Distributed MIMO Systems and Reconfigurable Intelligent Surfaces

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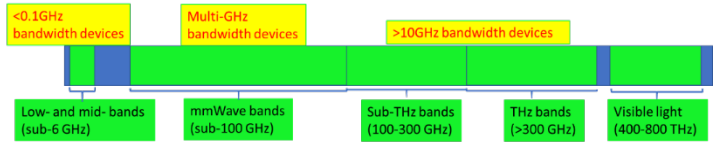
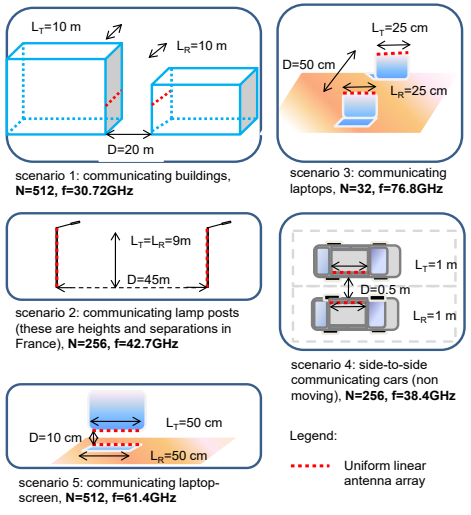
Outline

- Recap of key technical enablers for 6G
- From CoMP to D-MIMO Systems
- Reconfigurable intelligent surfaces (RIS)
- Standardization path for 6G
- Take home messages

Key 6G Technical Enablers: Densification & Integration…

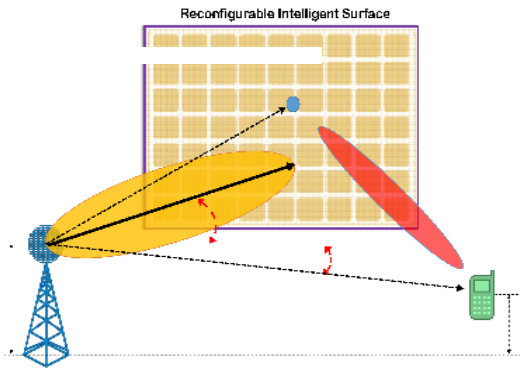


Massive MIMO at Both Tx, Rx (MMIMMO)



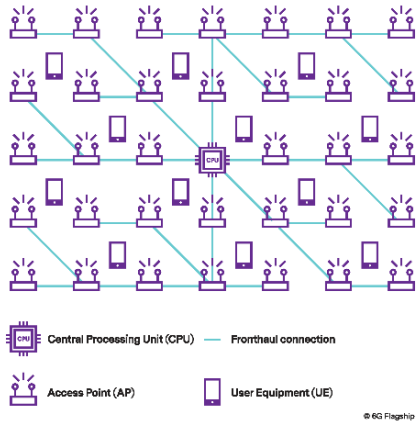
D.-T. Phan-Huy, P. Ratajczak, R. D'Errico, A. Clemente, J. Järveläinen, D. Kong, K. Haneda, B. Bulut, A. Karttunen, M. Beach, E. Mellios, M. Castaneda, M. Hunukumbure, T. Svensson, "Massive Multiple Input Massive Multiple Output for 5G Wireless Backhauling", IEEE Globecom'2017 ET5GB workshop.

Reconfigurable Intelligent Surfaces (RIS)



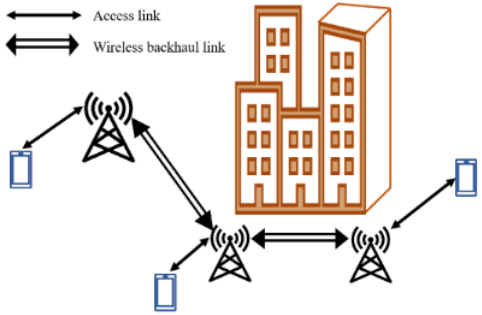
S. M. Razavizadeh, T. Svensson, "3D Beamforming in Intelligent Reconfigurable Surface-assisted Wireless Communication Networks", WSA'2020.

CoMP -> Distributed cell-free Large MIMO (D-MIMO)



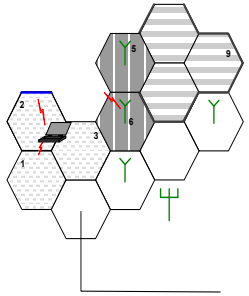
N. Rajatheva, I. Atzeni, S. Bicais, E. Björnson, A. Bourdoux, S. Buzzi, C. D'Andrea, J. B. Dore', S. Erkucuk, M. Fuentes, K. Guan, Y. Hu, X. Huang, J. Hulkkonen, J. M. Jornet, M. Katz, B. Makki, R. Nilsson, E. Panayirci, K. Rabie, N. Rajapaksha, M. J. Salehi, H. Sarieddeen, S. Shahabuddin, T. Svensson, O. Tervo, A. Tölli, Q. Wu, W. Xu , "Scoring the Terabit/s Goal: Broadband Connectivity in 6G", Submitted to IEEE Communications Surveys and Tutorials (COMST). arXiv: https://arxiv.org/pdf/2008.07220.pdf

Integrated Access and Backhaul (IAB)



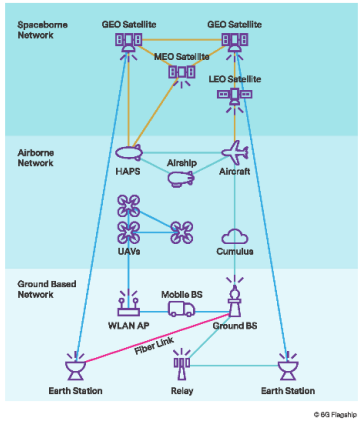
C. Madapatha, B. Makki, C. Fang, O. Teyeb, E. Dahlman, M. S. Alouini, T. Svensson, "On Integrated Access and Backhaul Networks: Current Status and Potentials", IEEE Open Journal of the Communications Society (OJ-COMS), vol. 1, pp. 1374-1389, 2020. arXiv: https://arxiv.org/abs/2006.14216

Integrated Mobility Support



X. Xu, X. Tao, C. Wu and P. Zhang, "Capacity and Coverage Analyses for the Generalized Distributed Cellular Architecture-Group Cell," 2006 International Conference on Communications, Circuits and Systems, Guilin, 2006, pp. 847-851.

Vertical Convergence



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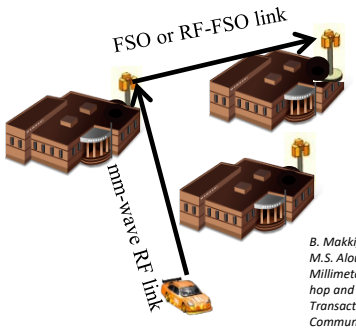
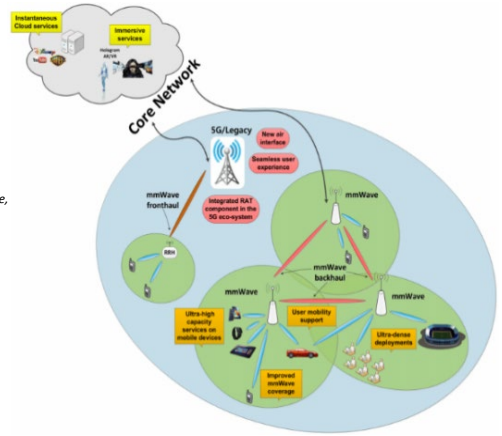
Joint mm-wave/sub-THz – FSO/ OWC

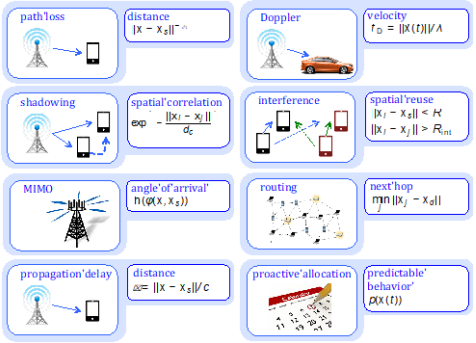


B. Makki, T. Svensson, M. Brandt-Pearce, M.S. Alouini, "On the Performance of Millimeter Wave-based RF-FSO Multi-hop and Mesh Networks", IEEE Transactions on Wireless Communications, vol. 16, no. 12, pp. 7746-7759, Dec. 2017.

Agile Converged Access/ Confluent Xhaul with Network Slicing Awareness

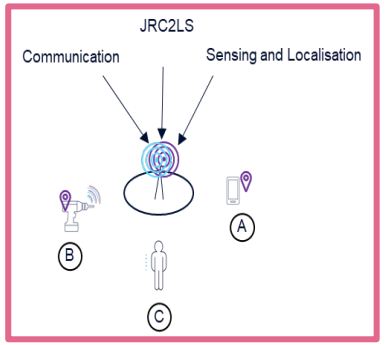


Localization/Context-aided Communications



Di Taranto, Rocco, Srikar Muppirisetty, Ronald Raulefs, Dirk Slock, Tommy Svensson, and Henk Wymeersch. "Location-aware communications for 5G networks: How location information can improve scalability, latency, and robustness of 5G." *IEEE Signal Processing Magazine* 31, no. 6 (2014): 102-112.

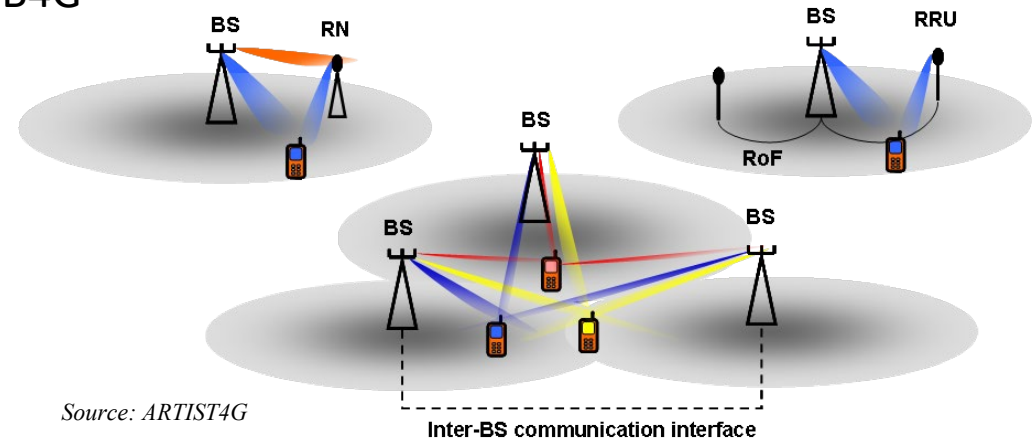
Joint Communications, Localization and Sensing



Hexa-X D1.3 Targets and requirements for 6G – initial E2E architecture C. de Lima, D. Belot, R. Berkvens, A. Bourdoux, D. Dardari, M. Guillaud, M. Isomursu, E. S. Lohan, Y. Miao, A. Barreto, M. R. K. Aziz, J. Saloranta, T. Sanguanpuak, H. Sarieddeen, G. Seco-Granados, J. Suutala, T. Svensson, M. Valkama, B. van Liempd, H. Wymeersch, "Convergent Communication, Sensing and Localization in 6G Systems: An Overview of Technologies, Opportunities and Challenges," in IEEE Access, vol. 9, pp. 26902-26925, 2021.

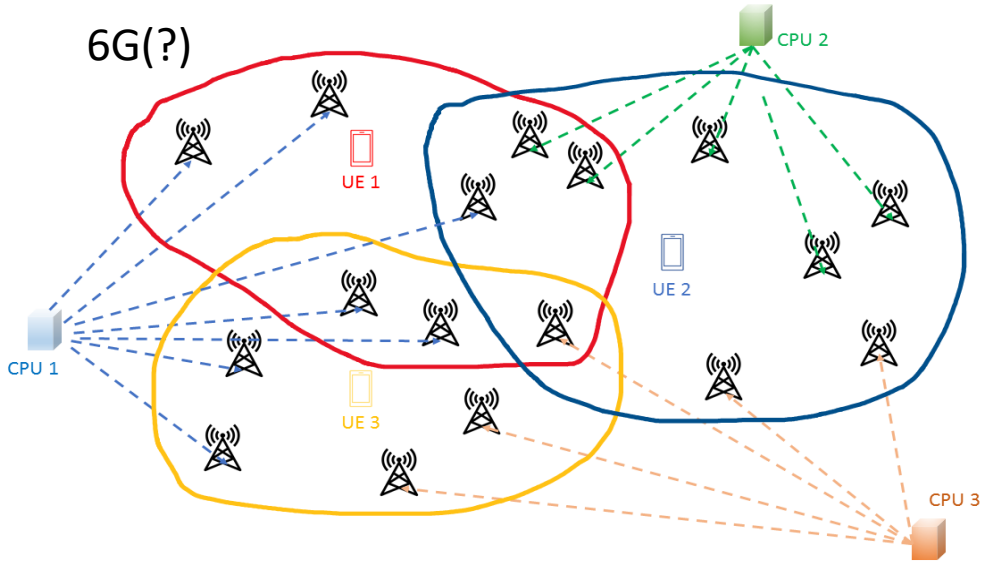
From CoMP to D-MIMO Systems

B4G



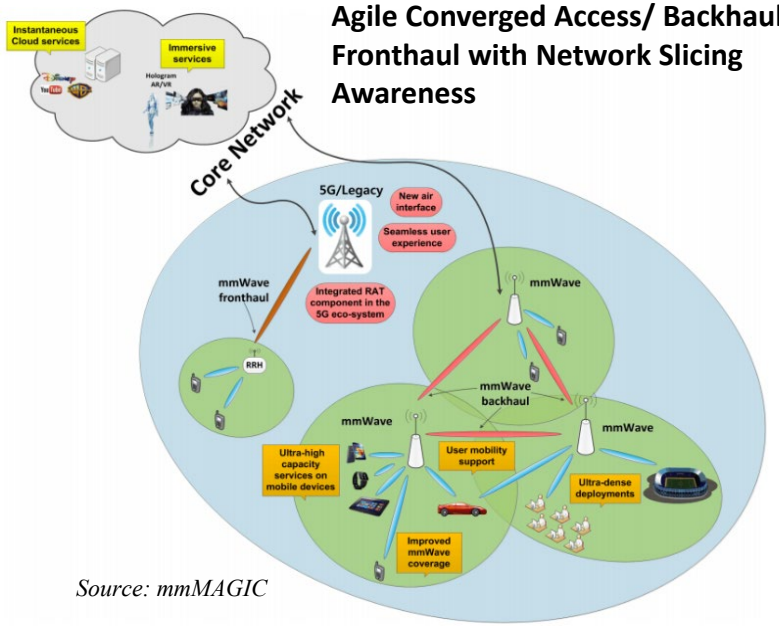
Source: ARTIST4G

6G(?)



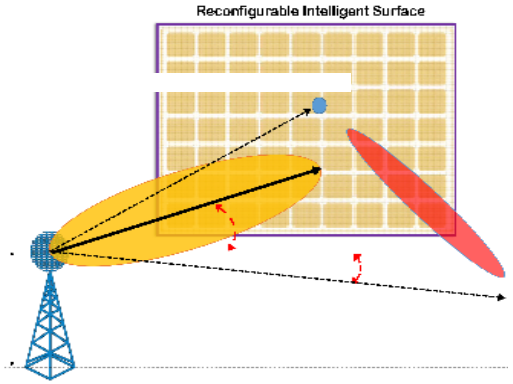
5G/B5G

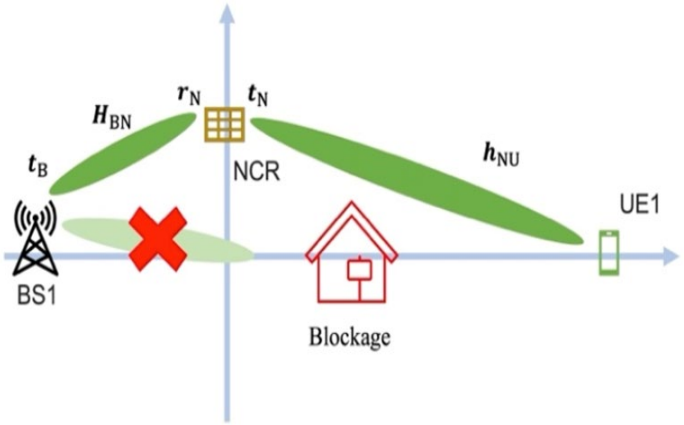
Agile Converged Access/ Backhaul/ Fronthaul with Network Slicing Awareness



Source: mmMAGIC

With RIS/NCR(?)

