Shaping the Wireless World: Intelligent Reflecting Surfaces and the Road to 6G

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About me

- **Piergiuseppe Di Marco**
- M.Sc. in Telecommunications Engineering
- Ph.D. @KTH Royal Institute of Technology (Stockholm)
- 5 years at Ericsson Research (Stockholm)
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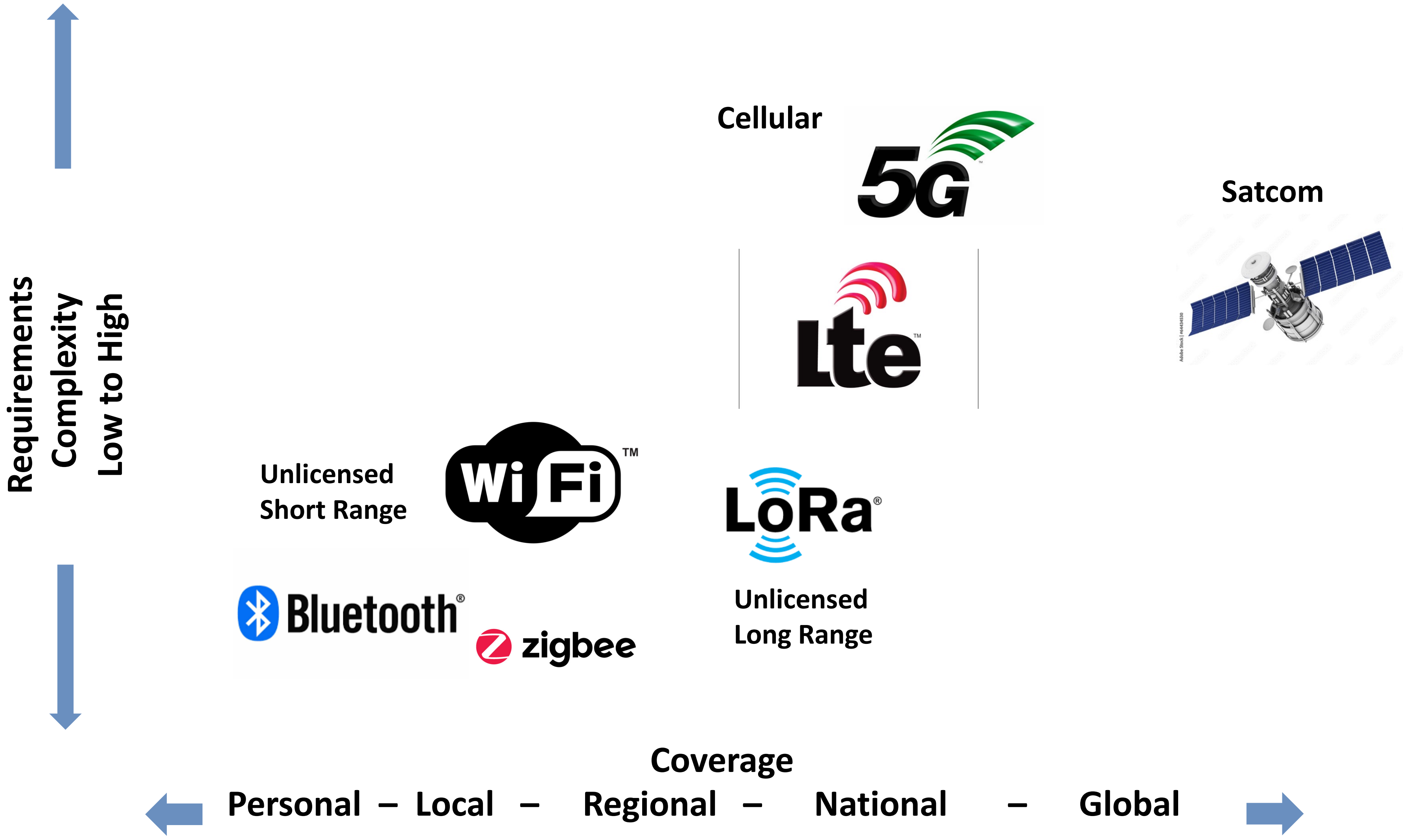
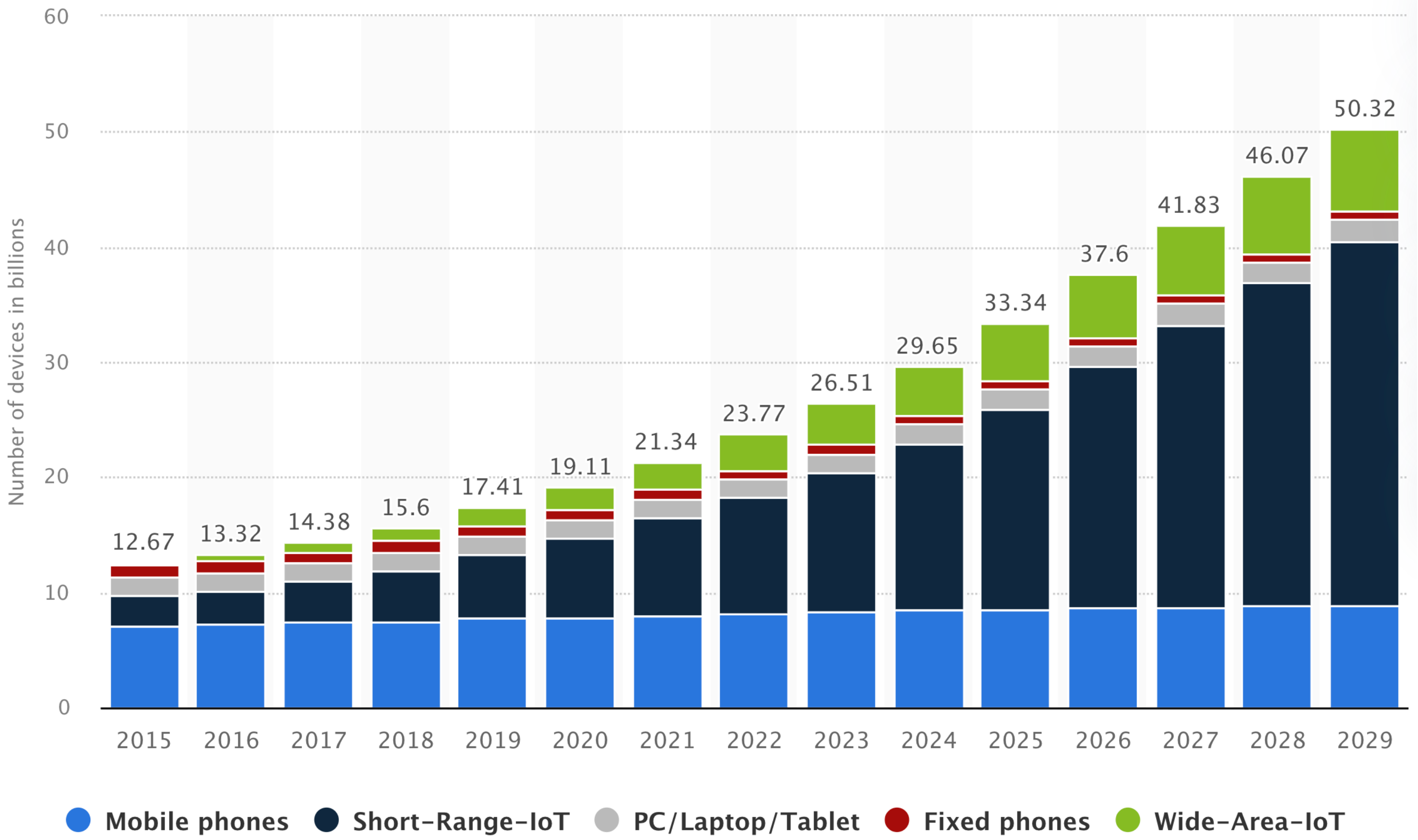
The "Wireless World"

- Wireless communication is the invisible backbone of our connected society
- From smartphones to satellites, it powers how we live, work, and move through the world

