Towards 6G

The New Challenges of a Wireless Future

Marco Di Renzo

France-Nokia Chair of Excellence in ICT

CNRS Research Director – Head of the iPhyCom group
Laboratory of Signals and Systems (L2S)
CNRS – CentraleSupélec – Paris-Saclay University
Paris, France
marco.di-renzo@universite-paris-saclay.fr

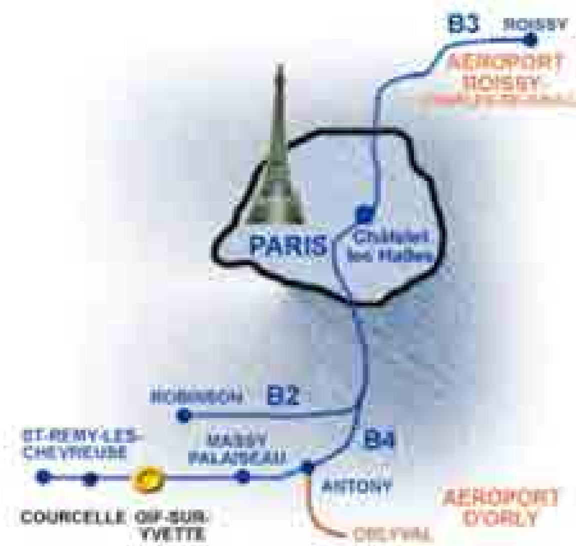
French Institute of Finland
Helsinki, Finland
November 7, 2024

Introduction

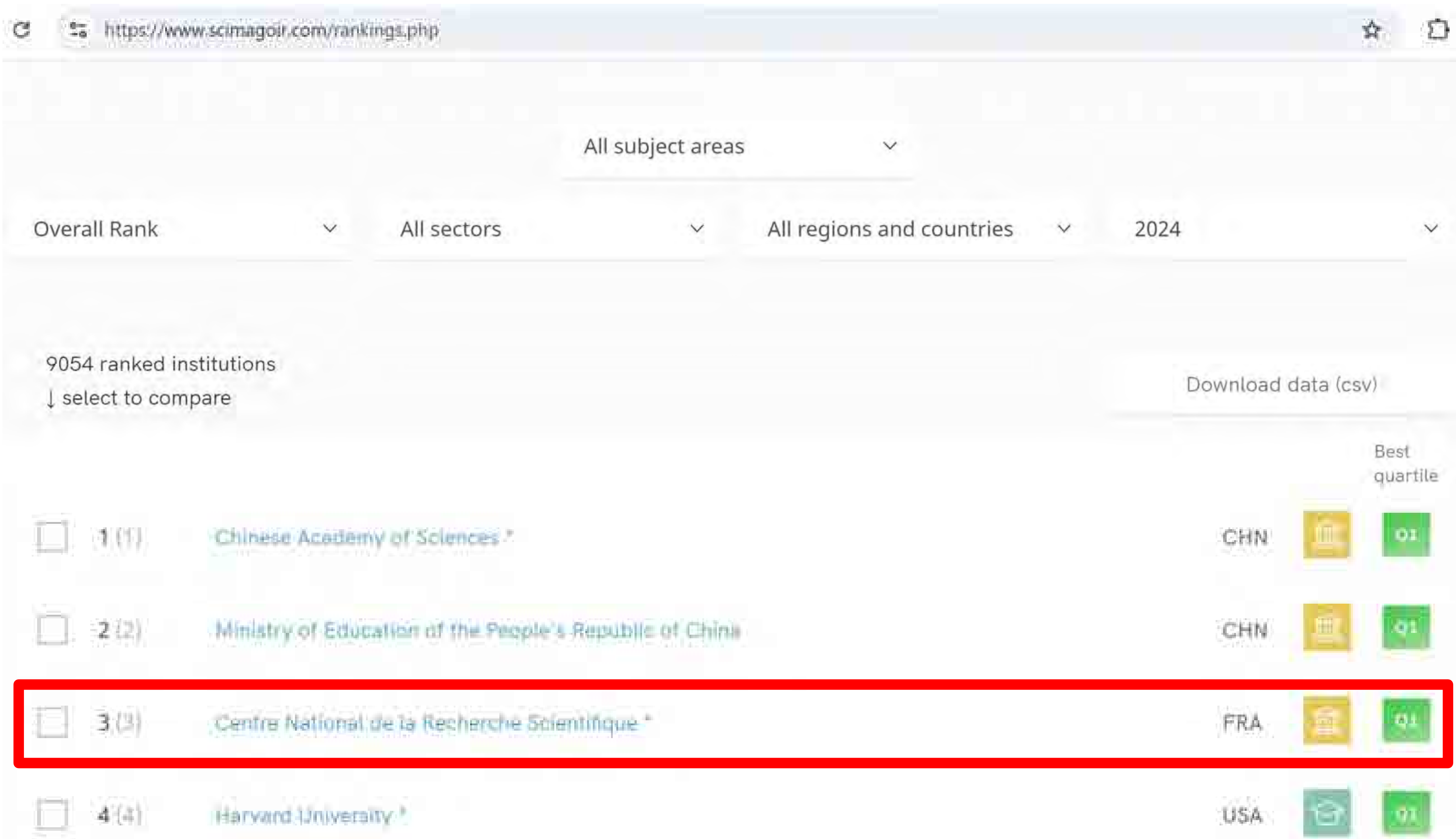
Introduction

CNRS & CentraleSupélec, Paris-Saclay University

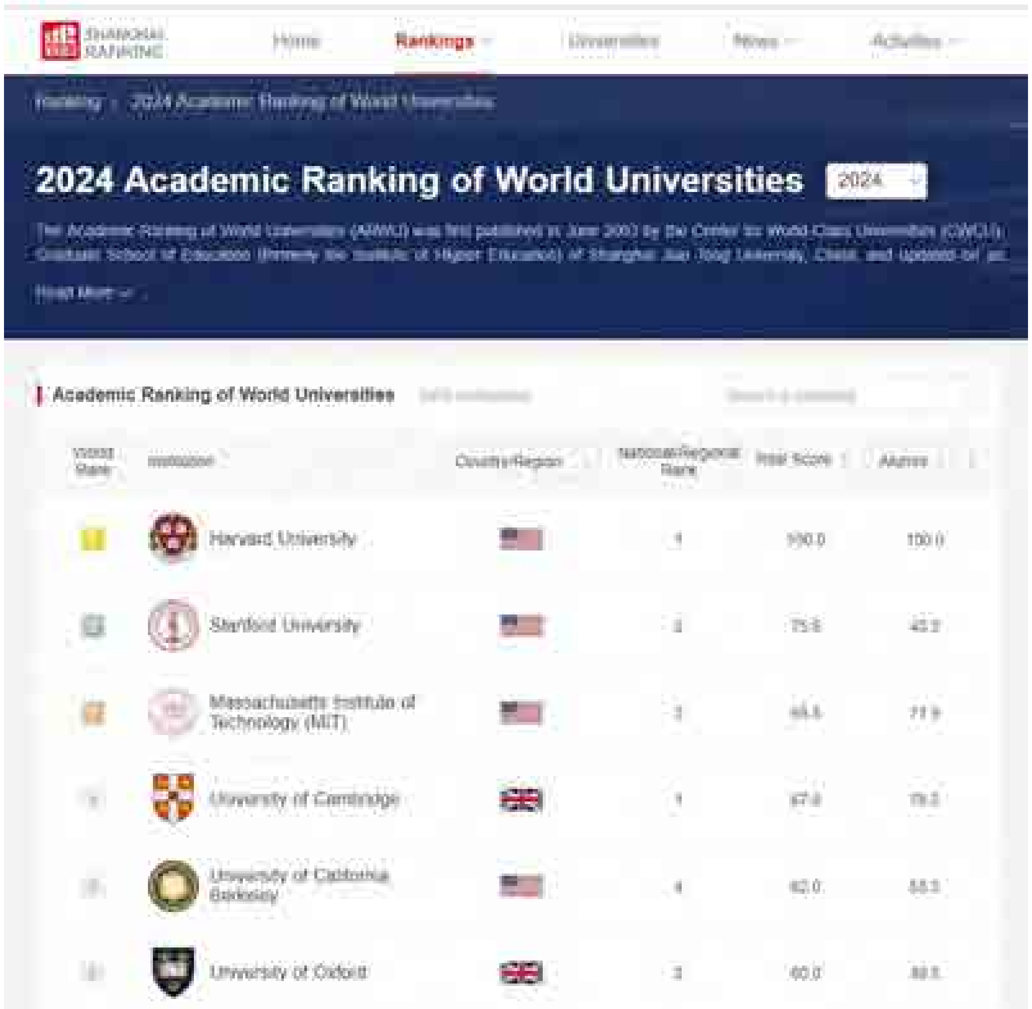
- Laboratory of Signals and Systems (L2S) in CentraleSupélec, Paris-Saclay University (UPSaclay), Gif-sur-Yvette, France
  - CNRS (world 3rd, Scimago Institutions Ranking 2023)
  - UPSaclay (world 12th, Europe 1st, telecom engineering 28th, Shanghai Ranking 2023)
  - CentraleSupélec (telecom engineering 14th, Shanghai Ranking 2019)

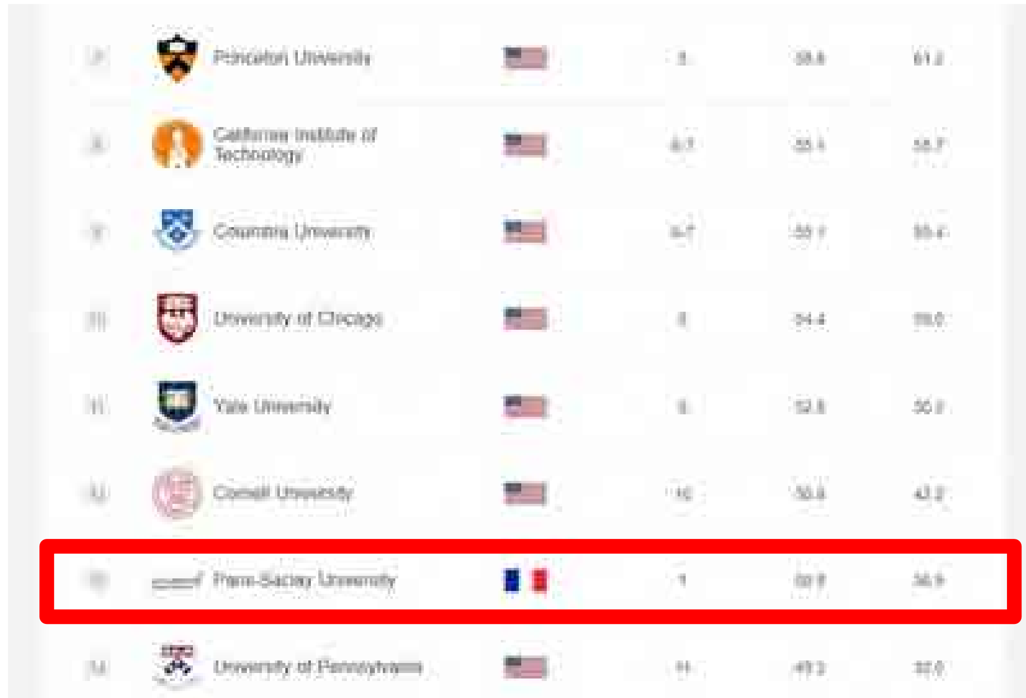


Introduction – CNRS



Introduction – Université Paris-Saclay





Introduction – The Laboratory at CentraleSupelec

CNRS & CentraleSupélec, Paris-Saclay University

- L2S – 3 departments: Communications & Networks, Signal Processing & Statistics, Control Theory & Systems (~ 100 faculty members)

- Marco Di Renzo
  - CNRS Research Director, CNRS - CentraleSupélec
  - Head, Intelligent Physical Communications Group (iPhyCom)
  - Member, Admission and Evaluation Committee, Ph.D. School on ICT, UPSaclay
  - ETSI, Vice-Chair, Rapporteur, Founder (ISG-RIS) and Founder (ISG-THz, ISG-ISAC)

- iPhyCom
  - 8 faculty members
  - 20 Ph.D. and Postdocs
  - Information and communication theories, waveform design and information processing, beyond "RF" communications, physics of communications, semantics of communications, learning for communications
  - Industry collaborations: Orange, Nokia, Huawei, NEC, SIRADEL, InterDigital,…

6G Flagship @ Oulu, Finland

6G FLAGSHIP | ABOUT US | 6G VISIONS | MAGAZINE | RESEARCH | GET INVOLVED | KNOWLEDGE BASE

WORLD'S FIRST 6G RESEARCH PROGRAMME

We Are 6G Flagship

6G Flagship is the world's first 6G research programme, a global leader in 5G adoption, and a preferred research partner in 6G development. We do high-quality 6G research to create future know-how and sustainable solutions for society's needs in the 2030s. We operate under the University of Oulu, which also funds us together with the Research Council of Finland.

LEARN MORE ABOUT US

6G FLAGSHIP
UNIVERSITY OF OULU

Towards 6G

6G Vision

IEEE COMMUNICATIONS SURVEYS & TUTORIALS, VOL. 25, NO. 2, SECOND QUARTER 2023 905

On the Road to 6G: Visions, Requirements, Key Technologies, and Testbeds

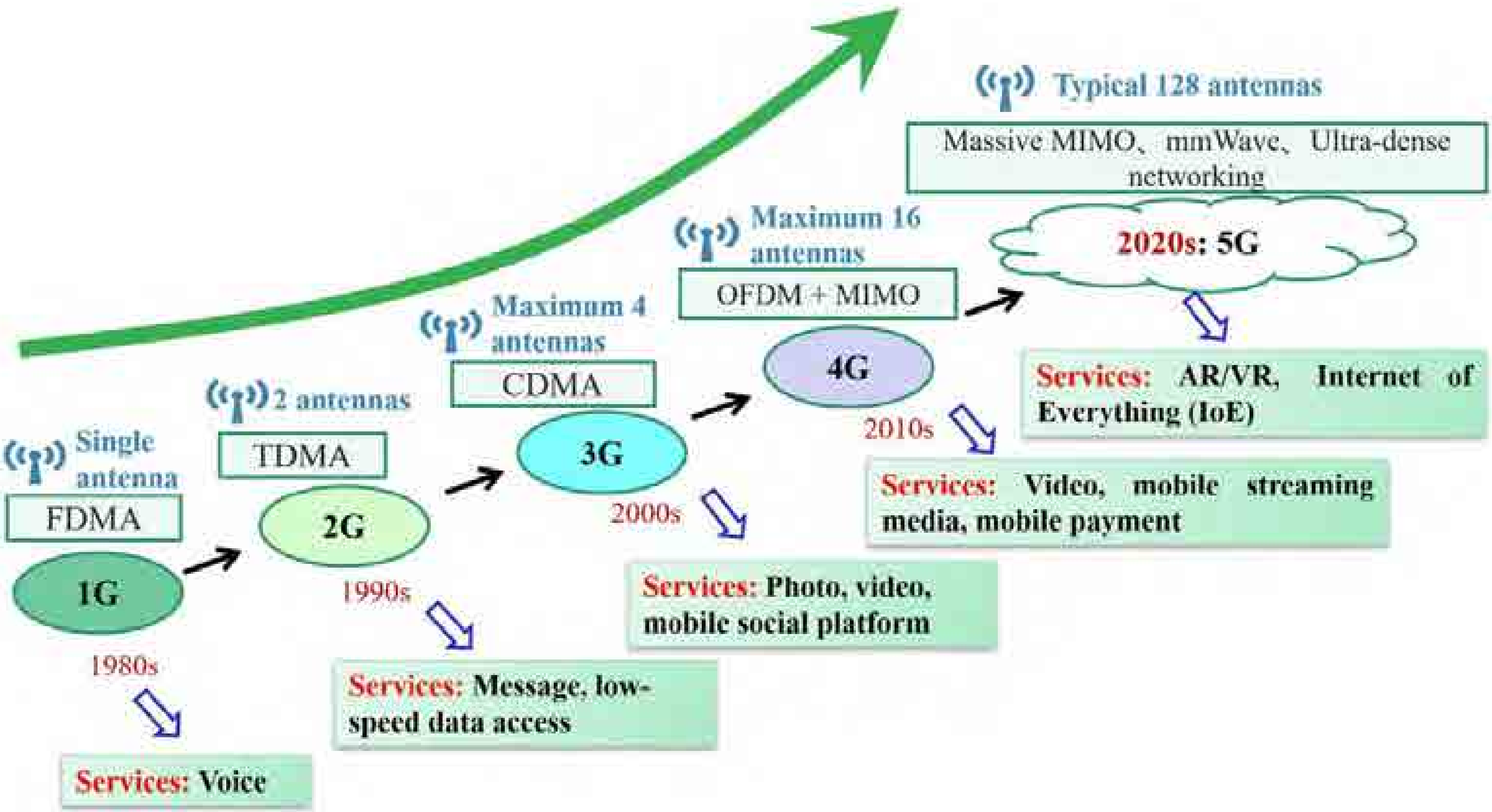
Cheng-Xiang Wang, *Fellow, IEEE*, Xiaohu You, *Fellow, IEEE*, Xiqi Gao, *Fellow, IEEE*, Xiuming Zhu, Zixin Li, Chuan Zhang, *Senior Member, IEEE*, Haiming Wang, *Member, IEEE*, Yongming Huang, *Senior Member, IEEE*, Yunfei Chen, *Senior Member, IEEE*, Harald Haas, *Fellow, IEEE*, John S. Thompson, *Fellow, IEEE*, Erik G. Larsson, *Fellow, IEEE*, Marco Di Renzo, *Fellow, IEEE*, Wen Tong, *Fellow, IEEE*, Peiying Zhu, *Fellow, IEEE*, Xuemin Shen, *Fellow, IEEE*, H. Vincent Poor, *Life Fellow, IEEE*, and Lajos Hanzo, *Life Fellow, IEEE*

***Abstract*—Fifth generation (5G) mobile communication systems have entered the stage of commercial deployment, providing users with new services, improved user experiences as well as a host of novel opportunities to various industries. However, 5G still faces many challenges. To address these challenges, international industrial, academic, and standards organizations have commenced research on sixth generation (6G) wireless communication systems. A series of white papers and survey papers have been published, which aim to define 6G in terms of requirements,**

I. Introduction

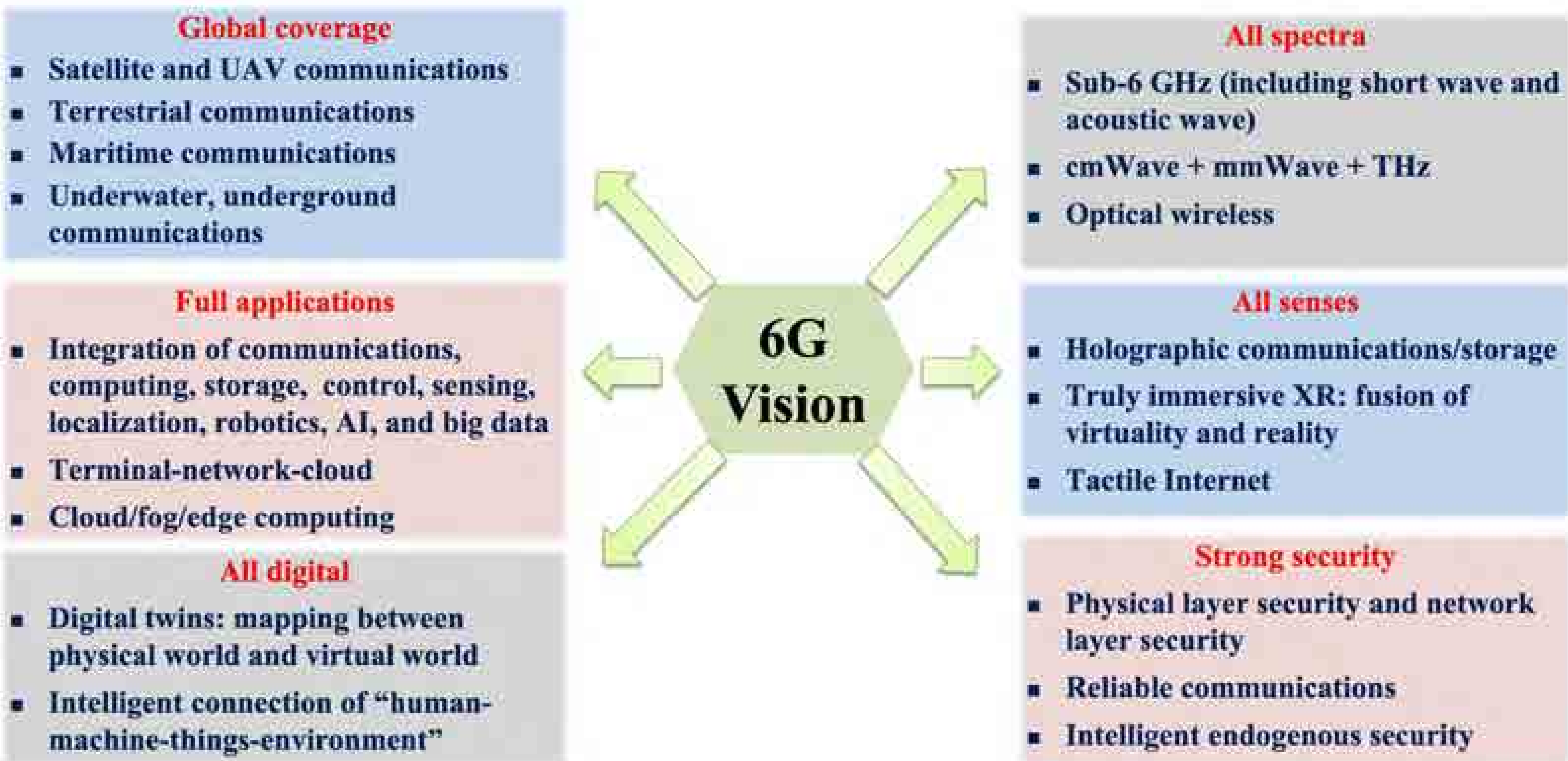
WITH the rapid development of communication applications, communication technologies are undergoing revolutionary changes generation after generation. Up till now, the development of cellular mobile communication systems has undergone five generations. From the first generation (1G) analog communication systems to fifth generation (5G) digital

6G Vision



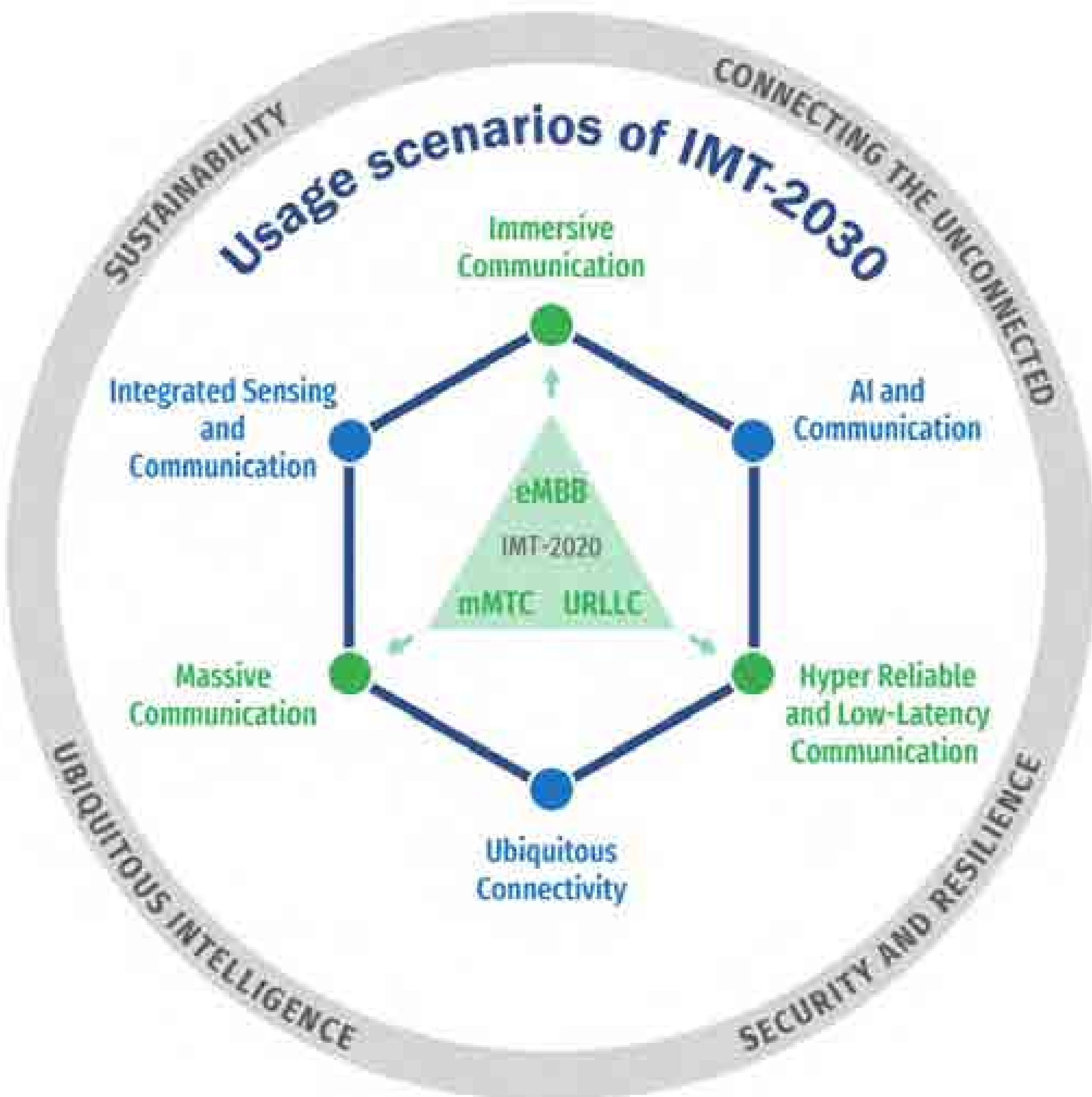
Typical 128 antennas
Massive MIMO、mmWave、Ultra-dense networking
2020s: 5G
Services: AR/VR, Internet of Everything (IoE)
Maximum 16 antennas
OFDM + MIMO
4G
2010s
Services: Video, mobile streaming media, mobile payment
Maximum 4 antennas
CDMA
3G
2000s
Services: Photo, video, mobile social platform
2 antennas
TDMA
2G
1990s
Services: Message, low-speed data access
Single antenna
FDMA
1G
1980s
Services: Voice