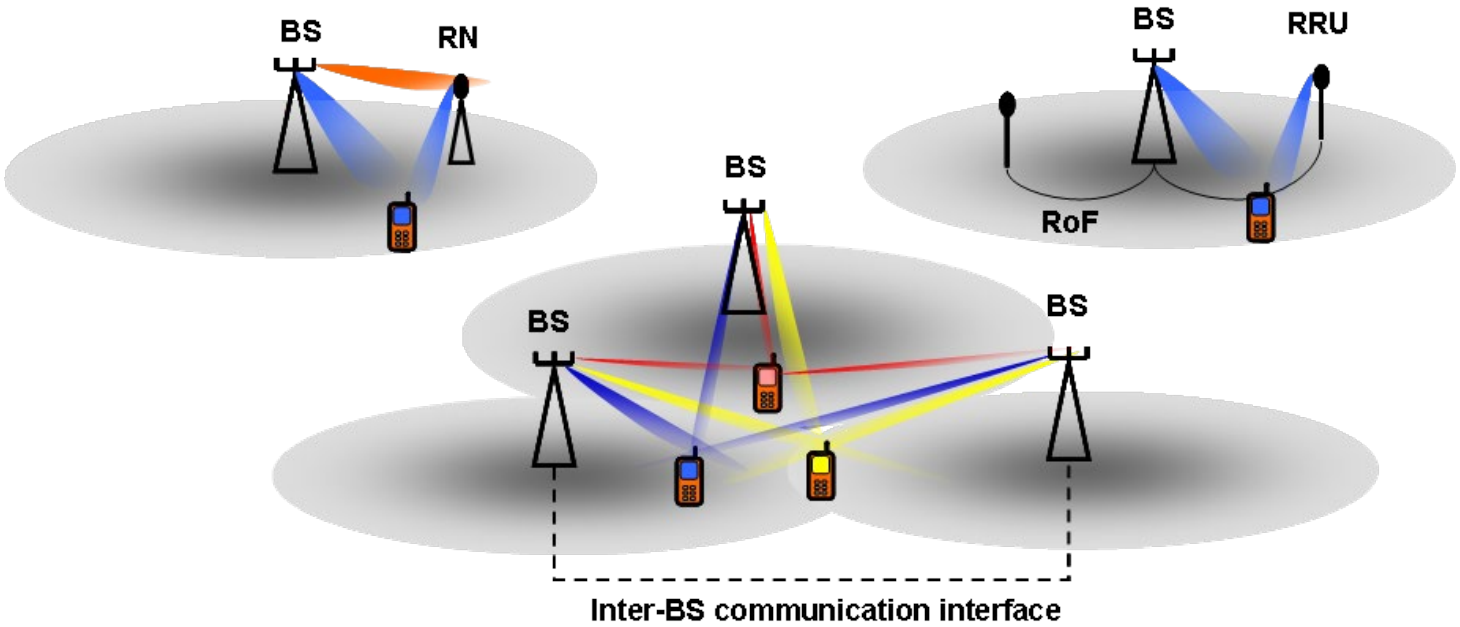




CoMP: Coordinated Multi-Point

D-MIMO: Distributed Multiple-Input Multiple-Output

CoMP Architectures



Three types of coordinated entities can be considered:

- Remote Radio Units (RRUs)
- Cells with intra-Base Station (BS) or inter-BS coordination
- Relay nodes (RNs)

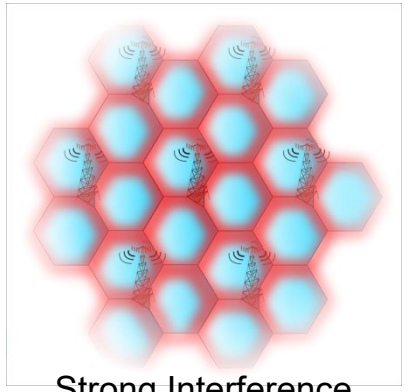
Combined multi-cell coordination with BSs, RRUs, and RNs in each cell.

Complexity of Network-wide Cooperation

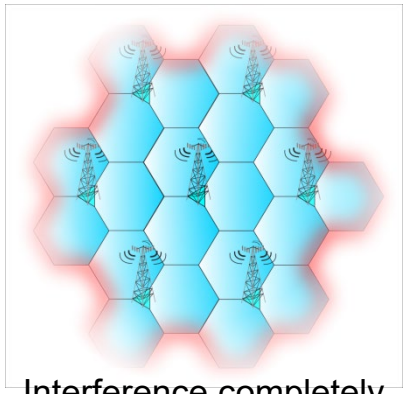
Cooperation Areas

Different degrees of cooperation have different influence on interference

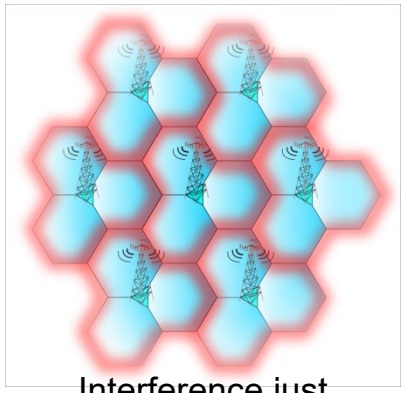
- No Cooperation
  - Strong interference between cells
- Full Cooperation
  - Interference completely avoided
  - Needs full CSI for the whole network (not realistic)
- Cooperation area (*'CA'*)
  - Cooperation only inside of a limited number of sectors



Strong Interference without cooperation



Interference completely avoided by full cooperation



Interference just between cooperation areas

How to Attain more of the Theoretical Gains?

1. Cooperation areas have to be designed carefully to provide gains for most users.
2. Interference from outside the CA needs to be reduced so that it does not swamp the intra-CA gains.
3. Groups of users that cooperate in a resource block need to be selected well, but still fast and efficiently.

Additional important aspects and practical constraints:

- Channel estimation/prediction accuracy
- Channel reporting feedback: accuracy and load in FDD
- Transmit power constraints
- Control signalling load, data distribution load limits
- Time synchronization limitations to/from multiple sites.

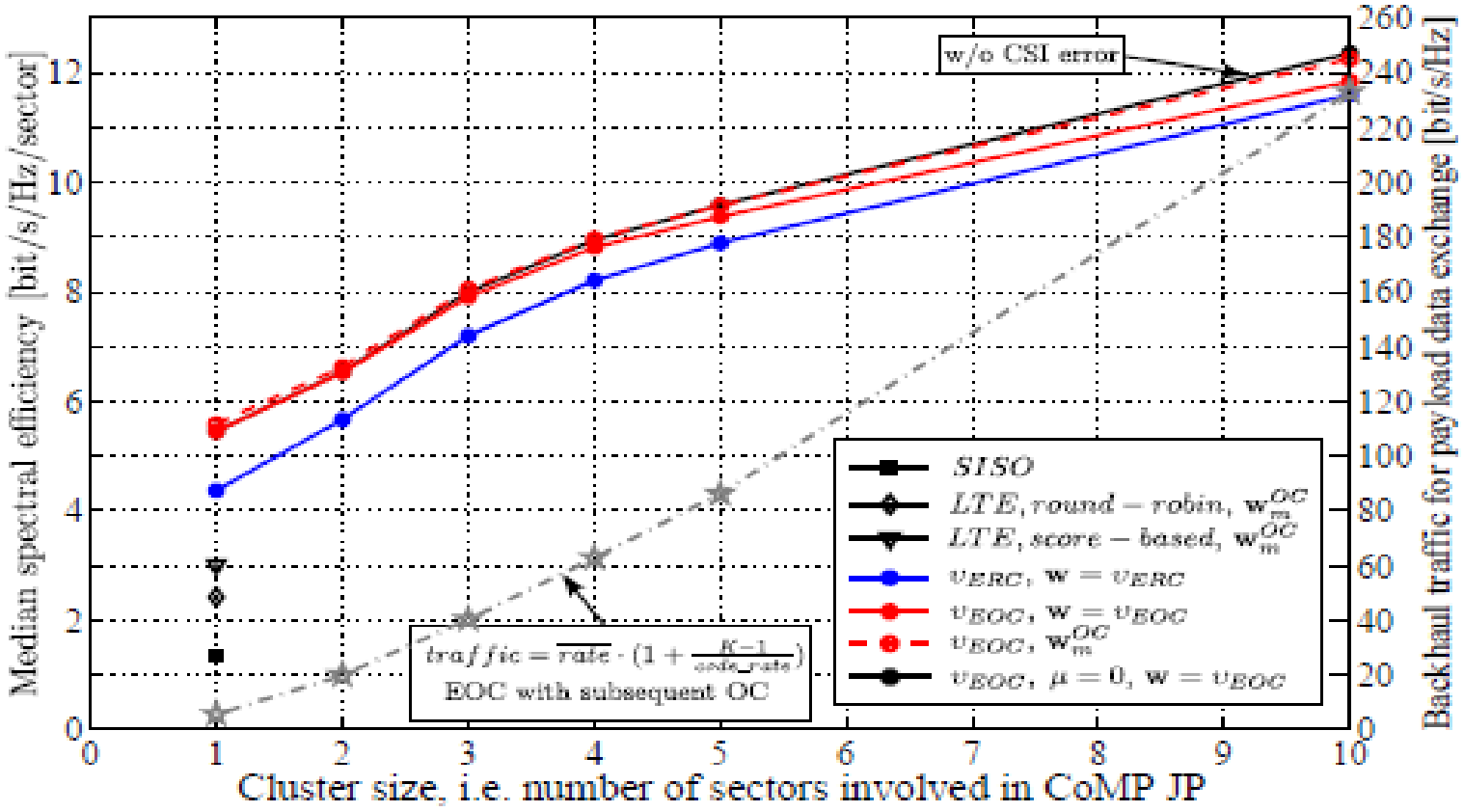
All these issues e.g. limit the practical cooperation area size.

Complexity of Network-wide Cooperation

Inter-cluster interference floor vs CA size

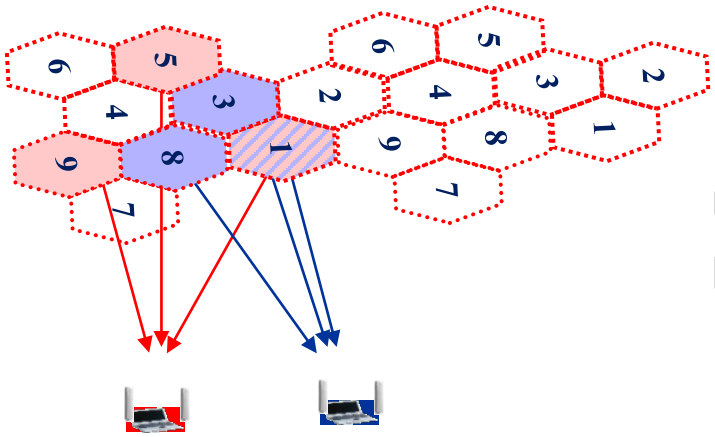
Performance asymptotically increasing with cluster size

However, inter-cooperation area interference is a serious limitation.



[Source: Lars Thiele et.al., Chapter 6.3 in P.March ed. *Coordinated Multipoint in Mobile Communications*, 2011]

Clustering: Enlarged Cooperation Areas



User-centric clustering would be ideal.

Problem with User-centric clustering :

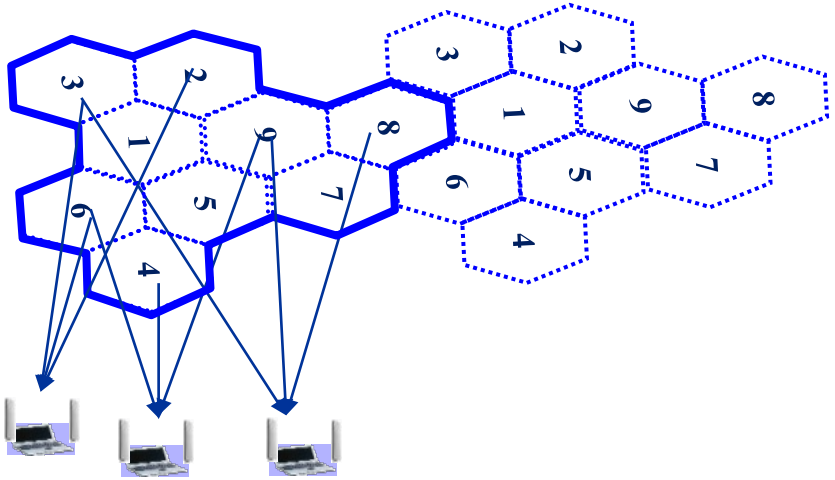
very low number of UEs wish same set of cells

→ low penetration rate and / or low CoMP gain

even with extensive optimization unsolvable!!

Solution Step 1): ***Use static, but enlarged, cooperation areas***

- 3 sites a' 3 cells leads to CAs of 9 cells
- practical approach with limited number of backhaul links
- high number of UEs having 3 strongest cells in one 9-cell-CA



Network-defined User-specific Clustering: Cover Shifts

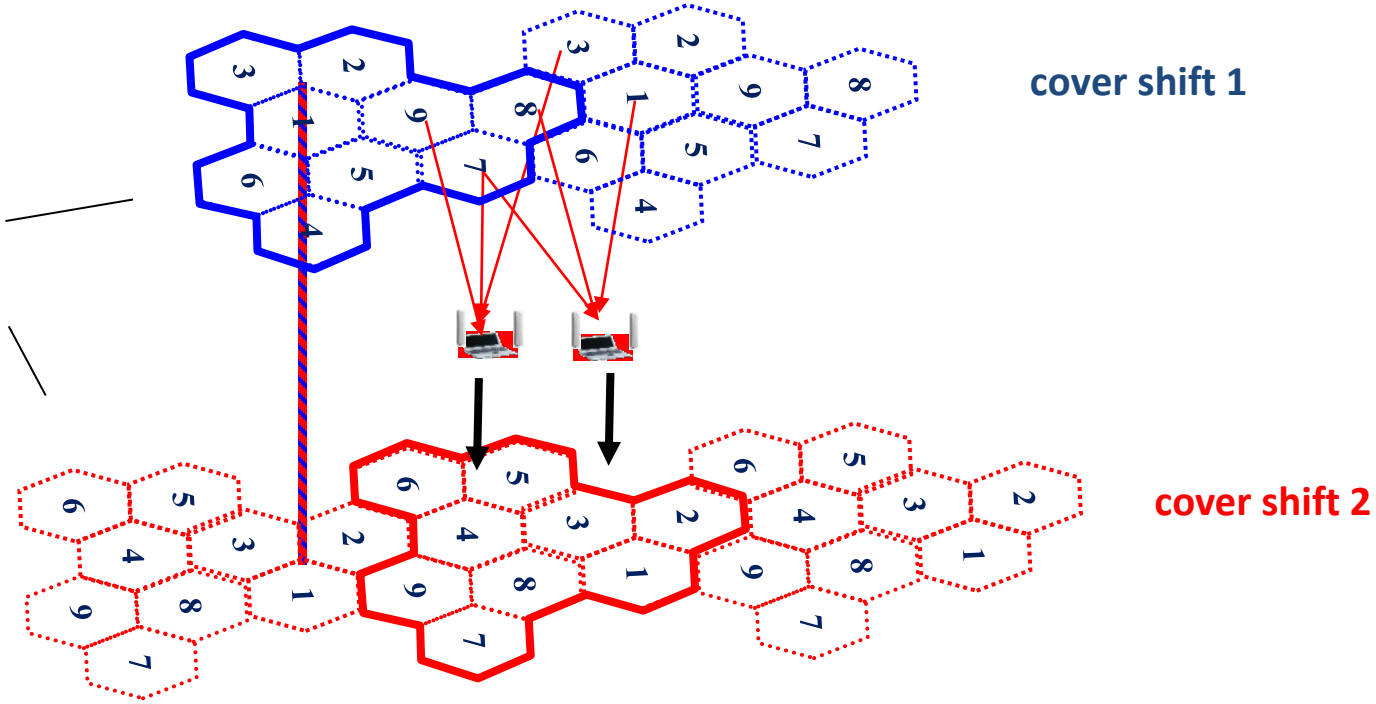
Solution Step 2): Cover Shifts

Cover shifts are orthogonal resources like frequency subbands or time slots used for *overlapping* setup of cooperation areas

eNBs schedule UEs into one or more best fitting cover shift(s)

→ e.g. 90% of UEs served user centric (3 strongest cells within CA)

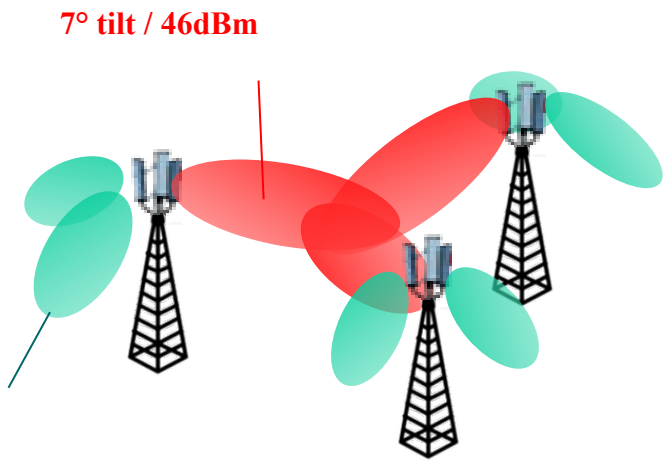
With six cover shifts all UEs having their 3 strongest cells within 3 adjacent sites are being served user centric

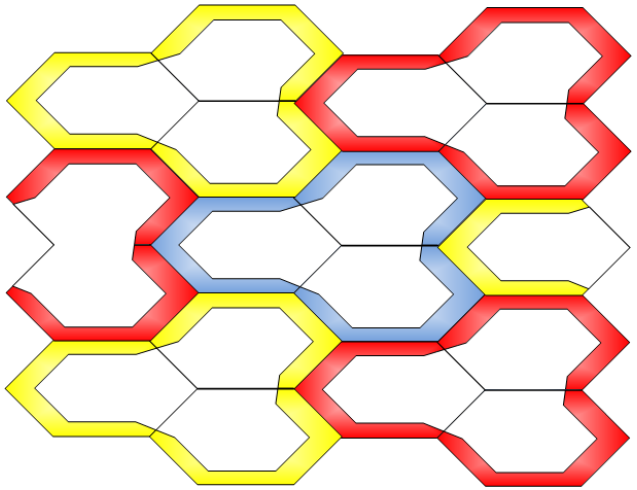


Note: this remains a frequency reuse 1 system!