Wireless connectivity options

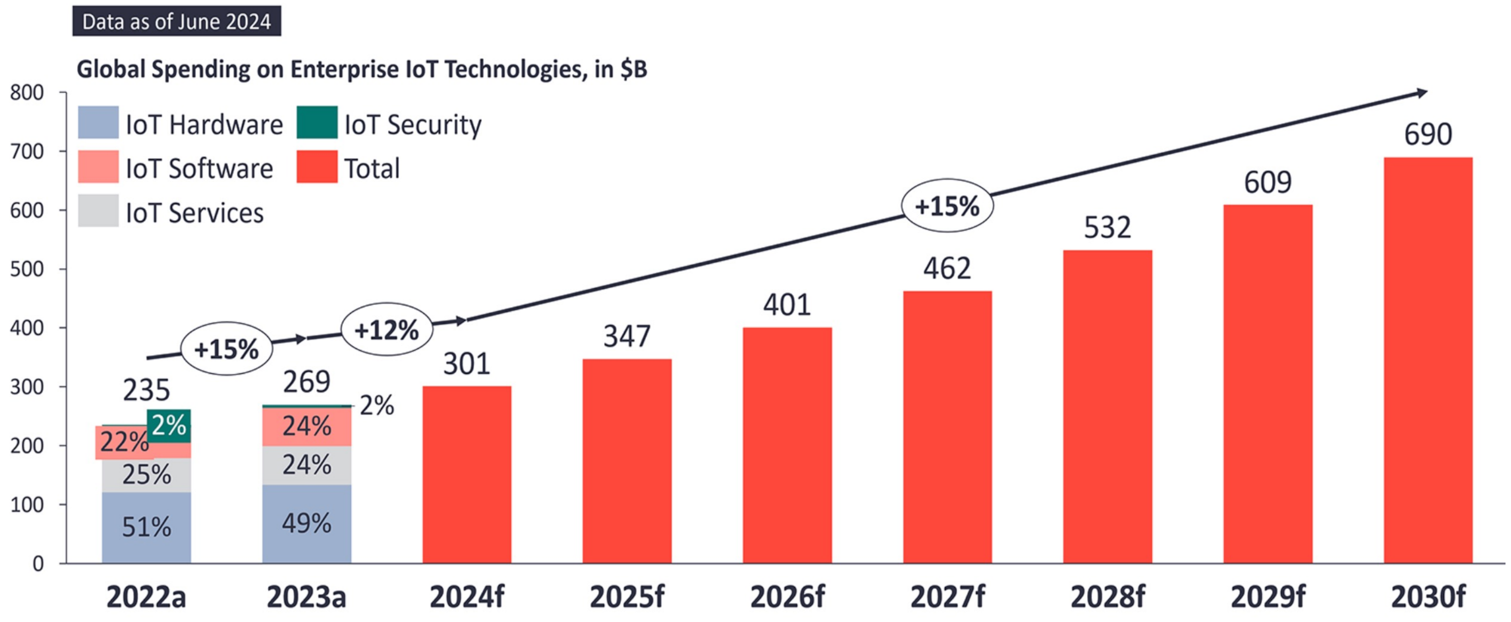


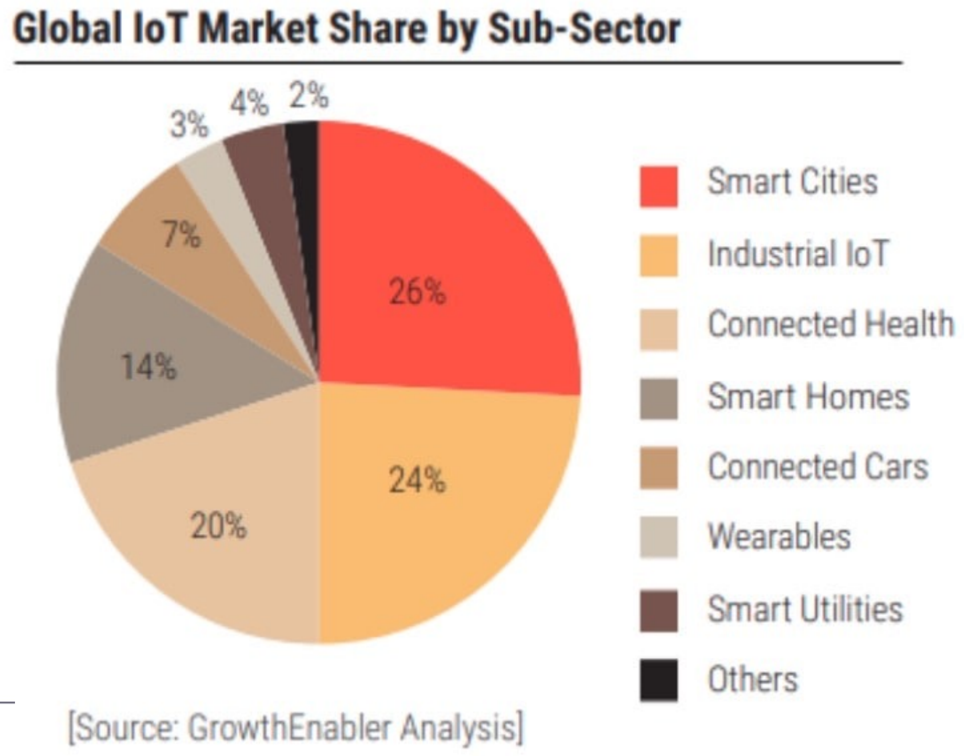
Number of connected devices



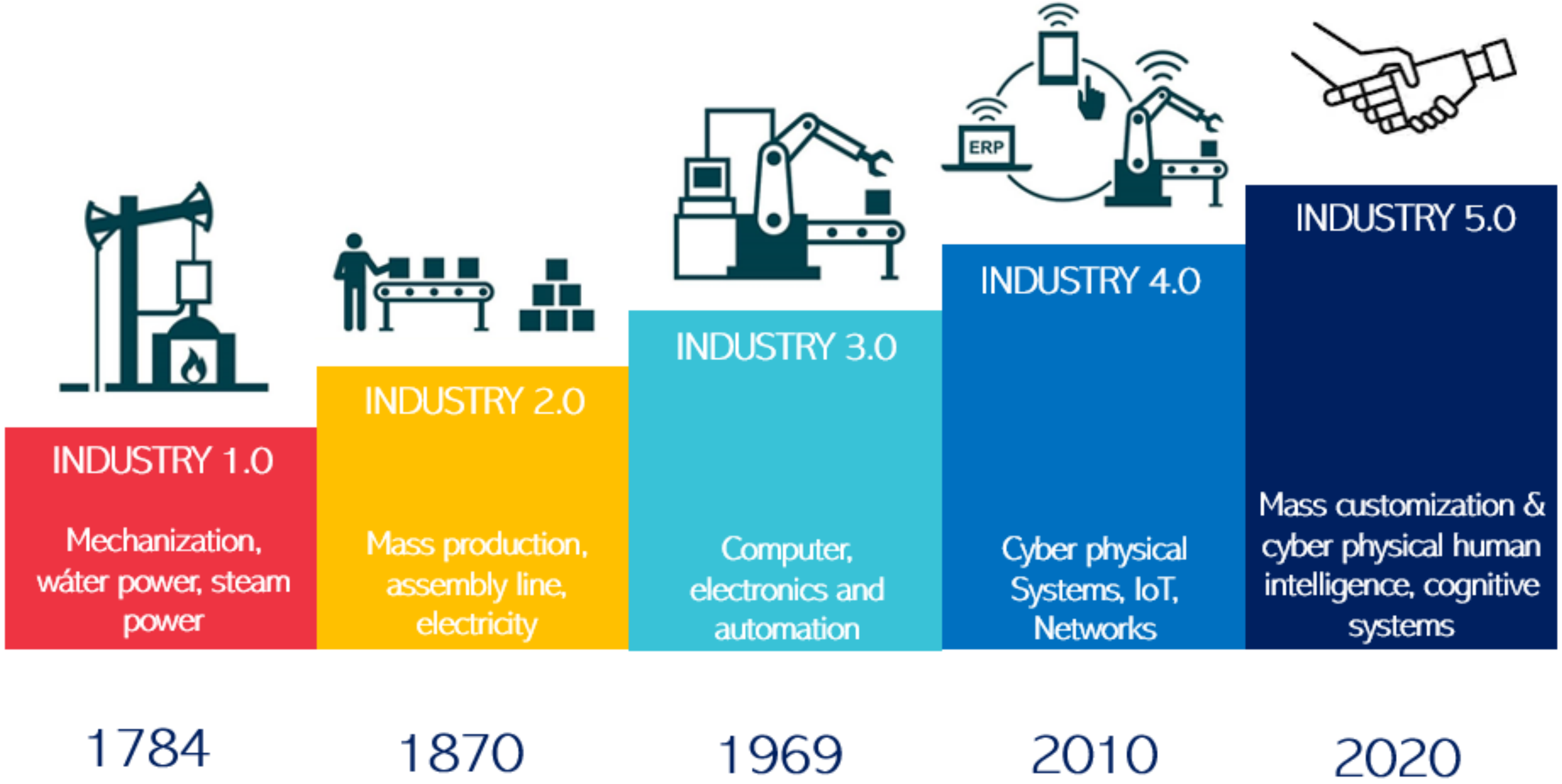
[Source: statista.com (2025)]