6G Vision



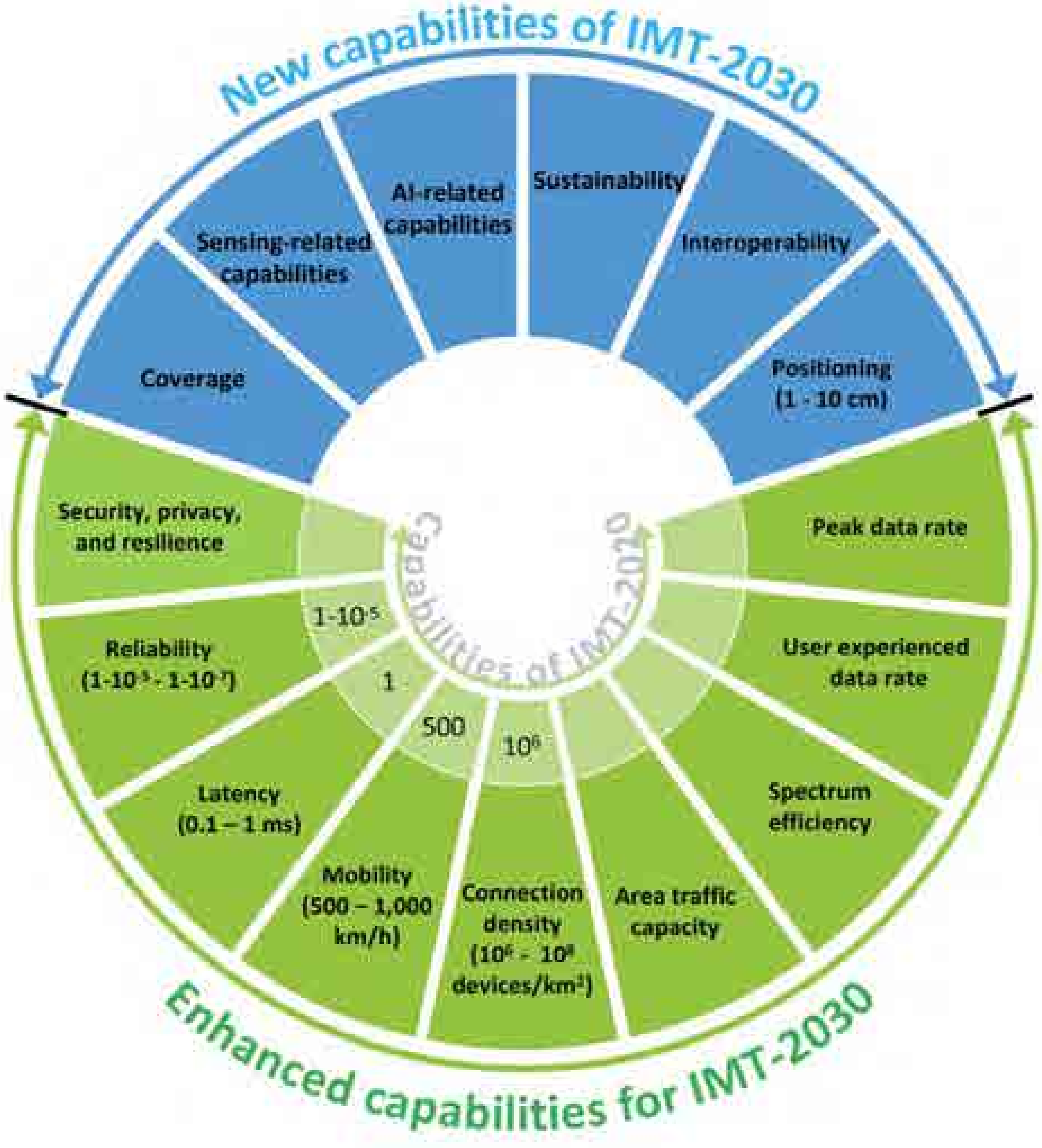
Global coverage
Satellite and UAV communications
Terrestrial communications
Maritime communications
Underwater, underground communications
Full applications
Integration of communications, computing, storage, control, sensing, localization, robotics, AI, and big data
Terminal-network-cloud
Cloud/fog/edge computing
All digital
Digital twins: mapping between physical world and virtual world
Intelligent connection of "human-machine-things-environment"
6G Vision
All spectra
Sub-6 GHz (including short wave and acoustic wave)
cmWave + mmWave + THz
Optical wireless
All senses
Holographic communications/storage
Truly immersive XR: fusion of virtuality and reality
Tactile Internet
Strong security
Physical layer security and network layer security
Reliable communications
Intelligent endogenous security

6G Vision

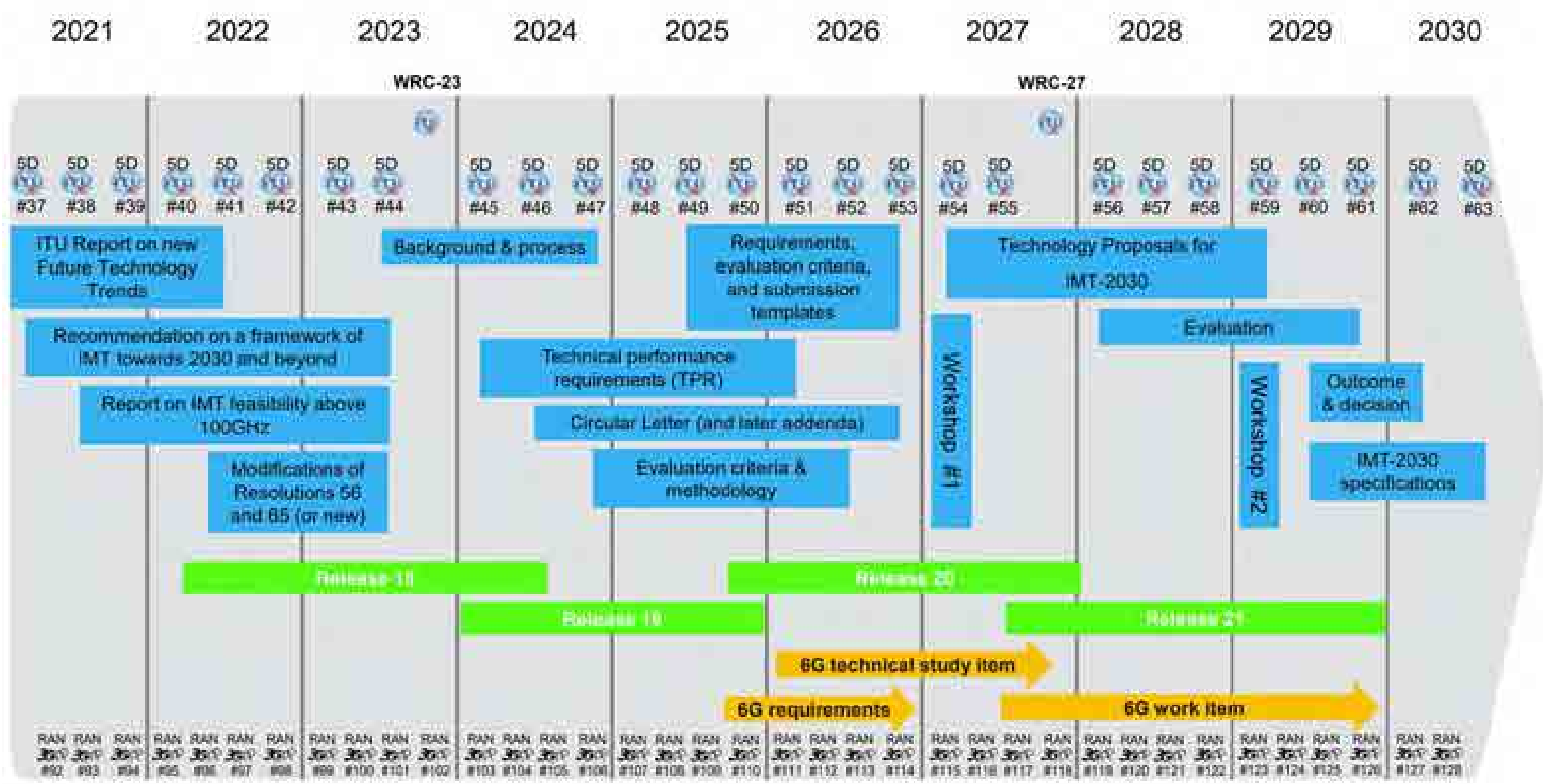


Usage scenarios of IMT-2030
SUSTAINABILITY
CONNECTING THE UNCONNECTED
UBIQUITOUS INTELLIGENCE
SECURITY AND RESILIENCE
Immersive Communication
Integrated Sensing and Communication
AI and Communication
Massive Communication
Hyper Reliable and Low-Latency Communication
Ubiquitous Connectivity
eMBB
IMT-2020
mMTC
URLLC

6G Vision


New capabilities of IMT-2030
Coverage
Sensing-related capabilities
AI-related capabilities
Sustainability
Interoperability
Positioning (1 - 10 cm)
Security, privacy, and resilience
Reliability ($1\text{-}10^{-5}$ - $1\text{-}10^{-7}$)
Latency (0.1 – 1 ms)
Mobility (500 – 1,000 km/h)
Connection density (10^6 - 10^8 devices/km^2)
Area traffic capacity
Spectrum efficiency
User experienced data rate
Peak data rate
$1\text{-}10^{-5}$
1
500
10^6
Capabilities of IMT-2020
Enhanced capabilities for IMT-2030

6G Vision



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5D #63
ITU Report on new Future Technology Trends
Background & process
Requirements, evaluation criteria, and submission templates
Technology Proposals for IMT-2030
Recommendation on a framework of IMT towards 2030 and beyond
Technical performance requirements (TPR)
Evaluation
Report on IMT feasibility above 100GHz
Circular Letter (and later addenda)
Workshop #1
Workshop #2
Outcome & decision
Modifications of Resolutions 56 and 65 (or new)
Evaluation criteria & methodology
IMT-2030 specifications
Release 18
Release 20
Release 19
Release 21
6G technical study item
6G requirements
6G work item

Reconfigurable Intelligent Surfaces

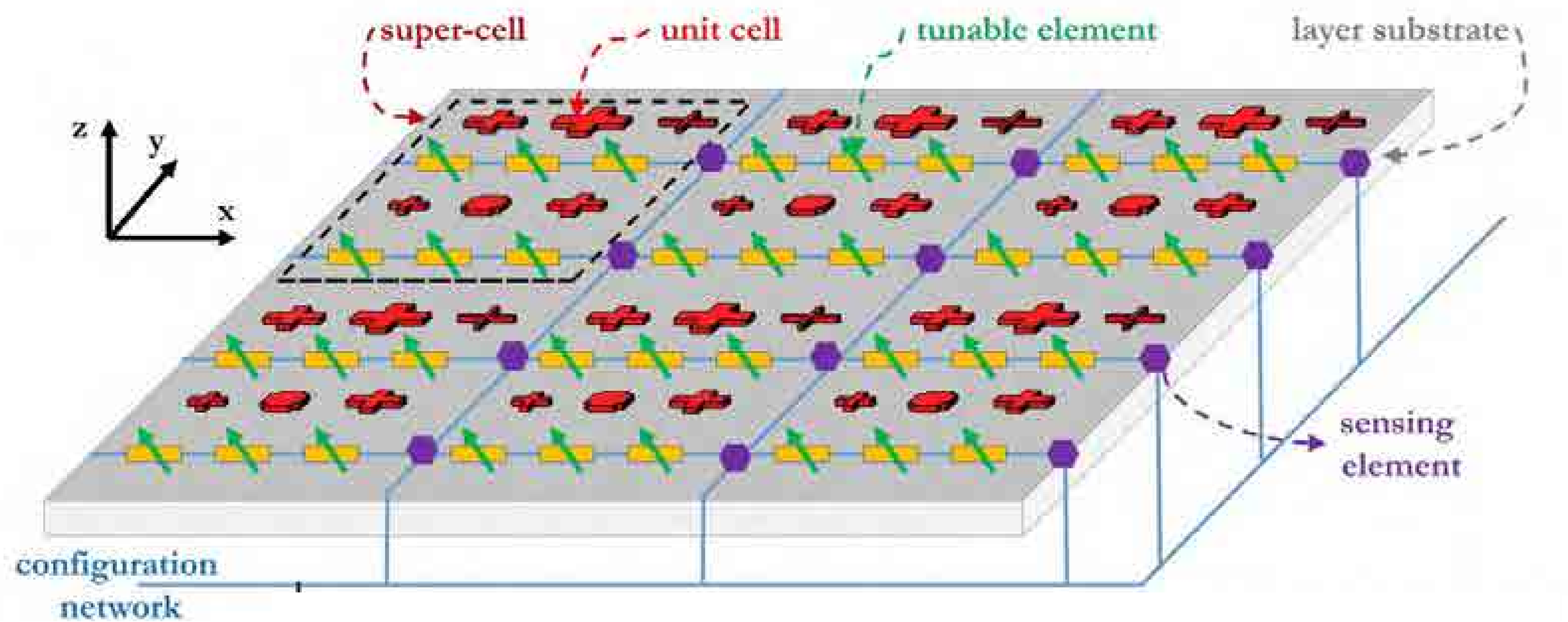
RIS in 2018

- **Proposed and started working on reconfigurable intelligent surfaces (metasurfaces) in 2018-2019 – Called RIS**

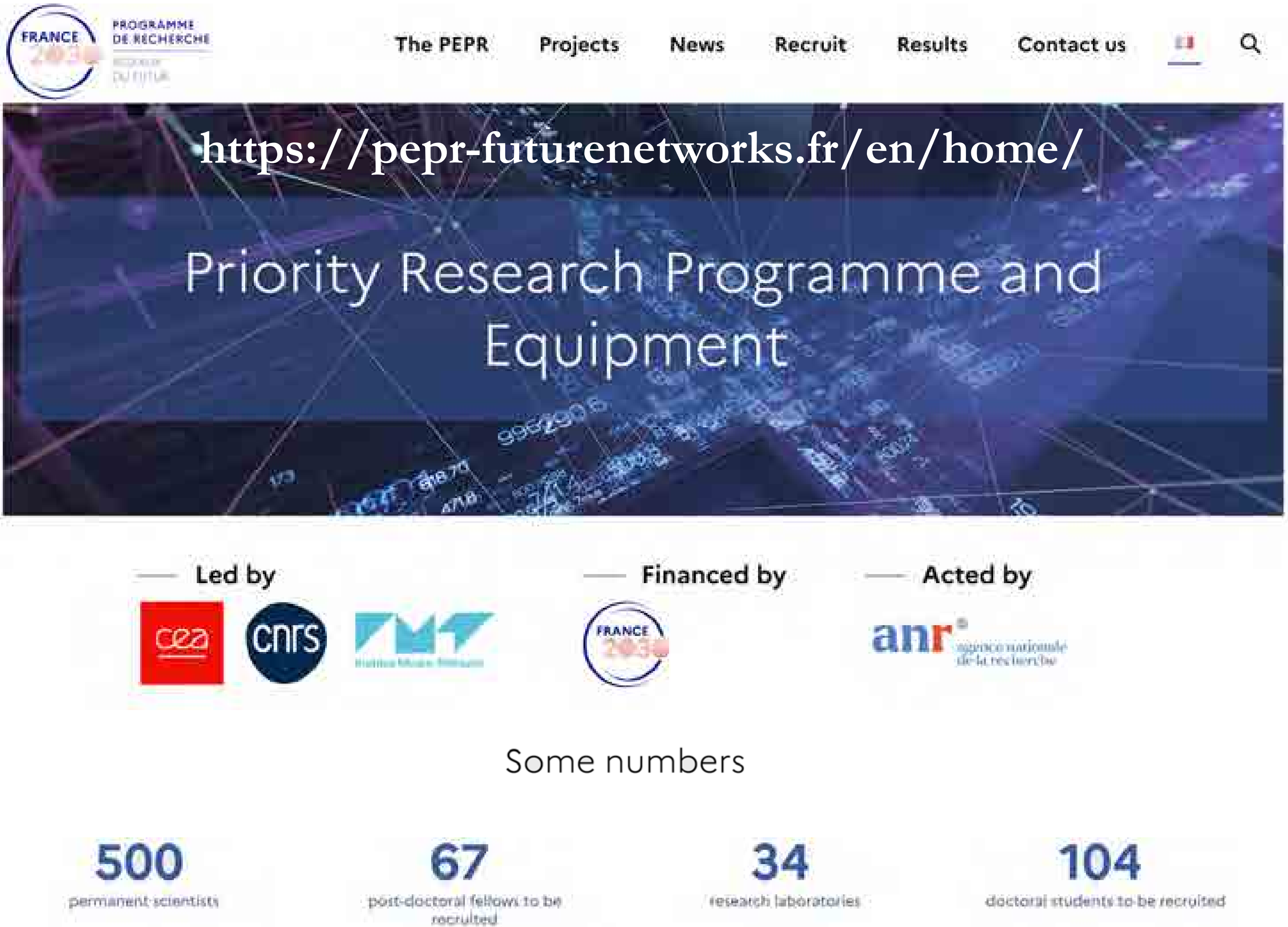
Best Paper Award

Example of RIS

- Proposed and started working on reconfigurable intelligent surfaces (metasurfaces) in 2018-2019 – Called RIS



RIS in 2023: The ANR PEPR Networks of the Future



RIS in 2023: The ANR PEPR Networks of the Future

VISION STRATÉGIQUE – RÉSEAUX DU FUTUR

Augmentation de la capacité, faible latence - mais surtout une convergence forte avec les verticaux

Industrie 4.0, Transports, Energie, Santé: réponses aux besoins spécifiques (contrôle industriel à distance, réalité mixte, doubles digitaux, communications immersives...)

Services multi-sectoriels
Nouvelle phase de la transformation Numérique

De 2D à 3D
Les reseaux non-terrestres

Fusion avec l'espace physique : Surfaces réfléchissantes intelligentes

Utilisation optimale du spectre, y compris vers le THz

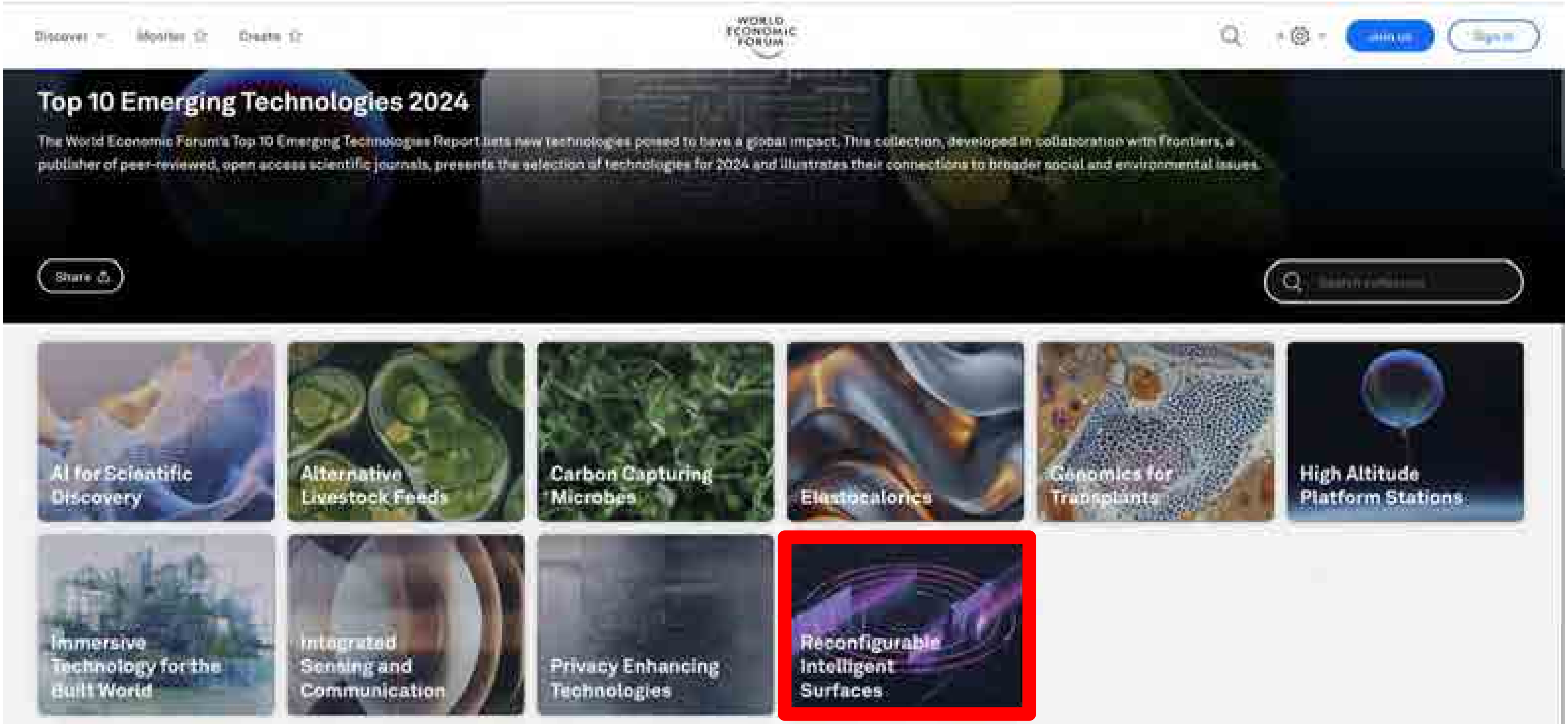
Nouveaux paradigmes architecturaux: convergence réseau-cloud-sensing, virtualisation, slicing, orchestration de BenB

Sécurisation et protection des données de bout en bout, par conception, dans un contexte multi-acteurs

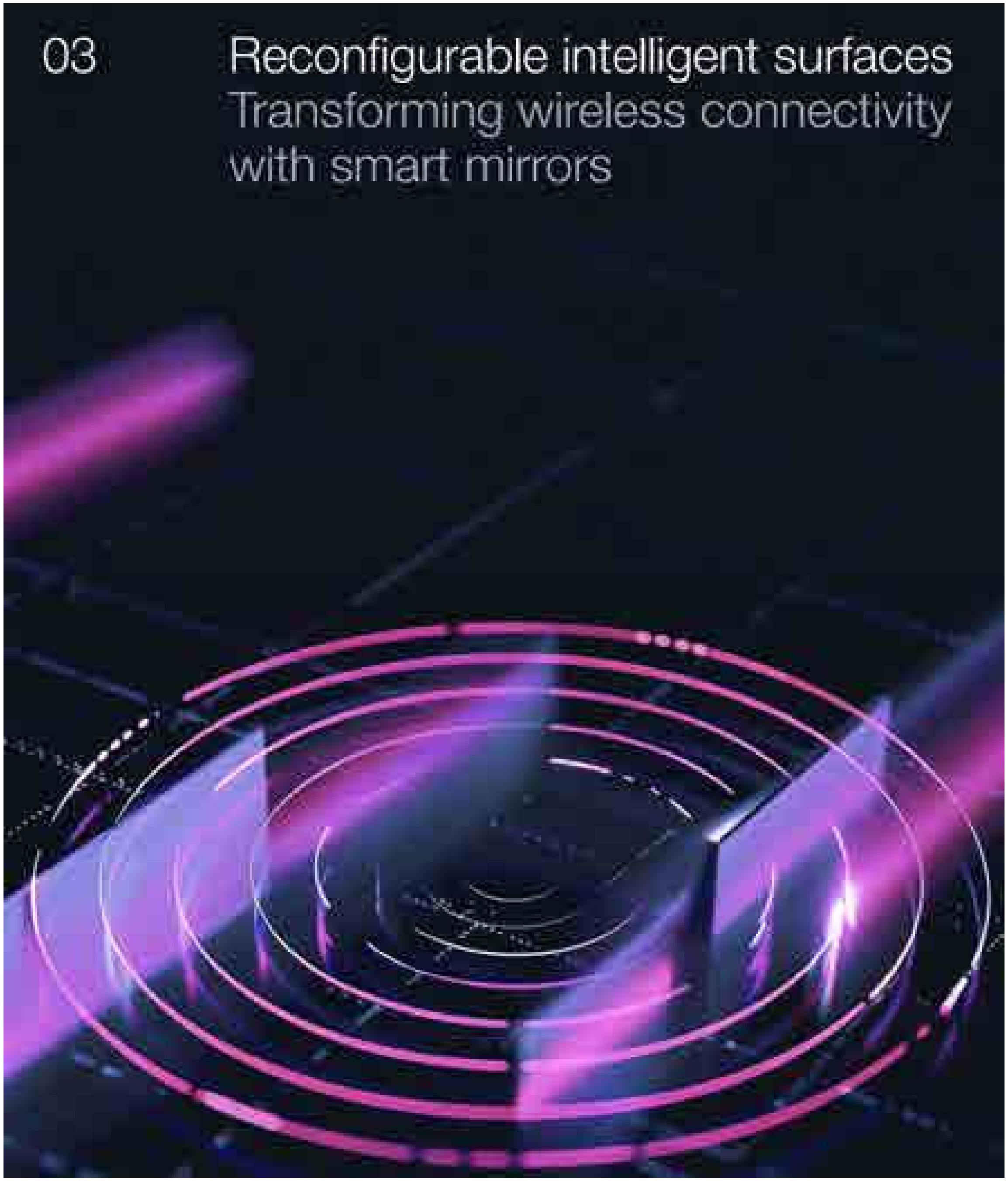
Sobriété dans la consommation de ressources, acceptabilité, nouveaux usages

PEPR 5G ET RÉSEAUX DU FUTUR 10.07.23 P 7

RIS in 2024: World Economic Forum



RIS in 2024: World Economic Forum



Mohamed-Slim Alouini
Al-Khwarizmi Distinguished Professor, Electrical and Computer Engineering, King Abdullah University of Science and Technology

Joseph Costantine
Associate Professor, Electrical and Computer Engineering, American University of Beirut

Marco Di Renzo
CNRS Research Director, Laboratory of Signals and Systems (L2S), Paris-Saclay University

Javier Garcia-Martinez
Professor, Chemistry and Director, Molecular Nanotechnology Lab, University of Alicante

RIS for
Smart Radio Environments

Explaining Example (@CentraleSupelec)

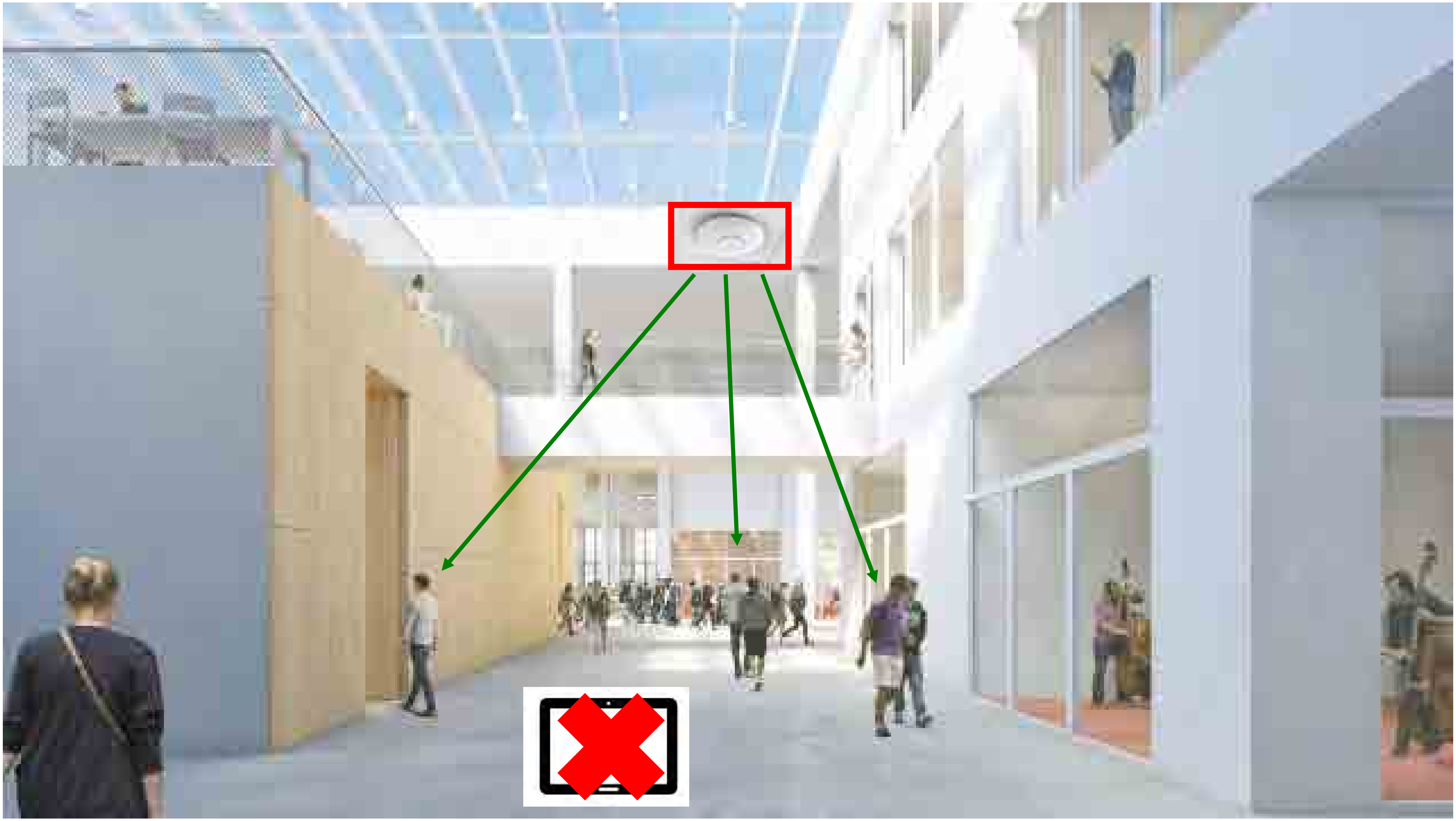
Explaining Example (@CentraleSupelec)

