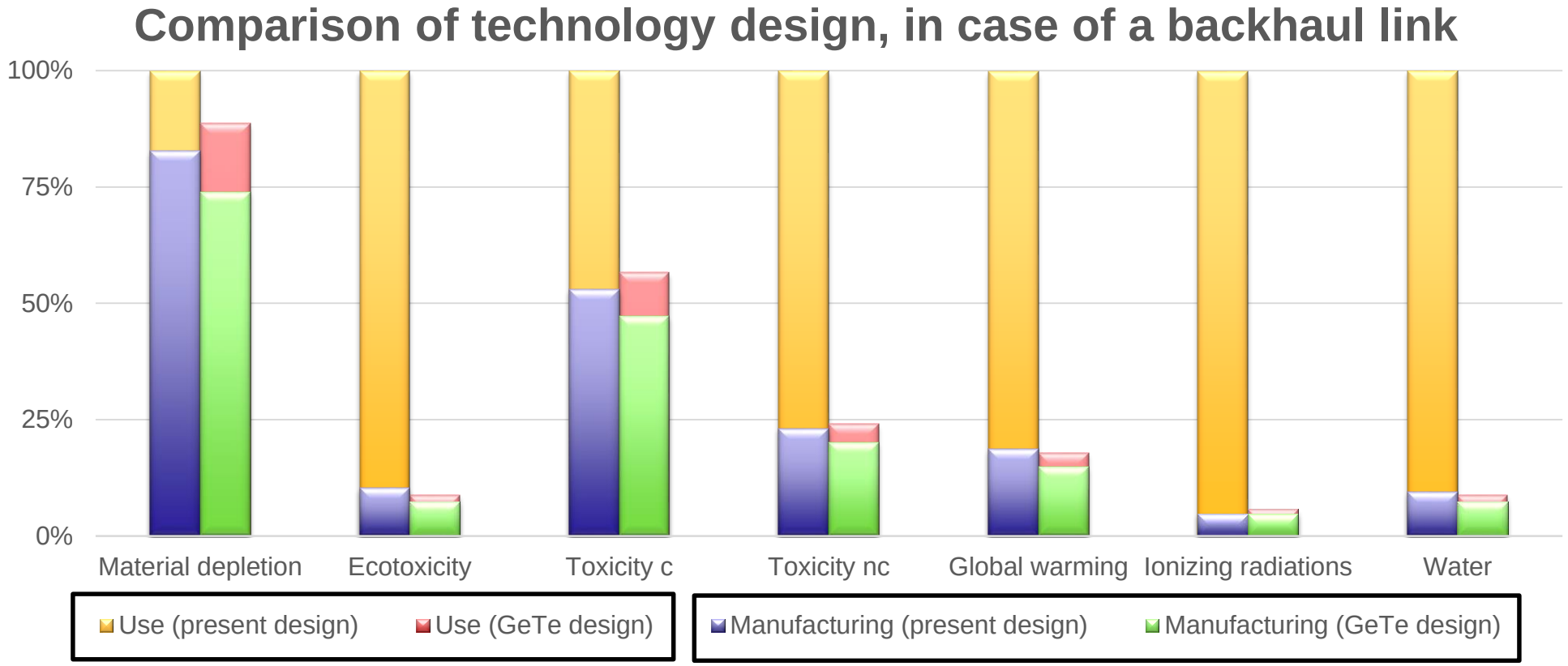
Toward Eco-design of a 5G mmWave Transmitarray Antenna Based on Life Cycle Assessment, Guerid et al, EUCNC2022

Life Cycle Assessment

› Eco design

20 W

0,874 mW



Strong reduction of impacts

No significant reduction on material depletion (Specific use-case)

NEW-6G

NANOELECTRONICS & WIRELESS FOR 6G

Establishing strong links between Microelectronics & Telecoms Worlds
while meeting societal expectations
& sustainability requirements