Market sectors



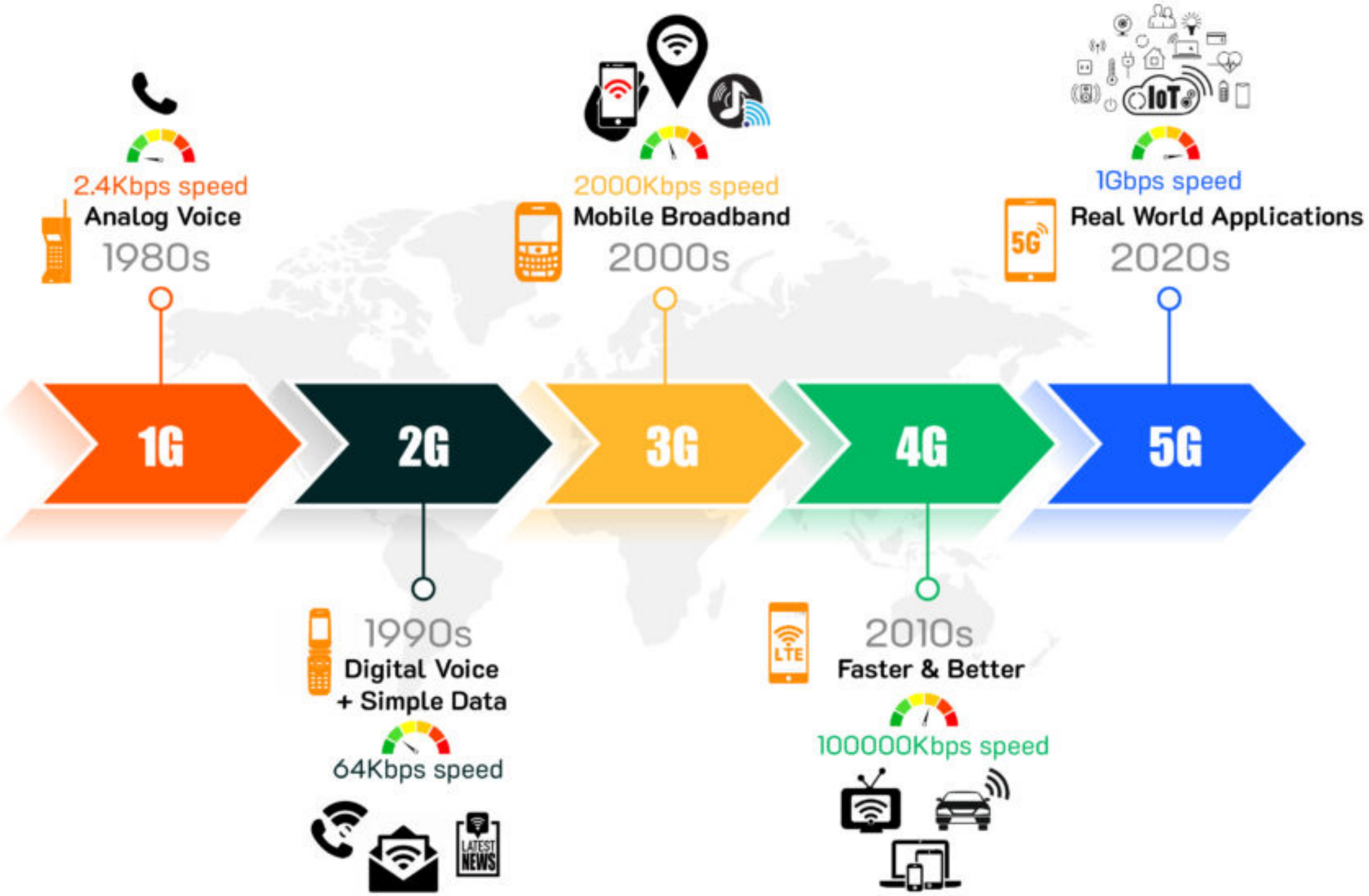


The industrial revolution

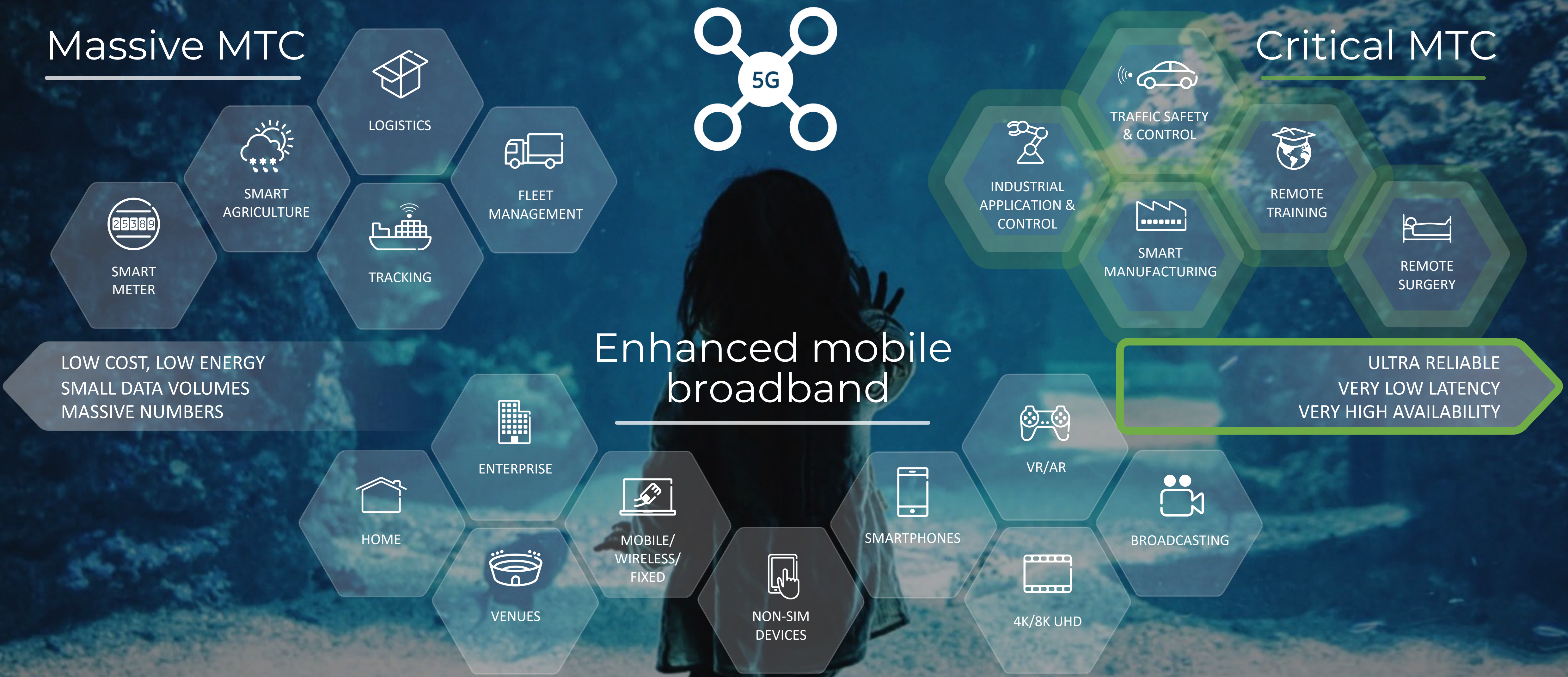


*Years are estimates

The evolution of mobile communications

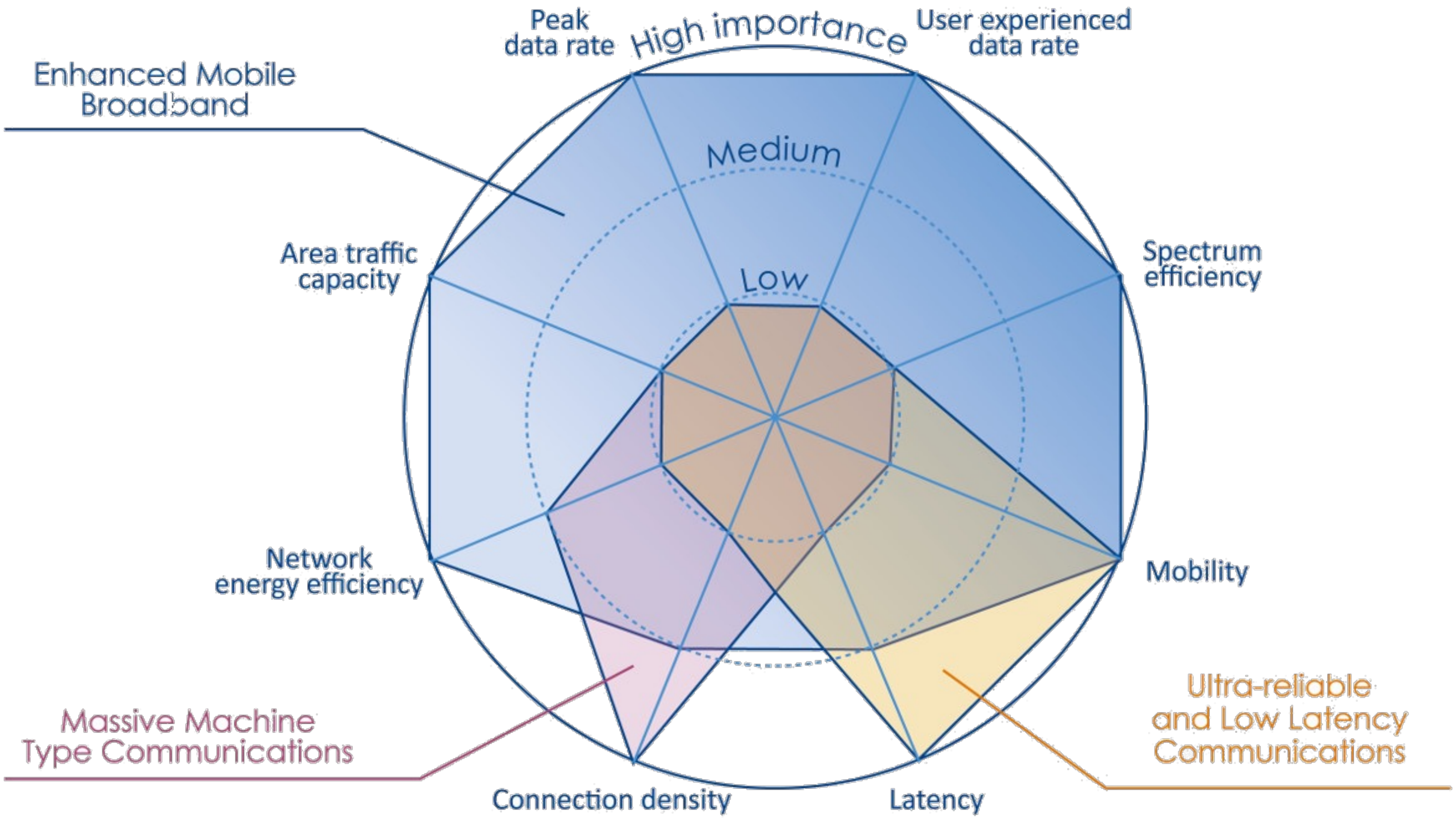


5G use cases

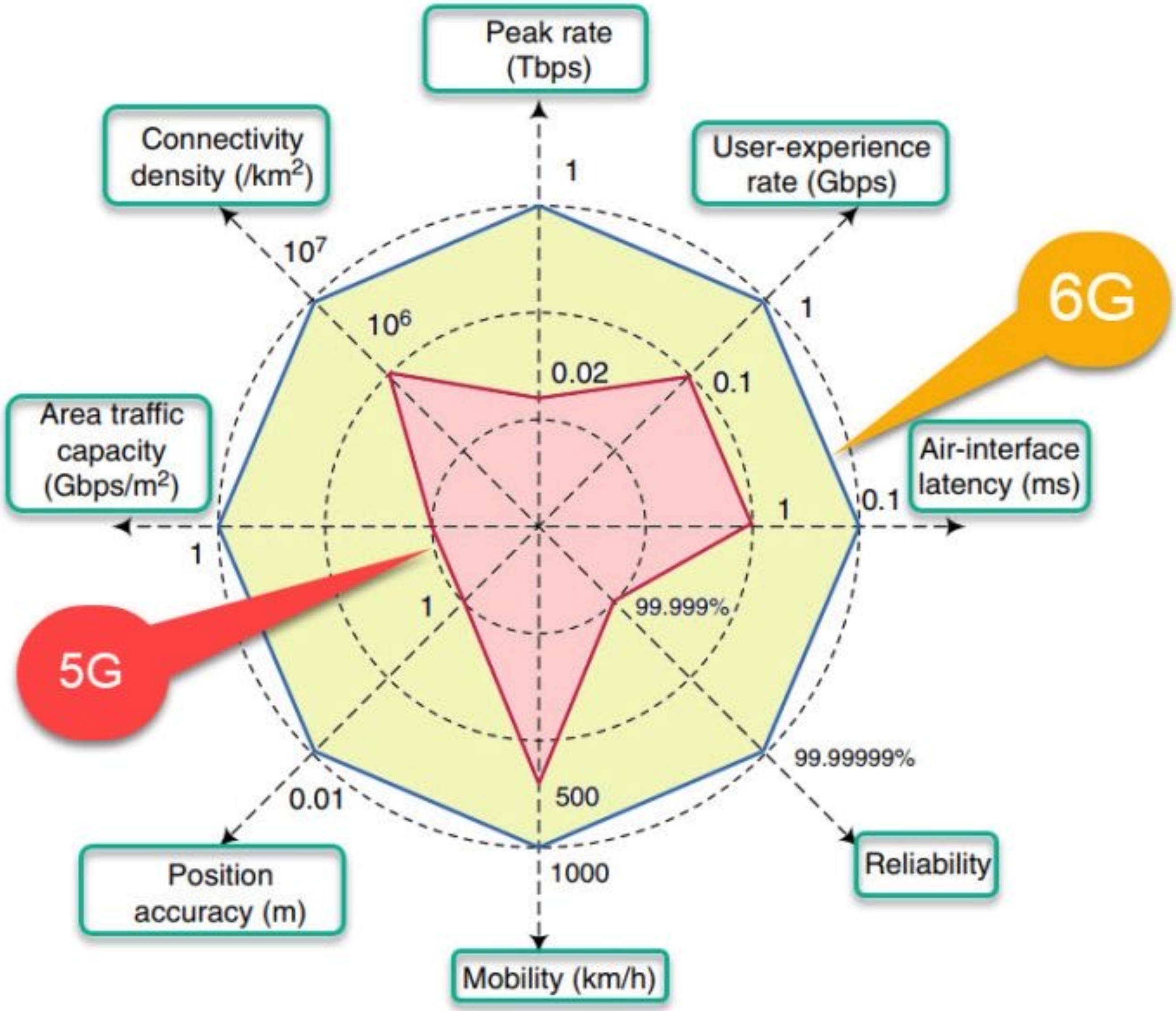


MTC – machine-type communication

5G requirements

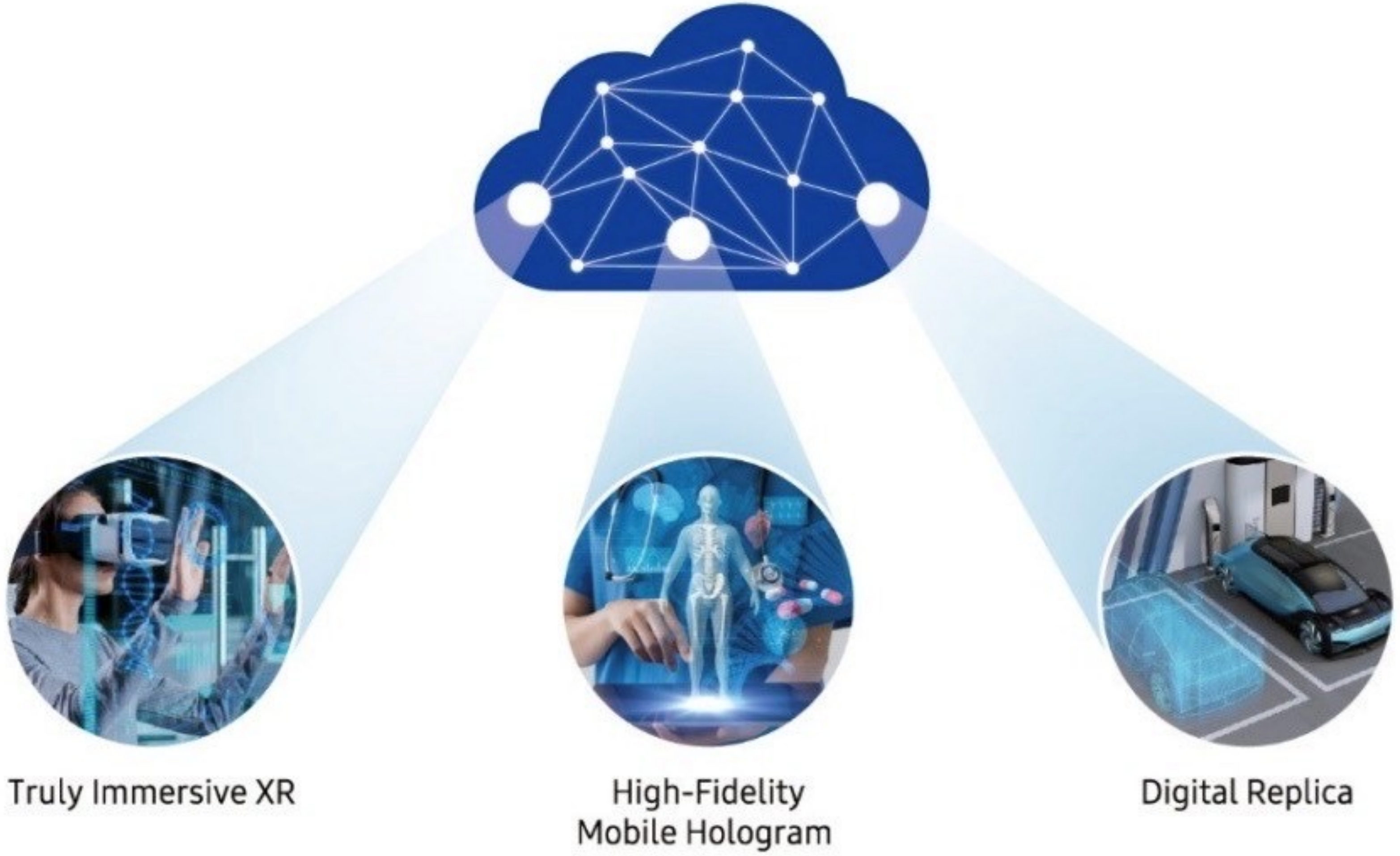


From 5G to 6G (2030 vision)



New use cases for 6G

- 6G systems will try to address new use cases, where the physical world and the digital world interact closely with the human world



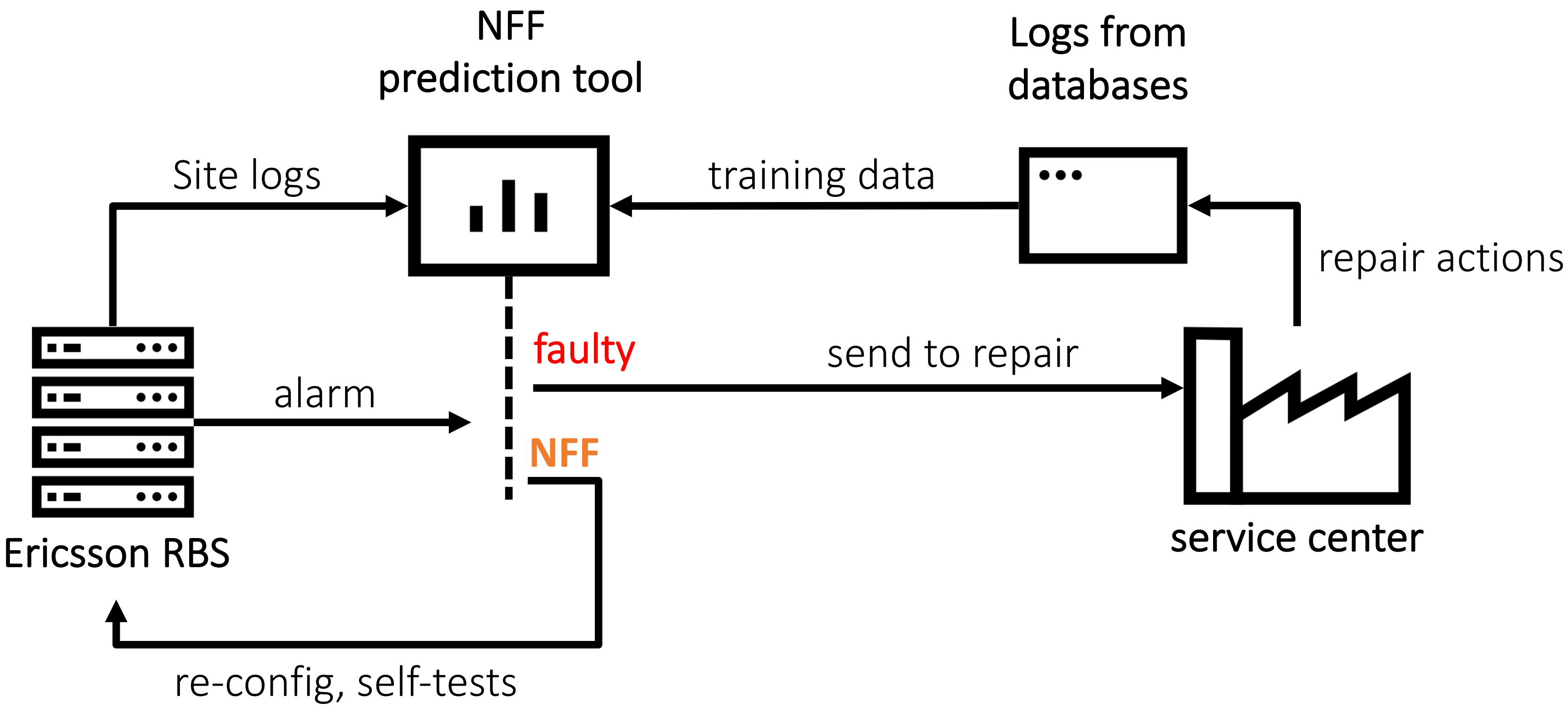
The key elements for 6G (1/2)

- **A native Artificial Intelligence (AI) architecture**