Explaining Example (@CentraleSupelec)

Explaining Example (@CentraleSupelec)

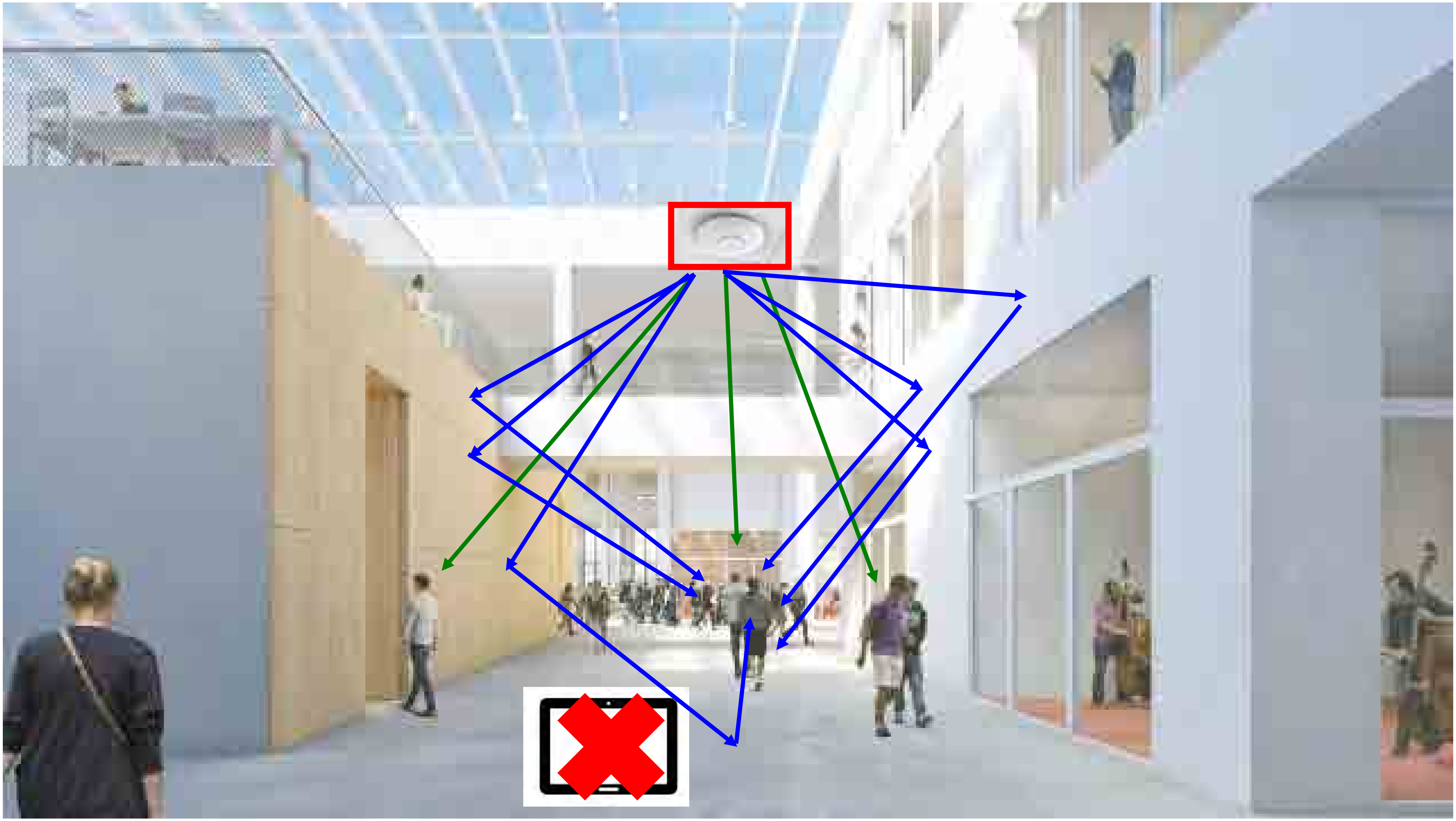
… at the first sight, it seems simple …

Explaining Example (@CentraleSupelec)



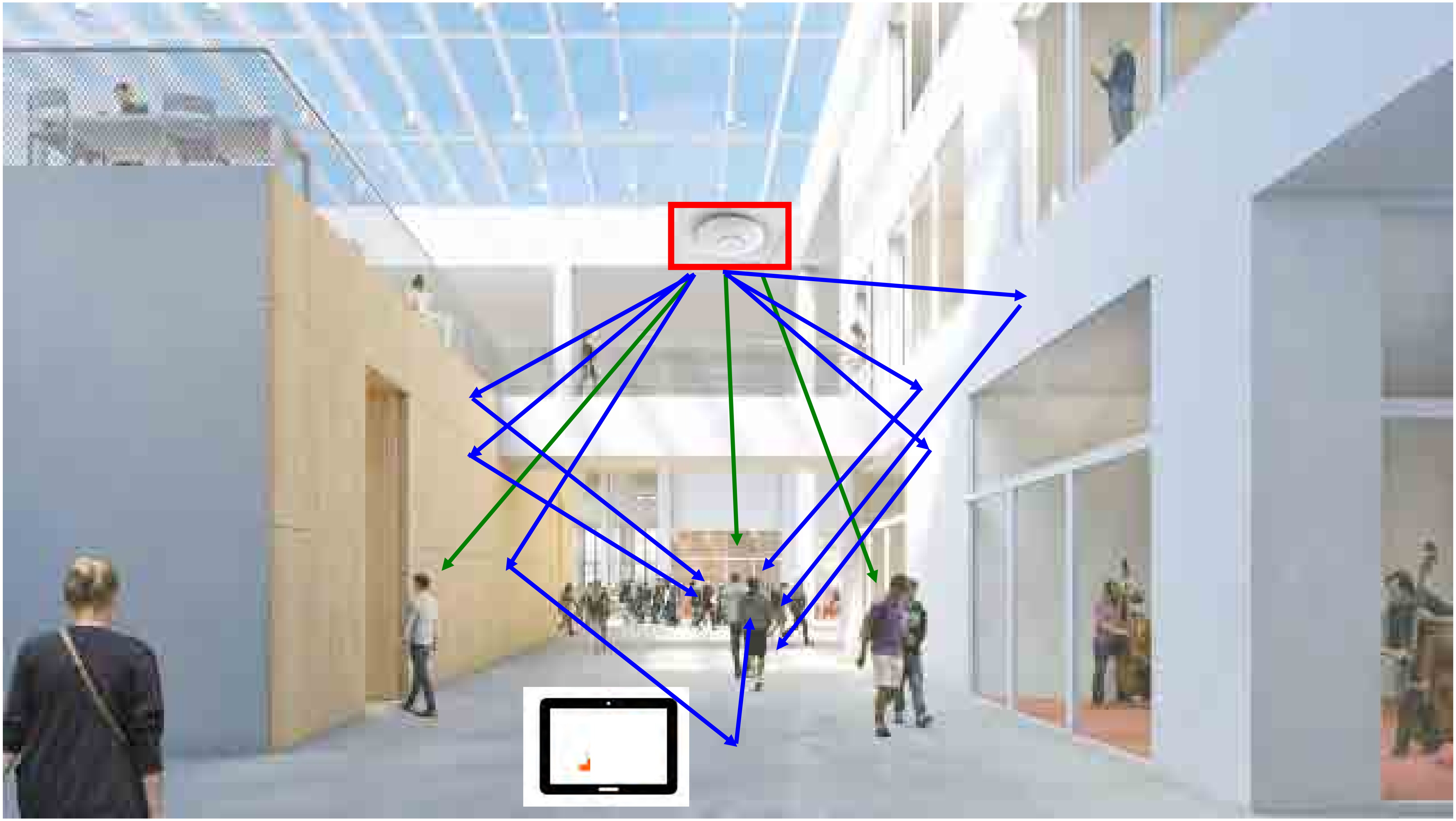
… but, it is not so simple … why ?

Explaining Example (@CentraleSupelec)



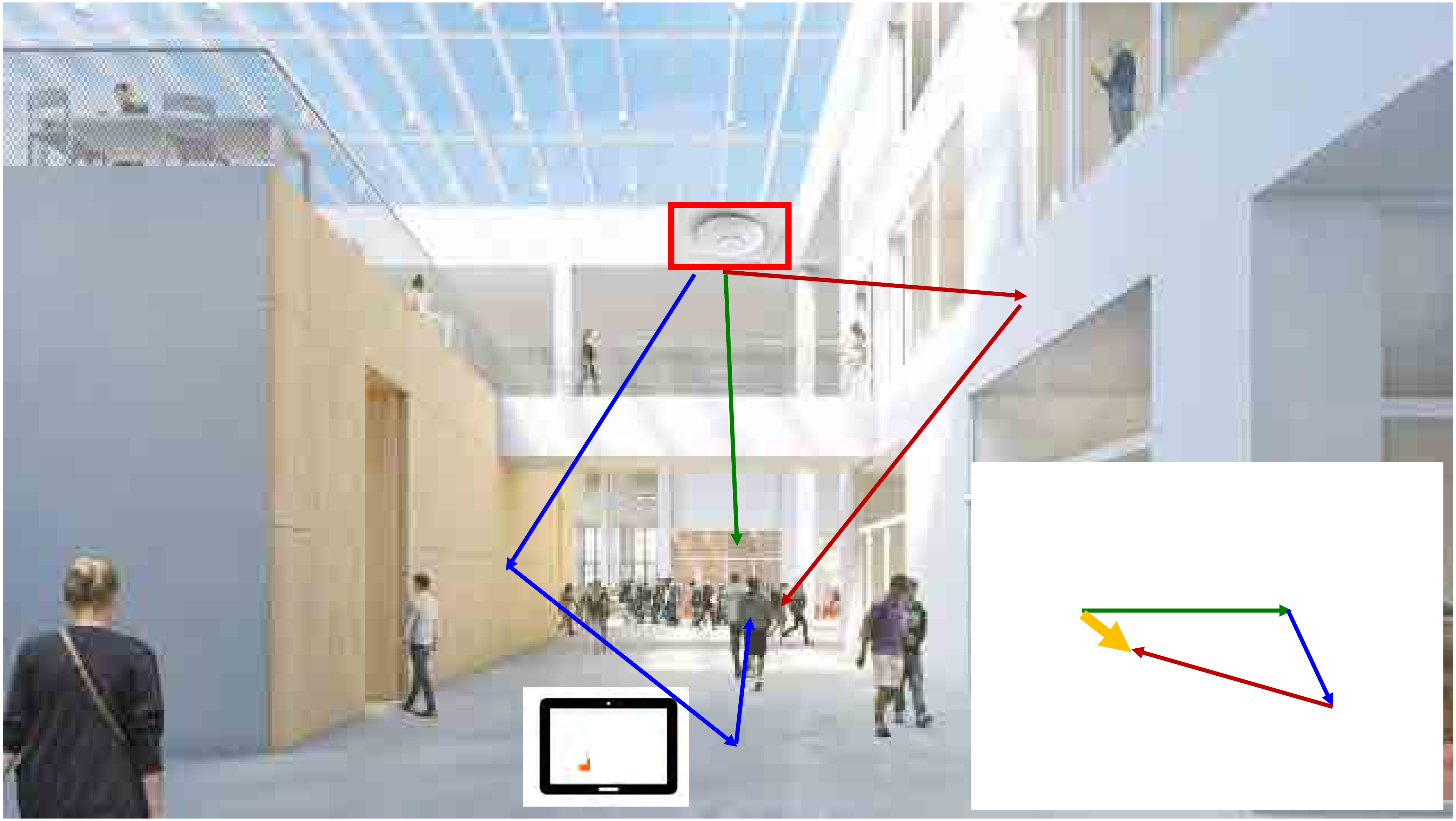
uncontrollable multipath propagation

Explaining Example (@CentraleSupelec)



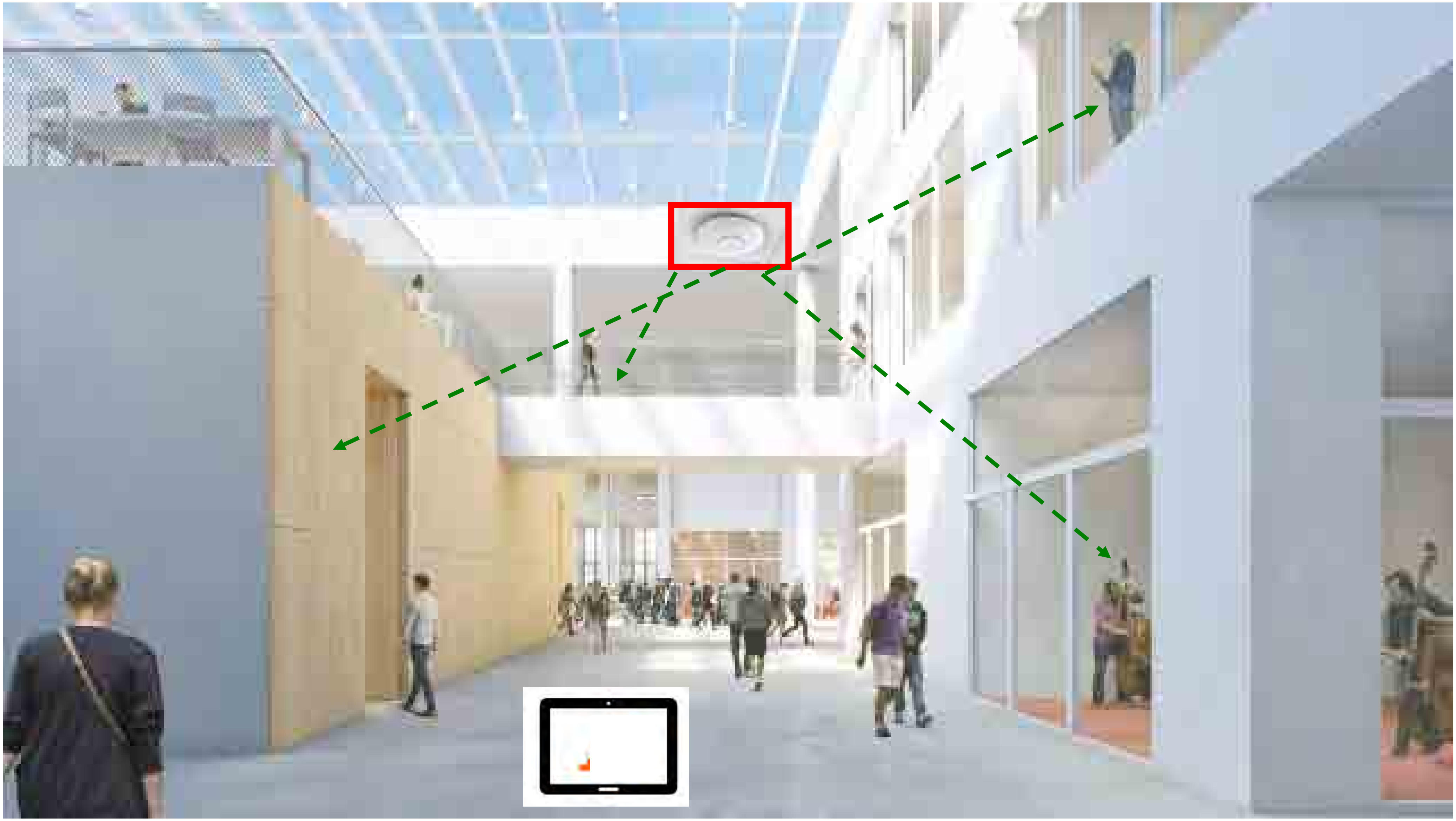
uncontrollable multipath propagation

Explaining Example (@CentraleSupelec)



uncontrollable multipath propagation

Explaining Example (@CentraleSupelec)



… even worse for some users …

Explaining Example (@CentraleSupelec)

How to solve the problem ?

Explaining Example (@CentraleSupelec)

Option 1: Complex digital signal processing at the receiver (3G)

Explaining Example (@CentraleSupelec)

Option 2: Ultra network densification (4G)

Explaining Example (@CentraleSupelec)

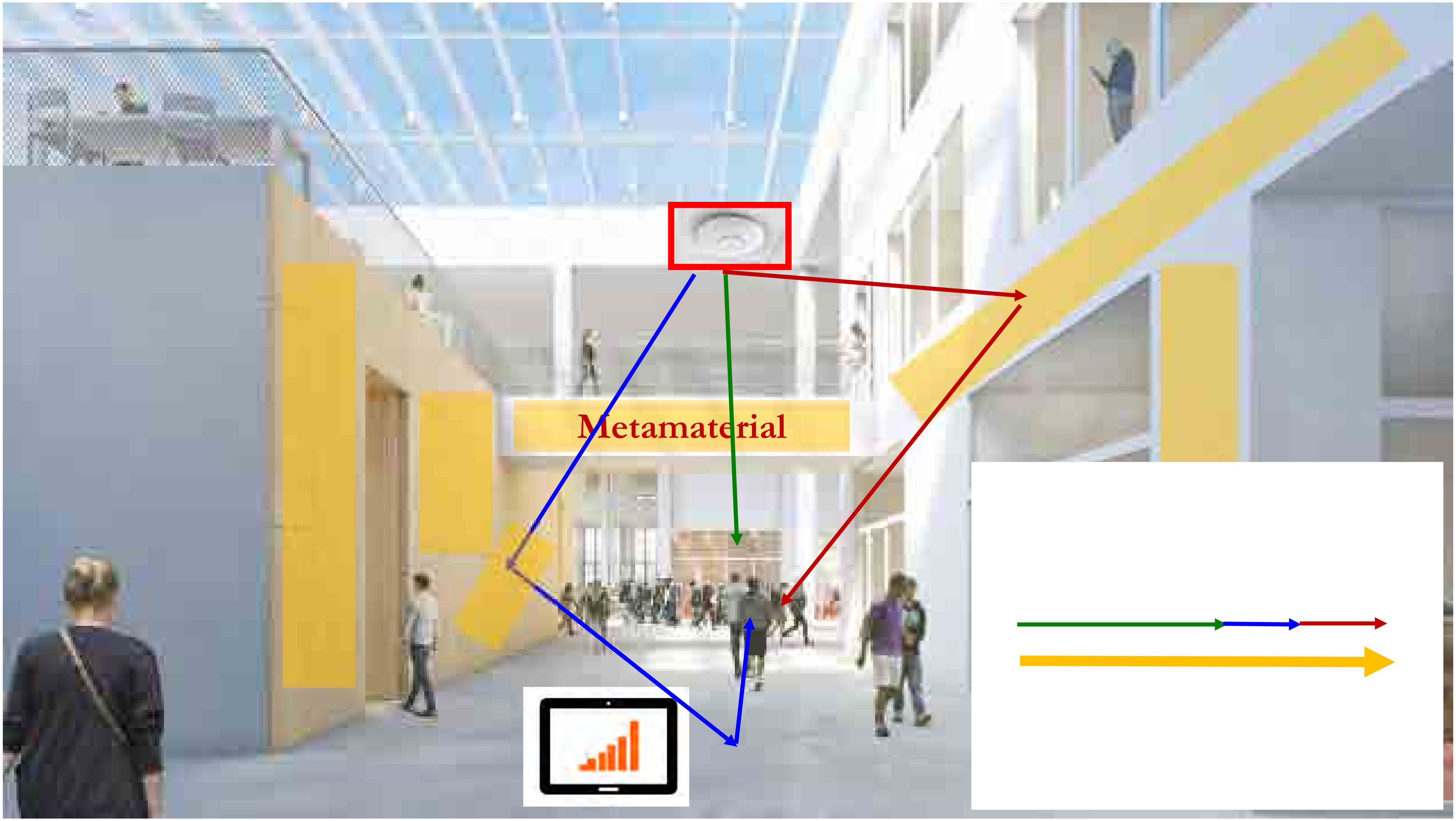
Option 3: (massive) Multi-antenna transmitters and receivers (5G)

Explaining Example (@CentraleSupelec)

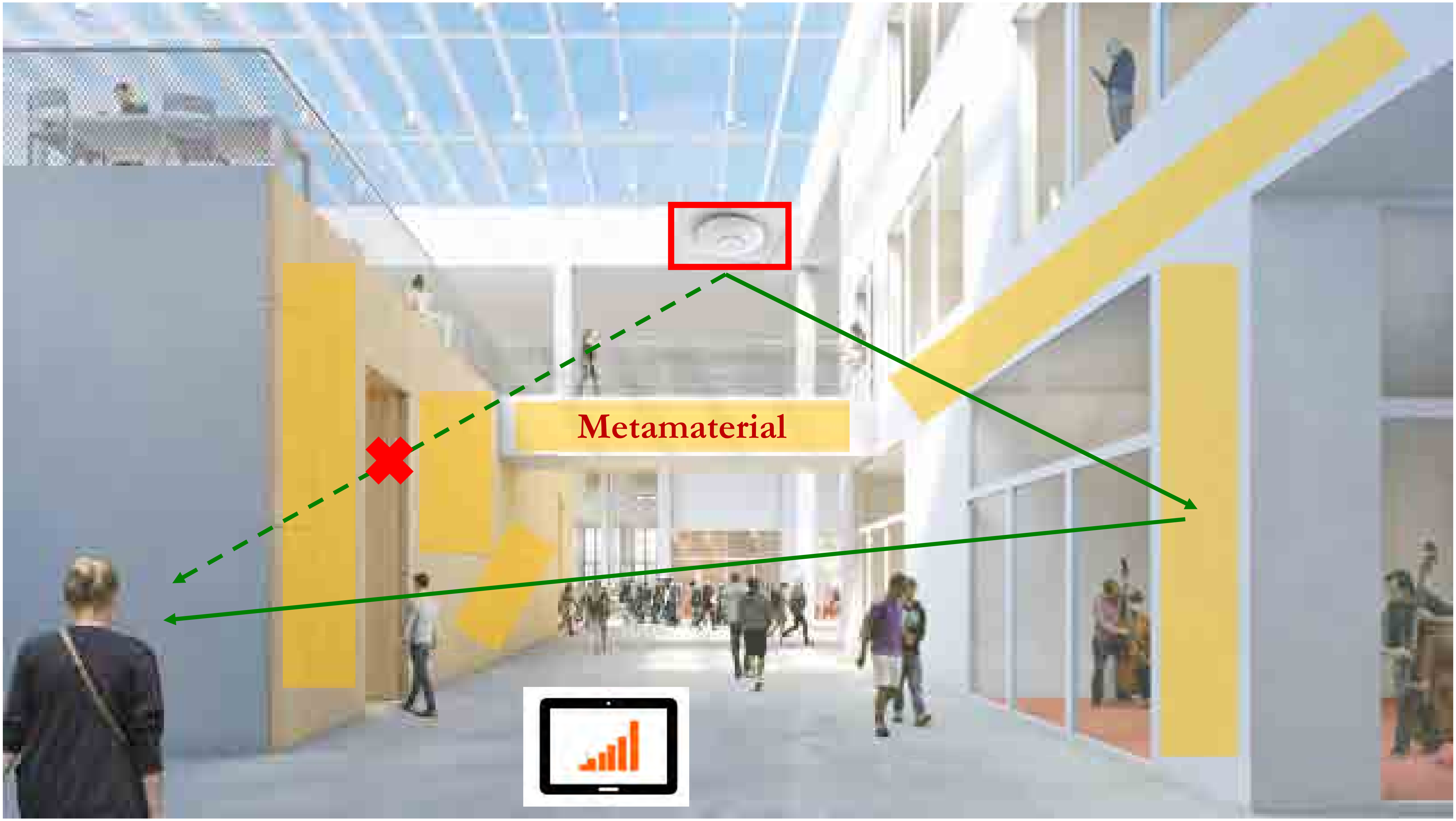
Mindset of options 1-3: Tx and Rx are adapted to the environment

Explaining Example (@CentraleSupelec)

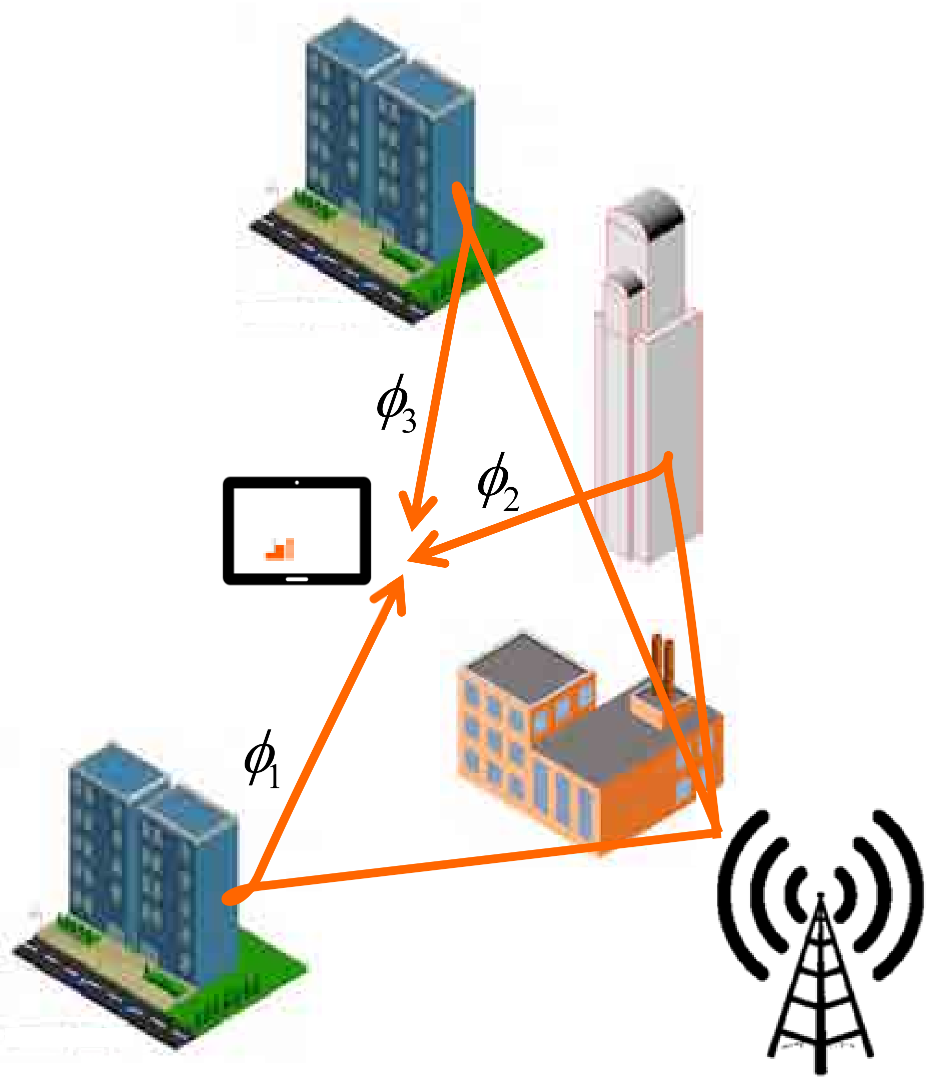
Explaining Example (@CentraleSupelec)