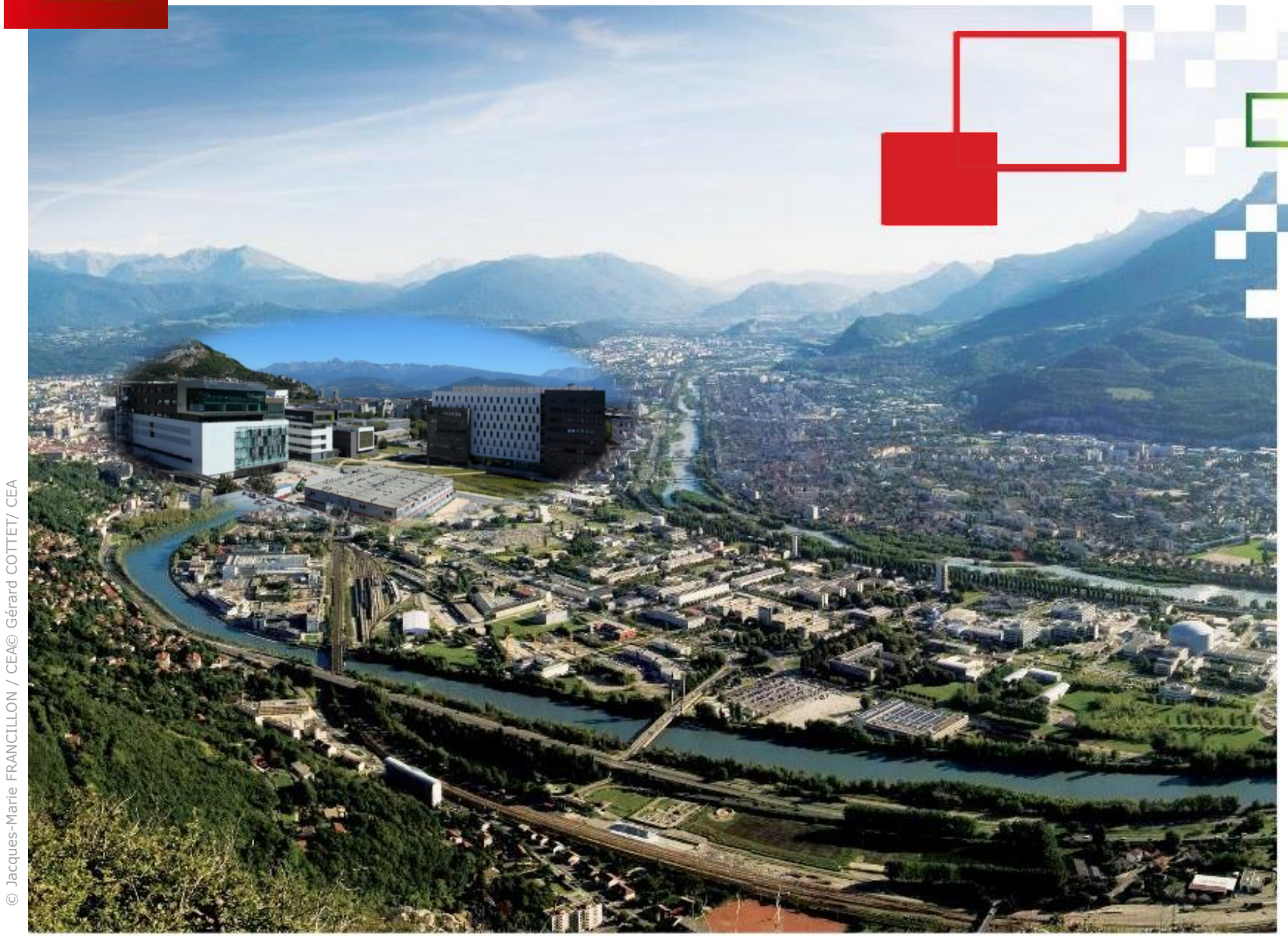
«Our future is a race between the growing power of our technology and the wisdom with which we use it»

Stephen Hawking[1]

[1] -L'enfer numérique: Voyage au bout d'un Like - Livre de Guillaume Pitron - 09/2021

Check out the press kit

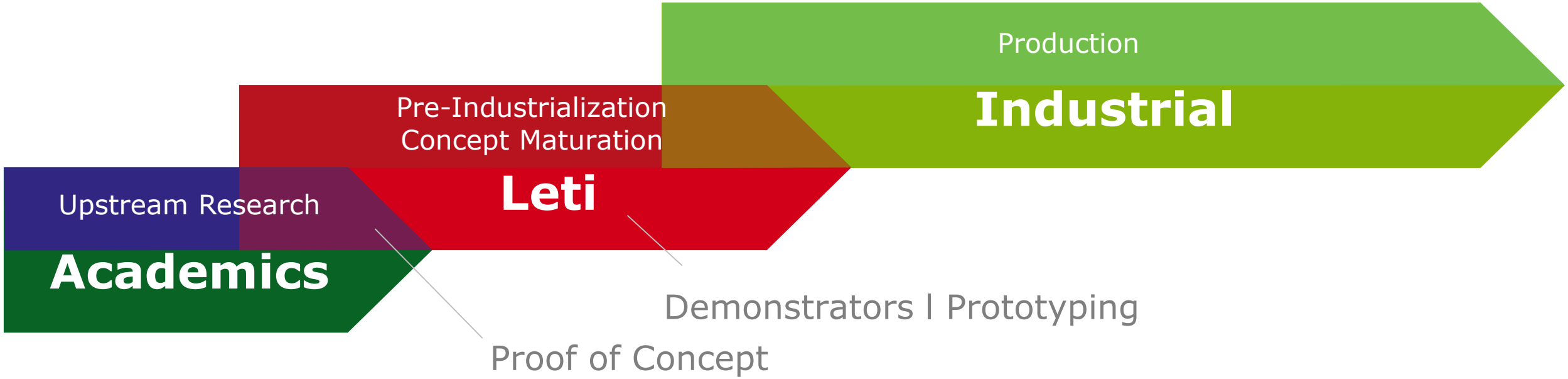
Key R&D partner to build your next best tech innovations



- Since **1967**
- France, USA, Japan
- **2,000** People
- **> 2,760** Patents in Portfolio
- **350** Industrial Partners
- **> 65** Startups Created
- **10,000 m²** Cleanroom 200-300mm
- **315 M€** Budget
  (**85%** from R&D contracts)

KEY R&D PARTNER TO BUILD YOUR NEXT BEST TECH INNOVATIONS

› Bridging the gap between academia & the semicon Industry



- **Long-term partnerships**
- **Milestones-oriented** projects
- Highly available and flexible teams