  - 6G networks will be integrating AI in the architecture for resource management, optimization, fault prediction and self healing
  - AI functions will be used at the edge of the network (i.e., close to the user) to enable fast and context-aware decisions
  - Semantic communication to transmit “meaning” instead of bits, reducing unnecessary traffic

AI for fault prediction

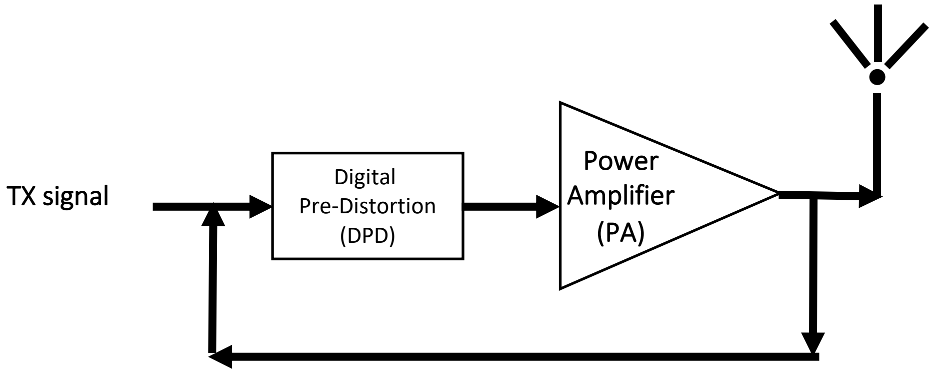
- **Case study:** Development of Machine Learning tool to assess faults in Ericsson radios. The tool should be able to detect and anticipate faults before alarms are triggered and predict no-fault-found (NFF) occurrences before units are sent to screening and repair.