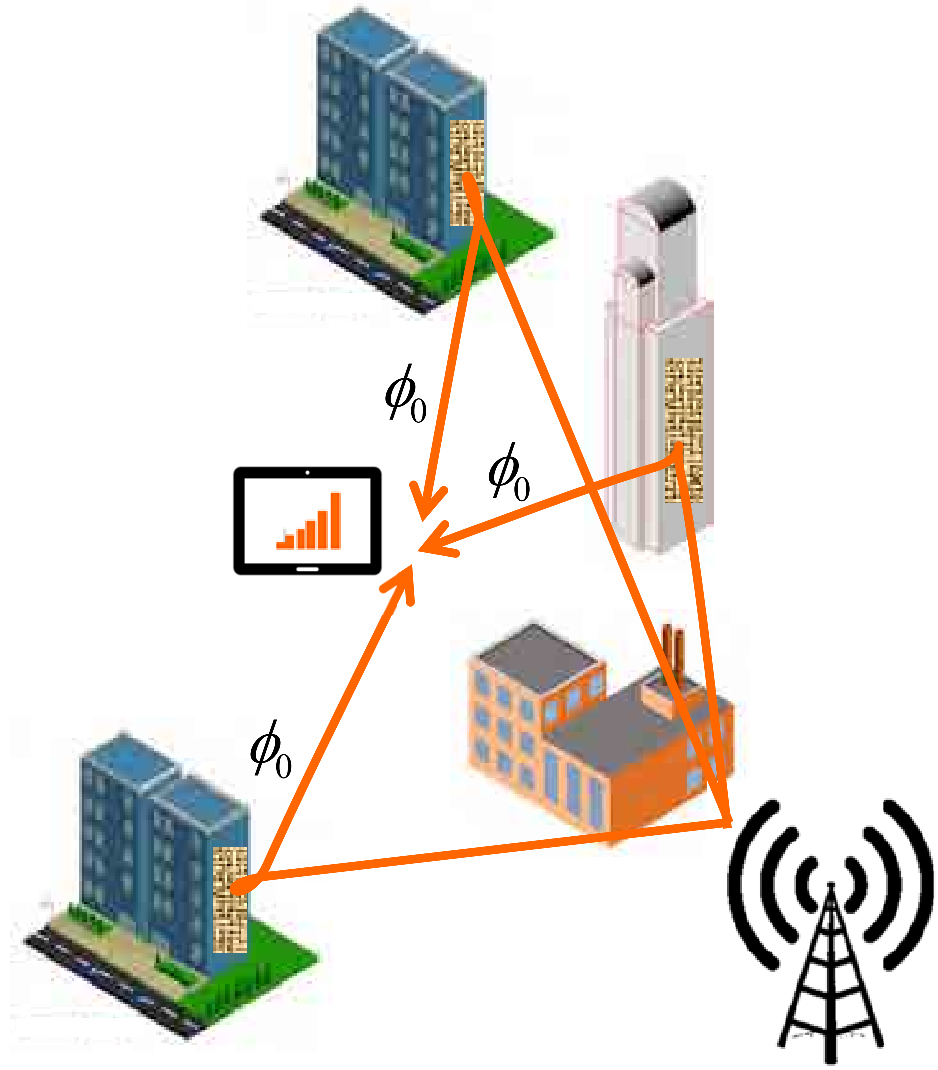
Explaining Example (@CentraleSupelec)



Explaining Example (outdoor)



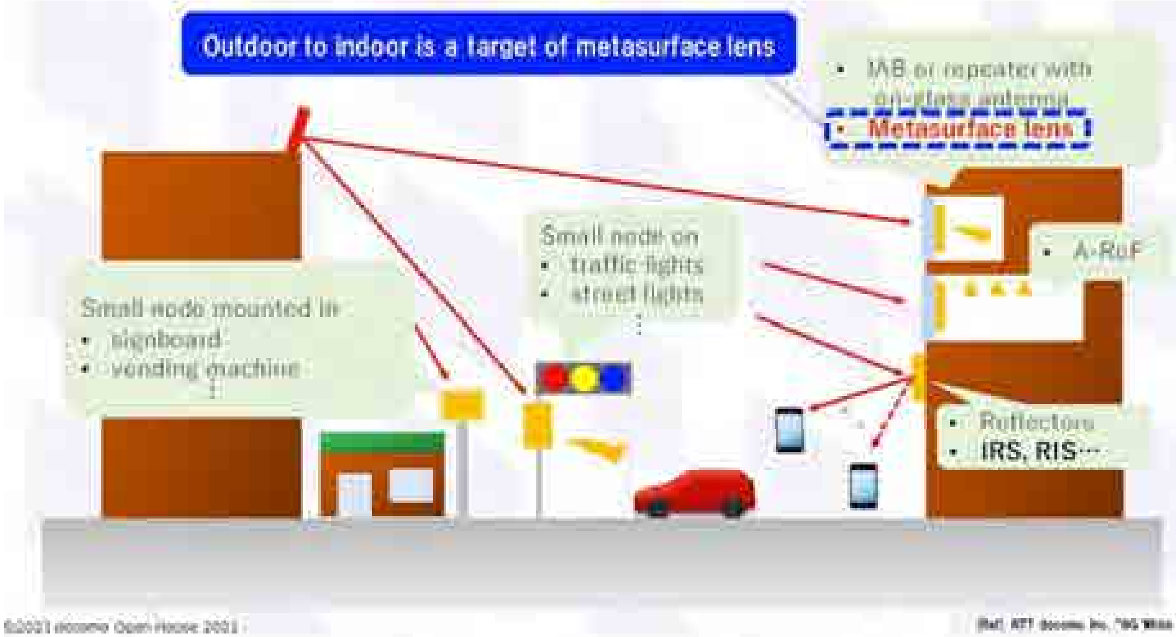
wireless environment



metamaterial-coated wireless environment

M. Di Renzo et al., Proceedings of the IEEE, 2022

Explaining Example (smart windows)

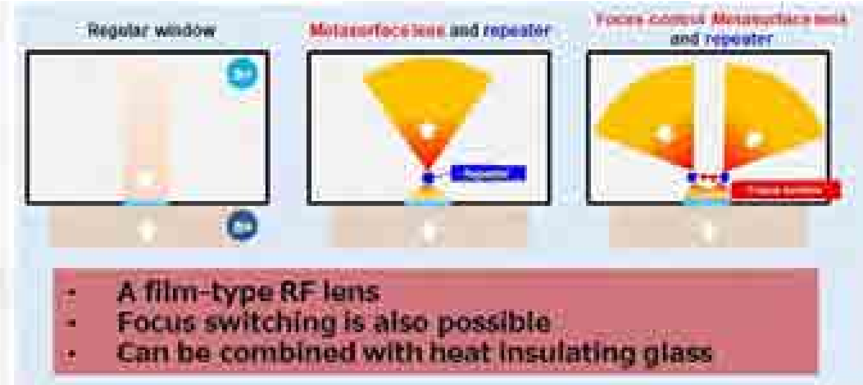


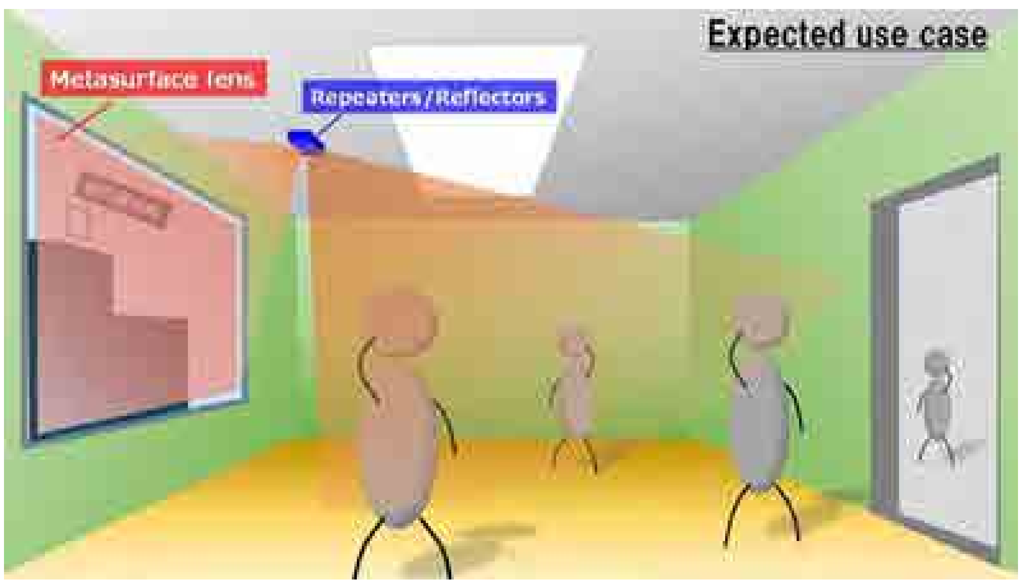
Collaboration partner

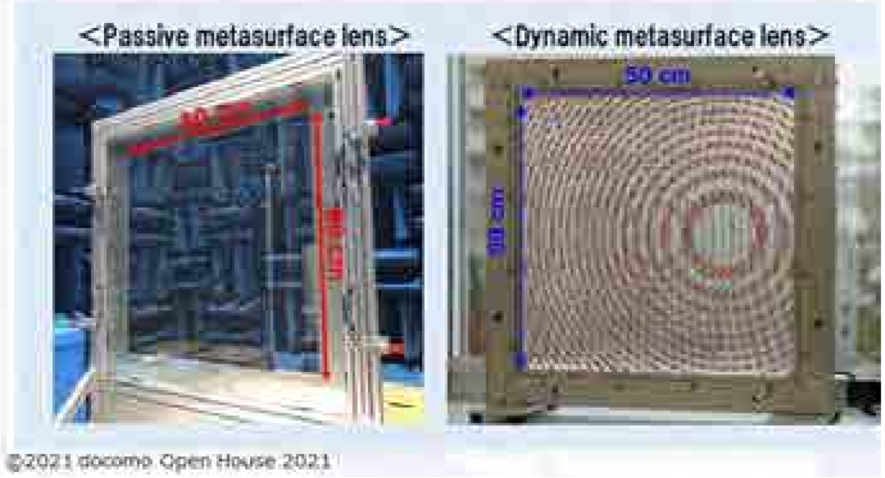
docomo × AGC

[Metasurface design]

[Transmission structure design]
[Microfabrication technologies]







https://docomo-openhouse.jp/2021/en/exhibition/022/

Long-Term: RISs → Transparent Films

Improve communications infrastructure by application of a transparent film without spoiling appearance

An innovative thin transparent and flexible film that can be attached to the any surface and can reflect radio waves in the Sub6 - mm wave - THz range

As radio waves become higher frequency, such as 5G and 6G, these waves will become harder to reach due to their high directivity and easy attenuation.

This transparent film can be applied anywhere, without power supply, without spoiling the surface's appearance, to improve the communication environment

It can be applied to walls, windows, wall-hung paintings, clocks, curved surfaces, pillars, etc.
It is very easy to apply to any irregularly shaped object, so just like pasting a poster.

It can also be easily reapplied, highly durable, and once installed, completely maintenance-free

It is an innovative product that eliminates network users' stress, supports IoT transformation, and significantly improves communications infrastructure.

SEKISUI

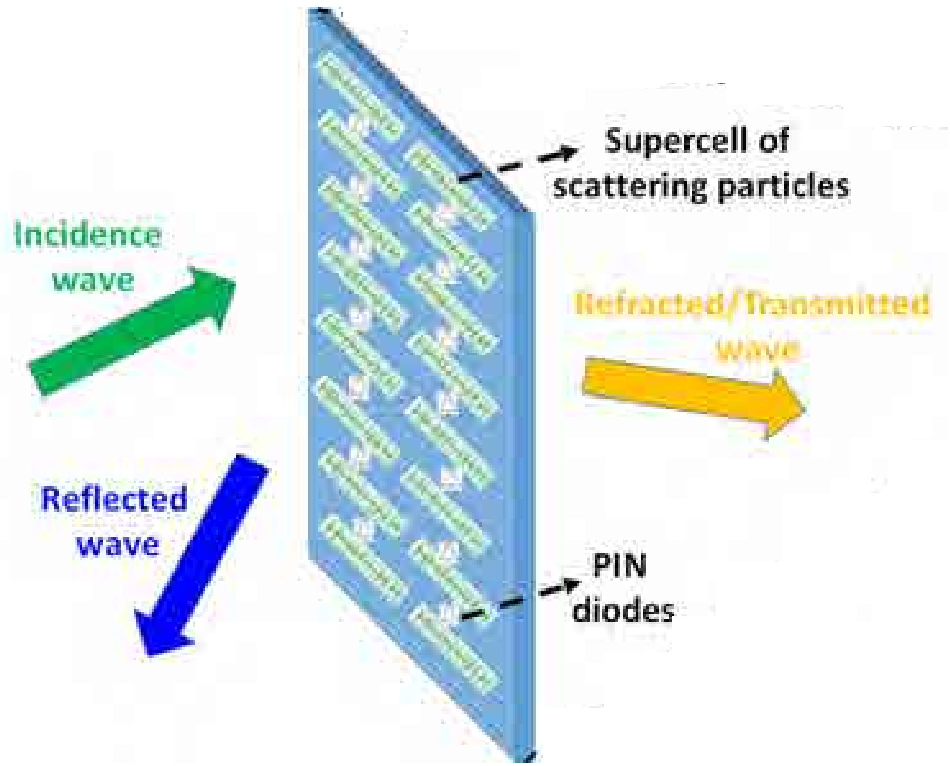
- Apply anywhere
- No need for power supply
- No need for maintenance

https://www.sekisui.co.jp/electronics/en/application/film.html

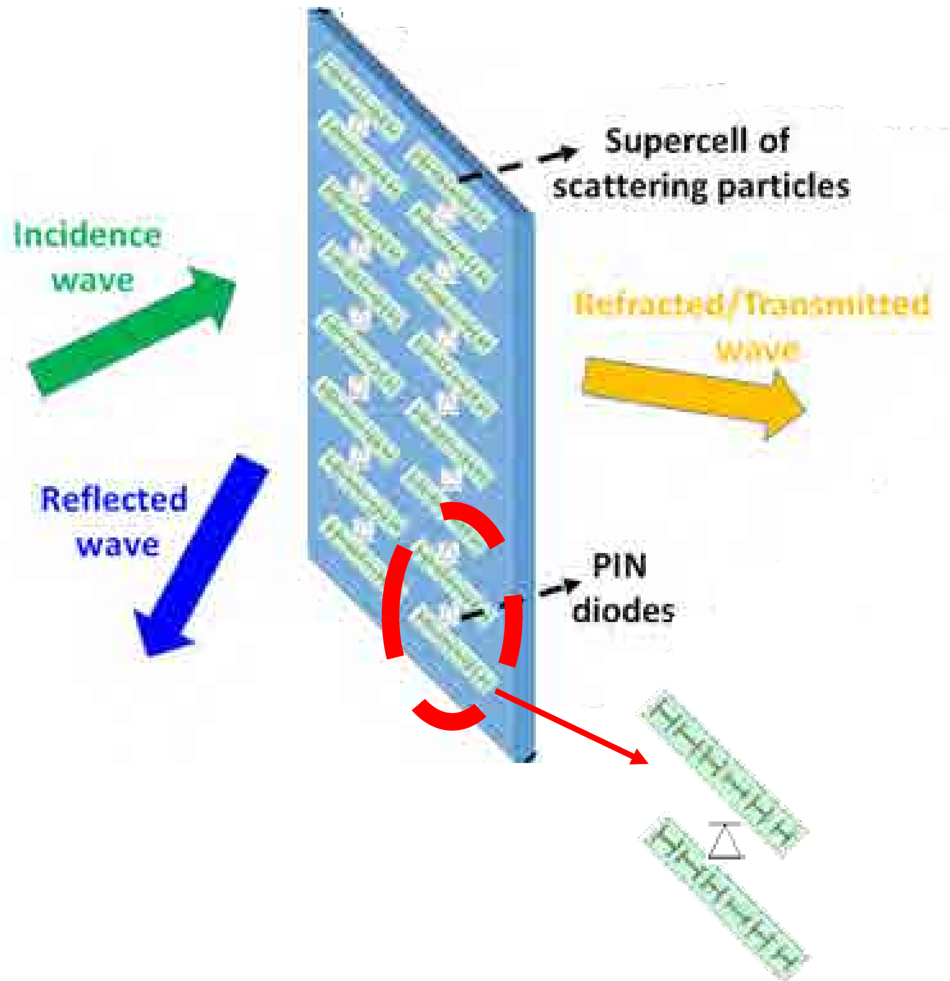
How to Shape the Electromagnetic Waves?

RISs: How it Works and Unique Features

Reconfigurable Intelligent Surfaces (RISs)

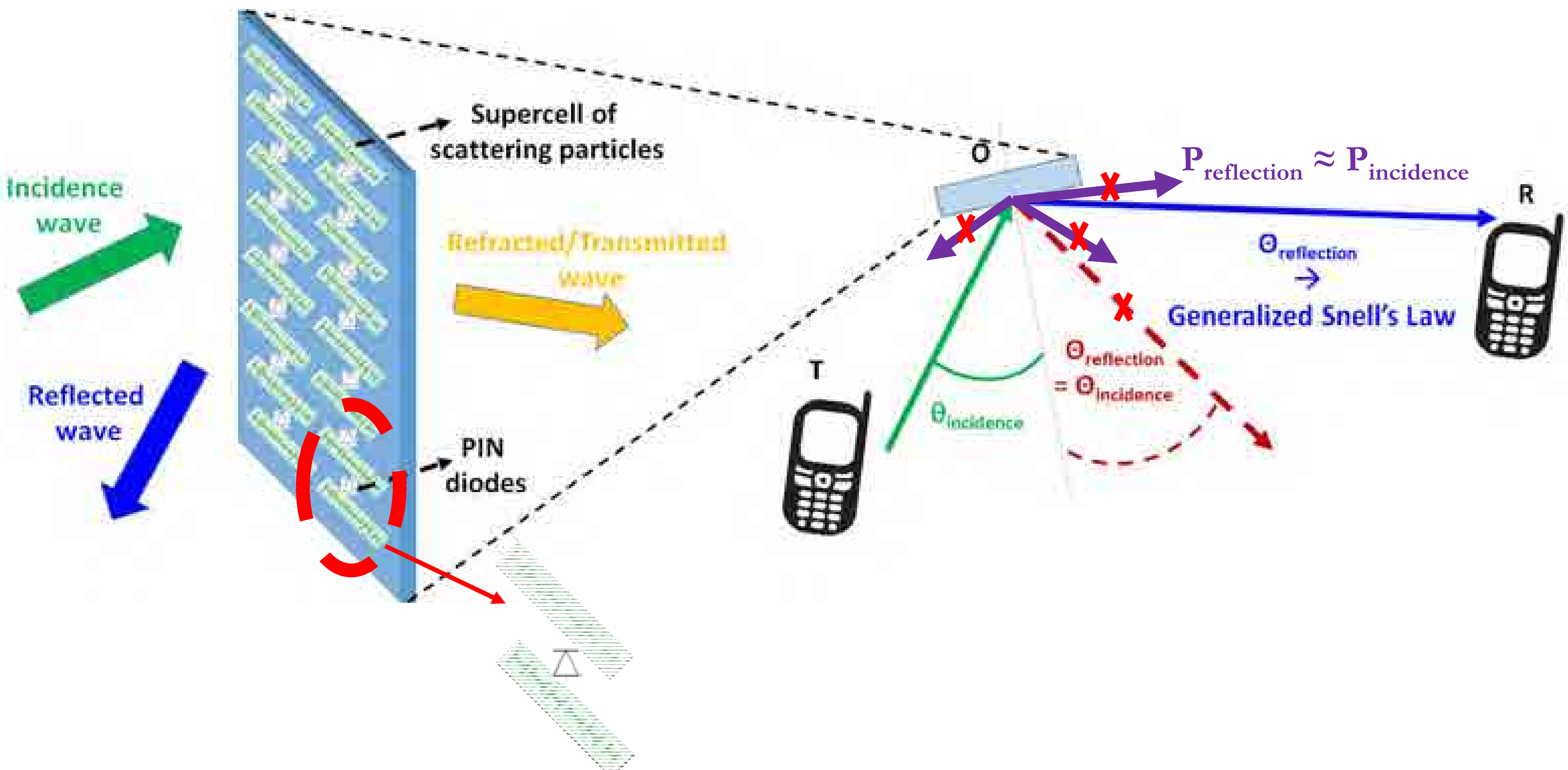


Reconfigurable Intelligent Surfaces (RISs)



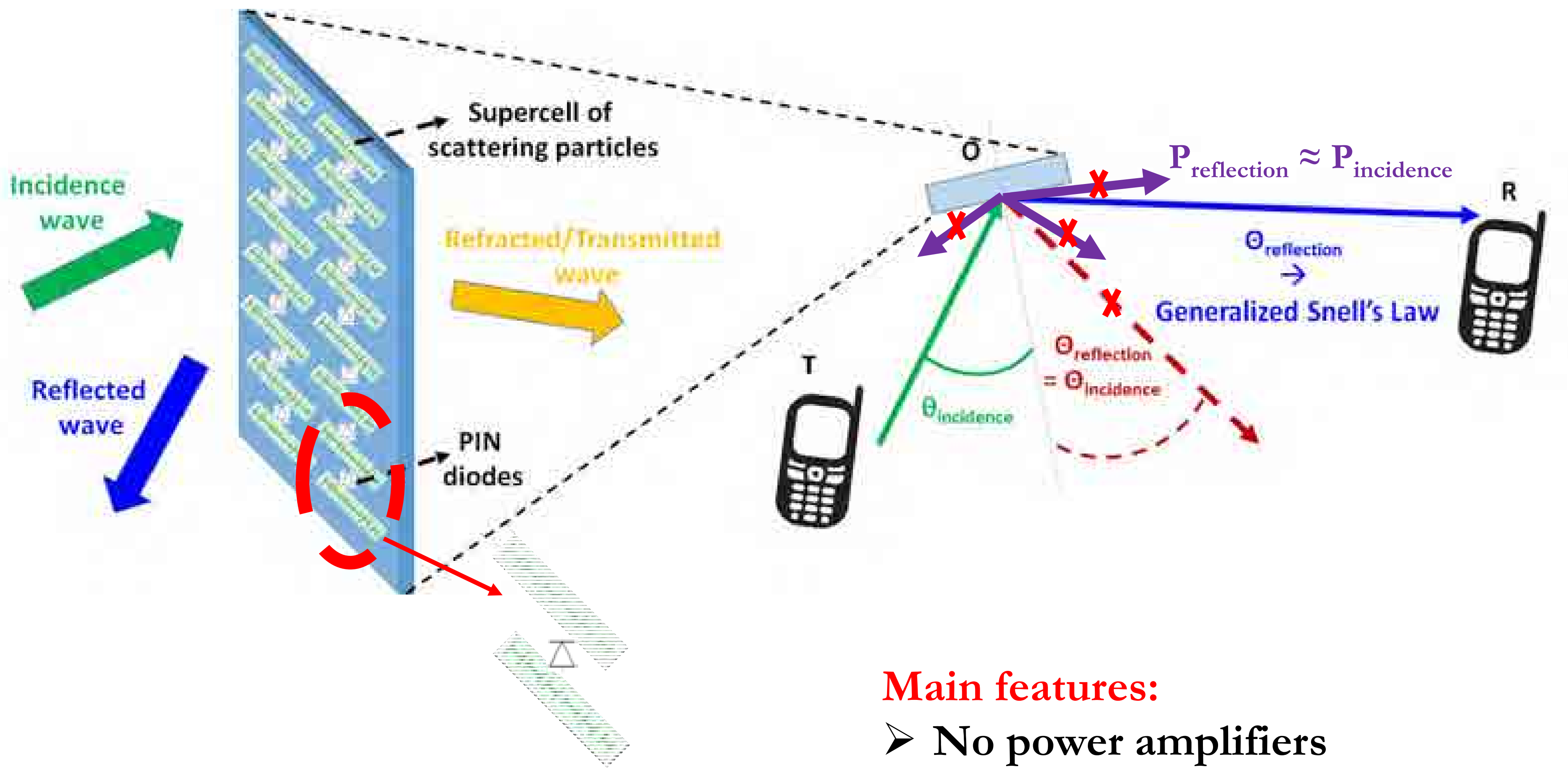
RISs: How it Works and Unique Features

Reconfigurable Reflecting Surfaces



Why is RIS-aided Wireless Fundamentally New?