Interference Floor Shaping

- Inter-CA interference limits gains, even for large CAs
- Frequency-dependent downtilts at each Cover shift edge using 3D beamforming
- Simpler alternative (less spectrally efficient): Fractional frequency reuse at each Cover shift edge





Potential of Multi-node Cooperation in mm-wave Systems

- With narrow beamforming mm-wave links, potentially less need for interference coordination(?), but also less knowledge of CSI
- Standalone (Homogeneous)
  - Macro-diversity gains towards shadowing/blocking
  - Power gains: potential EIRP limited
  - Increase multipath and thus (distributed) MIMO rank to better support (distributed) spatial multiplexing and massive MIMO gains at sparse mmWave channels
  - Spider handover
  - Load balancing
- Non-standalone (Heterogeneous macro/mm-wave) adds:
  - Low latency and robust out-of-band control
  - Coverage of mm-wave blind spots
  - Hybrid links for macro-diversity and rain fading diversity
- Integrated design of mm-wave backhaul and access can enable efficient user data delivery for cooperative communications

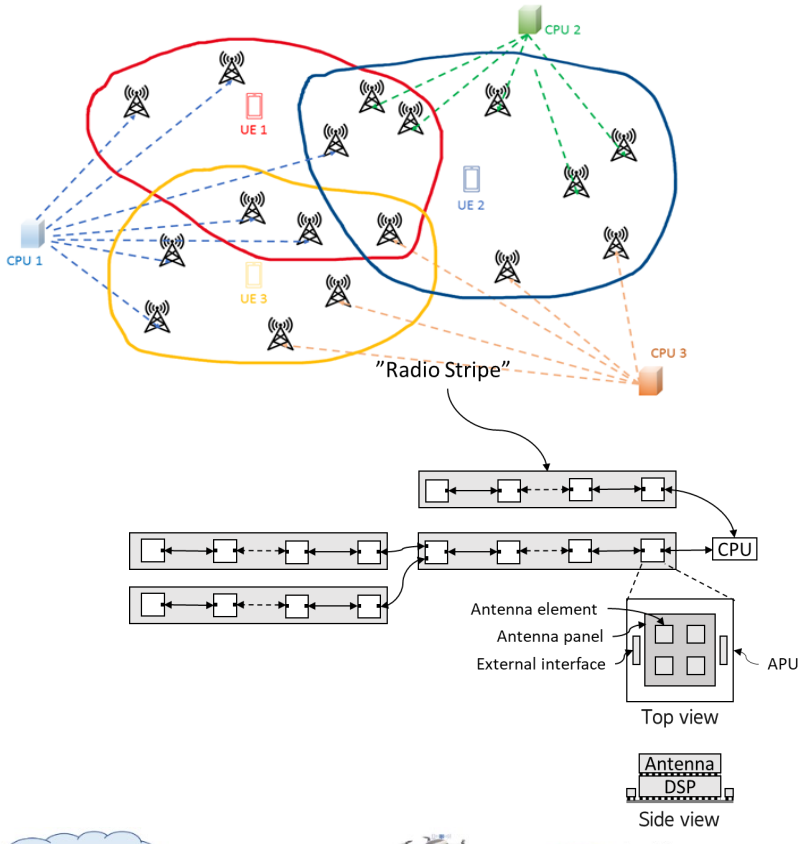
D-MIMO Radio Architecture Studies

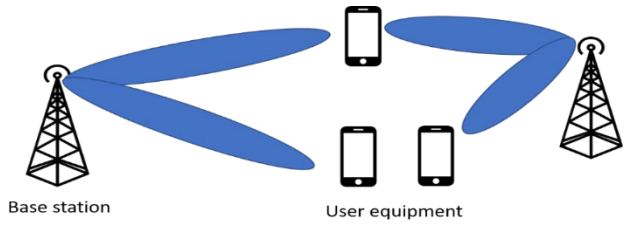
Potential benefits with D-MIMO:

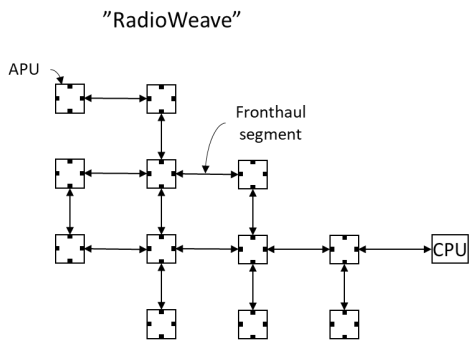
- Mitigate unreliable links due to shadowing/blockage thanks to macro diversity.
- Further densification of APs for increased and consistent area capacity.
- Achieve sufficient link margin despite output power limitations and high pathloss at upper mmW and (sub-)THz frequencies.
- Allows for lowering the EIRP, which simplifies deployment.

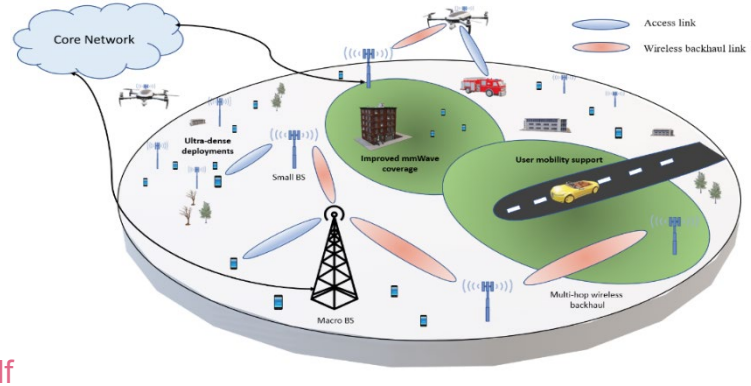
Recent results on key technical components in D2.2:

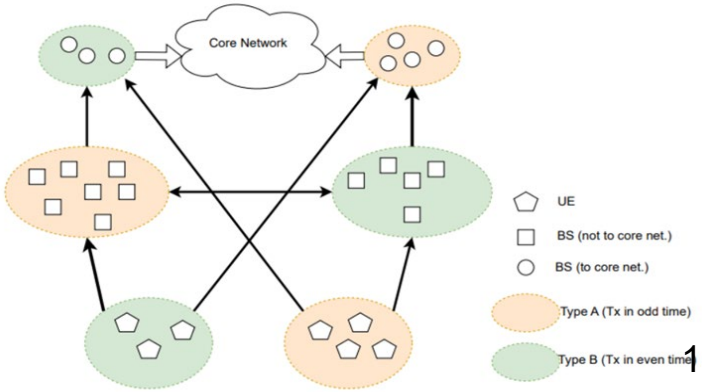
- Analog centralized beamforming
- Distributed digital beamforming
- Integrated access and backhauling









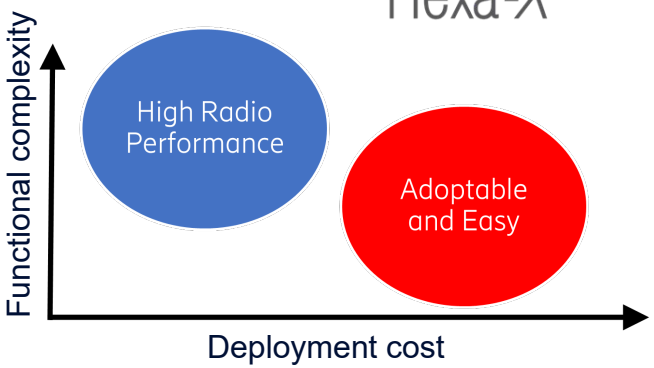


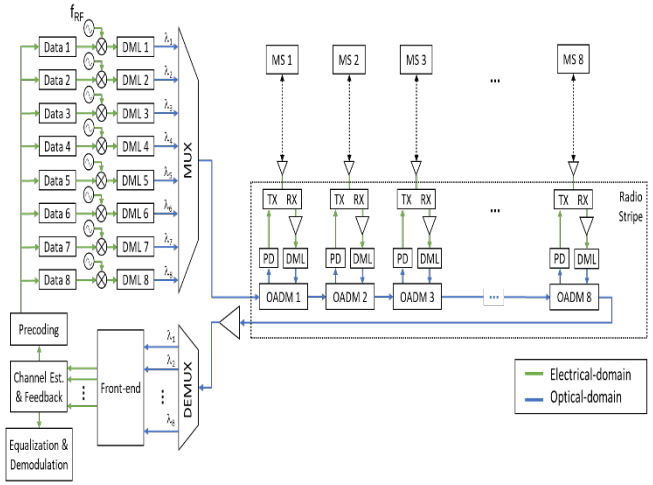
https://hexa-x.eu/wp-content/uploads/2022/01/Hexa-X-D2_2.pdf

D-MIMO Radio Architecture Studies

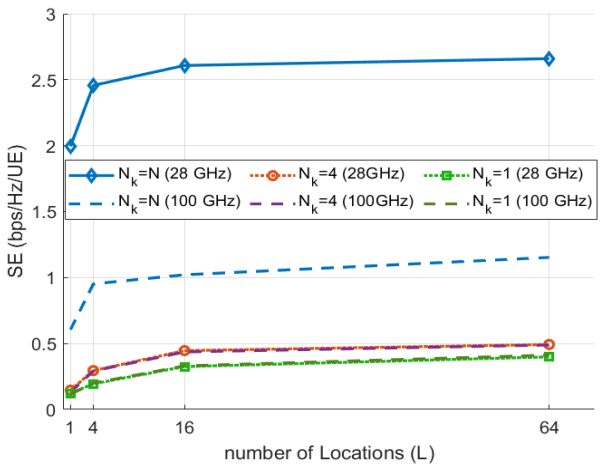
D2.2 Contributions on D-MIMO:

- Challenges and opportunities with D-MIMO and its potential role in 6G
- The different challenges at lower and upper mmW/THz bands were highlighted, calling for a scalable approach from digital to analog approaches.
- Emphasized the need for efficient backhaul fronthaul solutions by integrating fiber and in-band wireless solutions.

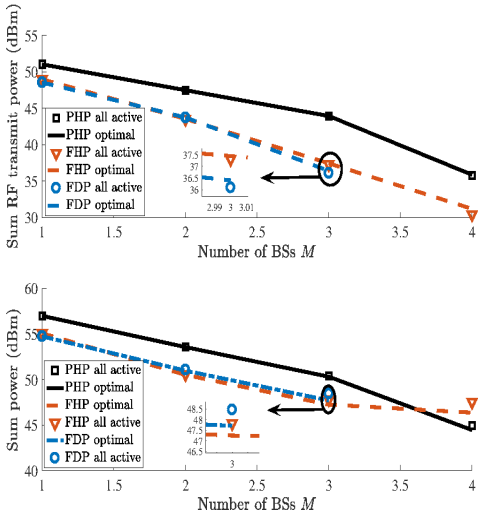




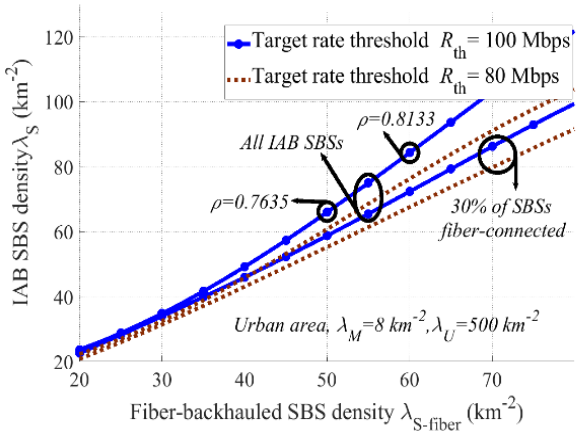
Wide bandwidth D-MIMO system implemented using analog radio over fiber (ARoF) and WDM.



Spectral efficiency for collocated (L = 1), partially (L = {4, 16}) and fully distributed (L = 64) interference aware distributed zero-forcing for different operating frequencies with cluster sizes N_k = {1, 4, 64}.



Comparison of power efficiency of optimized fully digital, and fully/partly connected hybrid beamforming (FDP/FHP/PHP), with/without silence mode activated vs node density.



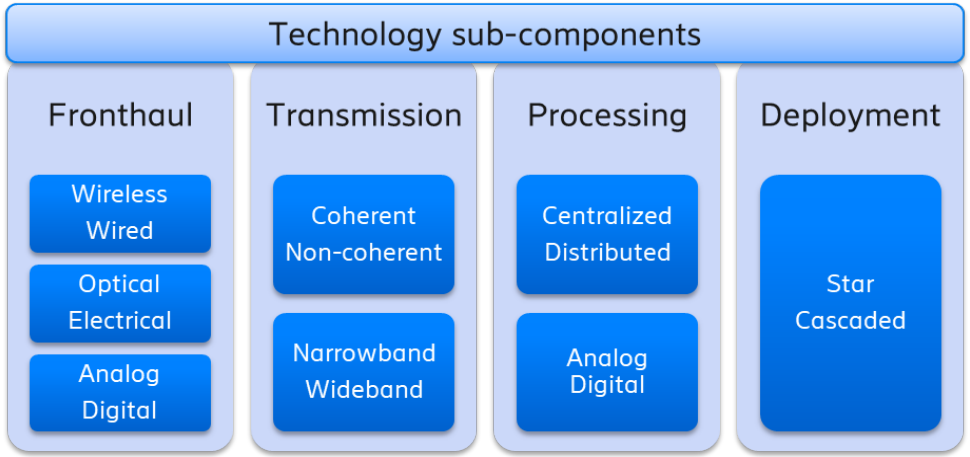
Service coverage probability as a function of percentage of fractional fibre-backhauled small cell base stations for IAB.

Recent results in D2.3, https://hexa-x.eu/wp-content/uploads/2023/04/Hexa-X-D2_3_v1.0.pdf:

- Layer-1 mobility and non-coherent joint transmission
- Channel estimation for D-MIMO in dynamic scenarios
- Analog D-MIMO: Conformance testing and validation
- Comparison study of network controlled repeater (NCR) and reconfigurable intelligent surface (RIS)
- Mesh based integrated access and backhaul (IAB) with multi-connectivity access
- Constrained IAB deployment optimization

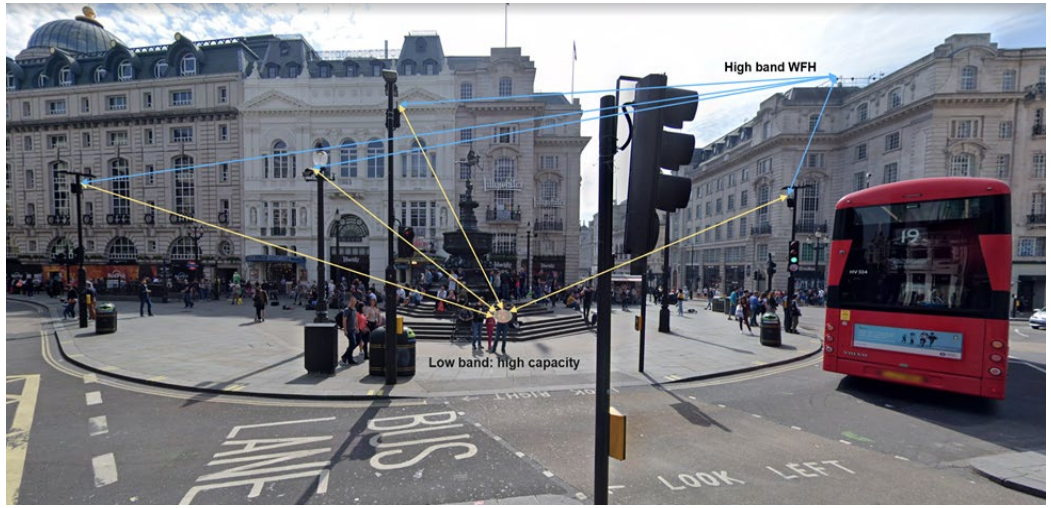
D-MIMO Radio Architecture Studies

Architectural options for D-MIMO

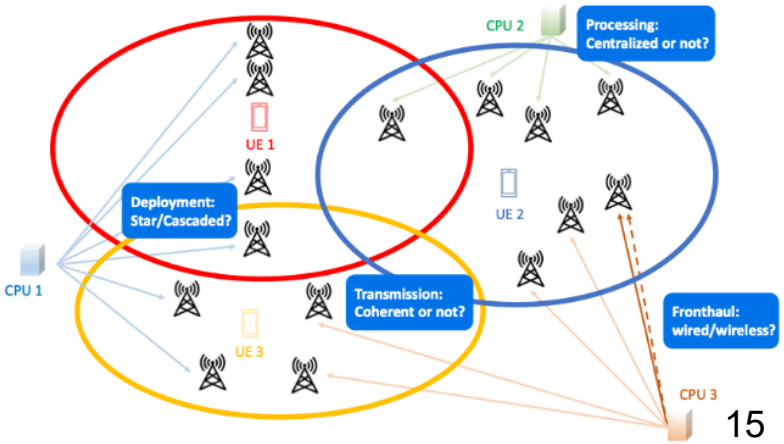


1. Transport media: The backhaul/fronthaul can either be wired or wireless.
2. Signalling: Digitally encoded or analogue signal modulated onto a carrier.
3. Processing: Can either be performed analogue/digital or centralized/distributed.
4. Transmission: Coherent or non-coherent

D-MIMO with wireless fronthaul operating at high bands while access links at low bands.