- NFF units prediction
- Local tests on NFF

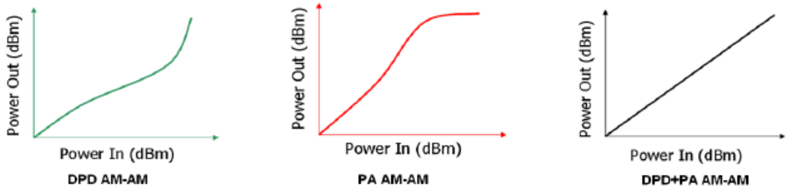


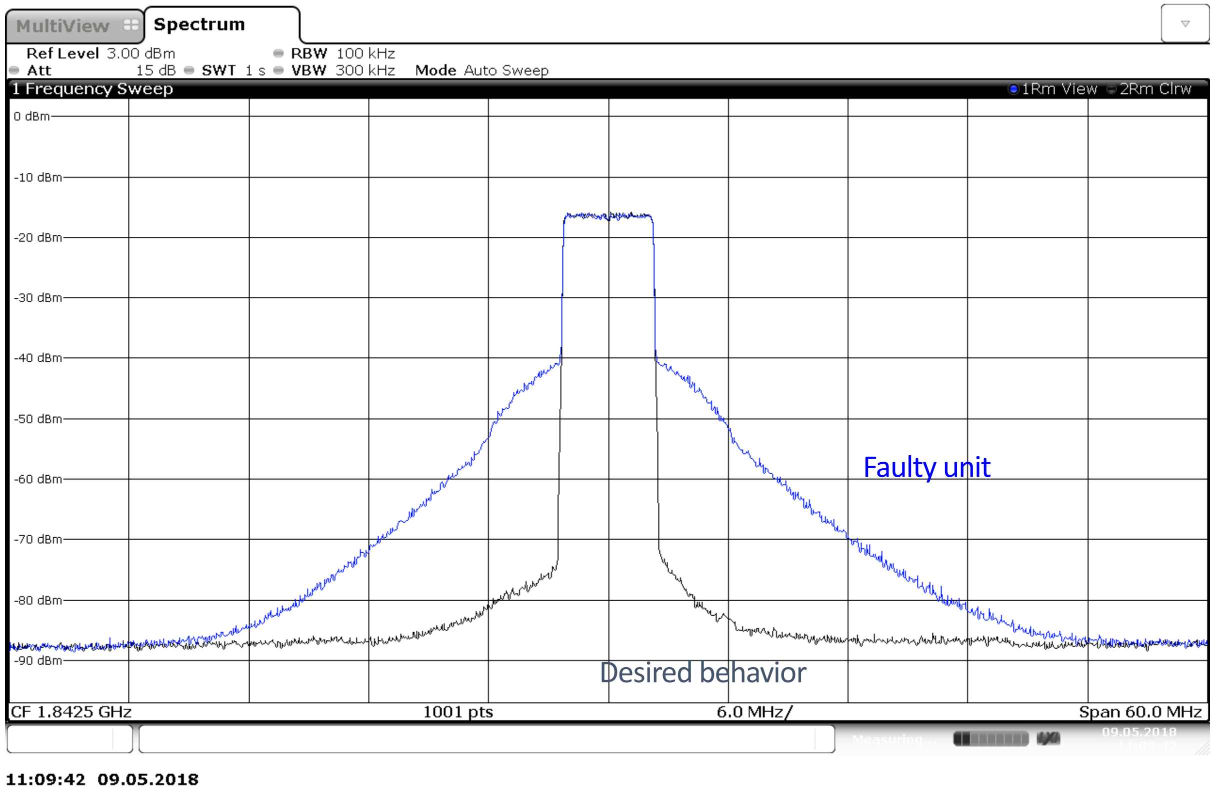
AI for fault prediction

- We focused on **linearization error in the digital pre-distortion DPD**



DPD samples the nonlinear PA output to make it more linear





AI for fault prediction

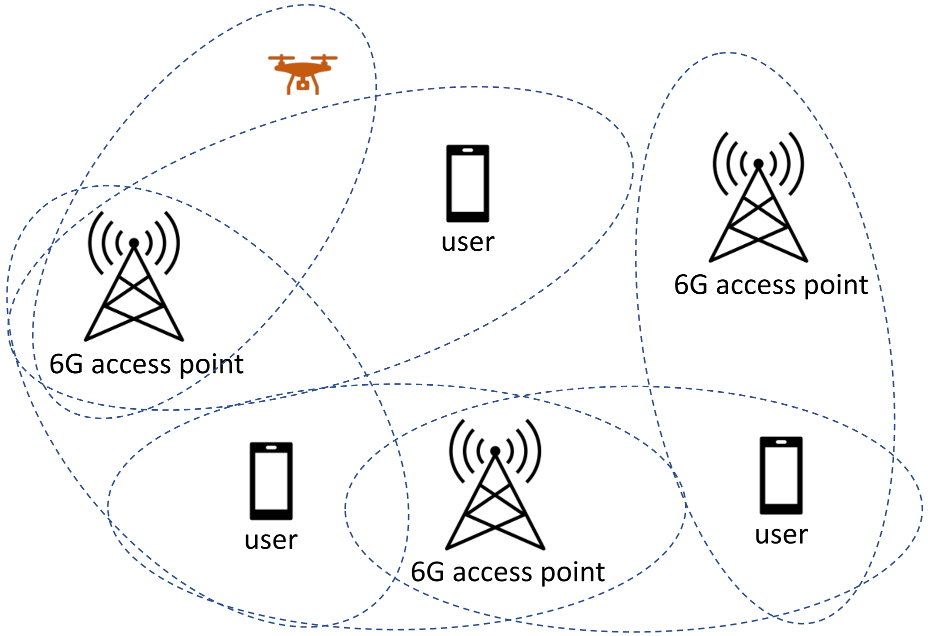
Results

Training	Dummy model	SVC		Nearest Neighbors		Random Forest	
	Score	Score	AUC	Score	AUC	Score	AUC
Balanced (25%)	0,49	0,84	0,64	0,71	0,69	0,73	0,79
Unbalanced (25%)	0,63	0,78	0,55	0,80	0,69	0,80	0,68
Unbalanced (70%)	0,63	0,75	0,57	0,80	0,69	0,77	0,74

The selected Machine Learning models achieve up to 80% probability of correct NFF detection.

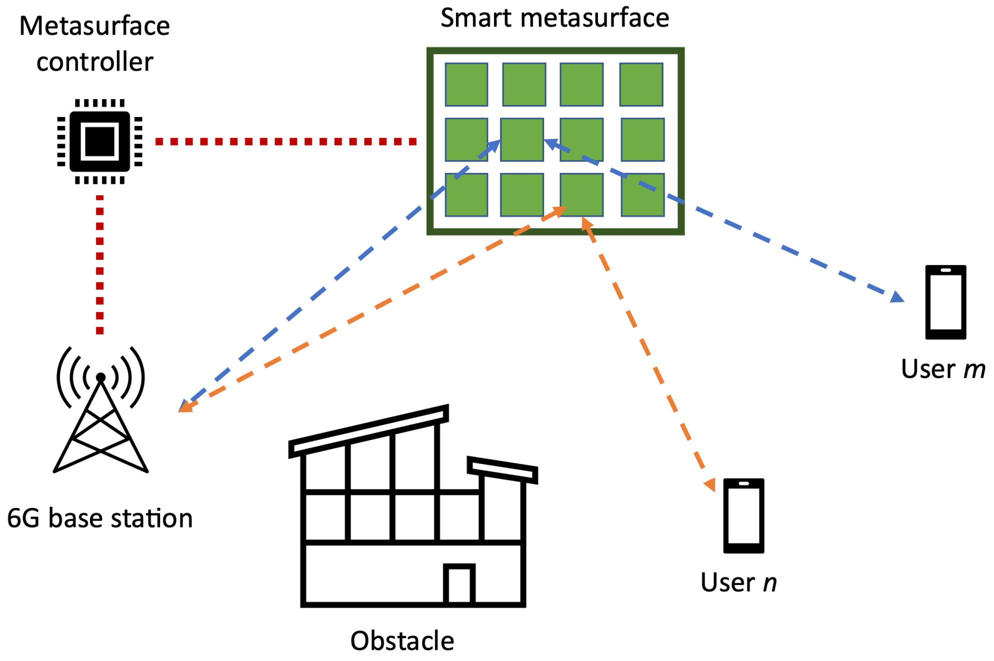
The key elements for 6G (2/2)

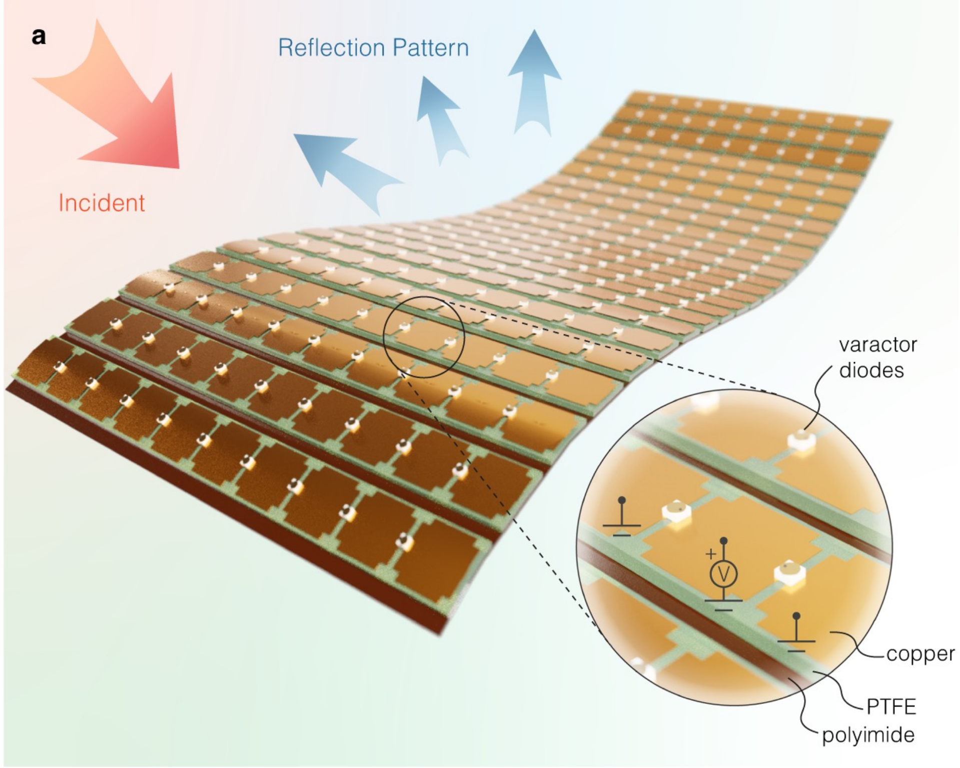
- **A reconfigurable propagation environment**
  - THz communications (100 GHz to 1 THz band) for ultra-high-speed and short-range data
  - Integrated Sensing and Communication (ISAC), using wireless signals simultaneously for data and environmental sensing.
  - Intelligent reflecting surfaces to adapt the propagation conditions and improve coverage



Intelligent reflecting surfaces

- Intelligent reflecting surfaces can aid by reflecting signals around obstacles and creating a virtual line-of-sight (LoS) propagation between a source and the destinations that are not in visibility.





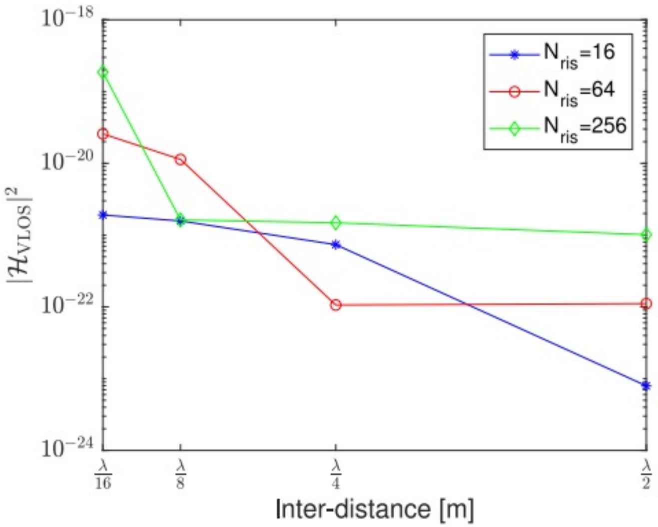
- Surfaces can be applied on buildings, on the road surface or on the body of moving vehicles