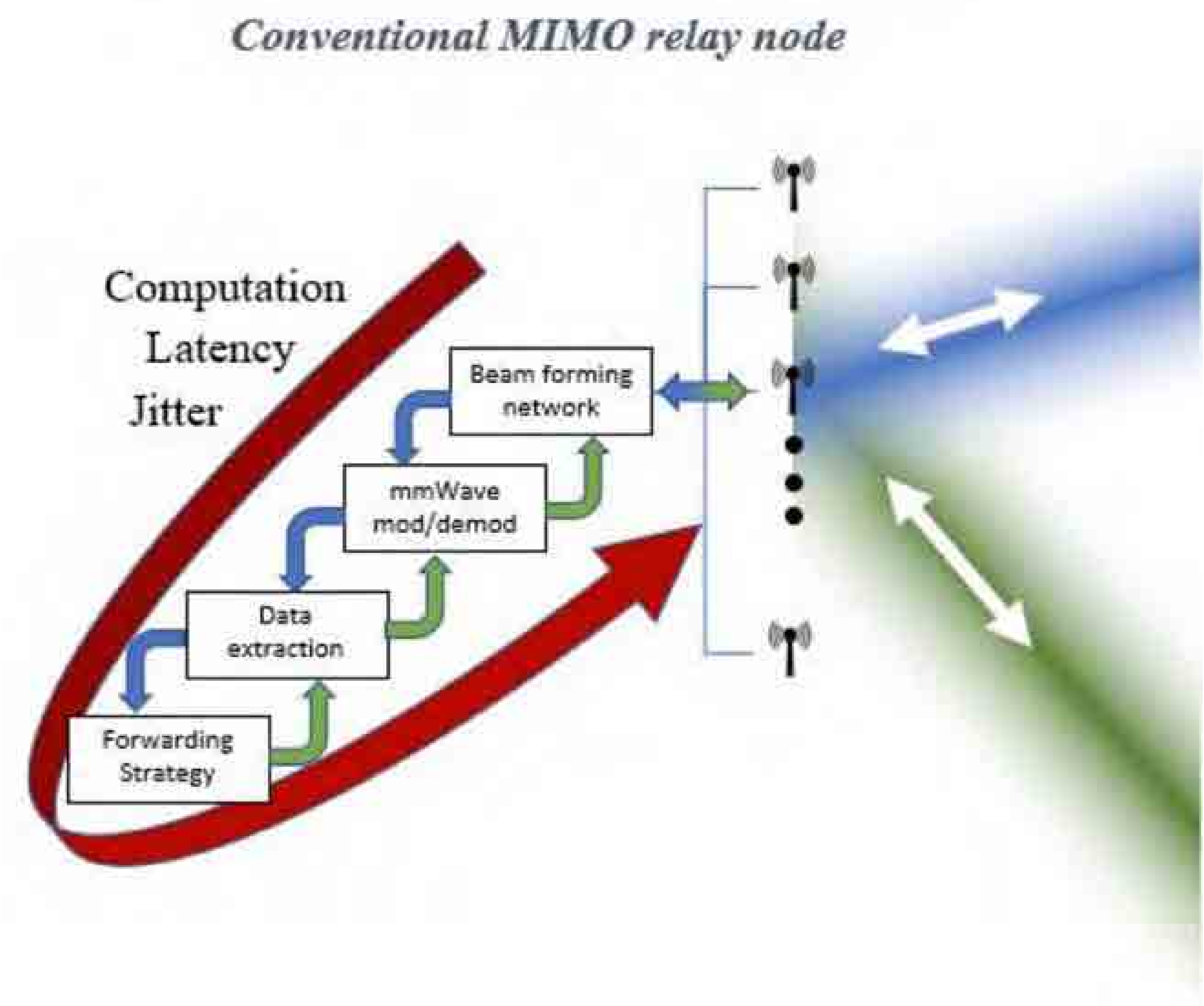
Reconfigurable Reflecting Surfaces



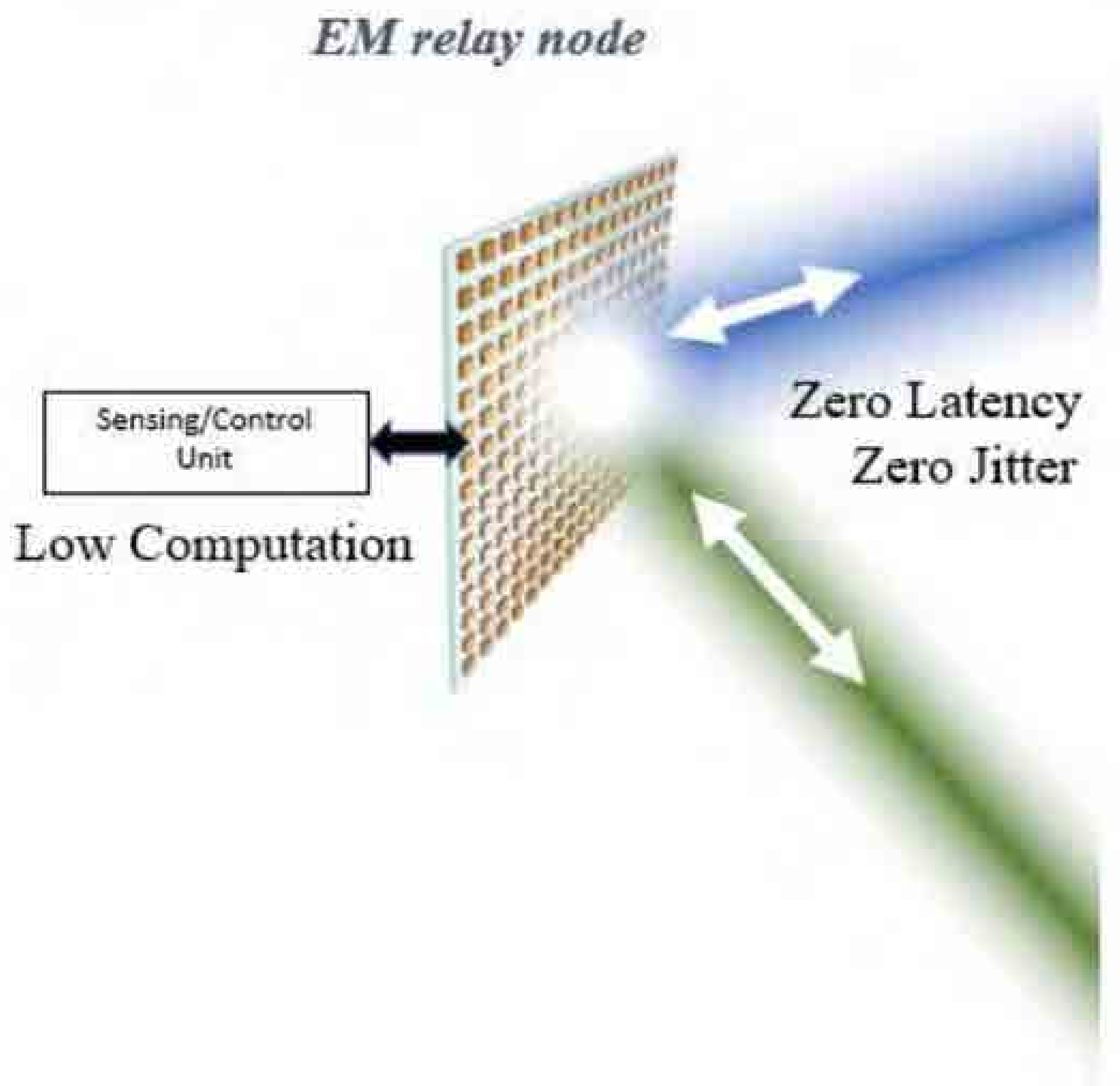
Main features:

- No power amplifiers
- No digital signal processing
- No radio frequency chains

RISs: How it Works and Unique Features



RISs: How it Works and Unique Features



Great Interest from Industry

ETSI ISG-RIS (founding vice-chair)

- ETSI: European Telecommunications Standards Institute
- ISG: Industry Specification Group (ISG) on RIS – Approved on June 8, 2021 by the Director General (kickoff: September 30, 2021)

" *Provide an opportunity for ETSI members to coordinate their pre-standards research efforts on RIS technology across various EU/UK collaborative projects, extended with relevant global initiatives, towards paving the way for future standardization of the technology* "

60+ members

EU project RISE-6G (2021-2023)

European Commission | CORDIS EU research results

English EN | Search

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HORIZON 2020

Reconfigurable Intelligent Sustainable Environments for 6G Wireless Networks

Fact Sheet | Reporting | Results | News & Multimedia

Project description

DE EN ES FR IT PL

Reinforcing the B5G/6G vision

The EU-funded RISE-6G project is building on the latest advancements in reconfigurable intelligent surfaces technology for radio wave propagation control, aiming to achieve intelligent, sustainable and dynamically programmable wireless environments that go well beyond the 5G capabilities developed under 5G PPP Release 16. The project will actively participate in standardisation bodies and bring its technically advanced vision into the planned industrial exploitation, thus securing European technology leadership and supporting the creation of new European conceived service and business opportunities in the B5G/6G domain.

Show the project objective

Fields of science

engineering and technology > electrical engineering, electronic engineering, information engineering > information engineering > telecommunications > telecommunications networks > mobile network > 5G

natural sciences > computer and information sciences > computer security > data protection

engineering and technology > electrical engineering, electronic engineering, information engineering > information engineering > telecommunications > radio technology

Keywords

B5G | 6G | RIS | IRS | metasurface | EMF | EnergyEfficiency | Sustainability | intelligent environment

Project information

RISE-6G
Grant agreement ID: 101017011

DOI
10.3030/101017011

Closed project

EC signature date
8 December 2020

Start date 1 January 2021 | **End date** 31 December 2023

Funded under
INDUSTRIAL LEADERSHIP - Leadership in enabling and industrial technologies - Information and Communication Technologies (ICT)

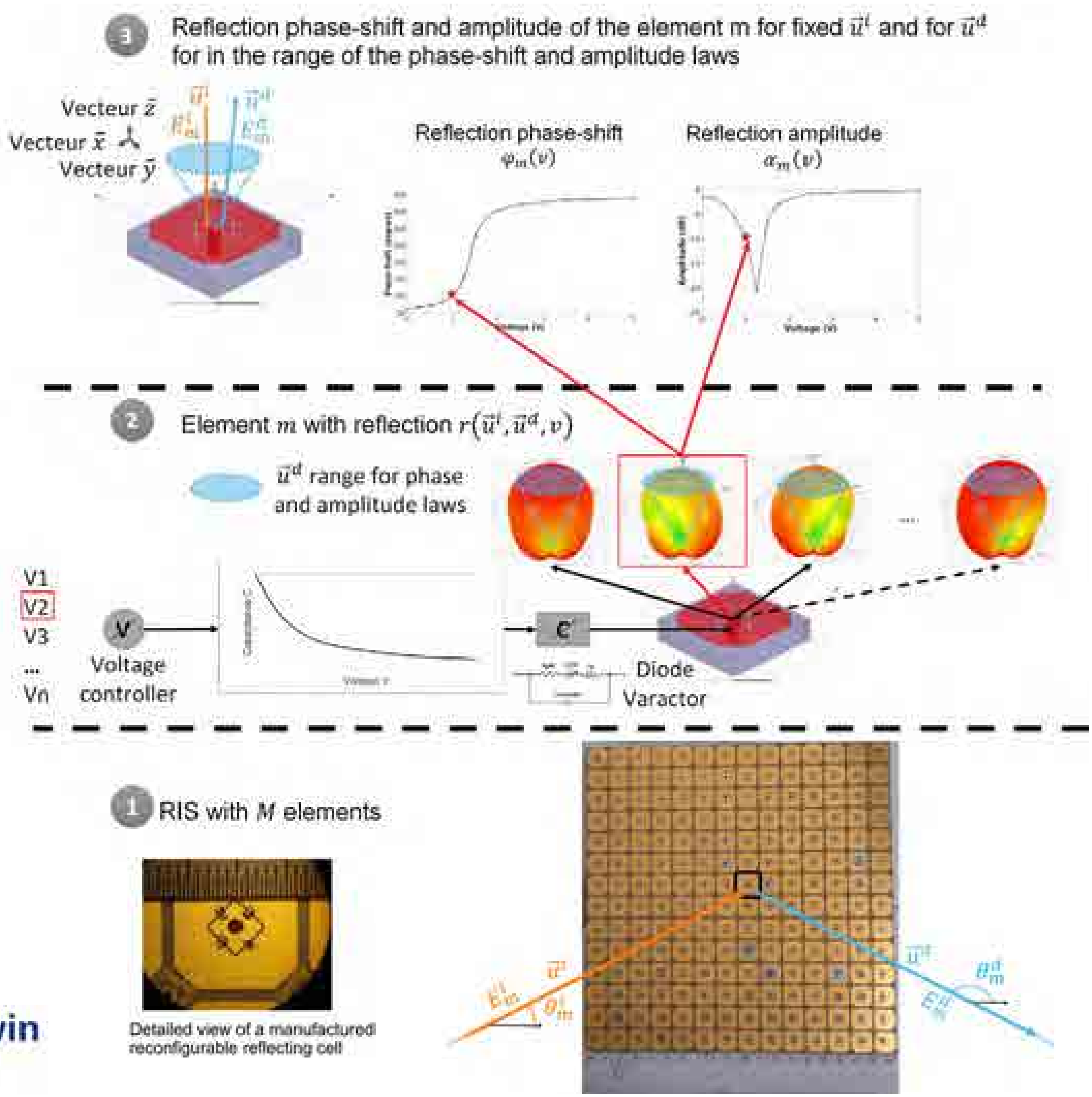
Total cost
€ 6 499 613,75

EU contribution
€ 6 499 613,75

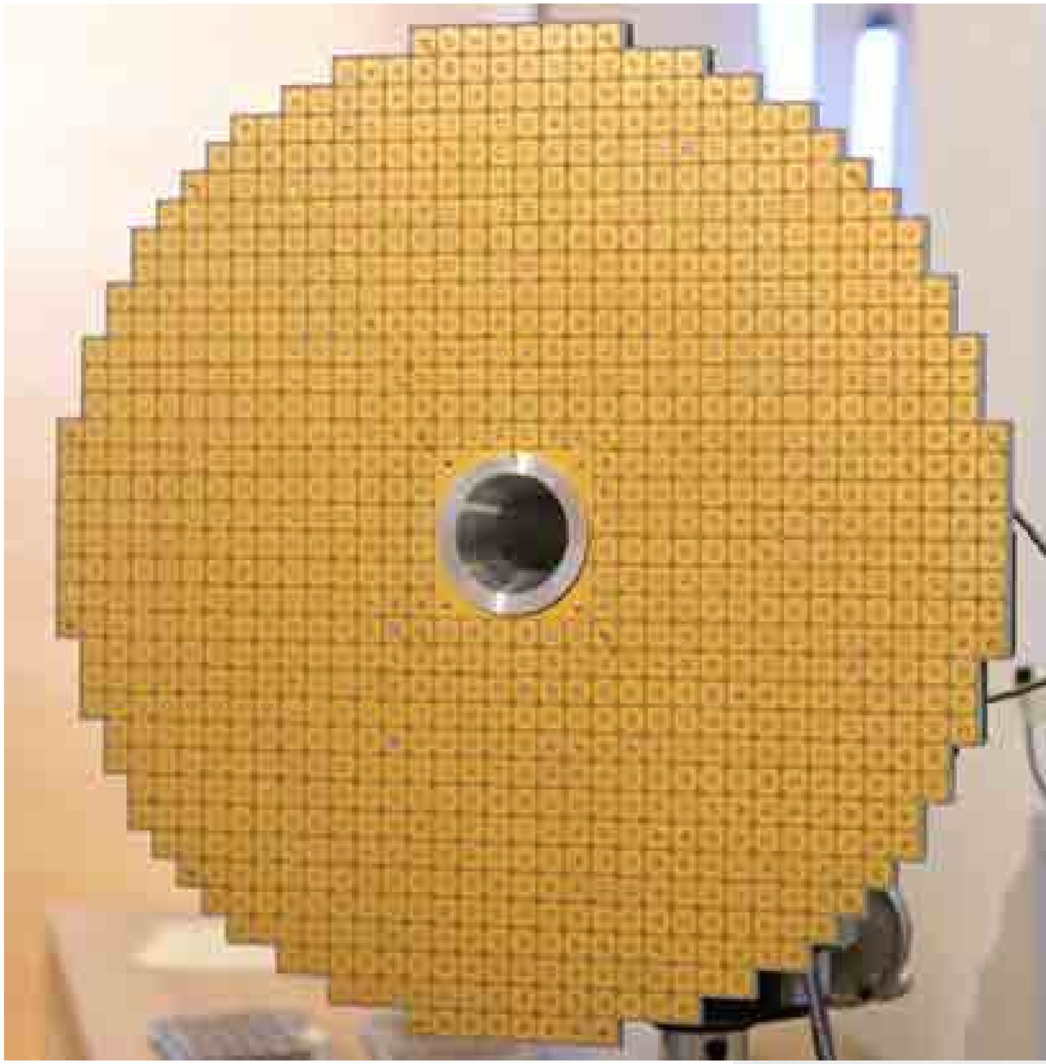
Coordinated by
COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES
France

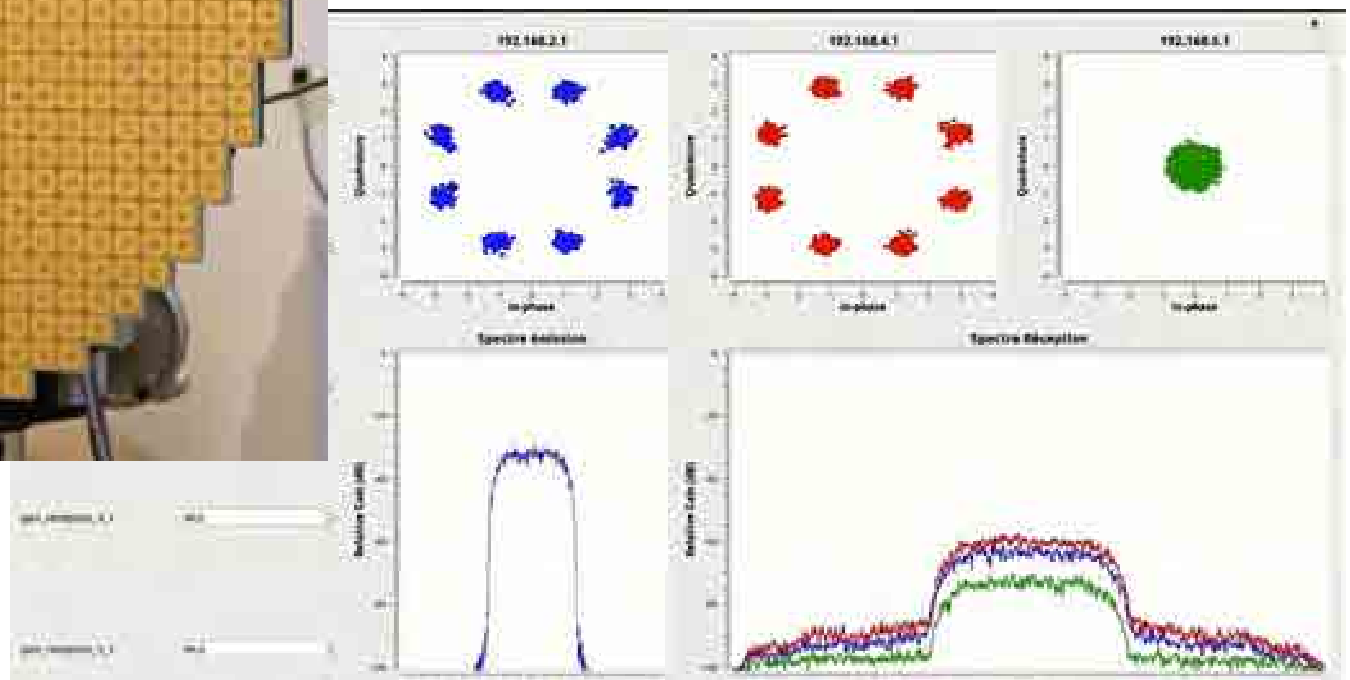
Collaboration with Orange Labs

Collaboration with Orange Labs



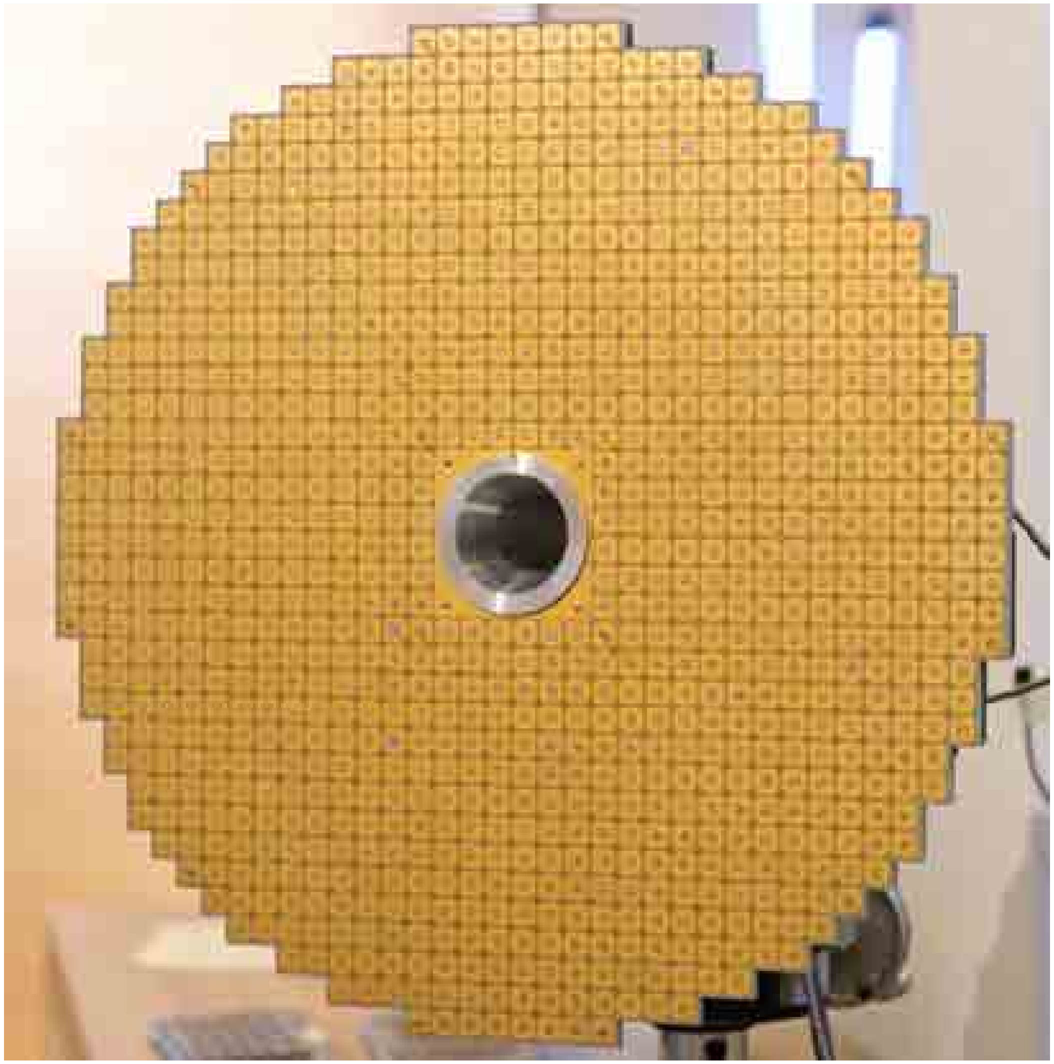
Collaboration with Orange Labs





Orange: https://mastermedia.orange-business.com/publicMedia?t=pmVrAN57IS

Collaboration with Orange Labs



Collaboration with Huawei Sweden

Collaboration with Huawei Sweden

Hangzhou, China (30° 16’ 58.8” N, 120° 9’ 21.6” E)

Collaboration with Huawei Sweden

Hangzhou, China (30° 16’ 58.8” N, 120° 9’ 21.6” E)

Current 5G network deployment:

Rate @ Cell-edge = 0.96 bps/Hz (3.5 GHz)

Rate @ Cell-edge = 0.13 bps/Hz (28 GHz)

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Shannon’s limit:
3.46 bps/Hz (10 dB)

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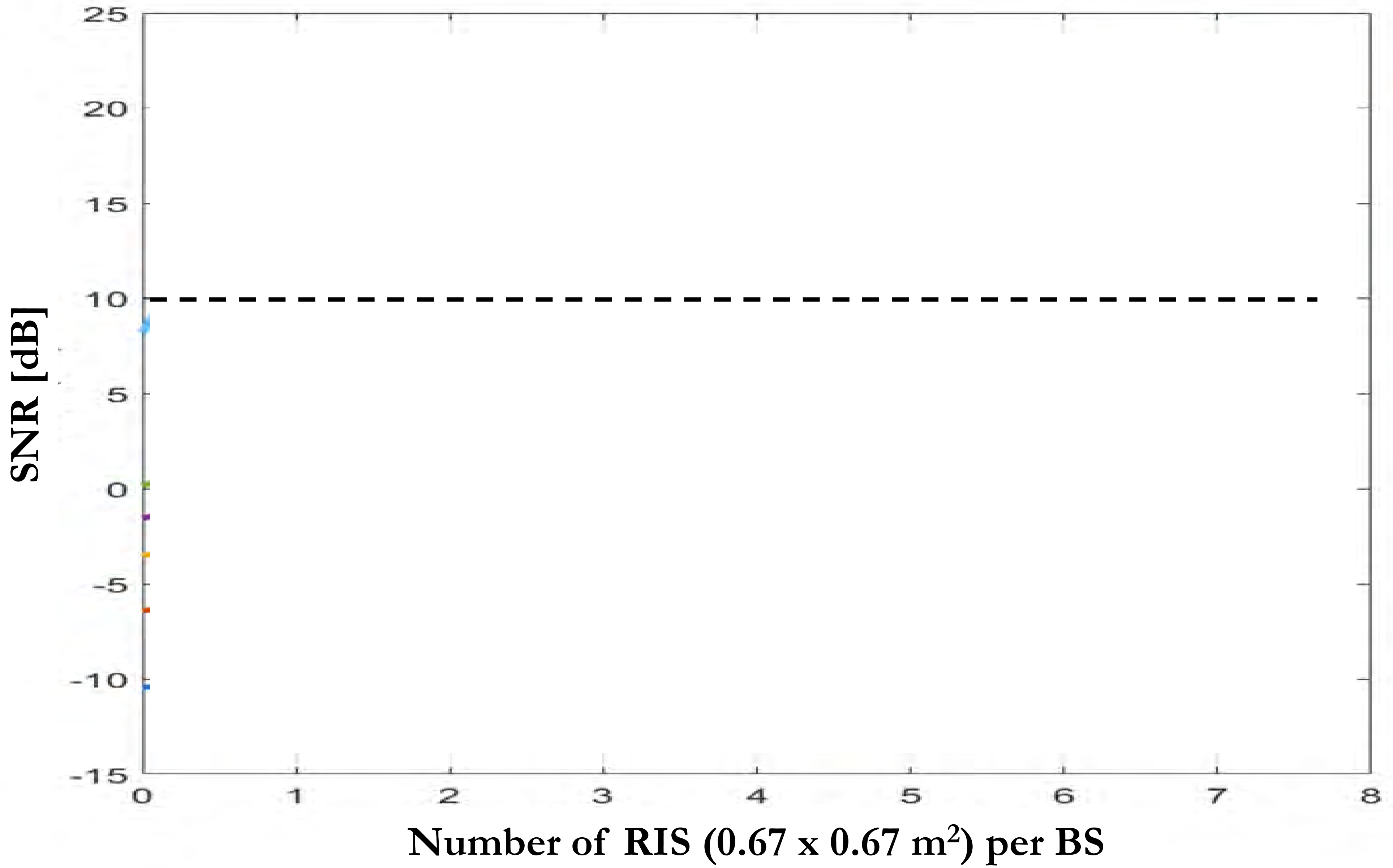
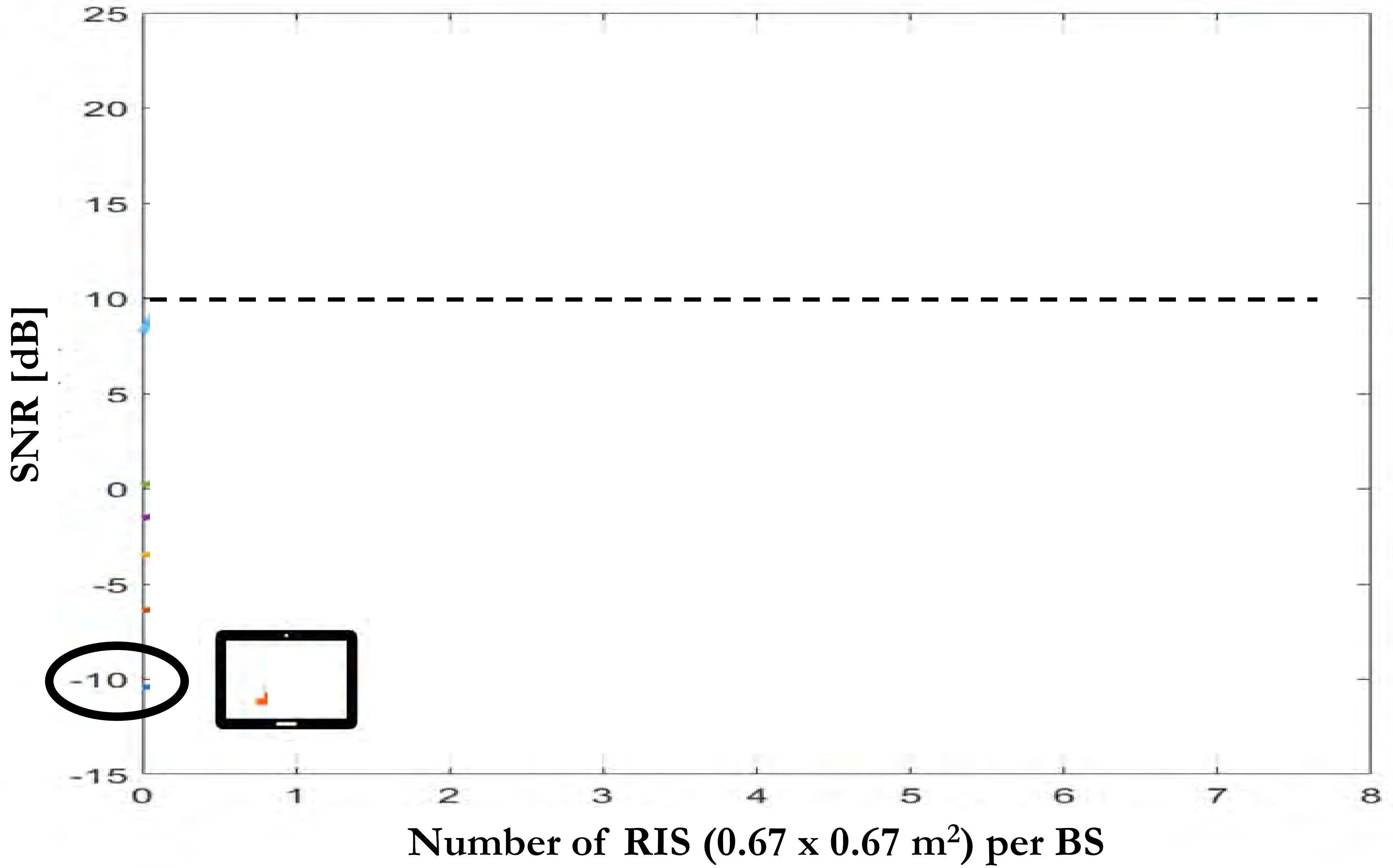