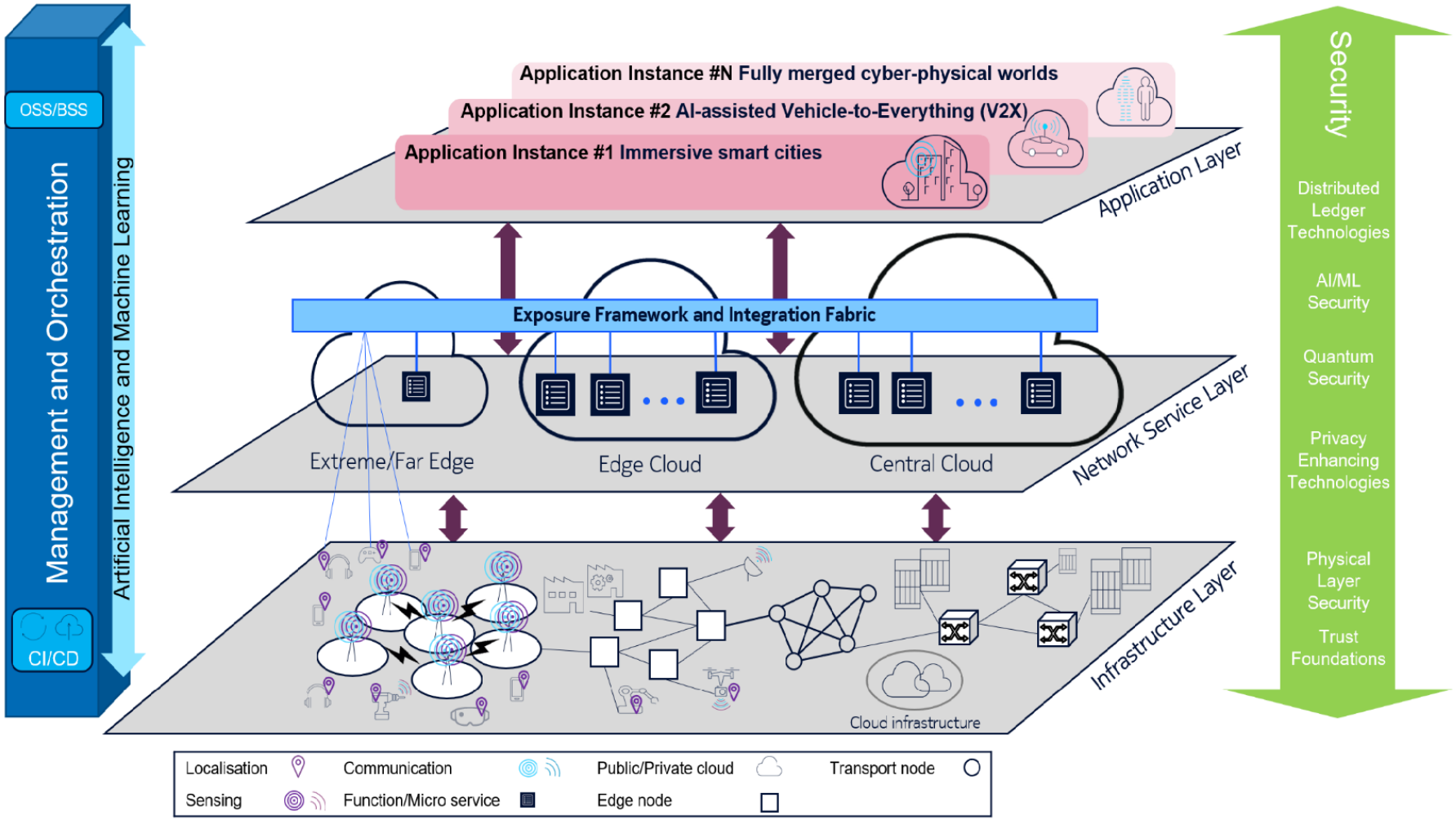
Distributed MIMO with key design options



Conclusions

- Densification key enabler to meet coverage and reliability targets at higher frequency bands — there seems to be sufficient spectrum available.
- Thus, low-cost solutions are more important than spectral efficiency, at least in the early roll-out phases.
- In the lower mmW bands the need for higher spectral efficiency calls for digital less distributed approaches.

Integration in End-to-end Architecture



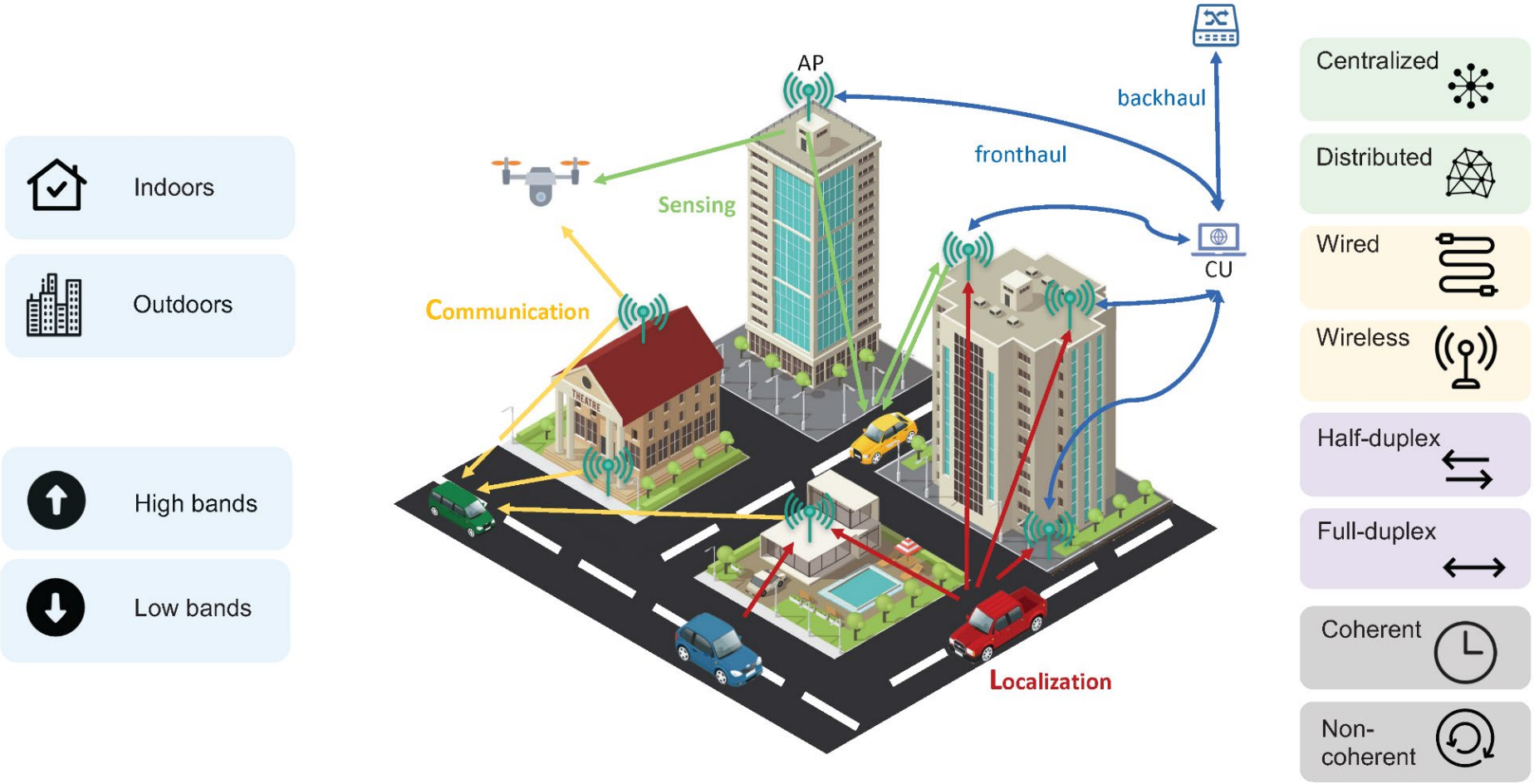
D2.1 Large D-MIMO Gap Analysis

Research on distributed large MIMO systems for Beyond 5G/6G are still needed to be conducted in several areas

- Scalability for availability, such as distributed joint precoder/decoder design without CSI exchange
- Precoding schemes (especially for the upper mmW bands) including joint multi-tx/multi-rx with HW and backhaul-fronthaul constraints awareness
- Precoding (and other resource allocation) schemes in case of multi-antenna UEs
- UE beamforming
- 3D cell-free massive MIMO systems employing vertical coordination/cooperation
- Wireless mesh networking in converged backhaul/fronthaul and access for reliability
- IAB in cell-free massive MIMO, including full duplex
- Converged IAB for cell-free massive MIMO, in which nodes can act as both access and backhaul nodes
- Cell-free massive MIMO using (sub-)THz bands for backhaul/fronthauling, access and joint access/backhaul/fronthauling
- Heterogeneous spectrum use in cell-free massive MIMO systems, in which lower bands are used to assist and coordinate access/backhaul/fronthauling at higher bands
- Distributed large MIMO systems using Reconfigurable Intelligent Surfaces (RIS)
- Interference handling in integrated access backhaul and pure fronthaul in mesh configurations operating beyond 100 GHz using beamforming/MIMO
- Dynamic blocking mitigation in mmW bands, enabled e.g. by location and mapping information
- Mobility support in cell-free massive MIMO systems

https://hexa-x.eu/wp-content/uploads/2021/06/Hexa-X_D2.1.pdf

Integrated Communication, Localization, and Sensing in 6G D-MIMO Networks



H. Guo, H. Wymeersch, B. Makki, H. Chen, Y. Wu, G. Durisi, M. F. Keskin, M. H. Moghaddam, C. Madapatha, H. Yu, P. Hammarberg, H. Kim, T. Svensson, "Integrated Communication, Localization, and Sensing in 6G D-MIMO Networks", https://arxiv.org/abs/2403.19785

SUITABILITY MATRIX OF ARCHITECTURAL OPTIONS COMBINATIONS WITH IMPLEMENTATION COMMENTS: EVALUATING COMMUNICATION AND LOCALIZATION & SENSING

Both options are feasible/possible

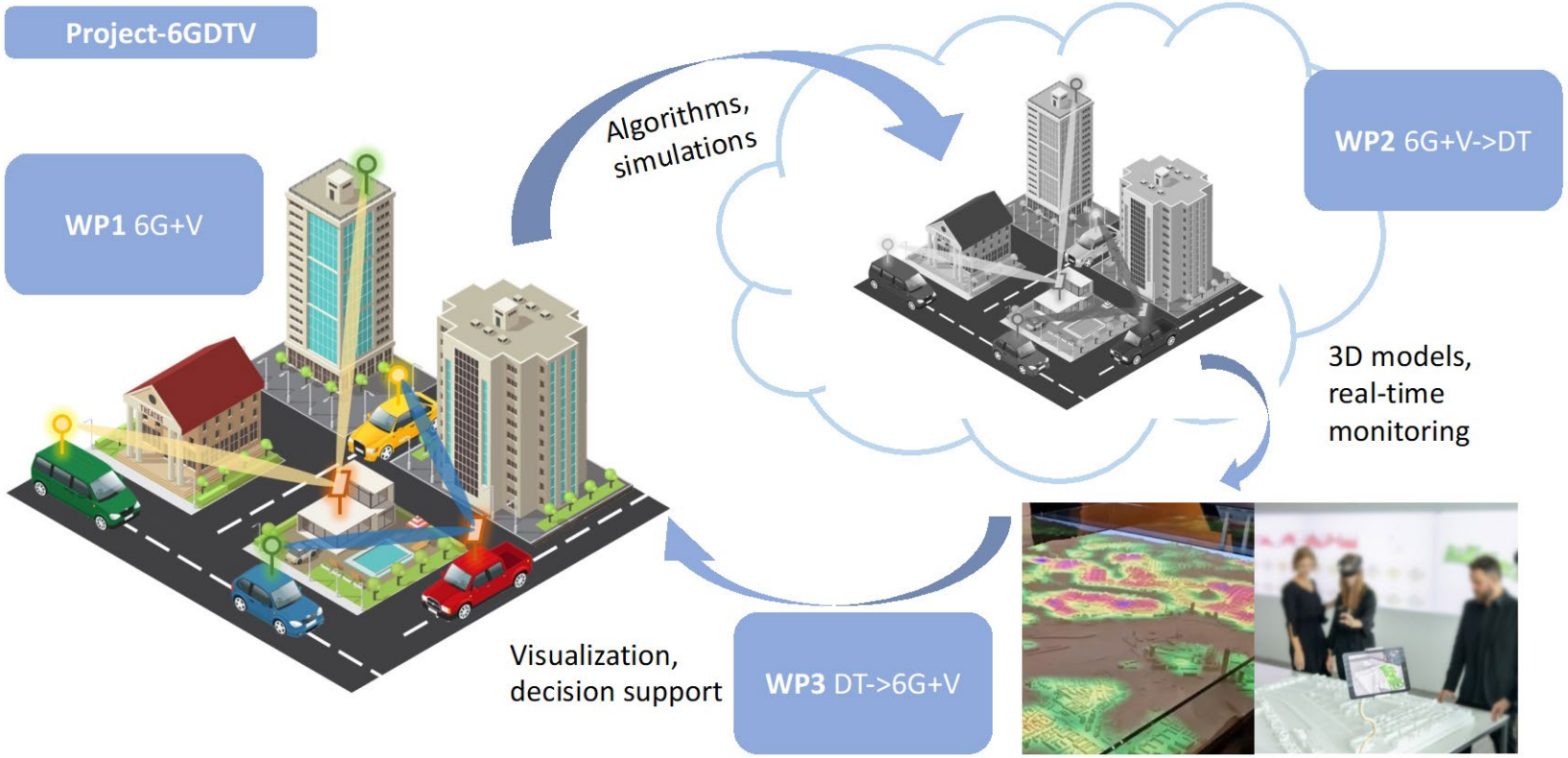
One of the options is preferable

	Indoor vs. Outdoor	**Higher bands vs. Lower bands**
Centralized	**Both options** are *feasible* **Com.**: improves spectral efficiency/dynamic blocking mitigation **L&S**: suitable for time- and phase-coherent processing, only lower mobility	**Higher bands** *preferred* (dense APs and low cost) **Com.**: fast control of narrow beams, but high requirements on backhaul/fronthaul **L&S**: phase-coherent capability
Distributed	**Both options** are *possible* **Com.**: improves scalability (less reliability for indoor) **L&S**: suitable for time-coherent processing	**Lower bands** *preferred* (less dense APs/high resolution converters) **Com.**: Lower data rates allow for more advanced APs, resulting in low backhaul requirements, but interference might limit spectral efficiency **L&S**: suitable for time-coherent processing
Wireless front- and backhaul	**Outdoor** *preferred* (*less blockers*) **Com.**: low cost and fast deployment, but less reliability **L&S**: time-coherent processing	**Higher bands** *preferred*, (IAB feasible, less restricted sync requirements) **Com.**: low cost and fast deployment, but less reliability **L&S**: time-coherent processing
Wired front- and backhaul	**Indoor** *preferred* (might be costly for outdoors) **Com.**: improves reliability and backhaul fronthaul capacity **L&S**: supports tight sync requirements for phase-coherent processing	**Both options** are *feasible* **Com.**: improves reliability and backhaul fronthaul capacity, important especially in higher bands **L&S**: not needed for higher bands, except for certain challenging cases or use of artificial intelligence (AI)
Half- Duplex	**Both options** are *possible* **Com.**: lower cost, but increased delays **L&S**: suitable for time- and phase-coherent processing	**Both options** are *possible* **Com.**: lower cost, but increased delays **L&S**: suitable for time-coherent processing (higher bands) phase-coherent processing (lower bands)
Full- Duplex	**Indoor** *preferred* (due to low transceiver signal strength difference) **Com.**: lower latency **L&S**: enables monostatic sensing, severe leakage challenges	**Higher bands** *preferred* (due to beam-based spatial transceiver isolation and short hops) **Com.**: flexible time division duplex (TDD) deployment **L&S**: enables monostatic sensing, severe leakage challenges
Non- coherent	**Both options** are *possible* **Com.**: lower cost but might result in insufficient reliability **L&S**: suitable for time-coherent processing	**Higher bands** *preferred* (low spectral efficiency and resolution in Lower bands) **Com.**: lower cost and might be sufficient for narrow beams and spatial multiflow **L&S**: suitable for time-coherent processing
Coherent	**I** **ndoor** *preferred* (due to short inter-AP distances) **Com.**: improves reliability **L&S**: suitable for time- and phase-coherent processing	**Lower bands** *preferred* (due to lower carrier frequency) **Com.**: improves reliability **L&S**: suitable for time- and phase-coherent processing

H. Guo, H. Wymeersch, B. Makki, H. Chen, Y. Wu, G. Durisi, M. F. Keskin, M. H. Moghaddam, C. Madapatha, H. Yu, P. Hammarberg, H. Kim, T. Svensson, "Integrated Communication, Localization, and Sensing in 6G D-MIMO Networks", https://arxiv.org/abs/2403.19785

(RF) Digital Twinning for Context-aided Communications?

Context-information: Any information that can guide the communications without explicit instantaneous measurements to adapt the use of time, frequency, and spatial resources.