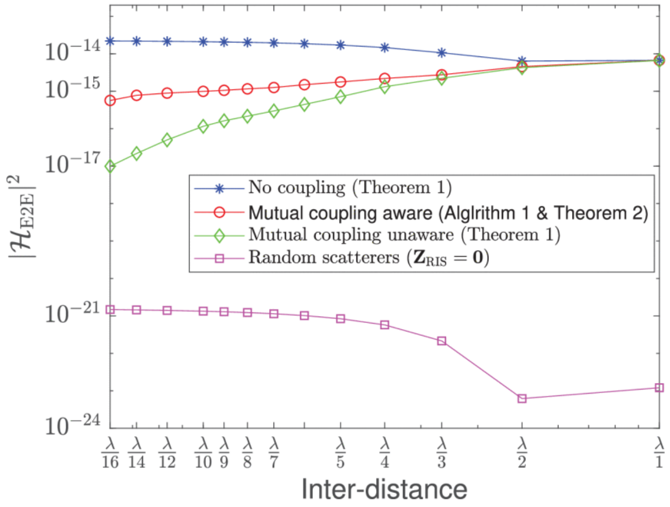
Terminology

- **Smart metasurfaces**: engineered array of structural elements composed by material that is capable of actively interacting with impinging electromagnetic waves (i.e., the focus is on the EM aspects)
- **Intelligent reflecting surfaces** (IRS): reflecting surfaces (passive or semi-passive) in a network infrastructure that are capable of deflecting signals in desired directions (i.e., the focus is on the signal processing aspects)
- **Reconfigurable holographic surface** (RHS): a programmable (typically active) surface capable of generating beams with desired direction (i.e., the focus is on the beamforming aspects)
- **Reconfigurable intelligent surfaces** (RIS): a programmable (typically passive or semi-passive) surface capable of deflecting signals in desired directions (i.e., the focus is on signal processing and optimization aspects)
- **Simultaneous transmitting and reflecting RIS** (STAR-RIS) a programmable active surface capable of reflecting and refracting signals concurrently in desired directions (i.e., the focus is on coverage aspects)

The challenges – EM characterization

- The electromagnetic (EM) characterization of the smart metasurfaces plays a key role in understanding the achievable performance.
- Mutual coupling among the scattering elements of the metasurface is shown to have a relevant impact to the performance [1] and optimization ability [2]



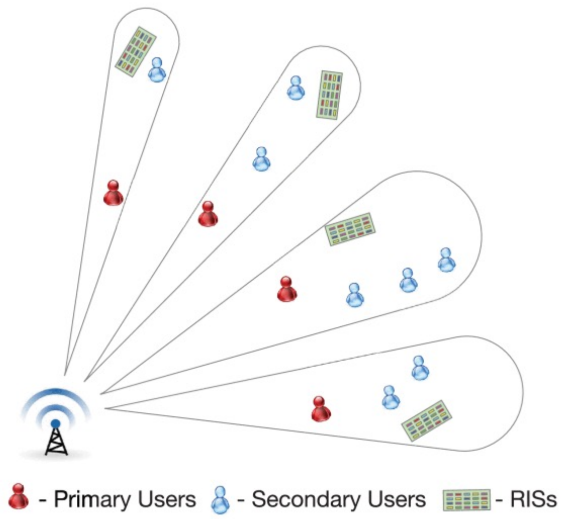


[1] G. Gradoni and M. Di Renzo, "End-to-End Mutual Coupling Aware Communication Model for Reconfigurable Intelligent Surfaces: An Electromagnetic-Compliant Approach Based on Mutual Impedances," in *IEEE Wireless Communications Letters*, vol. 10, no. 5, pp. 938-942, May 2021

[2] X. Qian and M. D. Renzo, "Mutual Coupling and Unit Cell Aware Optimization for Reconfigurable Intelligent Surfaces," in *IEEE Wireless Communications Letters*, vol. 10, no. 6, pp. 1183-1187, June 2021

The challenges – massive multiple access

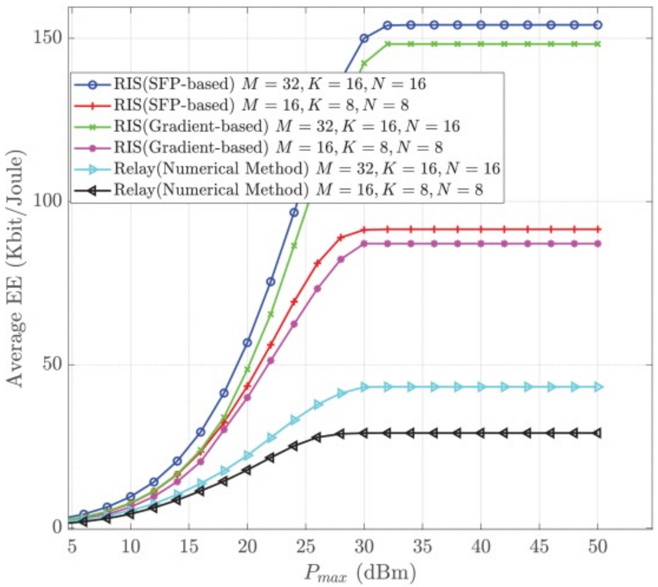
- 6G envisions advanced multiple access protocols to support massive user access and extreme ultra-reliable and low latency communications.
- Signals re-radiated from the scattering elements can add constructively and destructively.
- Intelligent reflecting surfaces can be used to add a degree of freedom to support interference cancelation.

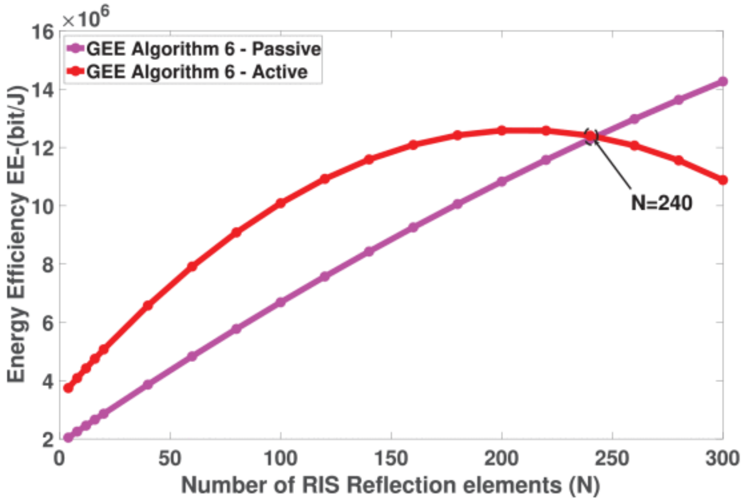


[7] Z. Ding *et al.*, "A State-of-the-Art Survey on Reconfigurable Intelligent Surface-Assisted Non-Orthogonal Multiple Access Networks," in *Proceedings of the IEEE*, vol. 110, no. 9, pp. 1358-1379, Sept. 2022

The challenges – energy aspects

- Intelligent reflecting surfaces represent a promising alternative to adding infrastructural elements, especially in terms of energy efficiency [8]
- However, there is a tradeoff in the energy efficiency between active and passive metasurfaces, due to higher degrees of freedom in the reflection [9]



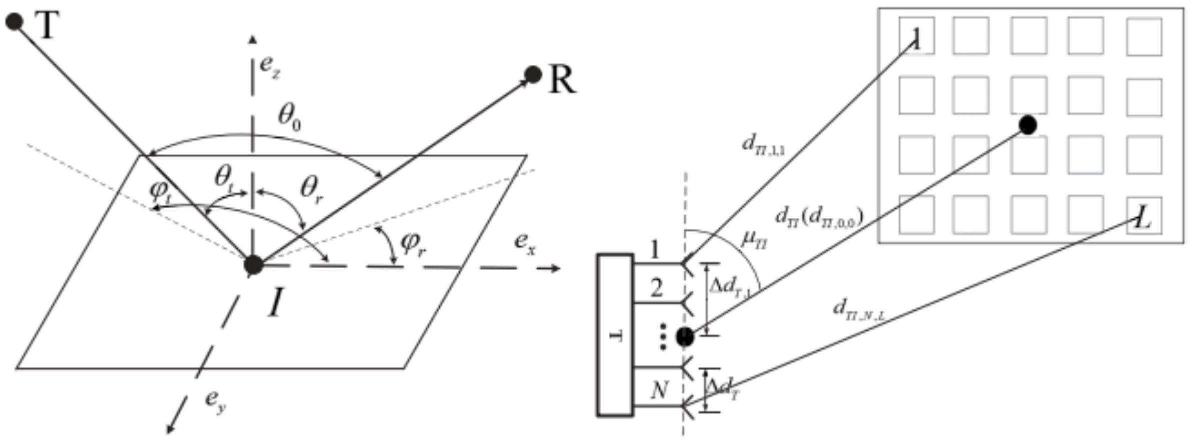


[8] C. Huang, *et. al*,: "Reconfigurable intelligent surfaces for energy efficiency in wireless communication," IEEE Trans. Wireless Commun., vol. 18, no. 8, pp. 4157–4170, Aug. 2019.

[9] R. K. Fotock, A. Zappone and M. D. Renzo, "Energy Efficiency Optimization in RIS-Aided Wireless Networks: Active Versus Nearly-Passive RIS With Global Reflection Constraints," in IEEE Transactions on Communications, vol. 72, no. 1, pp. 257-272, Jan. 2024

Joint physical and EM analysis

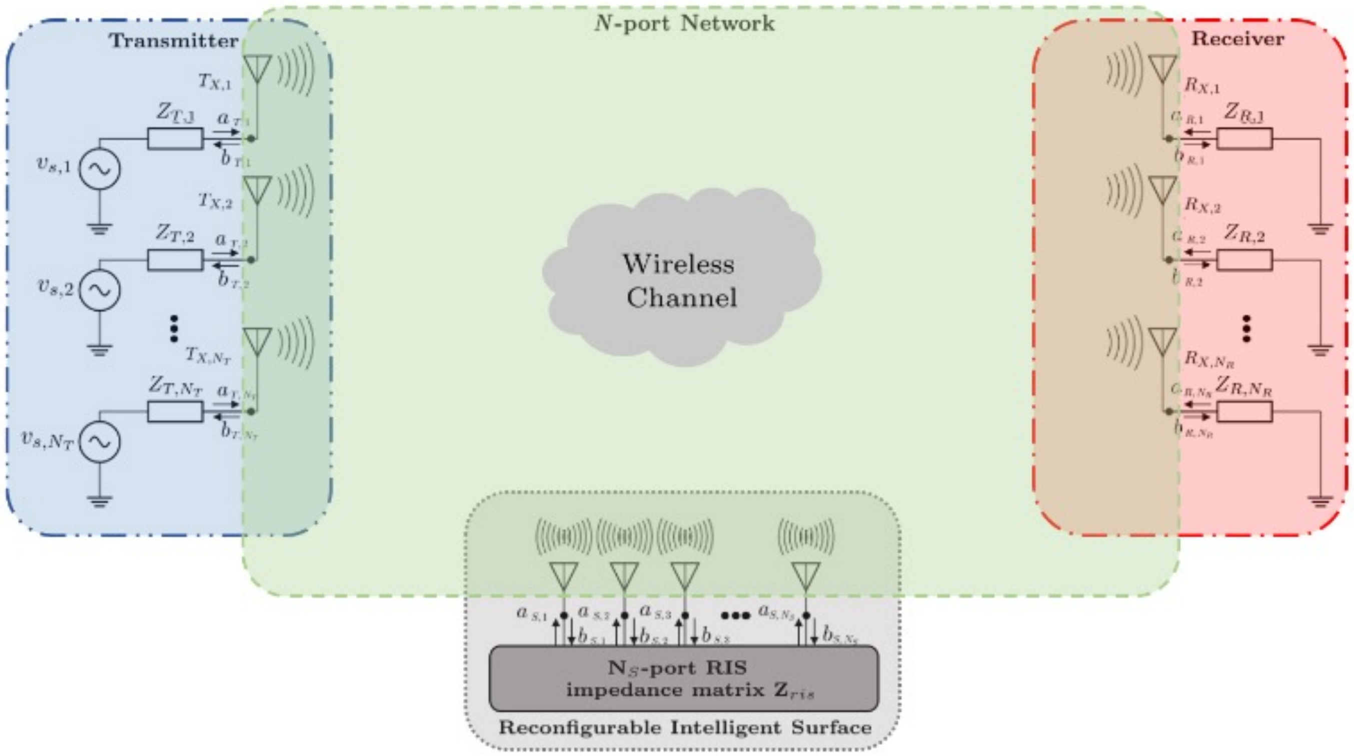
- The analysis and optimization of IRS-aided wireless systems call for sufficiently realistic and accurate, but also tractable physical models that account for the electromagnetic factors of the scattering elements [12].