Collaboration with Huawei Sweden



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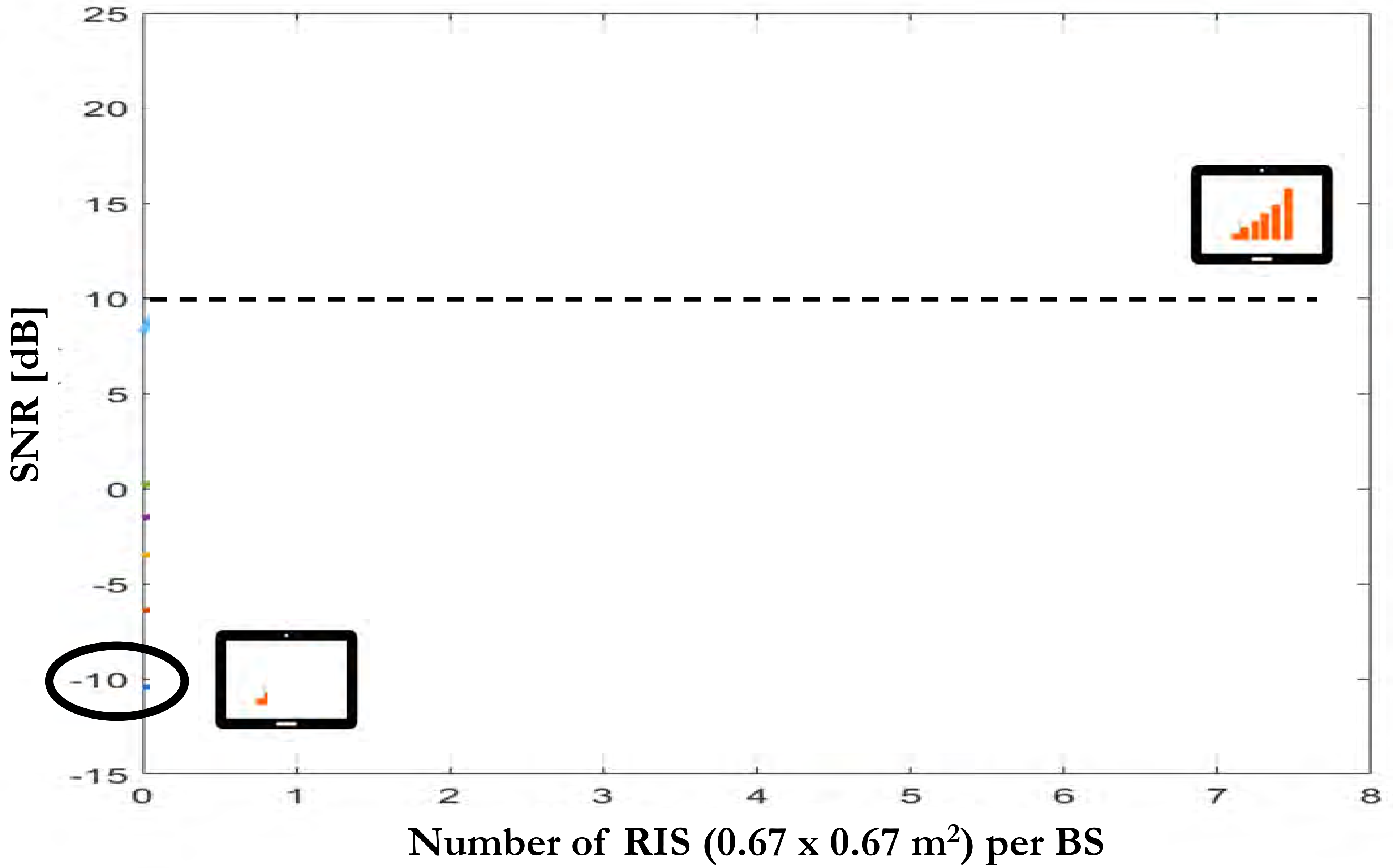
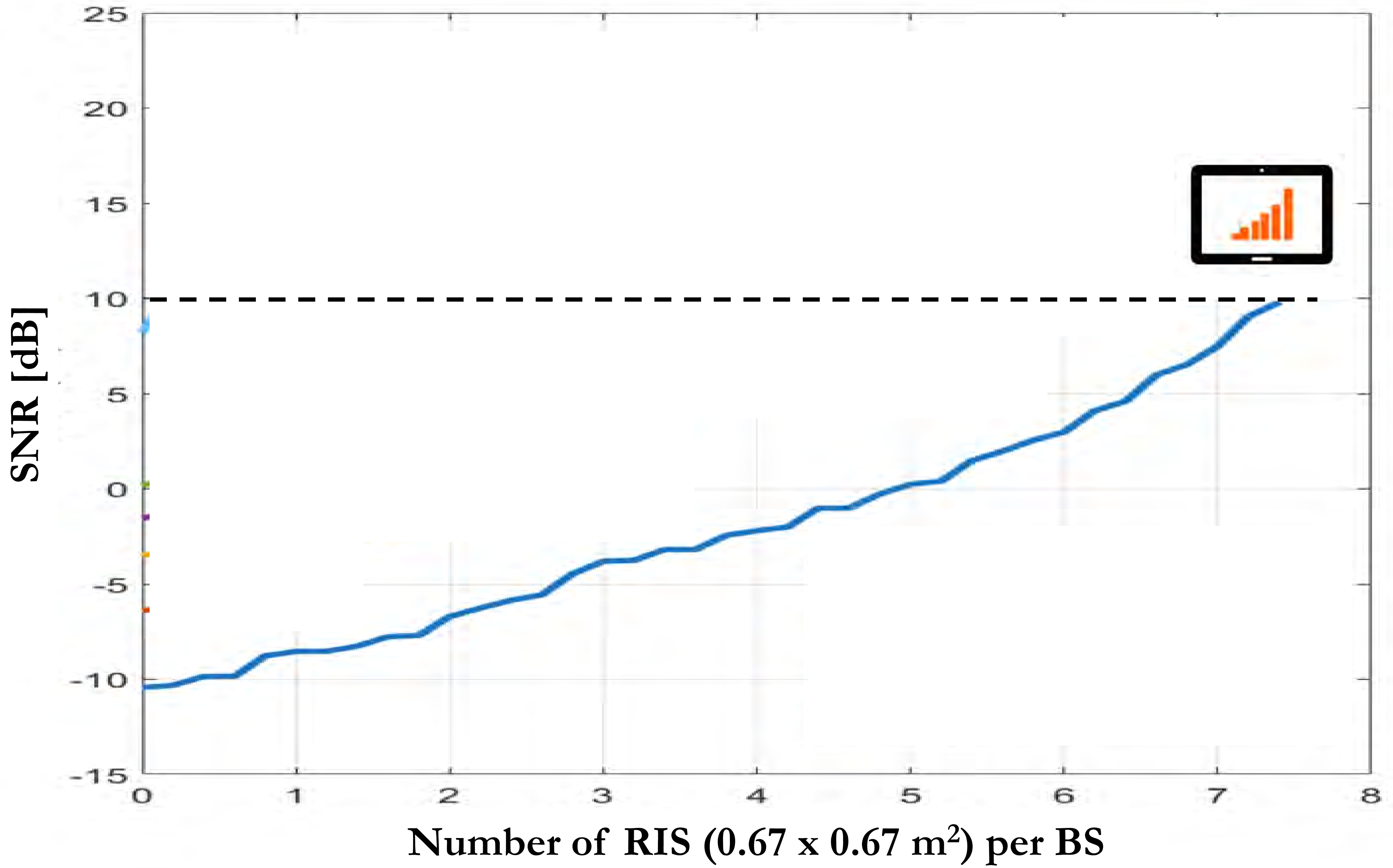
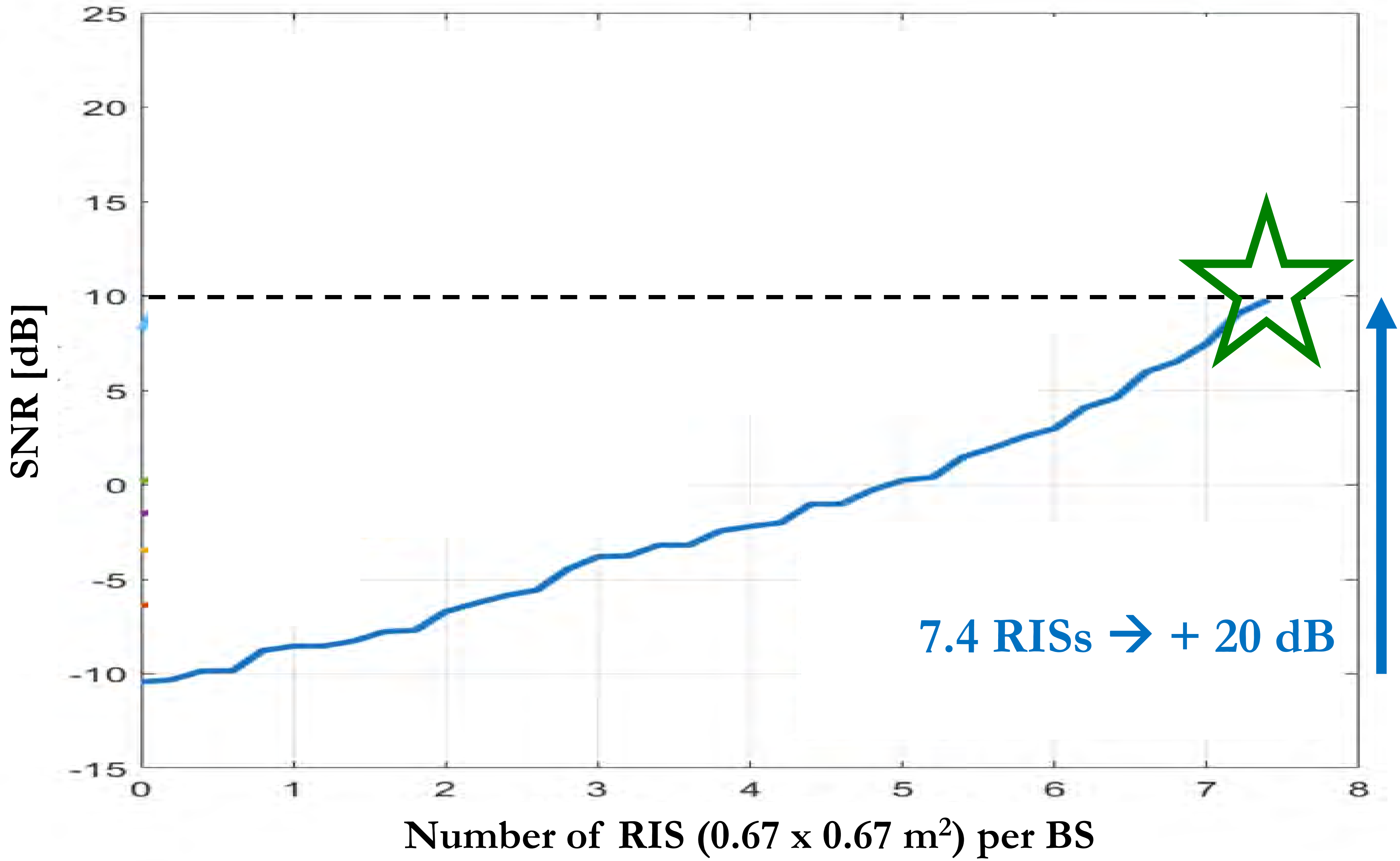


Collaboration with Huawei Sweden



Collaboration with Huawei Sweden



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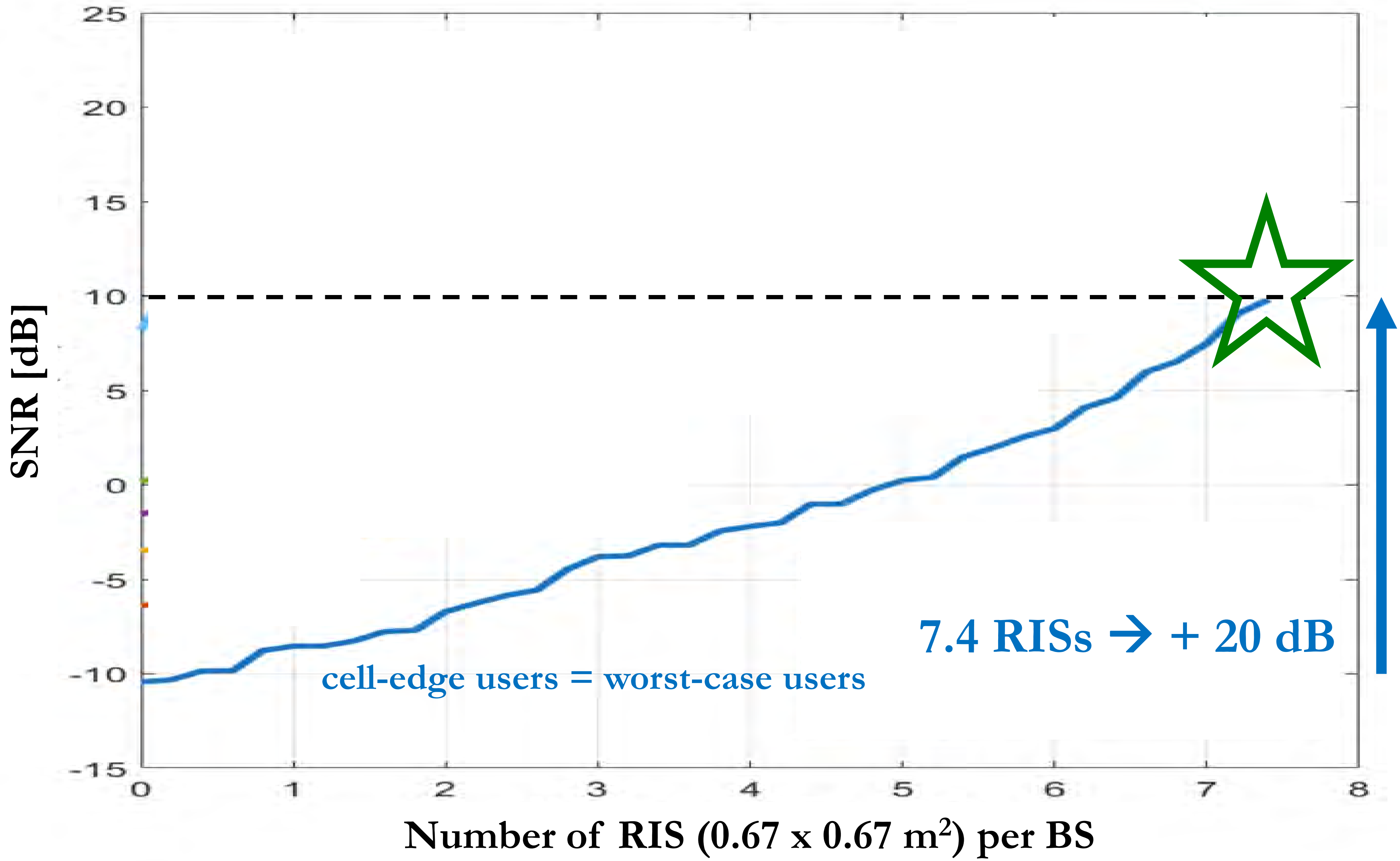
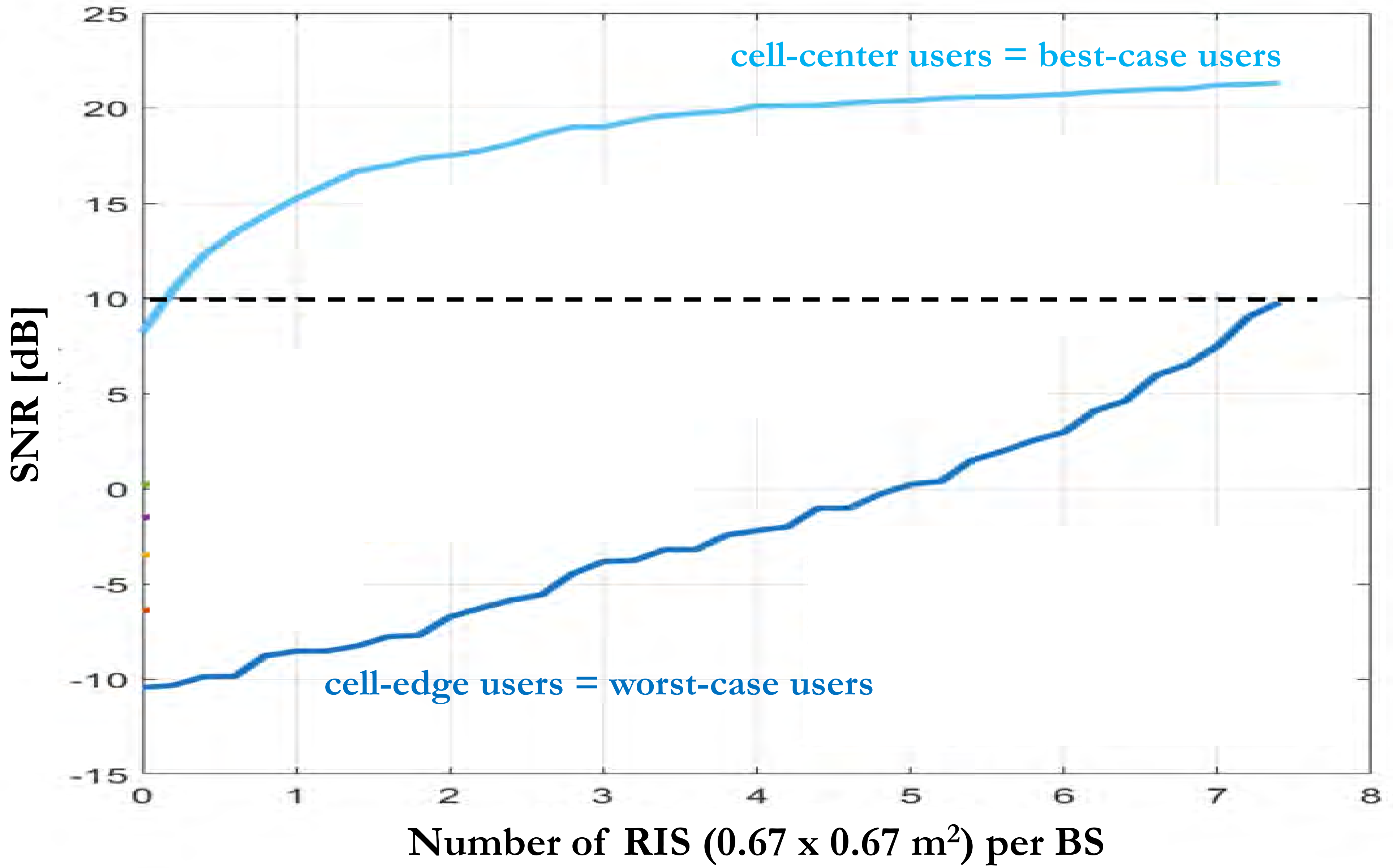
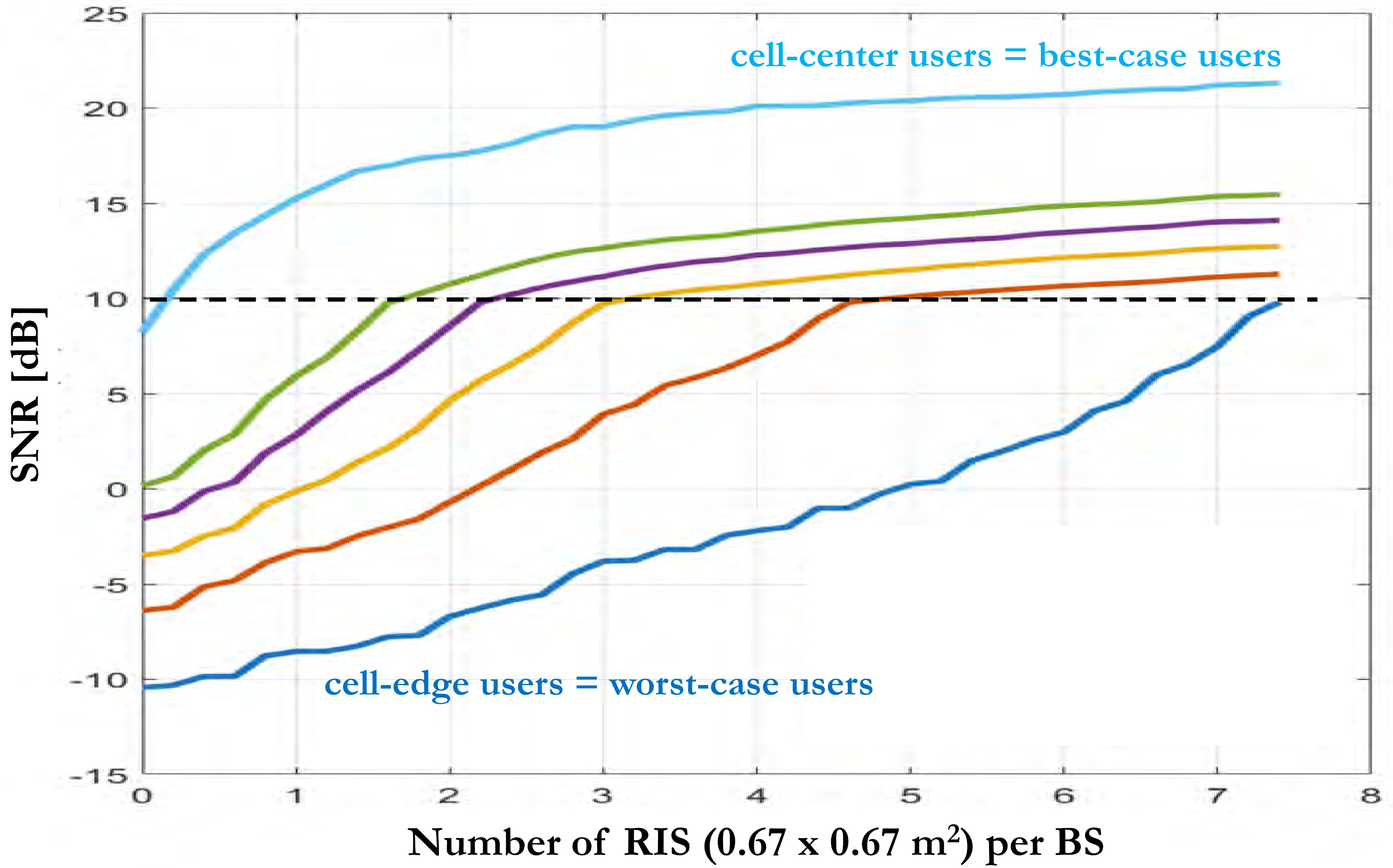