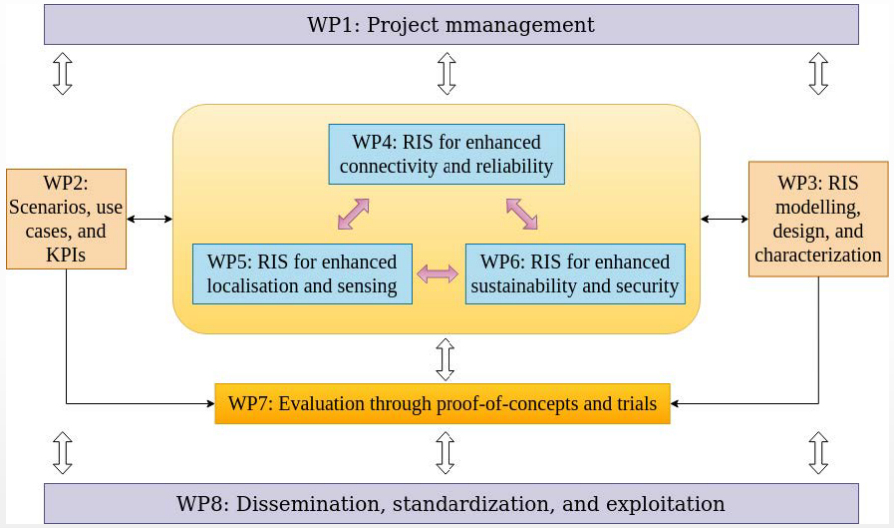


- Digital Twinning-assisted pro-active resource allocation
- Visualization and decision support tool

AoA TP DT6GV Project 2024-2025:
Towards Intelligent and Safe Urban Transport System: Where Digital Twining and 6G Vehicular Communications Meet

H. Guo and T. Svensson, "The Potential of Context-Aided Communications," 2023 International Workshop on Antenna Technology (iWAT), Aalborg, Denmark, 2023, pp. 1-3.

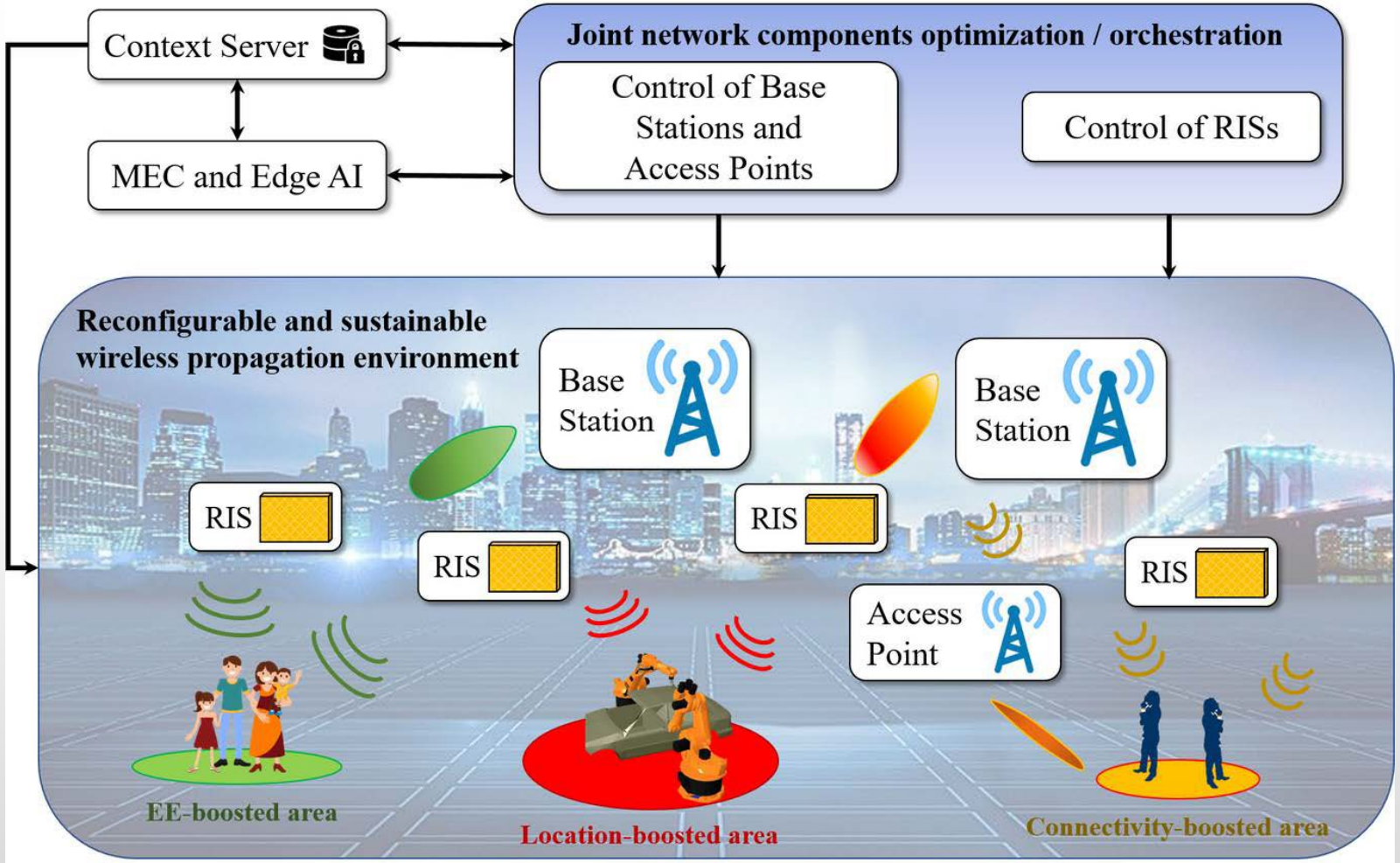
Reconfigurable Intelligent Sustainable Environments for 6G Wireless Networks



Coordinator: CEA-LETI
Duration: Jan 2021-Dec 2023

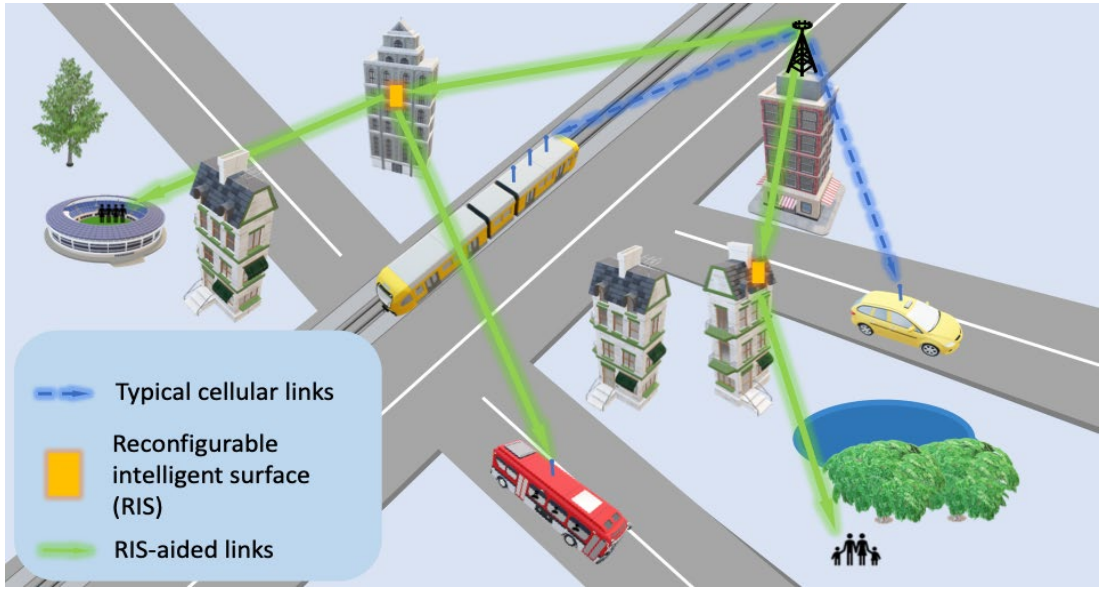
The Potential of Reconfigurable Intelligent Surfaces

- Surfaces comprised of hundreds or thousands of simple and ultra-low power circuitry elements with reconfigurable properties.
- Coat objects in the signal propagation environment, such as walls, mirrors, ceilings, or appliances.
- Anomalous reflector of impinging radio waves or as an analog processor of multipath scattering.
- Potentially play the role of a transmitter/ receiver/ sensor when equipped with relevant active radio-frequency elements.
- Supports a wide variety of functionalities:
  - Beamforming
  - Range/position estimation
  - Radio-frequency mapping/sensing
  - Obstacles/activity detection
  - Scattering enrichment
- Particularly suitable for:
  - Limiting EMF exposure.
  - Controlling wave propagation and channel geometry.
  - Reducing the transmission power at existing base stations and access points.



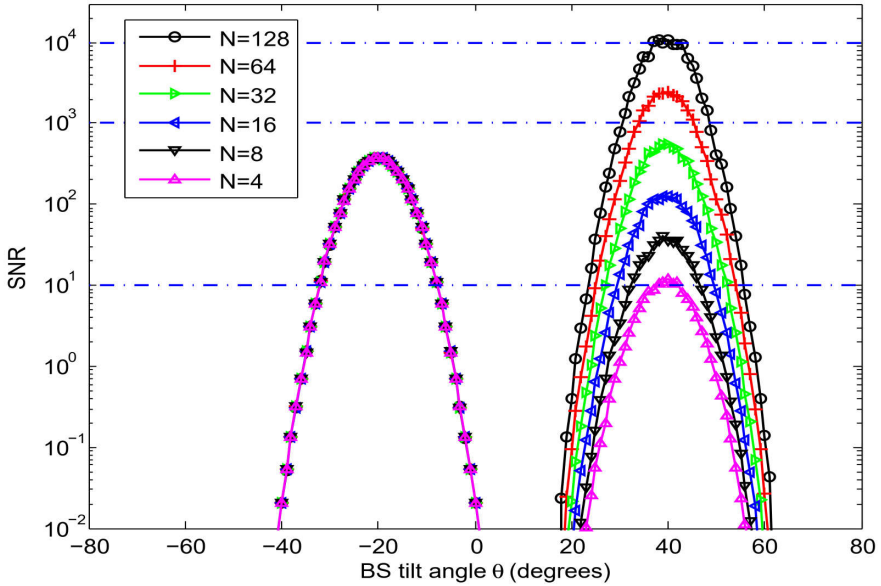
Potential of Reconfigurable Intelligent Surfaces in mm-wave Systems

- Fundamentally, RIS is a special case of D-MIMO, however
  - RISs can potentially accomodate much more radio elements than antenna arrays
  - Be deployed in new places and by other actors



- Sufficient number of RIS elements are needed for an overall gain

The effect of the # of RIS elements N on the received SNR with the optimum phase shifts at the RIS.



S. M. Razavizadeh, T. Svensson, "3D Beamforming in Intelligent Reconfigurable Surface-assisted Wireless Communication Networks", WSA'2020.

Recent work at Chalmers related to RIS:

- Dynamic blockage avoidance

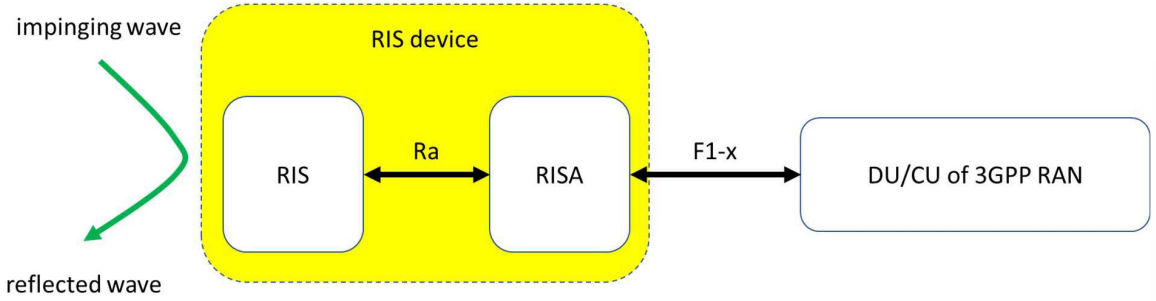
  H. Guo, B. Makki, M. Åström, M.-S. Alouini, and T. Svensson, "Dynamic blockage pre-avoidance using reconfigurable intelligent surfaces," submitted to IEEE Communications Magazine, 2022, arXiv:2201.06659.
- Electromagnetic Field Exposure Avoidance

  H. Guo, D. -T. Phan-Huy, and T. Svensson, "Electromagnetic Field Exposure Avoidance thanks to Non-Intended User Equipment and RIS," IEEE GLOBECOM Workshops, 2022.
- Network-controlled repeaters and reconfigurable intelligent surfaces

  H. Guo, C. Madapatha, B. Makki, B. Dortschy, L. Bao, M. Åström, T. Svensson, "A Comparison between network-controlled repeaters and reconfigurable intelligent surfaces," Nov. 2022, arxiv.org/abs/2211.06974
- RIS-Assisted Jammer Interference Mitigation

  A. Tabeshnezhad, A. L. Swindlehurst and T. Svensson, "RIS-Assisted Interference Mitigation for Uplink NOMA," 2023 IEEE Wireless Communications and Networking Conference (WCNC), Glasgow, United Kingdom.

RISE-6G D2.5: RIS Functional Elements



- **RIS (device):** reflect-array or meta-material directly controlled by an associated RIS actuator.
  - Expected time granularity between 100 microseconds and 10 ms.
- **RIS actuator (RISA):** in charge of actuating the logical commands received from a RISC, translating them into RIS configurations such as phase shifts or ad-hoc meta-material state changes.
  - Can provide feedback or limited sensing to the RISC.
  - Controlled by the RISC with an action time granularity between 1 and 20 ms.
- **RIS controller (RISC):** controls the RIS actuator with logical commands associated to the switching operations between the configurations/states of the RIS elements (e.g., predefined phase shifts).
  - RISC may have different levels of complexity and capabilities and can embed third-party apps to implement smart algorithms.
  - Can be controlled by other elements in the network (Controlled RIS), or operate on its own (Autonomous RIS). The expected action time granularity is between 20 ms and 100 ms.
- **RIS orchestrator (RISO):** placed on a higher (hierarchical) layer and orchestrates multiple RISCs. Action time granularity is expected to be between 100 ms and a few seconds.

T. Svensson, M. Crozzoli, V. Sciancalepore, M.-H. Hamon, D.-T. Phan Huy, Guillaume Grao, Philippe Ratajczak, Rita Ibrahim, G. C. Alexandropoulos, K. Katsanos, B. Denis, D. Micheli, A. Allasia, Fabio Saggese, Petar Popovski, EU H2020-ICT-2020-2-101017011 RISE-6G, D2.5 "RISE network architectures and deployment strategies analysis: first results", July 2022

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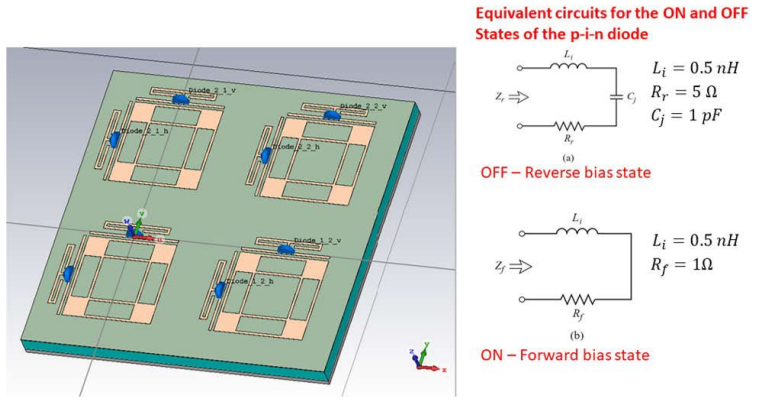
RISE-6G D2.5: RIS Hardware Category and Control Channel Taxonomy

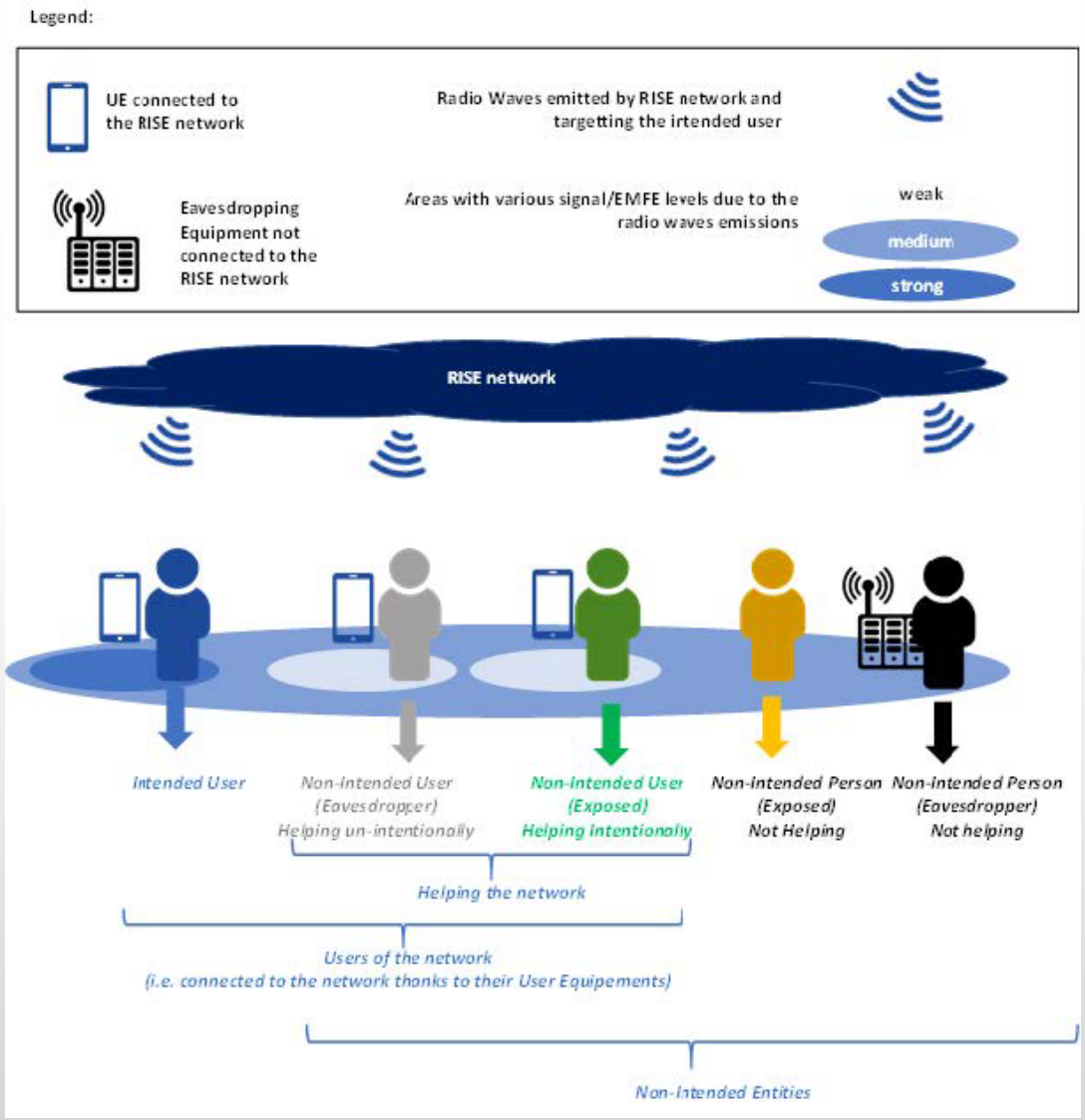


Hardware category	General definition	Capabilities
nearly-passive	No RF chains, only ultra-low-power elements to change the reflection states.	Changing the reflection state of RIS elements.
hybrid	No RF chains, limited sensing capabilities.	Changing the reflection state of RIS elements (like nearly-passive RIS) but with an additional limited sensing capabilities to detect (Tx/Rx) signal Angle-of-Arrival. This might be used for self-configuration and extended to many different use cases.
quasi-active	RF receiving chains are included in the RIS.	Changing the reflection state of RIS elements; it can also collect measurements in baseband for performing sensing/parameters estimation (in time-orthogonal manner with reflection or simultaneously); it can also have processing capabilities to perform localization, channel estimation, etc.
active	RF transmitting chains are included in the RIS.	Changing the reflection state of its elements; it can also perform reflection amplification or transmit its own signals.