[12] X. Cheng *et al*., "Joint Optimization for RIS-Assisted Wireless Communications: From Physical and Electromagnetic Perspectives," in *IEEE Transactions on Communications*, vol. 70, no. 1, pp. 606-620, Jan. 2022

Time-domain PEEC characterization

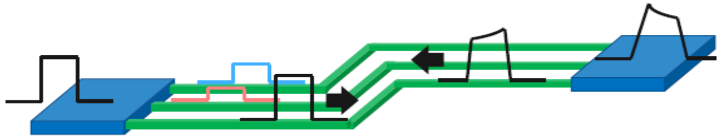
- A partial element equivalent circuit (PEEC) model for smart metasurfaces was developed in [14]



[14] Giuseppe Pettanice, *et. al*: *Mutual Coupling Aware Time-Domain Characterization and Performance Analysis of Reconfigurable Intelligent Surfaces Through the Partial Element Equivalent Circuit Method.* IEEE Transactions on Electromagnetic Compatibility. 65(6):1006-1020. December 2023.

The PEEC model

Geometry and materials



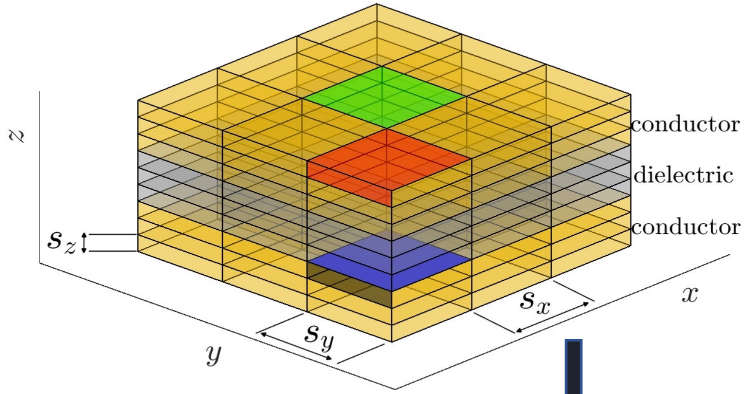
EFIE + Continuity

$$\boldsymbol{E}_0(\boldsymbol{r},t) = \frac{\boldsymbol{J}(\boldsymbol{r},t)}{\sigma} + \frac{\partial \boldsymbol{A}(\boldsymbol{r},t)}{\partial t} + \nabla\phi(\boldsymbol{r},t)$$

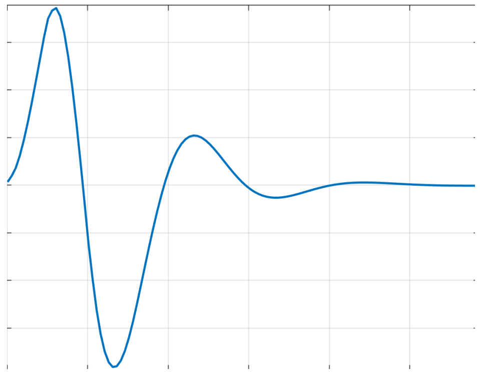
$$\nabla \cdot \boldsymbol{J}(\boldsymbol{r},t) = 0 \qquad \boldsymbol{r} \in V'$$

$$\hat{\boldsymbol{n}} \cdot \boldsymbol{J}(\boldsymbol{r},t) = \frac{\partial \sigma_s}{\partial t} \qquad \boldsymbol{r} \in S'$$

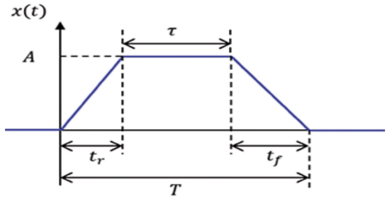
Volume and surface meshing



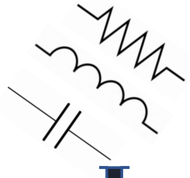
Responses



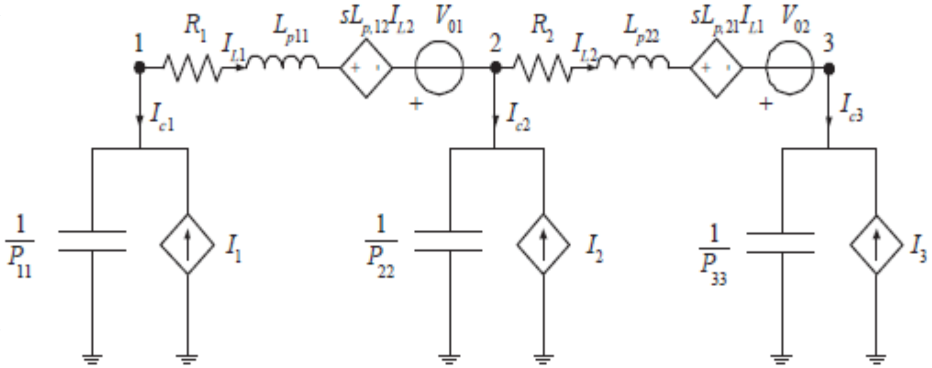
Sources



Port lumped elements



Equivalent circuit

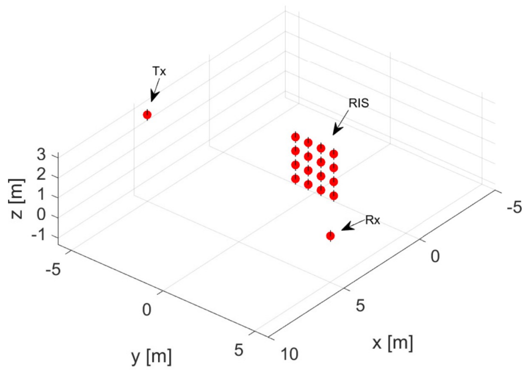


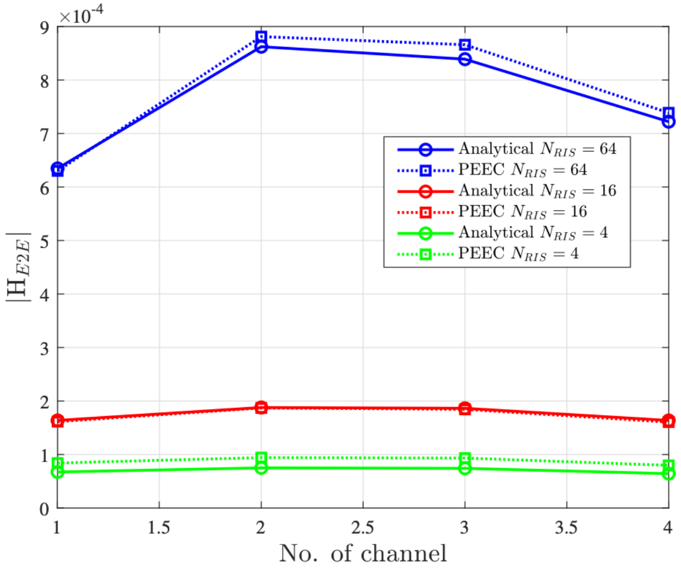
Mathematical model

$$\sum$$

Model validation via numerical simulations

- Our model has been proven valid for a wide range of parameters with PEEC numerical validations [16]

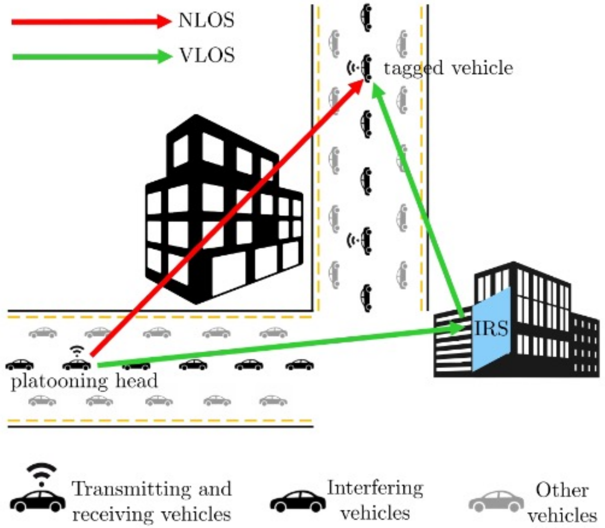


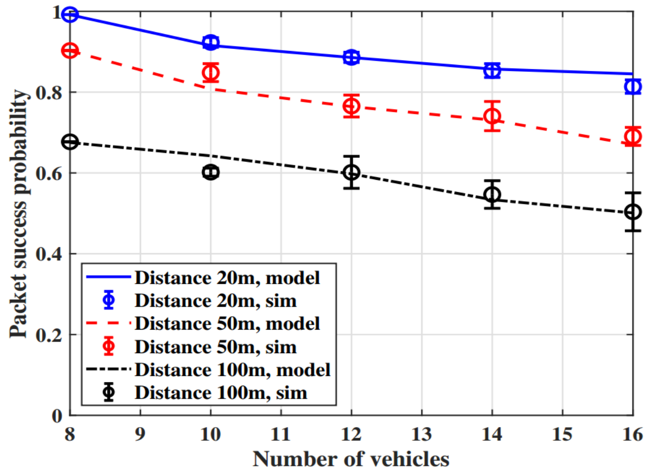


[16] Giuseppe Pettanice, Marco Di Renzo, Sumin Jeong, Roberto Valentini, Piergiuseppe Di Marco, Fortunato Santucci, Daniele Romano, and Giulio Antonini: *Multiport Network Modeling for Reconfigurable Intelligent Surfaces: Numerical Validation with a Full-Wave PEEC Simulator*. URSI Atlantic Radio Science Meeting (RASC), Gran Canaria. May 2024.

Application to ITS

- Ubiquitous connectivity among vehicles, infrastructure and with other road users is crucial to increase the safety of automated vehicles and their full integration into intelligent transport systems (ITS).
- Smart metasurfaces may be integrated in vehicular networks, placed on buildings and road-side units to enhance connectivity in e.g., side-link communication in platooning scenarios [17].





Abdul Rehman, Roberto Valentini, Elena Cinque, Piergiuseppe Di Marco, Fortunato Santucci: *On the impact of multiple access interference in LTE-V2X and NR-V2X sidelink communications*. Sensors. 23(10), 4901. May 2023.

An experimental infrastructure - EMERGE

- The University of L'Aquila hosts a Centre of Excellence on Connected, Geo-localized and Cyber-secure vehicles (EX-EMERGE).