Collaboration with Huawei Sweden



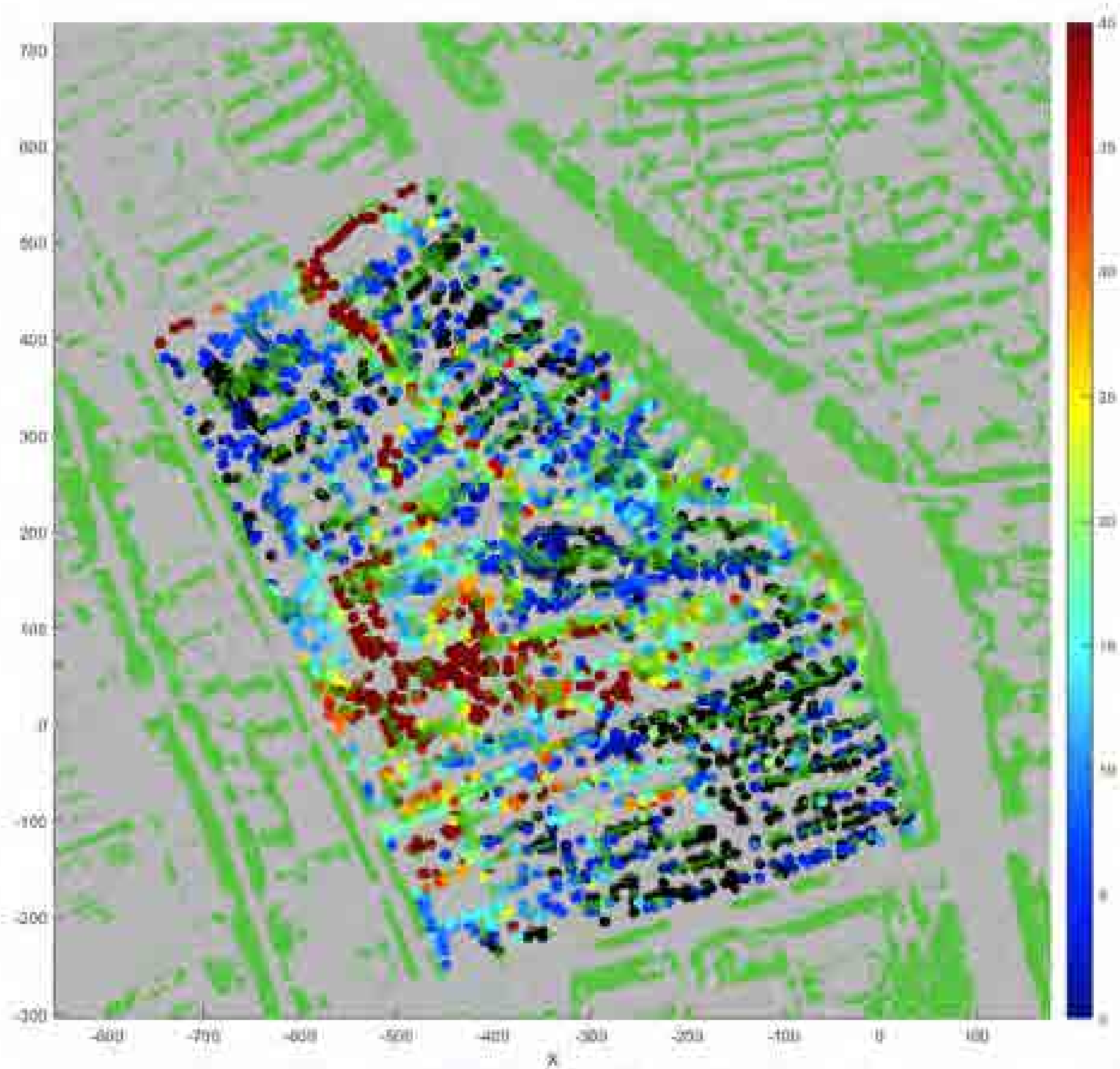
Collaboration with Huawei Sweden

HUAWEI



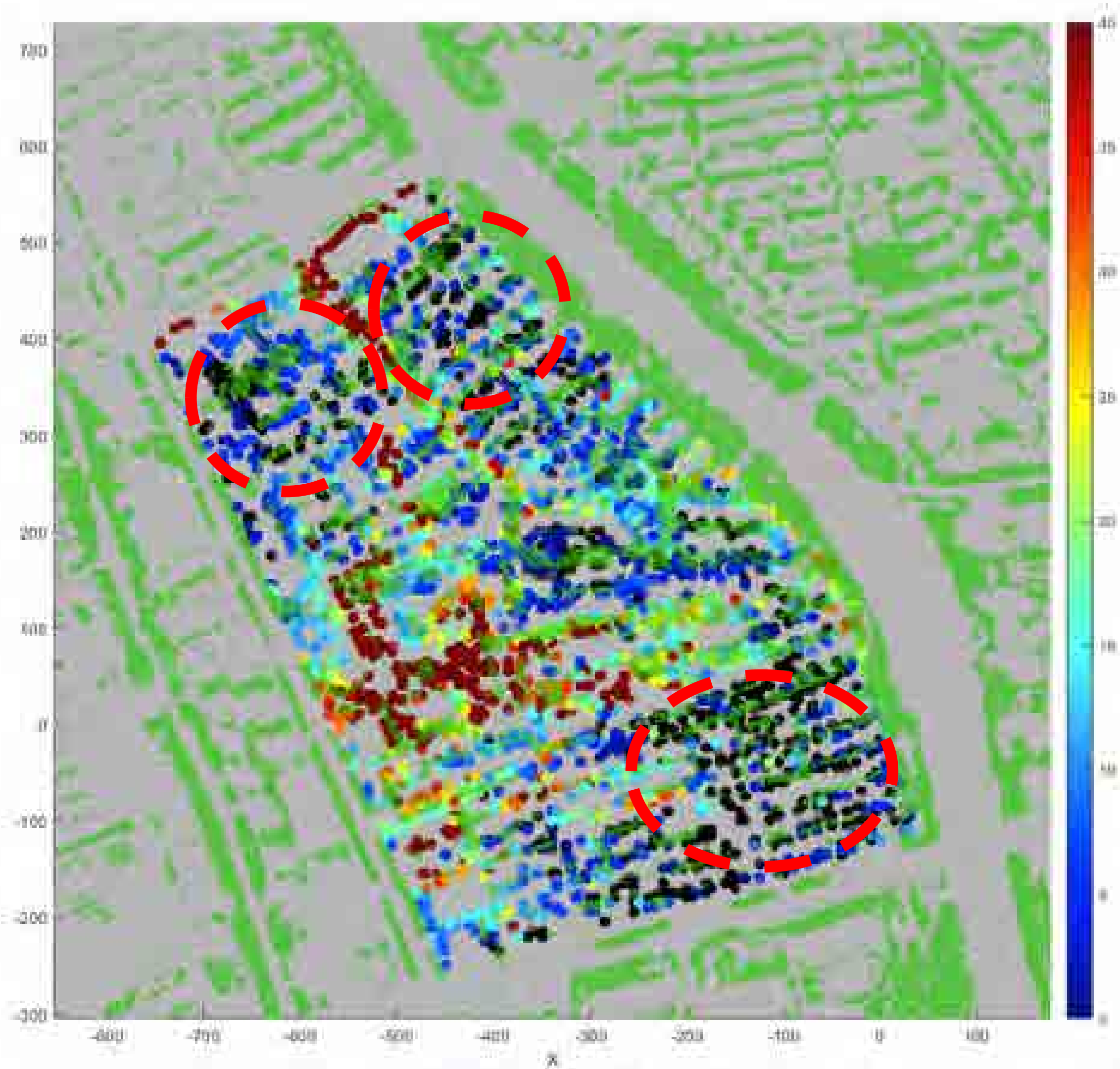
Collaboration with Huawei Sweden

SNR distribution without the RISs



Collaboration with Huawei Sweden

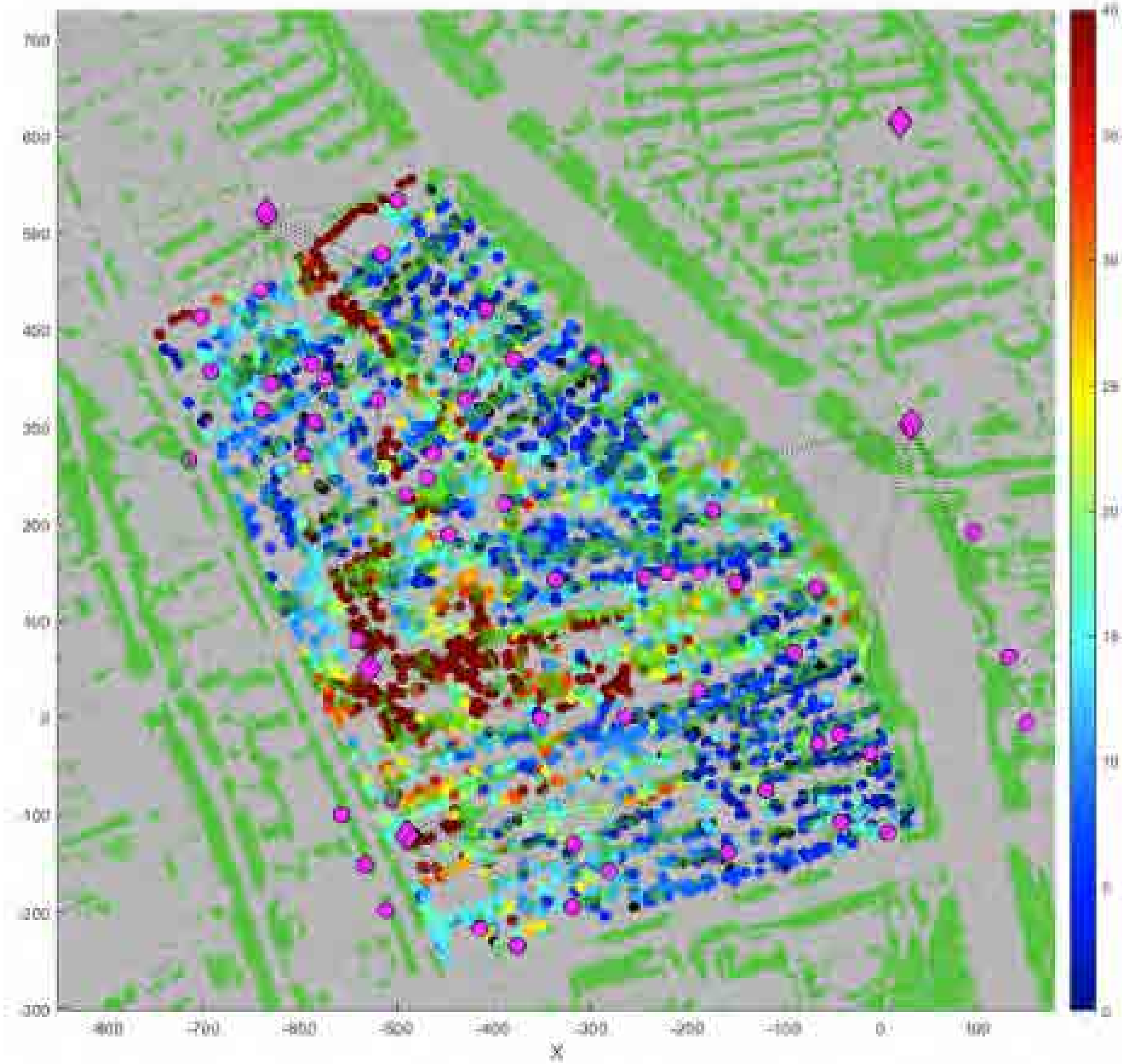
SNR distribution without the RISs



0 dB

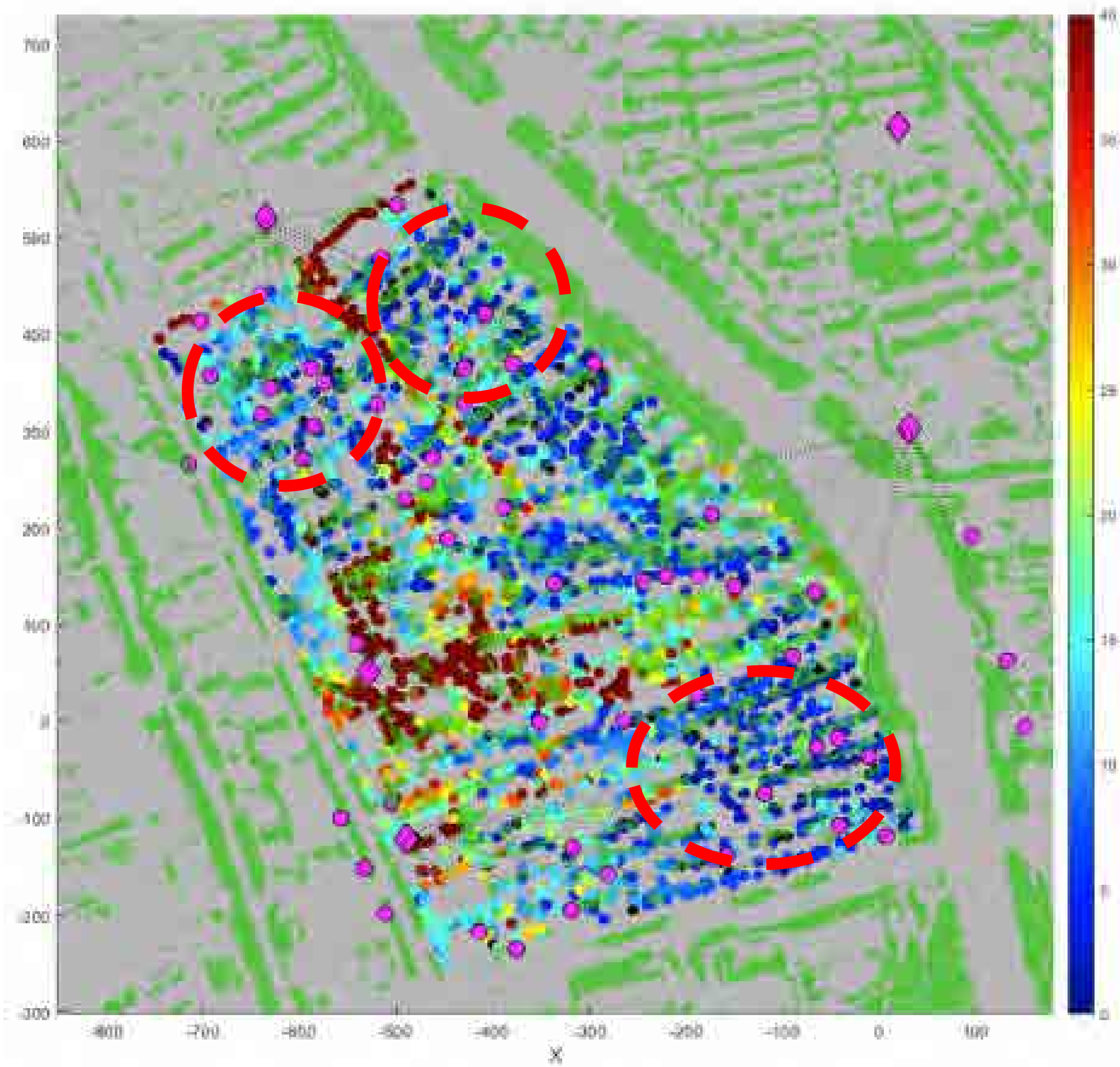
Collaboration with Huawei Sweden

SNR distribution with the RISs



Collaboration with Huawei Sweden

SNR distribution with the RISs

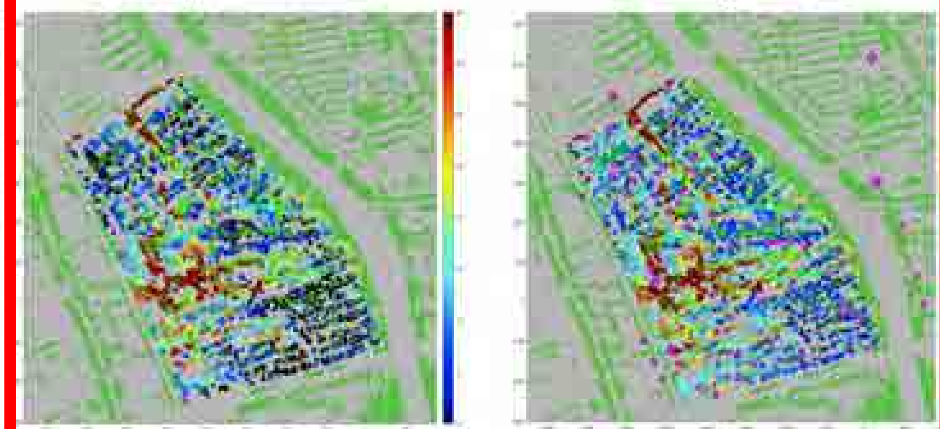


10-15 dB

Collaboration with Huawei Sweden

Grid point calculation

SNR map without RISs | SNR map with RISs



Size 1 at 28 GHz = 0.33x0.33 m^2

Size 3 at 28 GHz = 0.67x0.67 m^2

	Achievable Coverage [Required Number of RISs per BS]			
	No RIS	Few RISs		Total RISs
RIS – Size 1 at 3.5 GHz	77% [0]	80% [1]	88% [5]	95% [21]
RIS – Size 2 at 3.5 GHz	77% [0]	81% [1]	90% [5]	95% [12]
RIS – Size 3 at 3.5 GHz	77% [0]	83% [1]	92% [5]	95% [9]
RIS – Size 1 at 28 GHz	46% [0]	57% [1]	76% [5]	95% [20]
RIS – Size 2 at 28 GHz	46% [0]	63% [1]	86% [5]	95% [11.2]
RIS – Size 3 at 28 GHz	46% [0]	68% [1]	91% [5]	95% [7.4]
	Rate Improvement [Required Number of RISs per BS]			
	Cell-Edge			Cell-Average
	Few RISs		Total RISs	Total RISs
RIS – Size 1 at 3.5 GHz	3% [1]	34% [5]	253% [21]	12% [21]
RIS – Size 2 at 3.5 GHz	5% [1]	59% [5]	253% [12]	14% [12]
RIS – Size 3 at 3.5 GHz	11% [1]	115% [5]	258% [9]	16% [9]
RIS – Size 1 at 28 GHz	0% [1]	38% [5]	2508% [20]	45% [20]
RIS – Size 2 at 28 GHz	8% [1]	238% [5]	2508% [11.2]	53% [11.2]
RIS – Size 3 at 28 GHz	46% [1]	700% [5]	2508% [7.4]	62% [7.4]

Today: 46% of users get a good signal

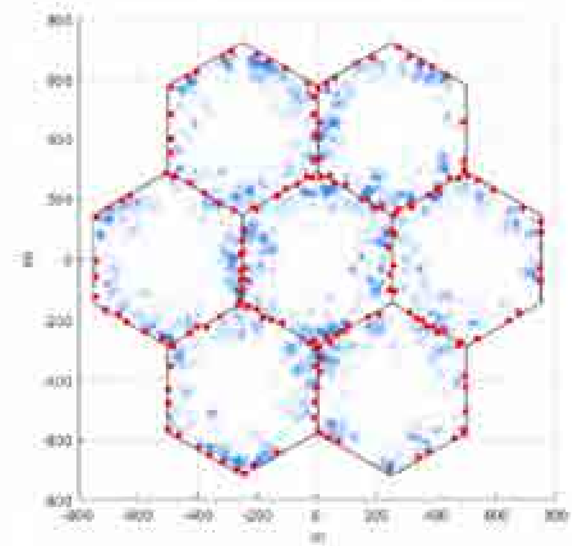
With RIS: 95% of users get a good signal

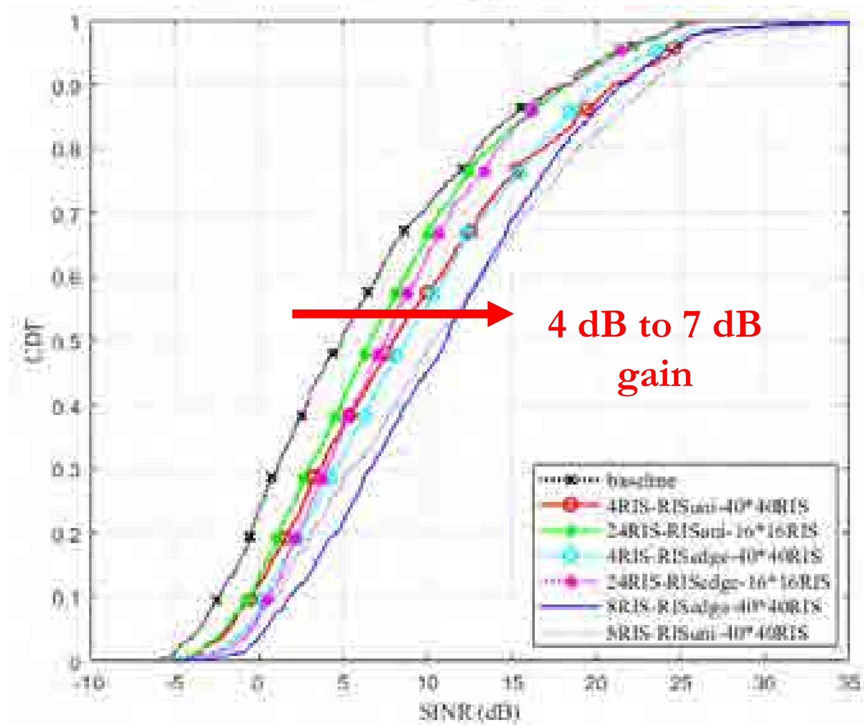
Collaboration with China Mobile

中国移动 China Mobile

Table 1 Simulation set up and parameters.

Parameter	Value
Number of cells	7 (e.g., 21 sectors), hexagonal macro
Operating band	2.6 GHz
Site-to-site dist.	500 m
Number of RIS panels per sector	4, 8, or 24, min distance of 25 m between RIS panels, uniformly distributed or at cell edges (e.g., 0.9~1.0 cell radius)
RIS antenna orientation	Facing towards its serving BS (azimuth)
Number of mobiles per sector	50 (100% outdoor), uniformly distributed or at cell edges (e.g., 0.85~0.9 cell radius
BS antenna height	25 m
BS antenna down-tilt	0^{o} (mechanical) and 4^{o} (electronic)
RIS panel height	15 m
RIS panel down-tilt	10^{o} (mechanical)
Mobile antenna height	1.5 m
BS transmit power	46 dBm
BS antenna gain	17 dBi for sector beam
Polarization	Vertical
MS antenna config	1×2, with random orientation
Pathloss model	ITU-Urban Macro for BS-RIS, RIS-UE and BS-UE links
RIS antenna pattern	BS antenna pattern in 3GPP TR 38.901, separately modeled for cascaded link, total gain of 5 dBi at boresight
Number of elements per RIS panel	16×16, or 40×40, with 0.4λ spacing both vertical and horizontal
Number of bits for RIS element phase	2 bits
Combining of RIS cascaded link and direct link	Non-coherent, e.g., gains added up

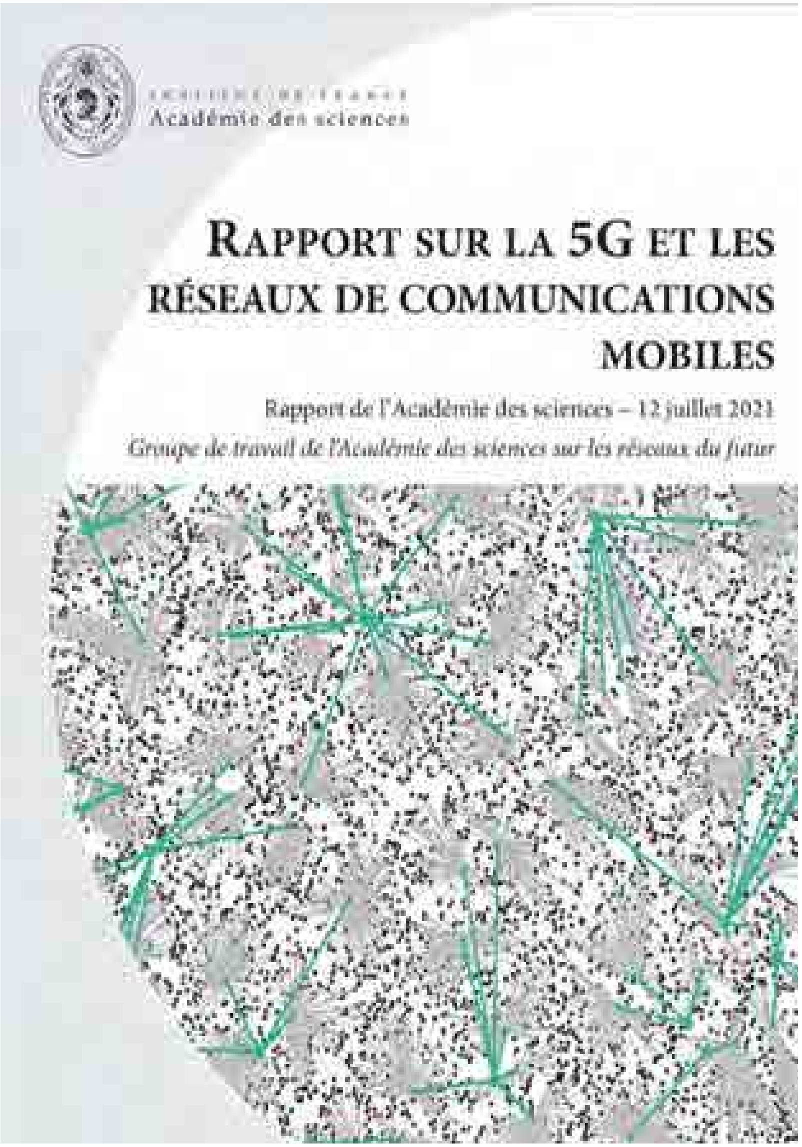




Collaboration with China Mobile

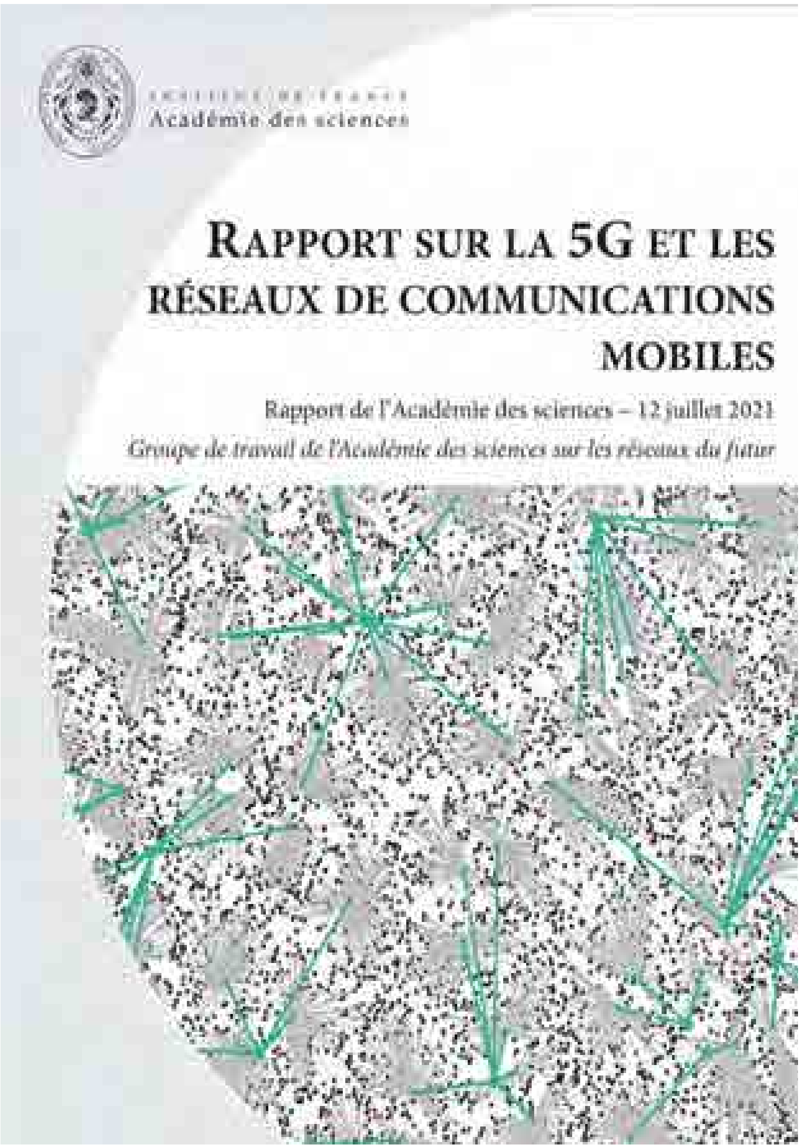
RIS for 6G

RIS @ Académie des Sciences



https://www.academie-sciences.fr/pdf/rapport/2021_07_12_rapport_5G.pdf

RIS @ Académie des Sciences



5.2. Question 2 : bases scientifiques et transformations technologiques

Quelles sont les bases scientifiques et les transformations technologiques qui sous-tendent la cinquième génération de réseaux cellulaires ?

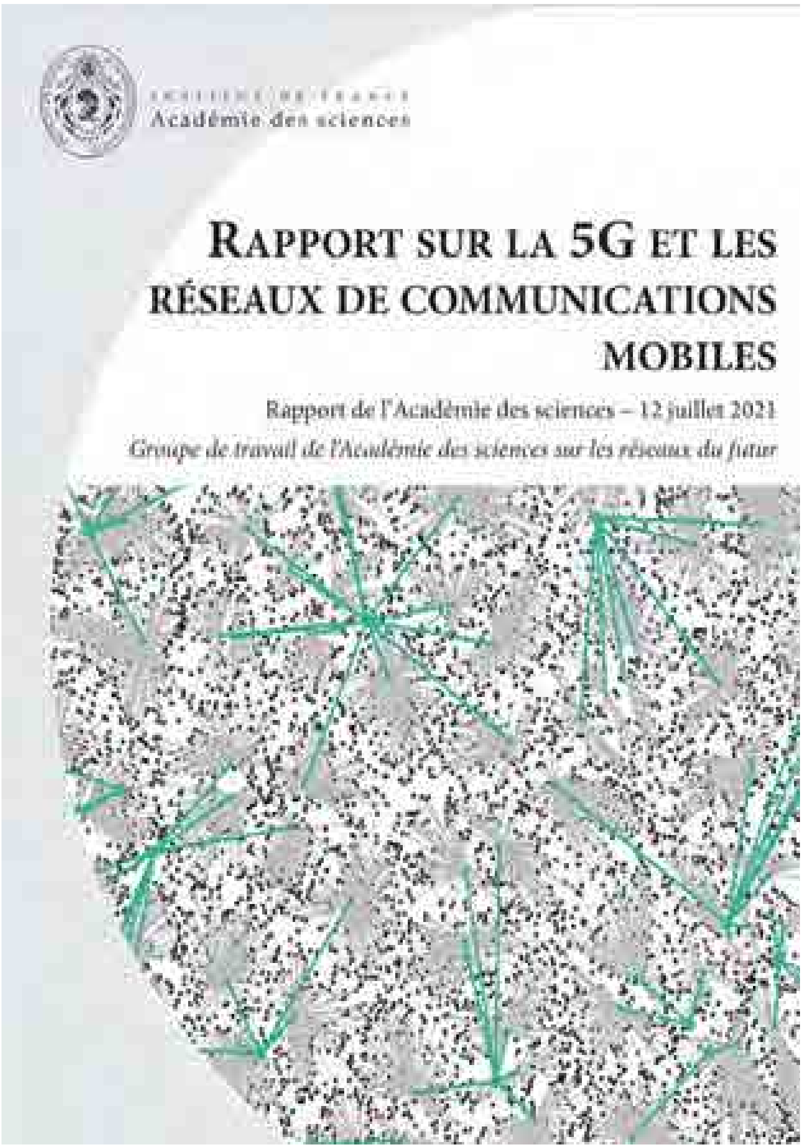
Références : [AS20], [Di19], [En20], [HT19], [Jo19], [Ma10], [NG15], [Te99].