Implicit CC		There is no dedicated CC or signal over which explicit instructions are sent to the RISC (but the synchronization signal). As such, all decisions wrt. RIS(A) operations must be made locally by the RISC; however, these decisions can be based on other received and interpreted signals (e.g. pilot symbols, user equipment (UE) scheduling information) which implicitly (indirectly) control the behavior of the RIS.
Explicit CC	Out-of-band	Any communication channel, either wireless or wired, that does not consume resources from the primary communication channel that is influenced by the RIS; examples include: wired channel, wireless channel in a different frequency band, free-space optical, etc. This allows for simpler CC design, but at the cost of possibly lower spectral efficiency.
	In-band	The CC employs resources overlapping RIS operational spectrum resources, so it does influence the operation of the RIS. This implies a more complex CC design, but with possibly higher spectral efficiency.

T. Svensson, M. Crozzoli, V. Sciancalepore, M.-H. Hamon, D.-T. Phan Huy, Guillaume Grao, Philippe Ratajczak, Rita Ibrahim, G. C. Alexandropoulos, K. Katsanos, B. Denis, D. Micheli, A. Allasia, Fabio Saggese, Petar Popovski, EU H2020-ICT-2020-2-101017011 RISE-6G, D2.5 "RISE network architectures and deployment strategies analysis: first results", July 2022

RISE-6G D6.2: Sustainable RIS Solutions for EE, EMFEU and SSE



EE: Energy-Efficiency
EMFEU: Electromagnetic-Field Exposure Utility
SSE: Secrecy Spectral Efficiency

D.-T. Phan Huy, N. Awarkeh, R. Ibrahim, P. Ratajczak, Y. Yu, M. Di Renzo, G. Gradoni, G. Tanner, L. Bastianelli, E. Colella, V. Mariani Primiani, E. Calvanese Strinati, F.-E. Fairod, H. Guo, T. Svensson, R. Kotaba, P. Popovski, G. C. Alexandropoulos, K. D. Katsanos, EU H2020-ICT-2020-2-101017011 RISE-6G, D6.2 "Sustainable RIS solutions design for EE, EMFEU and SSE (Intermediary Specifications)", June 2022

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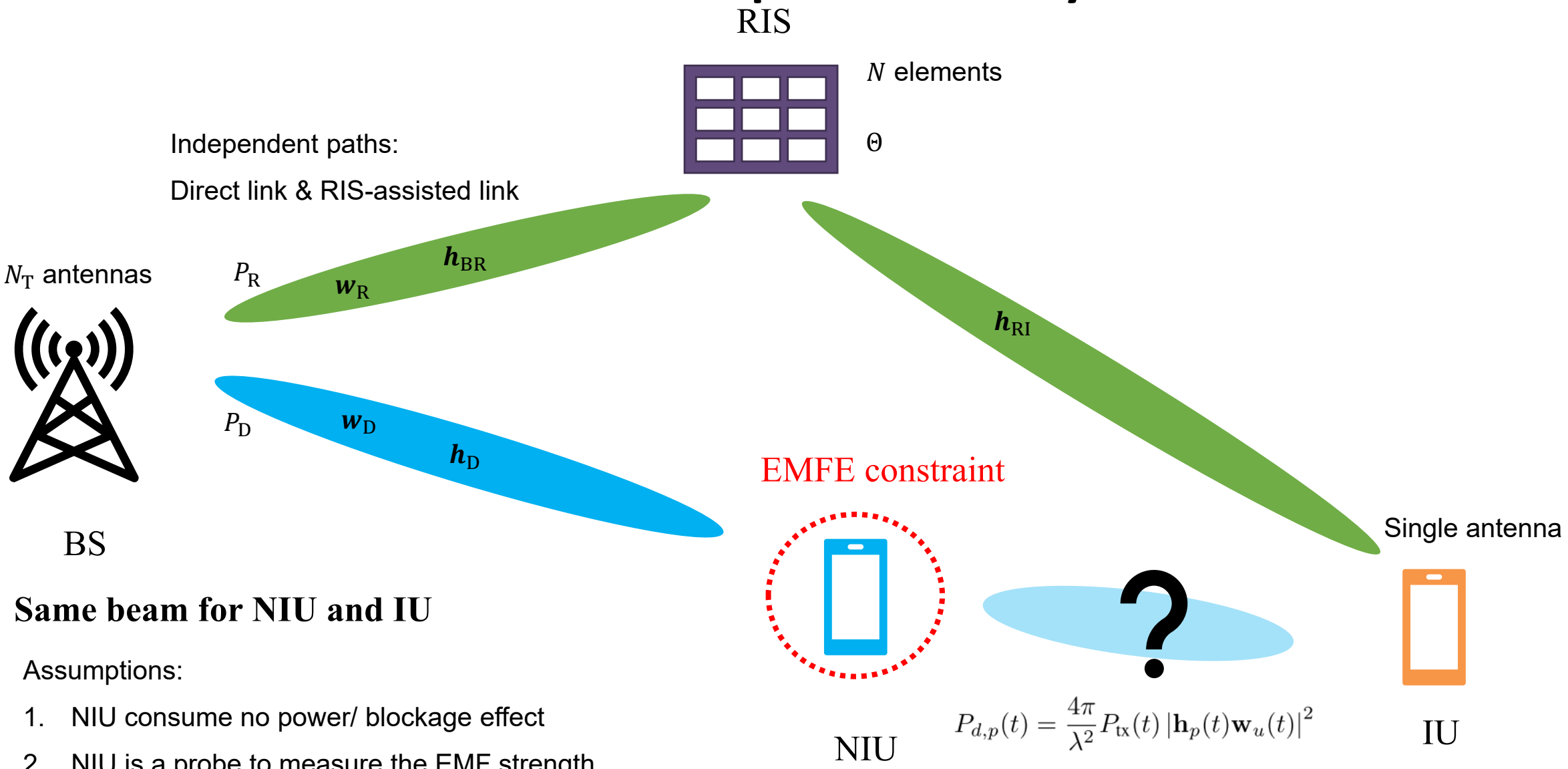
RISE-6G D6.2: RIS-EMFE optimization System Model



$$P_{d,p}(t) = \frac{4\pi}{\lambda^2} P_{tx}(t) \left|\mathbf{h}_p(t)\mathbf{w}_u(t)\right|^2$$

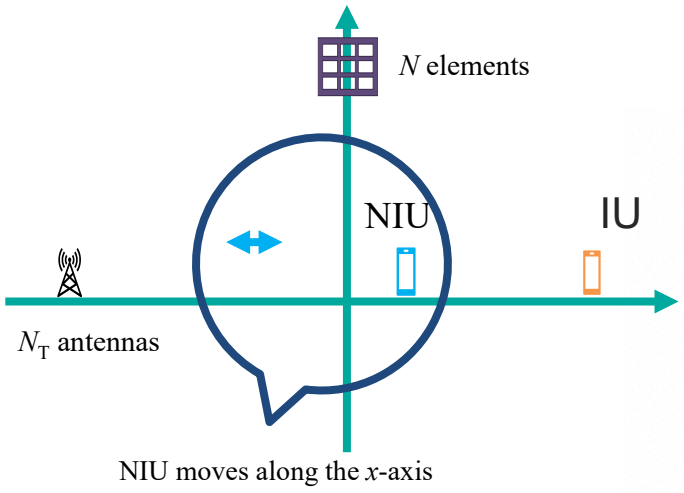
Same beam for NIU and IU

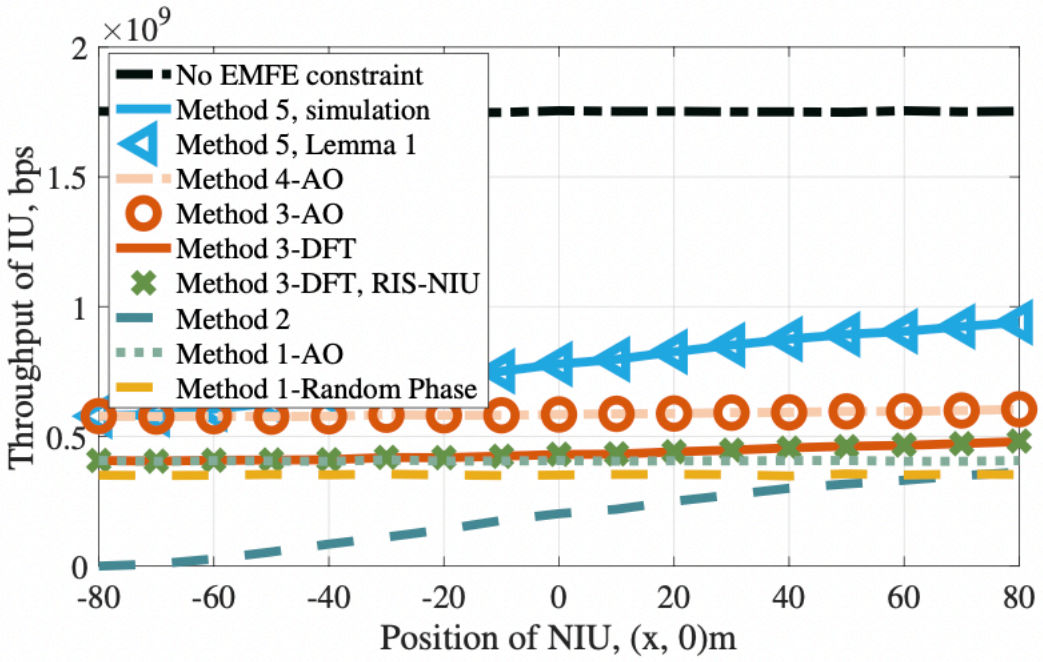
Assumptions:

1. NIU consume no power/ blockage effect
2. NIU is a probe to measure the EMF strength

H. Guo, D. -T. Phan-Huy, and T. Svensson, "Electromagnetic Field Exposure Avoidance thanks to Non-Intended User Equipment and RIS," IEEE GLOBECOM Workshop, Dec 2022.

RISE-6G D6.2:
RIS-EMF Results





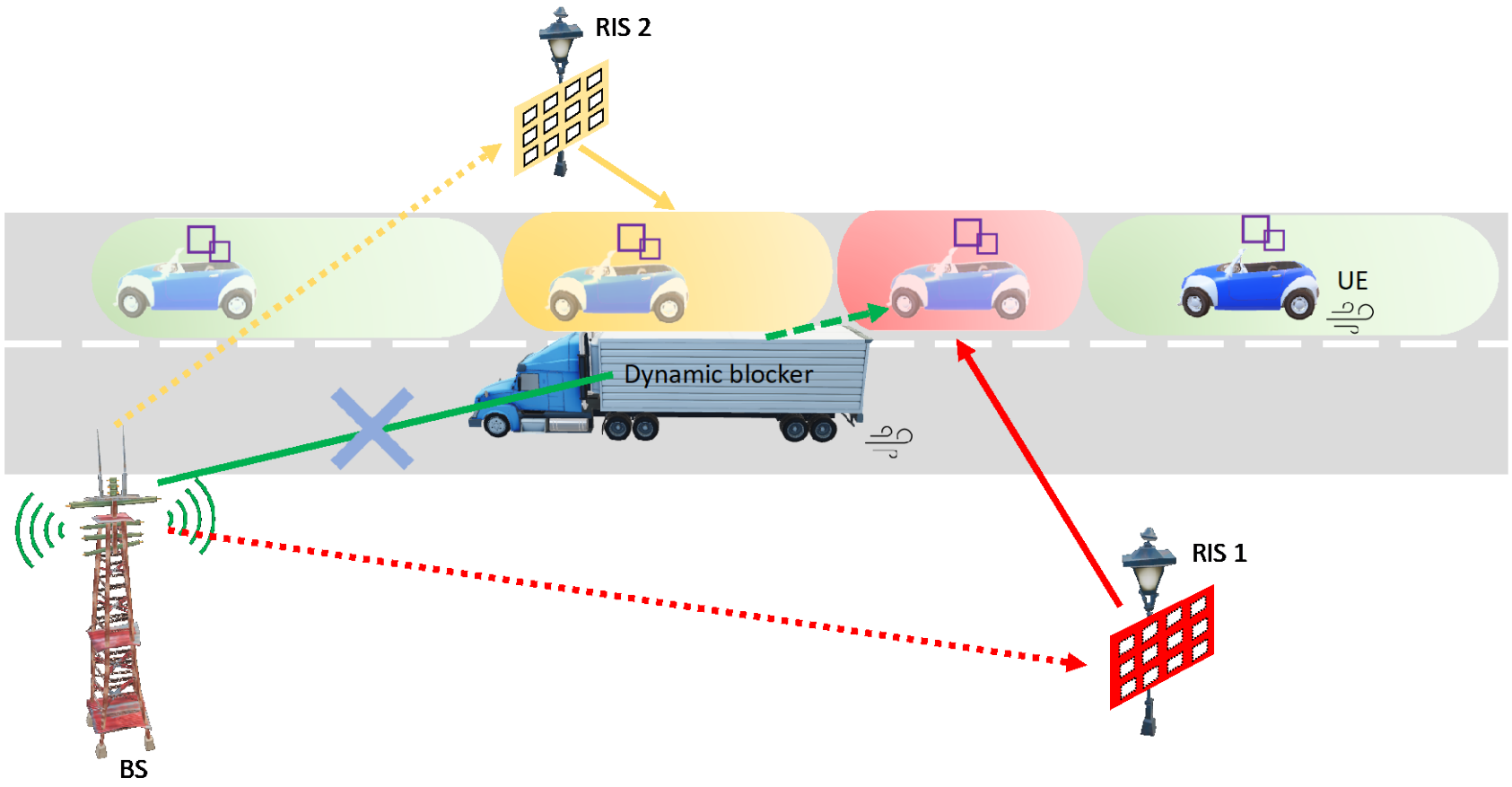
- The EMF constraint decreases with curves moving right
- Better to use the direct link with less EMF constraint
- DFT and AO reach similar performance
- Method 3 and 4 reach similar performance (fill in the direct link first, analytically proved)
- Analytical upper bound is tight with simulations

Conclusion:

- RIS can create more degree of freedom in space when EMF is considered
- It is beneficial to utilize the direct link with better propagation environment
- Comparable performance can be achieved with limited channel information

H. Guo, D. -T. Phan-Huy, and T. Svensson, "Electromagnetic Field Exposure Avoidance thanks to Non-Intended User Equipment and RIS," IEEE GLOBECOM Workshop, Dec 2022.