RadioLabs

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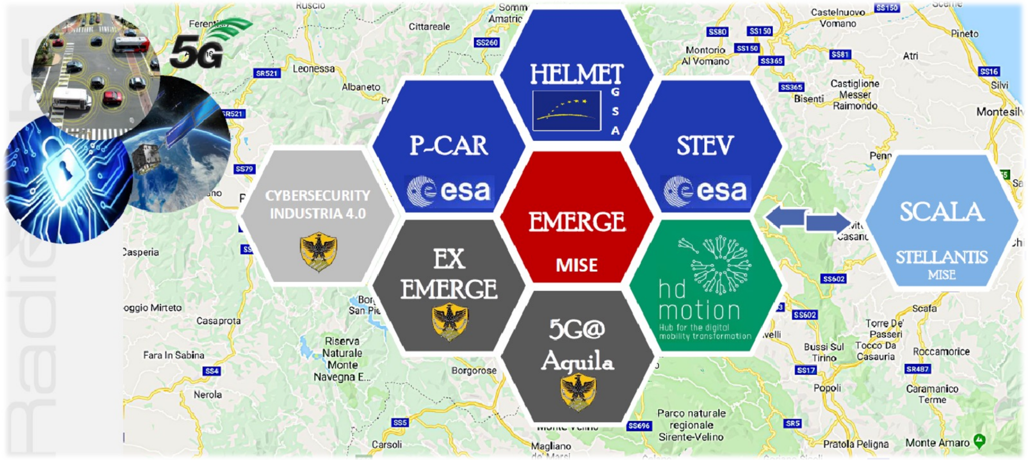
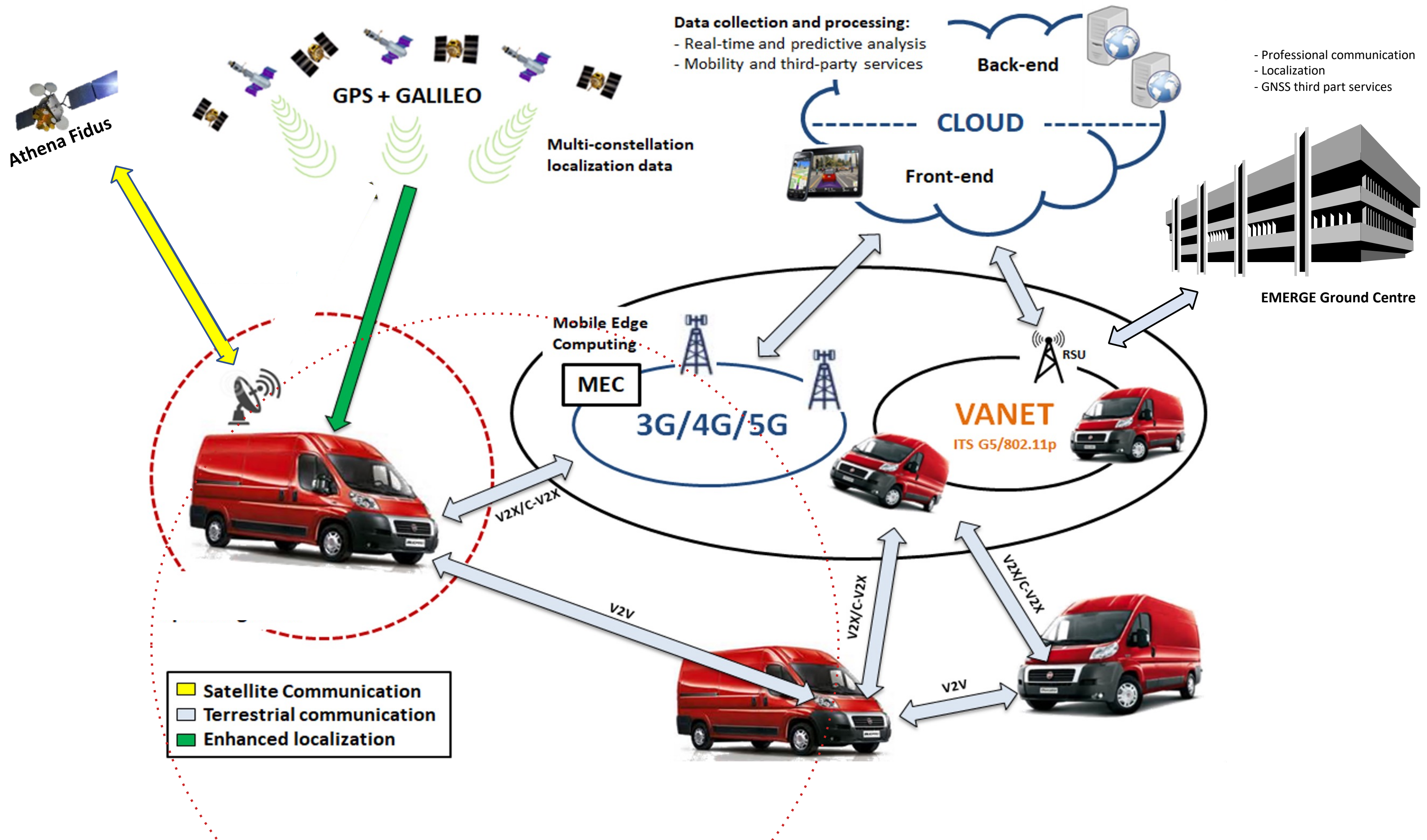


An experimental infrastructure - EMERGE

- The EMERGE architecture



An experimental infrastructure - EMERGE

- Dedicated mobile laboratories

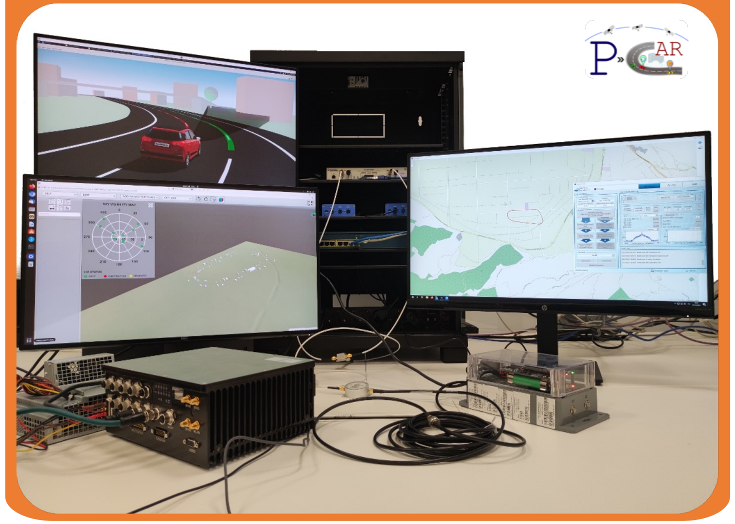
3 vehicles in 2 different configurations:

- **FULL** (1 vehicle) - GEO SATCOM on the move, SATNAV, IMU, 4G/5G/V2X Comms, IP cameras
- **MEDIUM** (2 vehicles) - SATNAV, IMU, 4G/5G/V2X Comms, IP cameras

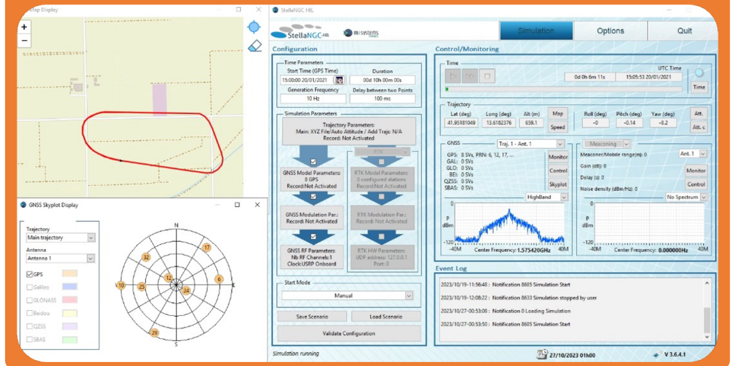


An experimental infrastructure - EMERGE

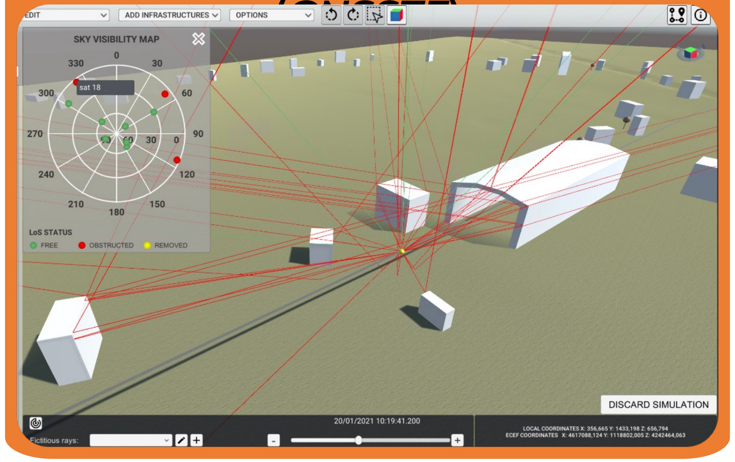
Hardware-in-the-Loop setup for GNSS and ADAS testing



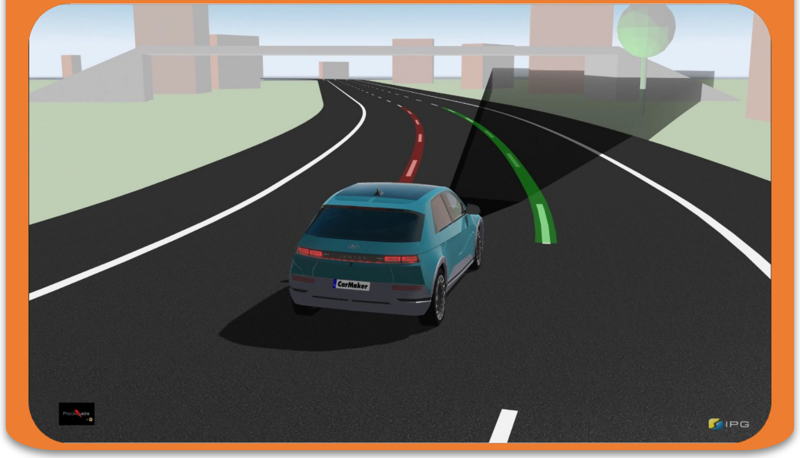
GNSS constellation emulation with SBAS and multipath



Environment-based GNSS deterministic multipath



Environment and vehicle modelling including perception sensors (e.g., *IPG CarMaker*)



Example of CCAM applications:

- Lane Departure Warning (LDW)
- Automated Lane Keeping (ALK)
- Automatic Emergency Braking (AEB)
- Intelligent Speed Adaptation (ISA)
- Adaptive Cruise Control (ACC)

Example of supported sensors:

- GNSS and inertial sensors
- Camera, Radar, LIDAR

A research initiative – RESTART

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