Surface intelligente : Il y a cependant de nombreuses configurations où la disposition des antennes de la station de base, relativement aux mobiles et à l'environnement, n'est pas favorable et ne permet pas d'obtenir un bon effet de focalisation. Il existe une autre approche qui consiste plutôt à modifier l'environnement, soit au voisinage de la station de base, soit près de la zone où sont situés les mobiles. Pour cela, on peut fabriquer des surfaces intelligentes (RIS pour *Reconfigurable Intelligent Surface* ou LIS pour *Large Intelligent Surface*) qui fonctionnent comme des miroirs pour les ondes électromagnétiques et qui sont formées de nombreuses petites cellules élémentaires rapidement reconfigurables. C'est l'équivalent pour le domaine électromagnétique de ce qui est fait en

[Di19] Di Renzo M. et al. *Smart Radio Environments Empowered by Reconfigurable AI Meta-surfaces: An Idea Whose Time Has Come.* EURASIP J. Wireless Communication. Networks, vol. 129, pp. 1-20 (2019).

https://www.academie-sciences.fr/pdf/rapport/2021_07_12_rapport_5G.pdf

RIS @ Académie des Sciences



5.4. Question 4 : vers la 6G ?

Peut-on anticiper ce que sera la 6G ?

Y a-t-il de la recherche en France et en Europe sur ces questions ?

Références : [Di19], [He21], [SW20].

5.4.1. Les apports prévus de la 6G

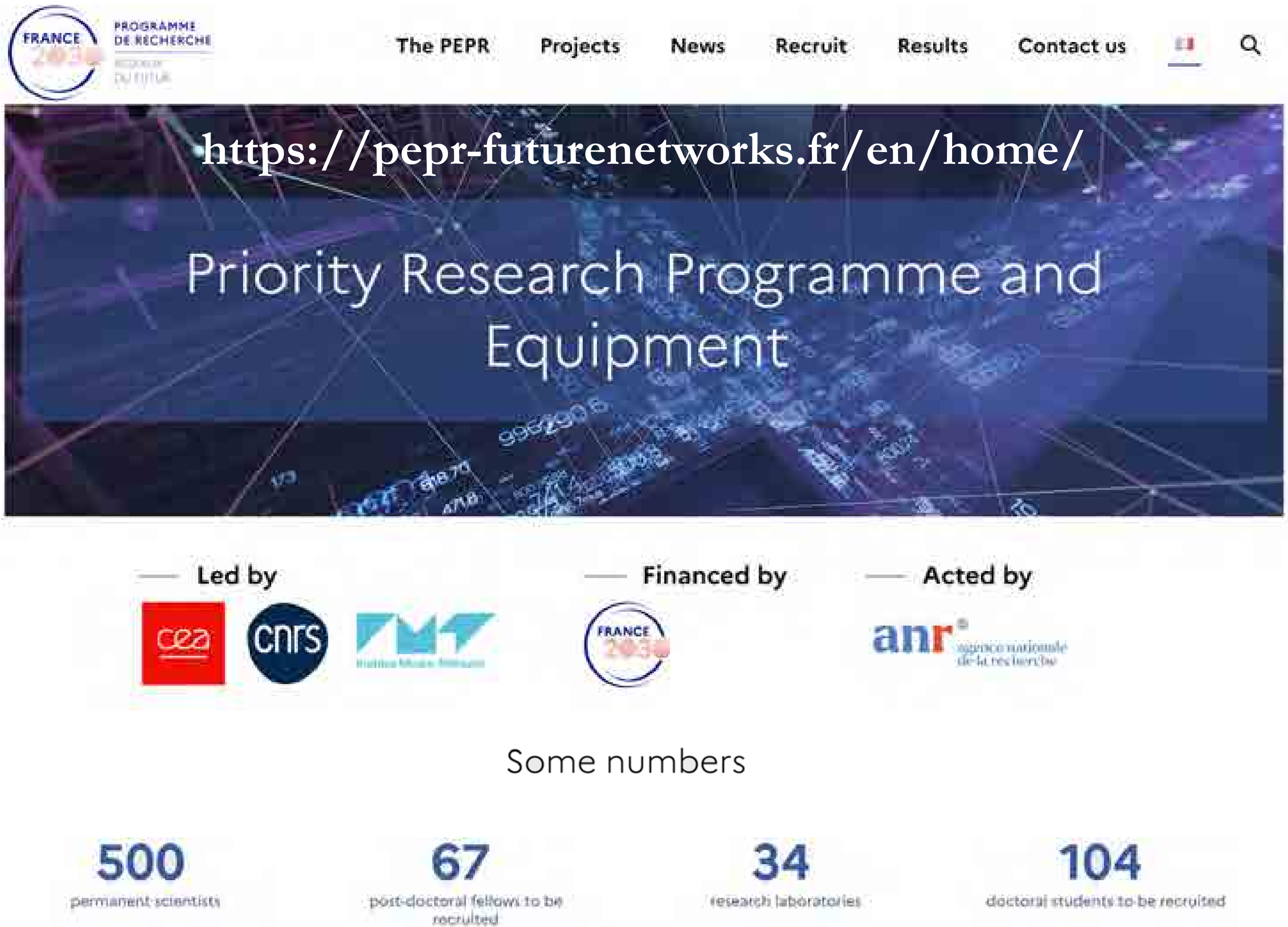
Il est essentiel de comprendre qu'il y a et qu'il y aura dans ces domaines un flot continu d'innovations scientifiques et technologiques structuré en générations successives. La 6G ne commencera à être normalisée que dans une dizaine d'années ; ce nom reste donc encore informel. Mais les recherches sur une nouvelle génération sont déjà bien engagées. Parmi les innovations étudiées, citons les suivantes :

L'utilisation de surfaces intelligentes pour améliorer l'accès radio et diminuer la consommation énergétique. Ces surfaces se comportent comme des miroirs intelligents qui redirigent toute l'énergie électromagnétique quelles captent sur les mobiles des utilisateurs. Ces surfaces sont divisées en quelques centaines de pixels agissant comme un ensemble de micromiroirs qui sont contrôlés en temps réel pour orienter de façon optimale le faisceau réfléchi vers l'utilisateur. Ces surfaces passives intelligentes pourront devenir très bon marché en ne consommant pratiquement aucune énergie. Ceci est à comparer à la consommation des nombreux composants électroniques qui gèrent la focalisation à partir des réseaux multiples d'antennes de la 5G. Ces surfaces pourront ainsi permettre de diminuer de façon très significative l'énergie envoyée par les stations de base classiques.

[Di19] Di Renzo M. et al. *Smart Radio Environments Empowered by Reconfigurable AI Meta-surfaces: An Idea Whose Time Has Come.* EURASIP J. Wireless Communication. Networks, vol. 129, pp. 1-20 (2019).

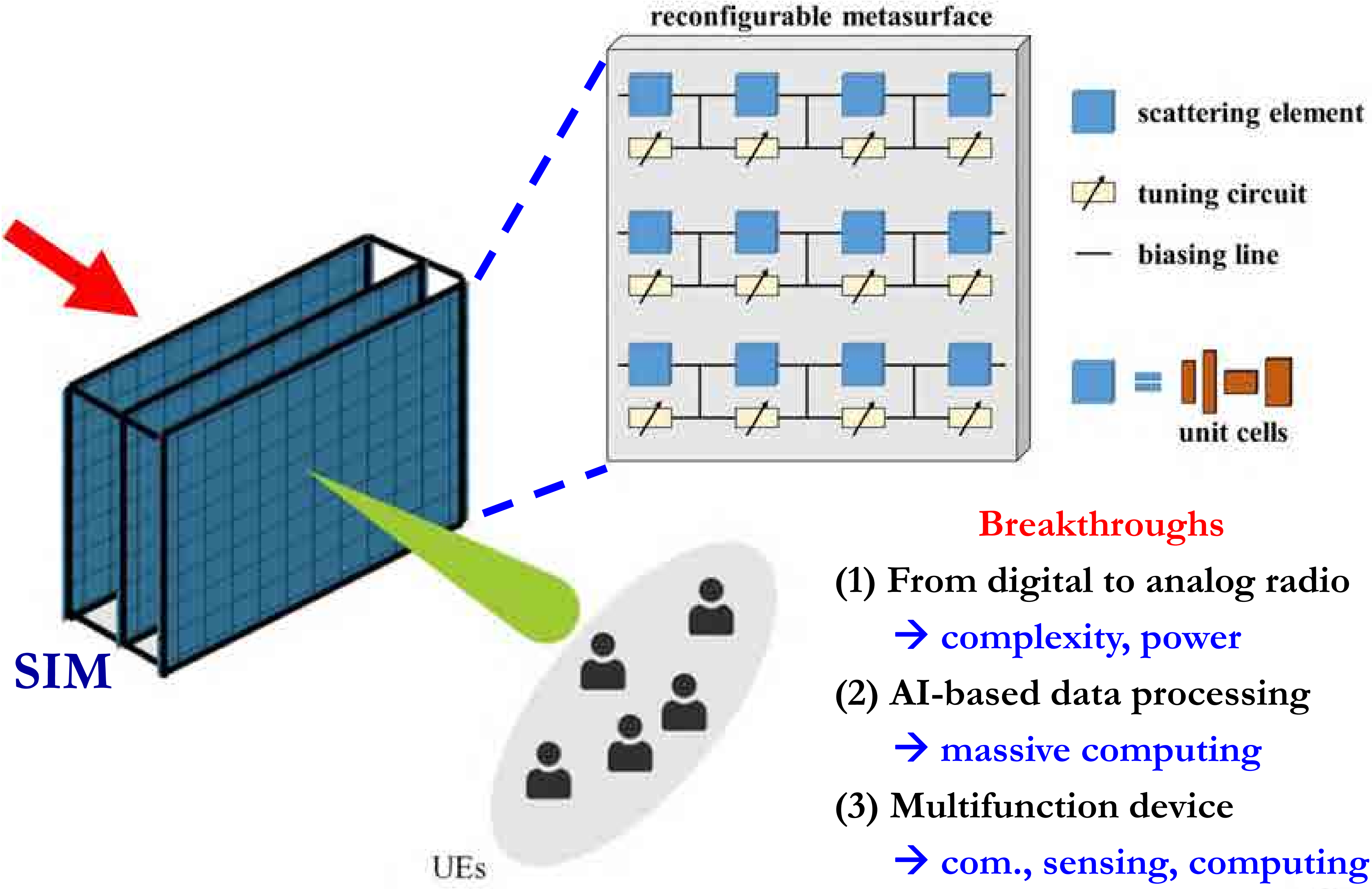
https://www.academie-sciences.fr/pdf/rapport/2021_07_12_rapport_5G.pdf

RIS in 2023: The ANR PEPR Networks of the Future



What's Next?

Stacked Intelligent Metasurface



Breakthroughs

(1) From digital to analog radio

→ complexity, power

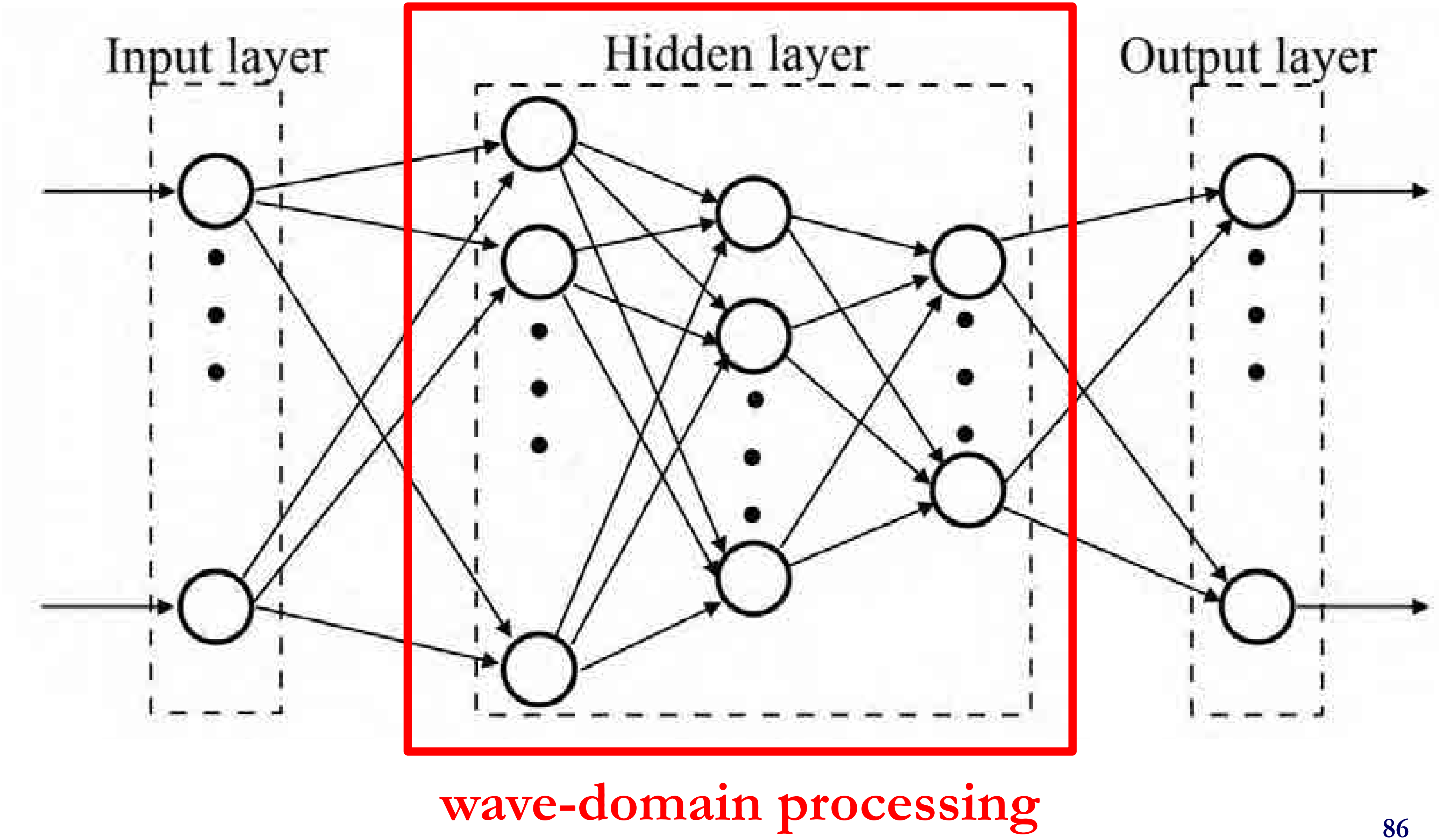
(2) AI-based data processing

→ massive computing

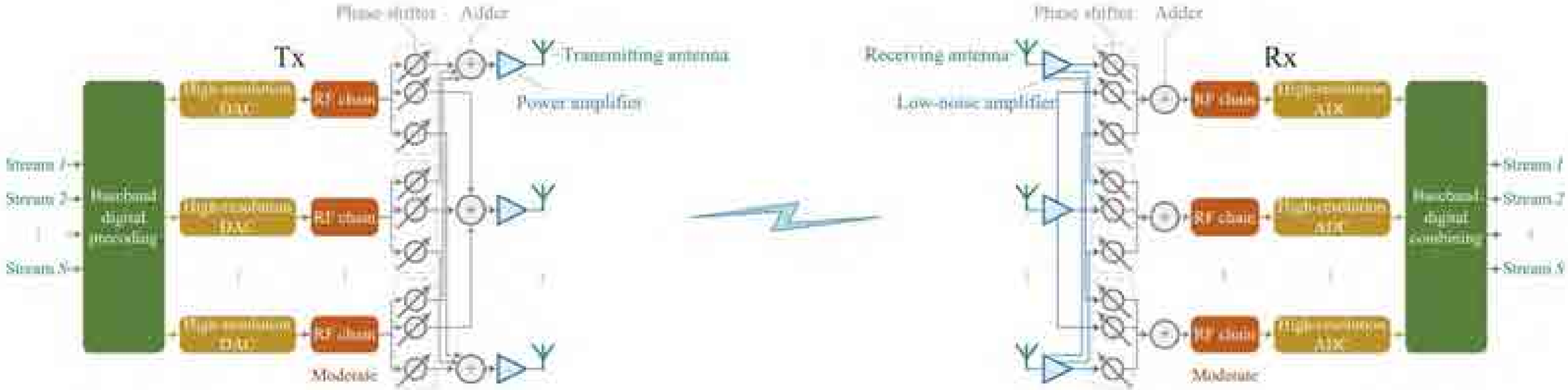
(3) Multifunction device

→ com., sensing, computing

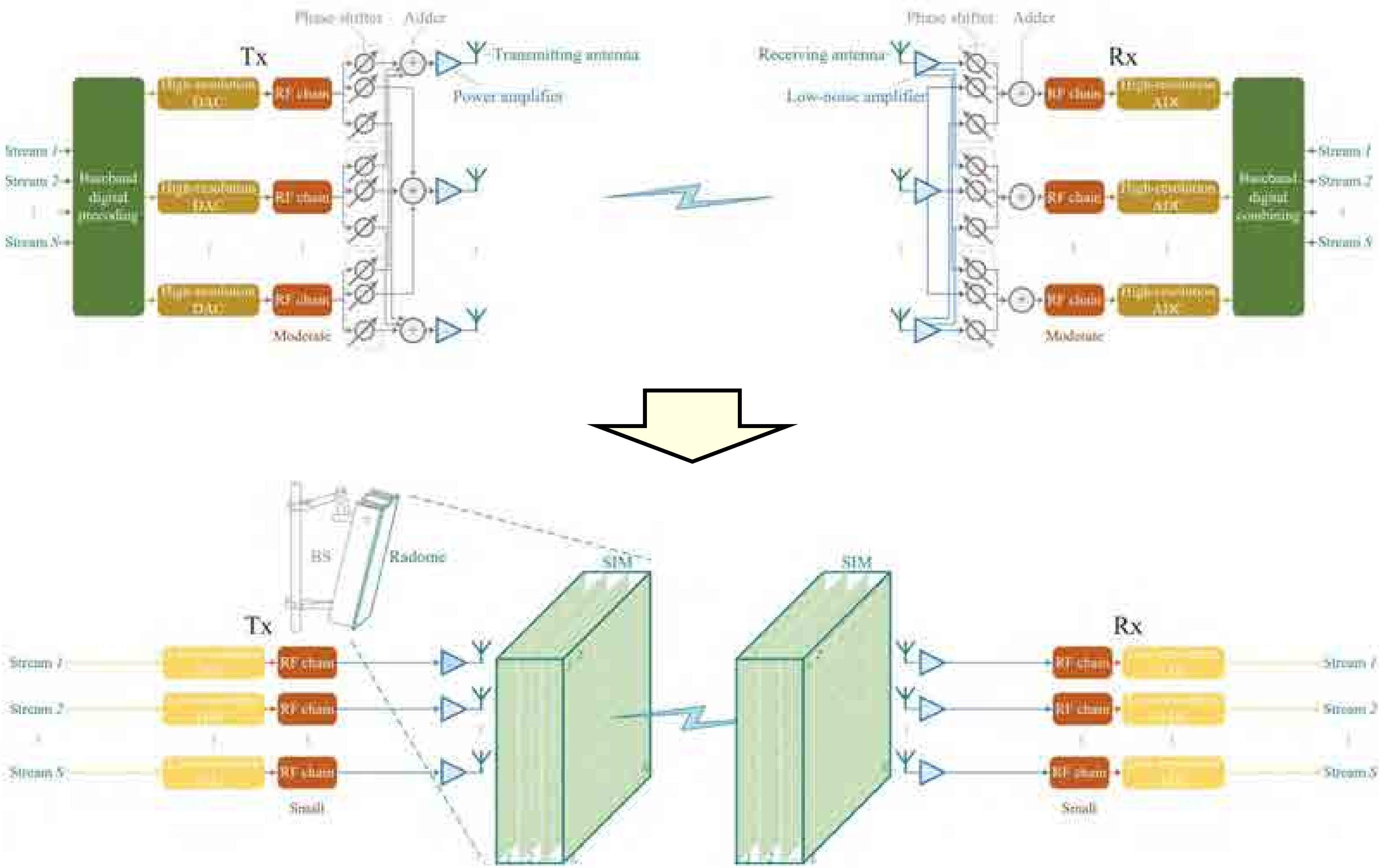
From Digital-Domain to Wave-Domain Processing



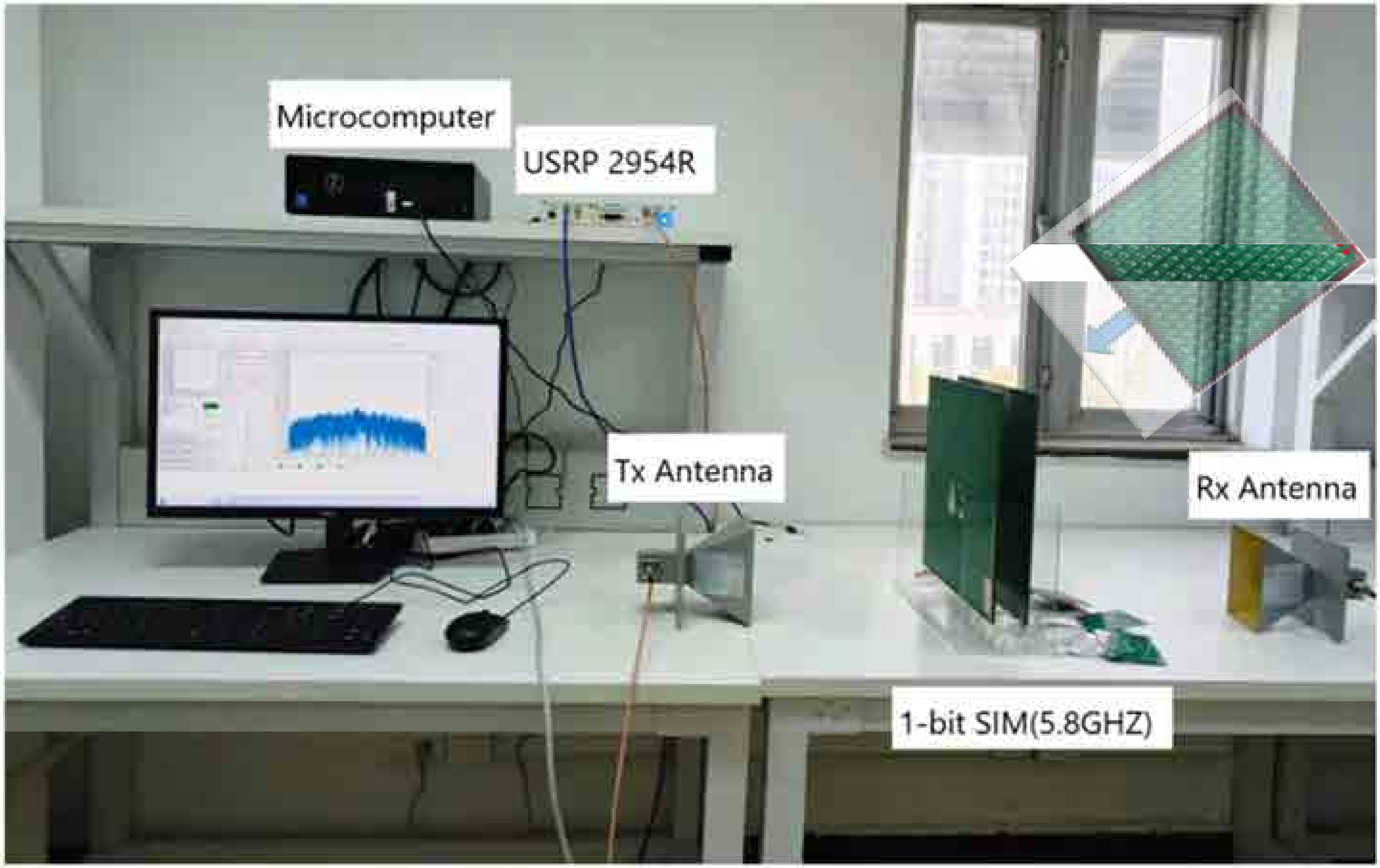
Example: Efficient Transmitters



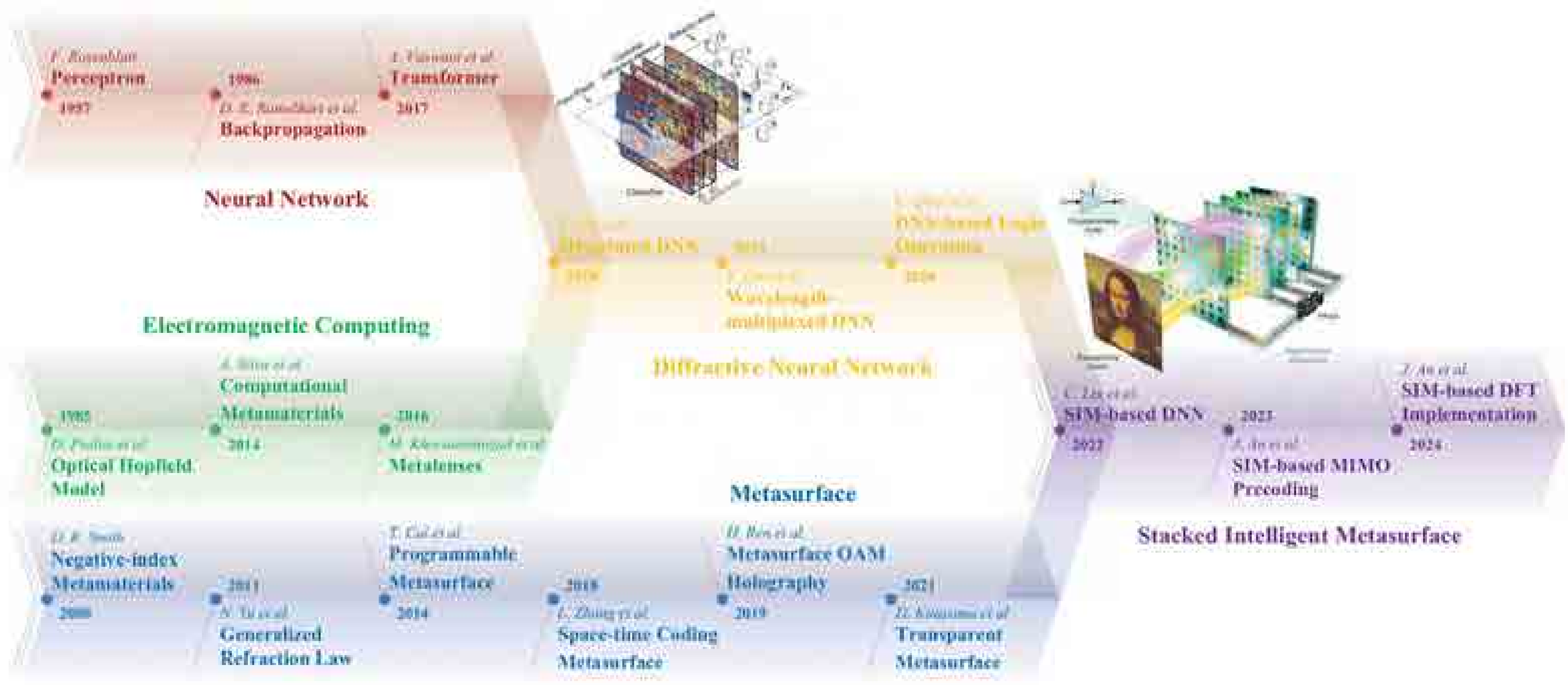
Example: Efficient Transmitters



Example: Prototype



Example: Prototype



Towards 6G

The New Challenges of a Wireless Future

Marco Di Renzo

France-Nokia Chair of Excellence in ICT

CNRS Research Director – Head of the iPhyCom group
Laboratory of Signals and Systems (L2S)
CNRS – CentraleSupélec – Paris-Saclay University
Paris, France
marco.di-renzo@universite-paris-saclay.fr

French Institute of Finland
Helsinki, Finland
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