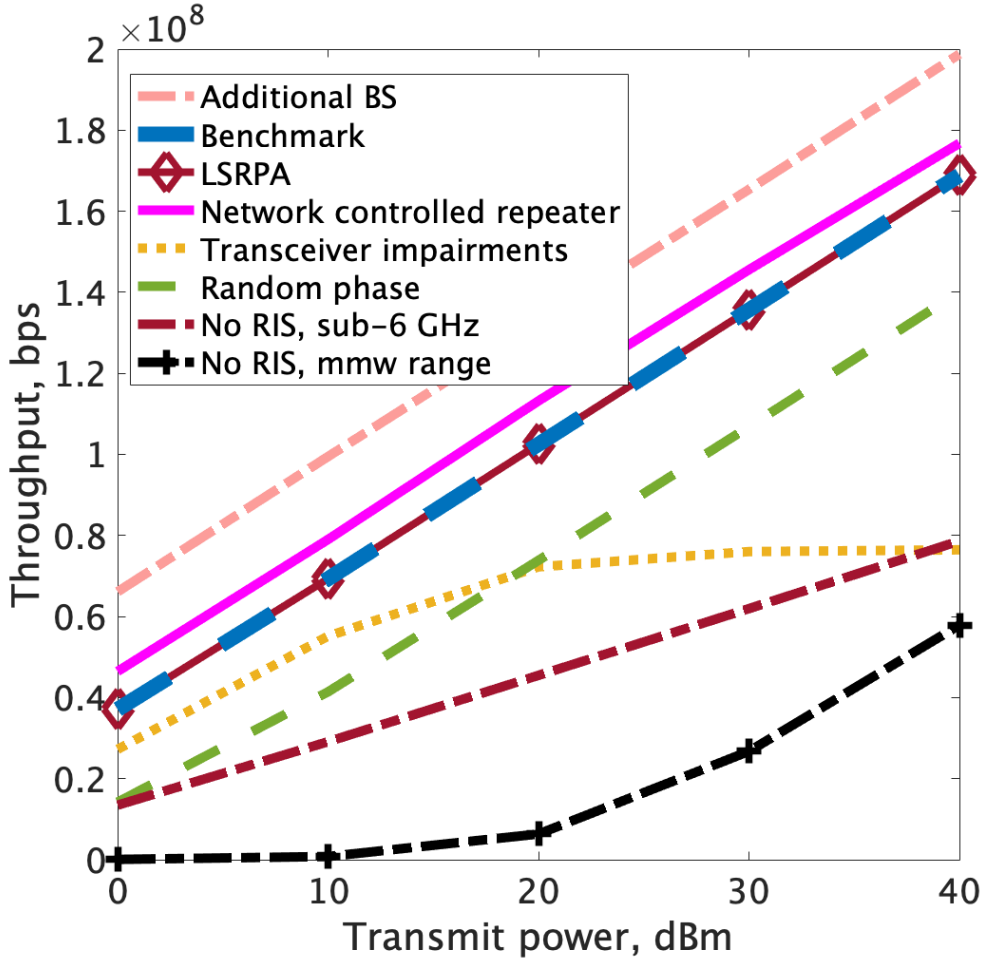
Context-aided Communications: RIS in IoV with Predictor Antenna (PA)



- Potentials and challenges of RIS-based IoV communications in highways with dynamic blockage pre-avoidance
- A large-scale fading-based service region prediction scheme to reduce the CSIT overhead, together with PA
- The hardware aspects of RIS system are also studied

H. Guo, B. Makki, M. Åström, M.-S. Alouini, and T. Svensson, "Dynamic blockage pre-avoidance using reconfigurable intelligent surfaces," submitted to IEEE Communications Magazine, 2022, https://arxiv.org/pdf/2201.06659.pdf.

Selected Results



We propose a large-scale based RIS pre-assignment (LSRPA) with alternative methods:

1. The proposed LSRPA scheme can obtain the same performance compared to the exhaustive method with full configuration (benchmark), but low overhead

2. Additional BS and network controlled repeater outperforms RIS-based method, but more costly

3. Transceiver impairments and random phase could affect the performance remarkably

H. Guo, B. Makki, M. Åström, M.-S. Alouini, and T. Svensson, "Dynamic blockage pre-avoidance using reconfigurable intelligent surfaces," submitted to IEEE Communications Magazine, 2022, https://arxiv.org/pdf/2201.06659.pdf.

Mitigation of Active Jammers for NOMA with Absorbing RIS

Objective: Minimize total transmit power under SINRs constraints

$$\mathbf{\Phi} = \begin{bmatrix} \beta_1 e^{j\theta_1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \beta_M e^{j\theta_M} \end{bmatrix}$$

$$0 \le \beta \le 1$$
$$0 \le \theta \le 2\pi$$

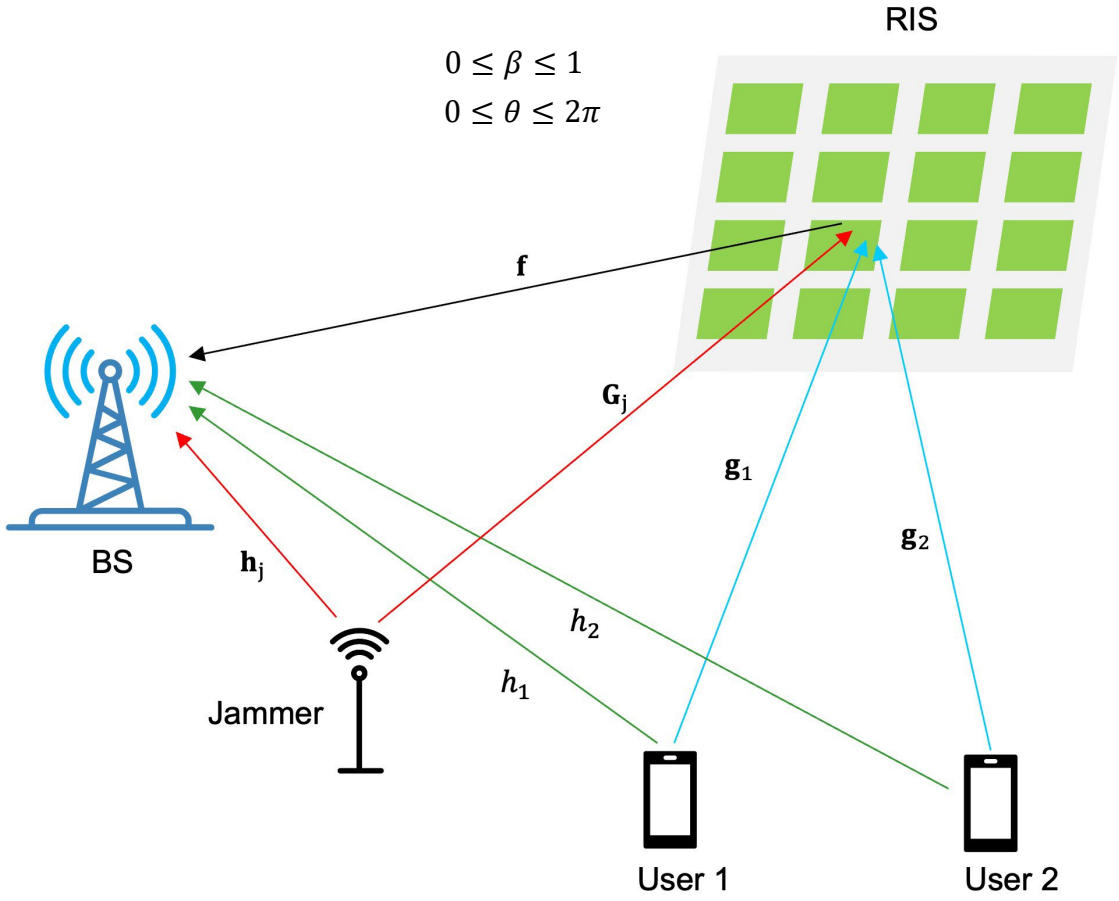
Direct channel from user 1 to BS

$$\mathrm{SINR}_1 = \frac{p_1 |h_1 + \mathbf{f}^T \mathbf{\Phi} \mathbf{g}_1|^2}{\mathrm{P_j} \left\| \mathbf{h}_\mathrm{j}^T + \mathbf{f}^T \mathbf{\Phi} \mathbf{G}_\mathrm{j} \right\|^2 + p_2 |h_2 + \mathbf{f}^T \mathbf{\Phi} \mathbf{g}_2|^2 + \sigma^2}.$$

Channel between jammer- BS

Direct channel from user 2 to BS

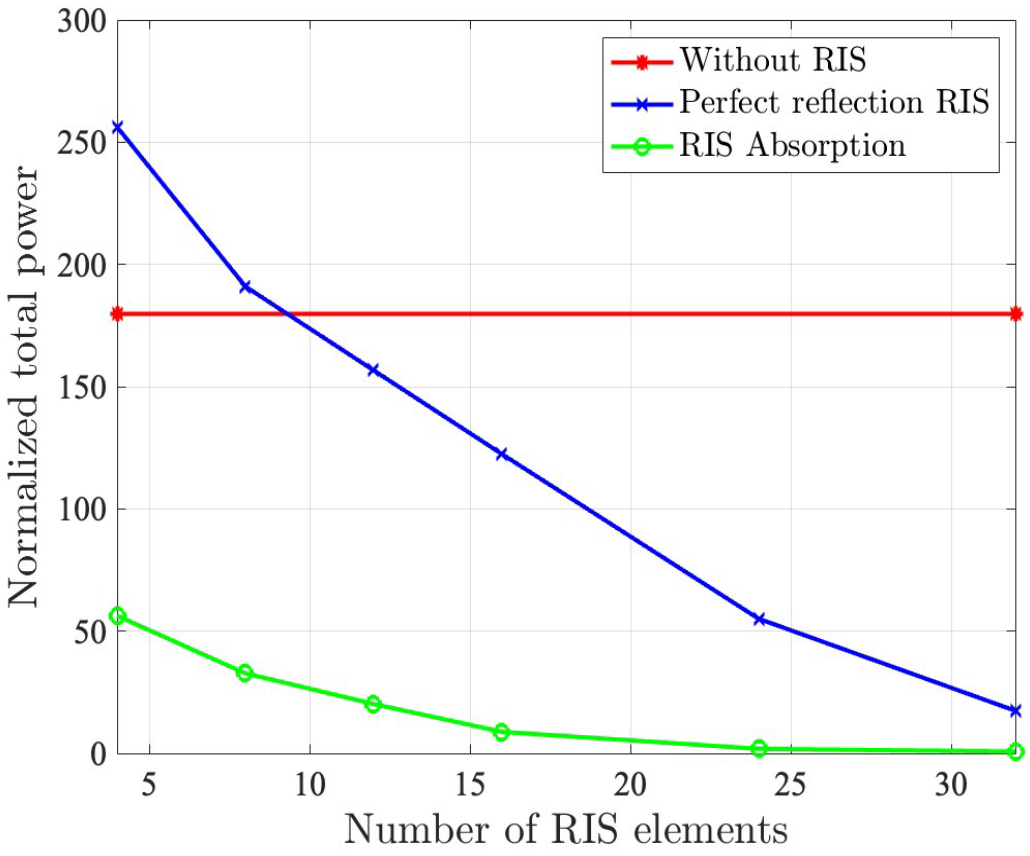
$$\mathrm{SINR}_2 = \frac{p_2 |h_2 + \mathbf{f}^T \mathbf{\Phi} \mathbf{g}_2|^2}{\mathrm{P_j} \left\| \mathbf{h}_\mathrm{j}^T + \mathbf{f}^T \mathbf{\Phi} \mathbf{G}_\mathrm{j} \right\|^2 + \sigma^2}.$$



A. Tabeshnezhad, A. L. Swindlehurst, T. Svensson, "RIS-Assisted Interference Mitigation for Uplink NOMA", IEEE WCNC'2023 Workshops, March 2023. To appear.

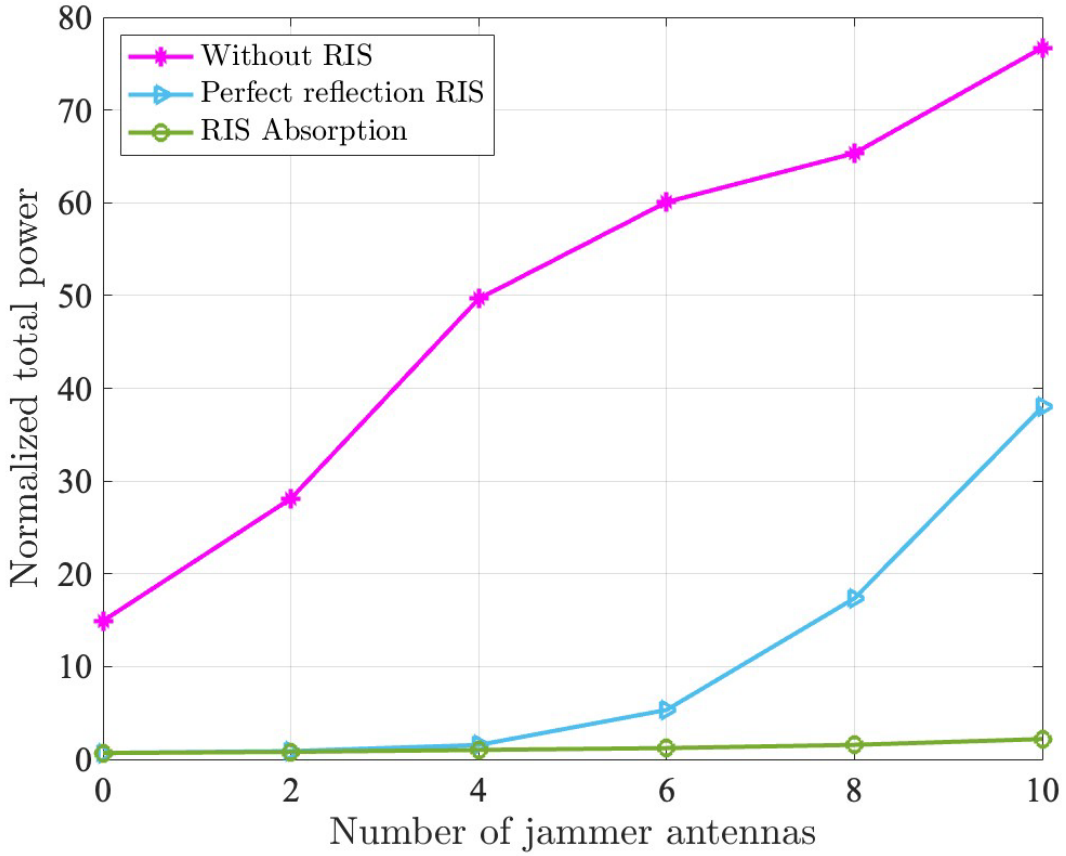
Chalmers studies on RIS: NOMA-RIS

Simulation results



M = 16

- Required total transmit power to meet the user quality of service requirements in the presence of a jammer *with M = 16 antennas*

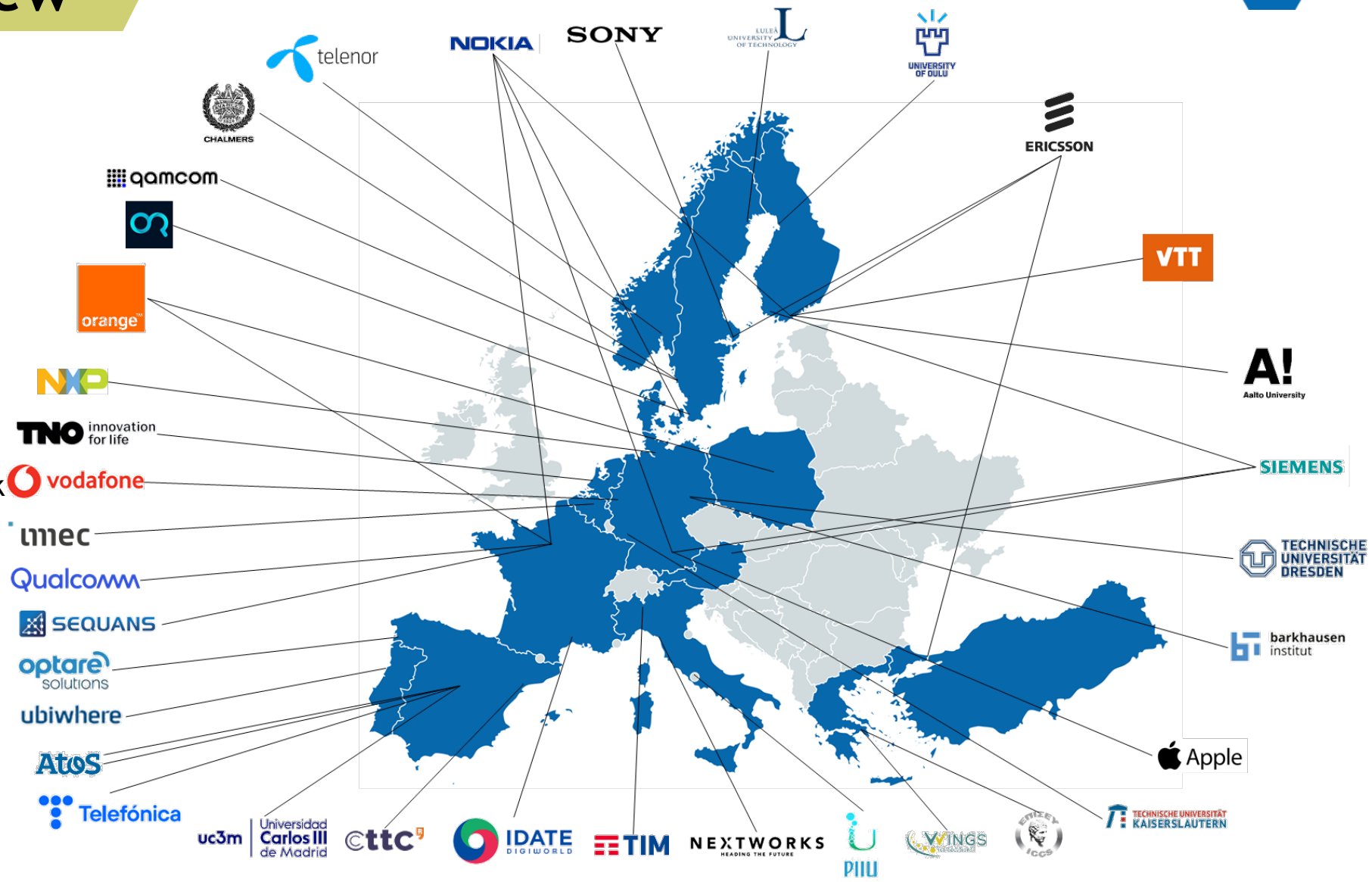


- Required total transmit power to meet the user quality of service requirements, as a function of the number of jammer antennas

A. Tabeshnezhad, A. L. Swindlehurst, T. Svensson, "RIS-Assisted Interference Mitigation for Uplink NOMA", IEEE WCNC'2023 Workshops, March 2023.

Hexa-X-II overview

- Hexa-X-II is the ongoing European level 6G Flagship project, started 1 Jan 2023 (2,5 years)
- Focus is on continued technology development and definition of the 6G platform and system
- Funded through Horizon Europe SNS-JU
- 44 partners
  - Cover the entire value-stack
    - hardware
    - system
    - platforms
    - applications
    - service providers
    - strong academic presence
- Nokia overall leader
- Ericsson technical manager

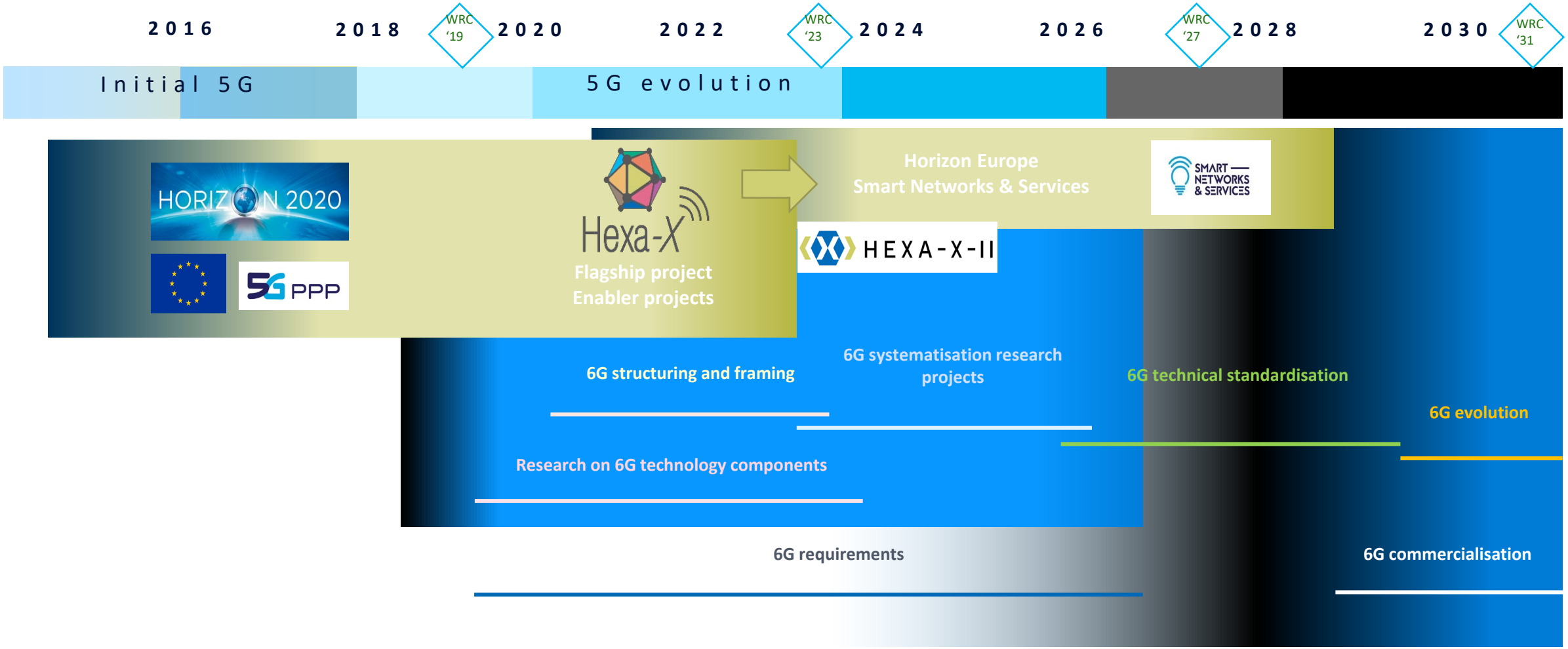


Consortium

	Academia and RTO	SME	Large enterprise
Service providers	PIIU, TNO		orange, TIM, vodafone, Telefónica, telenor
Applications and software		IDATE DIGIWORLD, optare solutions, ubiwhere SUITING THE FUTURE	
Platform	TECHNISCHE UNIVERSITÄT DRESDEN, ttc, UNIVERSITY, VTT, CHALMERS UNIVERSITY OF TECHNOLOGY, ICCS	WINGS ICT SOLUTIONS, NEXTWORKS ENGINEERING FORWARD	SONY SIEMENS, NOKIA, ERICSSON, Atos
System and technology	Aalto University, TECHNISCHE UNIVERSITÄT KAISERSLAUTERN, uc3m Universidad Carlos III de Madrid, LULEÅ TEKNISKA UNIVERSITET, barkhausen institut	qamcom	Apple
Chipset and hardware	imec	SEQUANS COMMUNICATIONS	Qualcomm, NXP

6G ecosystems and offering

Timeline


2016
2018
WRC '19
2020
2022
WRC '23
2024
2026
WRC '27
2028
2030
WRC '31
Initial 5G
5G evolution
HORIZON 2020
5G PPP
Hexa-X
Flagship project
Enabler projects
Horizon Europe
Smart Networks & Services
SMART NETWORKS & SERVICES
HEXA-X-II
6G structuring and framing
6G systematisation research projects
6G technical standardisation
6G evolution
Research on 6G technology components
6G requirements
6G commercialisation

Overall objectives of Hexa-X-II

A holistic flagship towards the 6G platform and system to inspire digital transformation for the world to act together in meeting needs in society and ecosystems with novel 6G services

Hexa-X

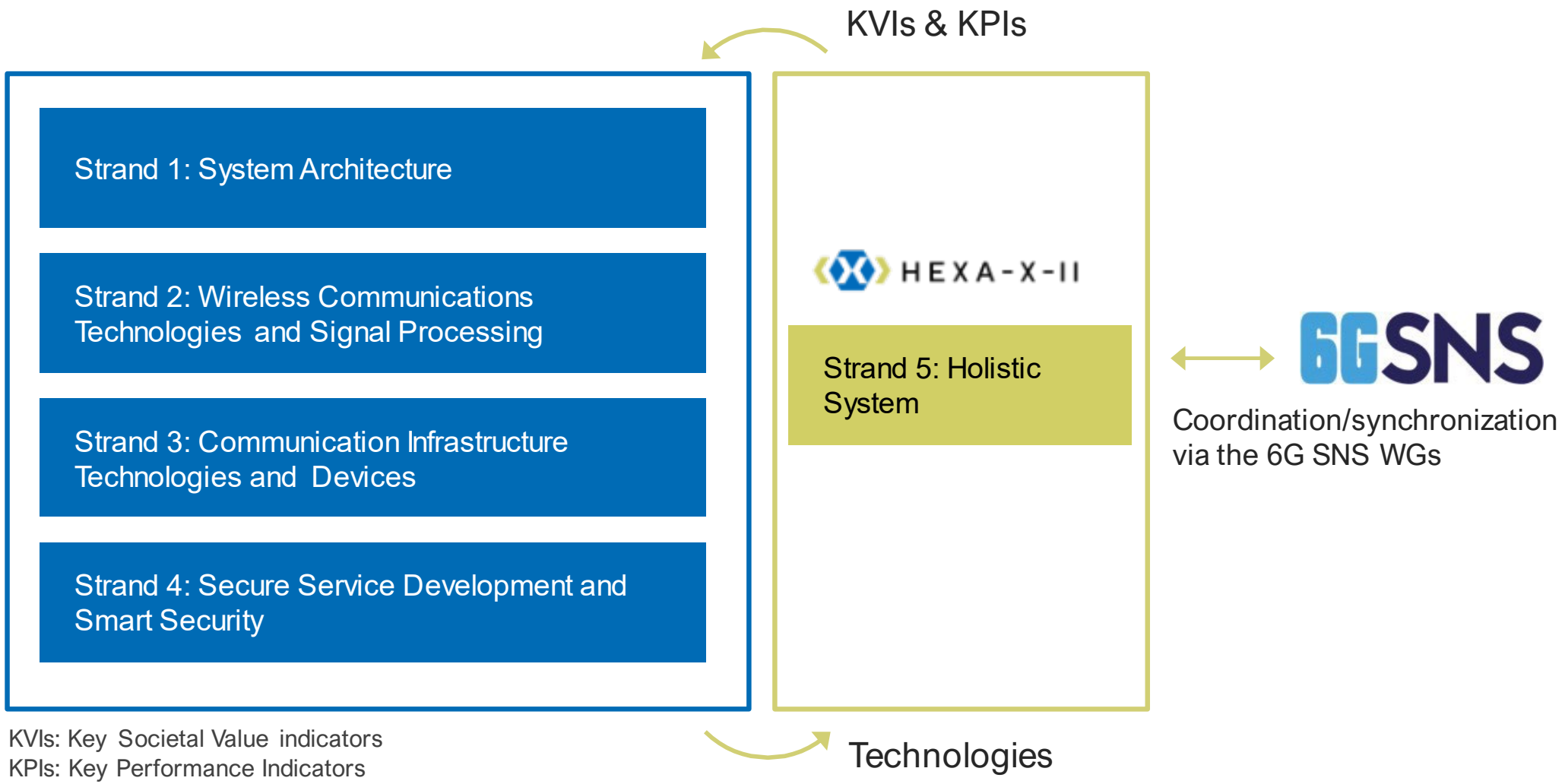
Hexa-X & Horizon-2020 candidate enablers →

HEXA-X-II

6G use cases, services, and requirements	Value for society
6G system blueprint and platform	Global dissemination impact
6G technology readiness	Strategic autonomy

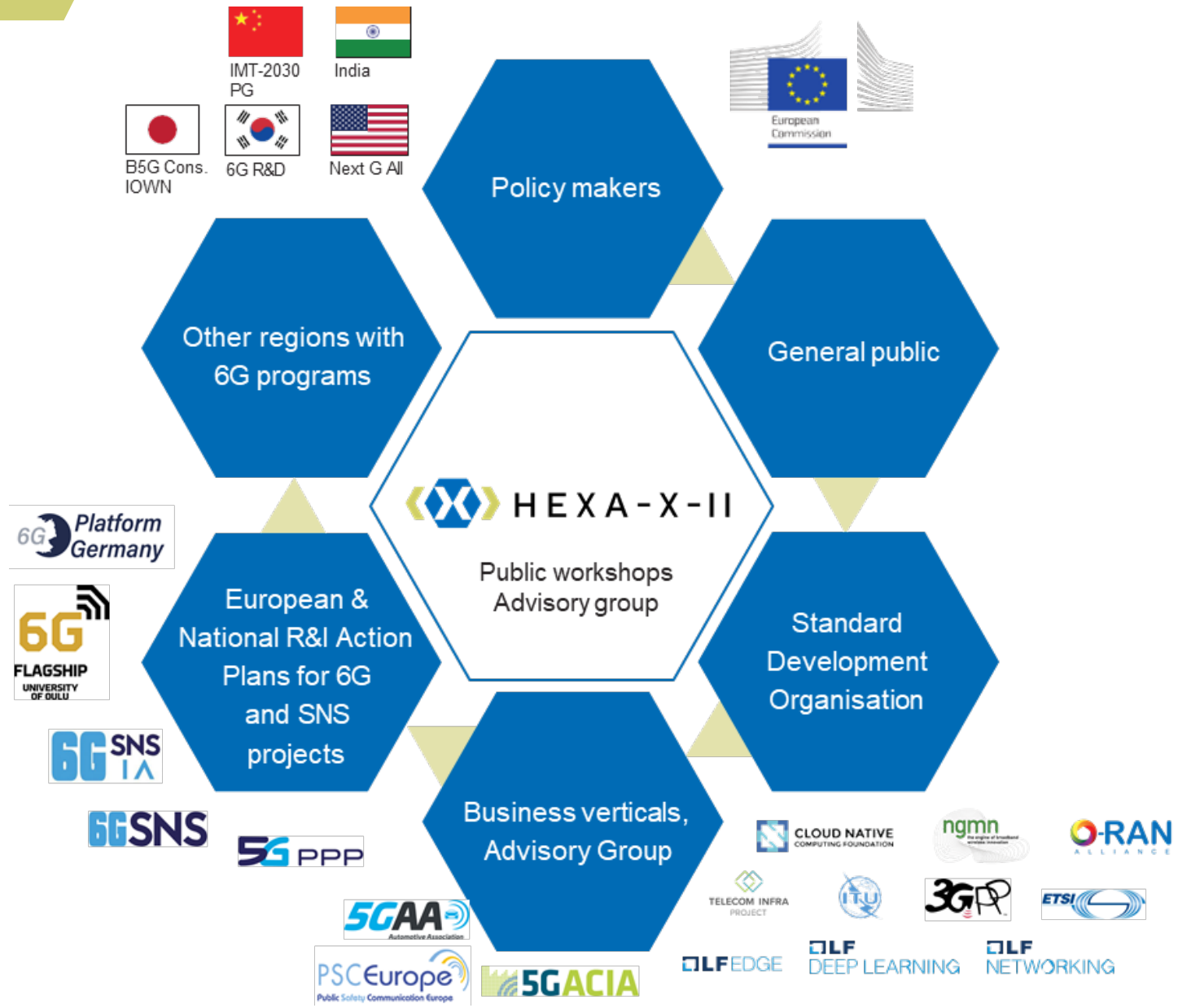
↑ SNS stream B projects

Interactions with other SNS JU projects

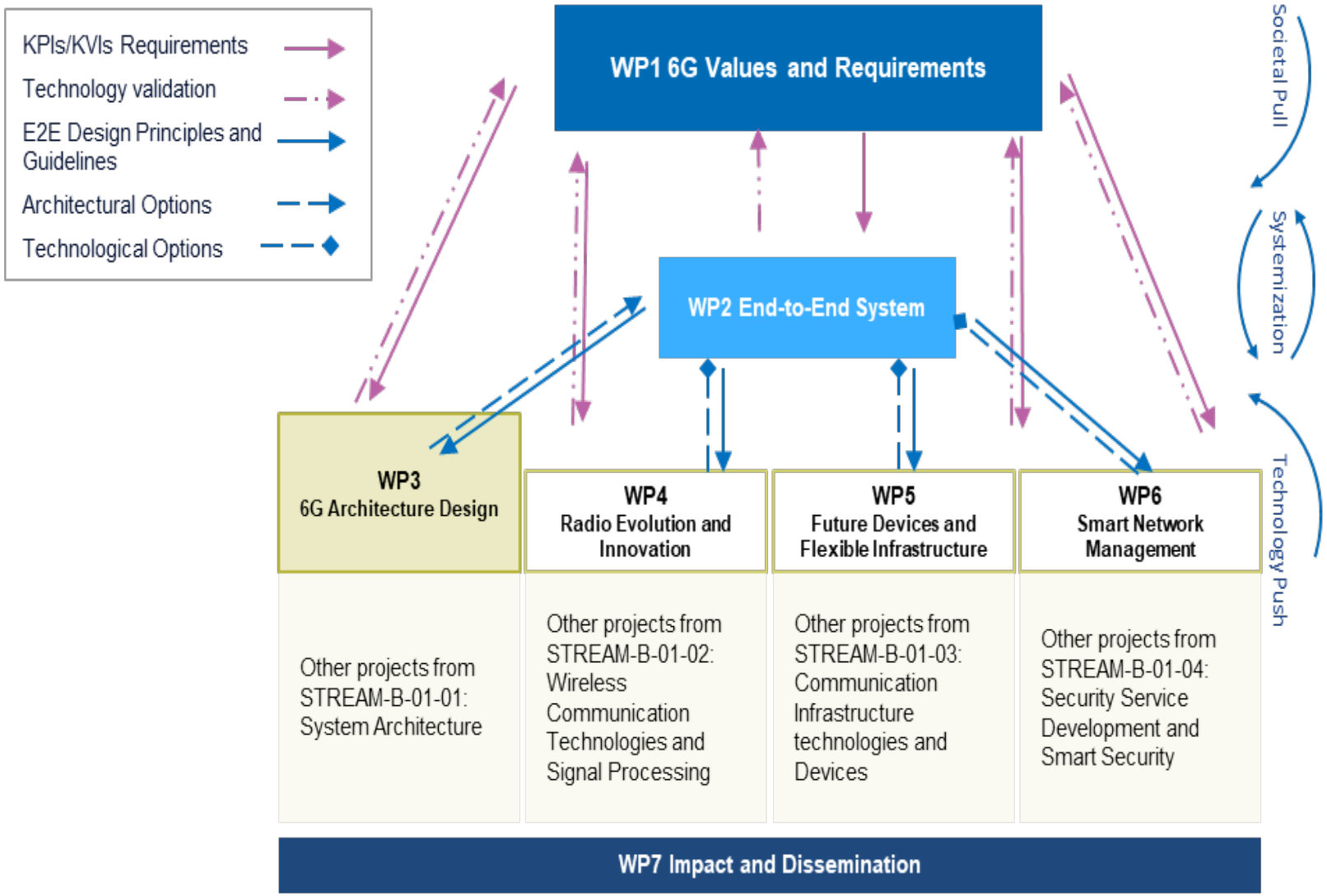


KVIs: Key Societal Value indicators
KPIs: Key Performance Indicators

Relation of Hexa-X-II to major stakeholders



WP structure



6G Use cases and requirements

Objective 1 – WP1 Requirements for the sustainable, inclusive, and trustworthy network platform

6G system blueprint and network platform

Objective 2 – WP2 Design blueprint of the sustainable, inclusive, and trustworthy network platform, and system validation

6G technology readiness

Objective 3 – WP3,4,5
Enhanced connectivity for 6G service

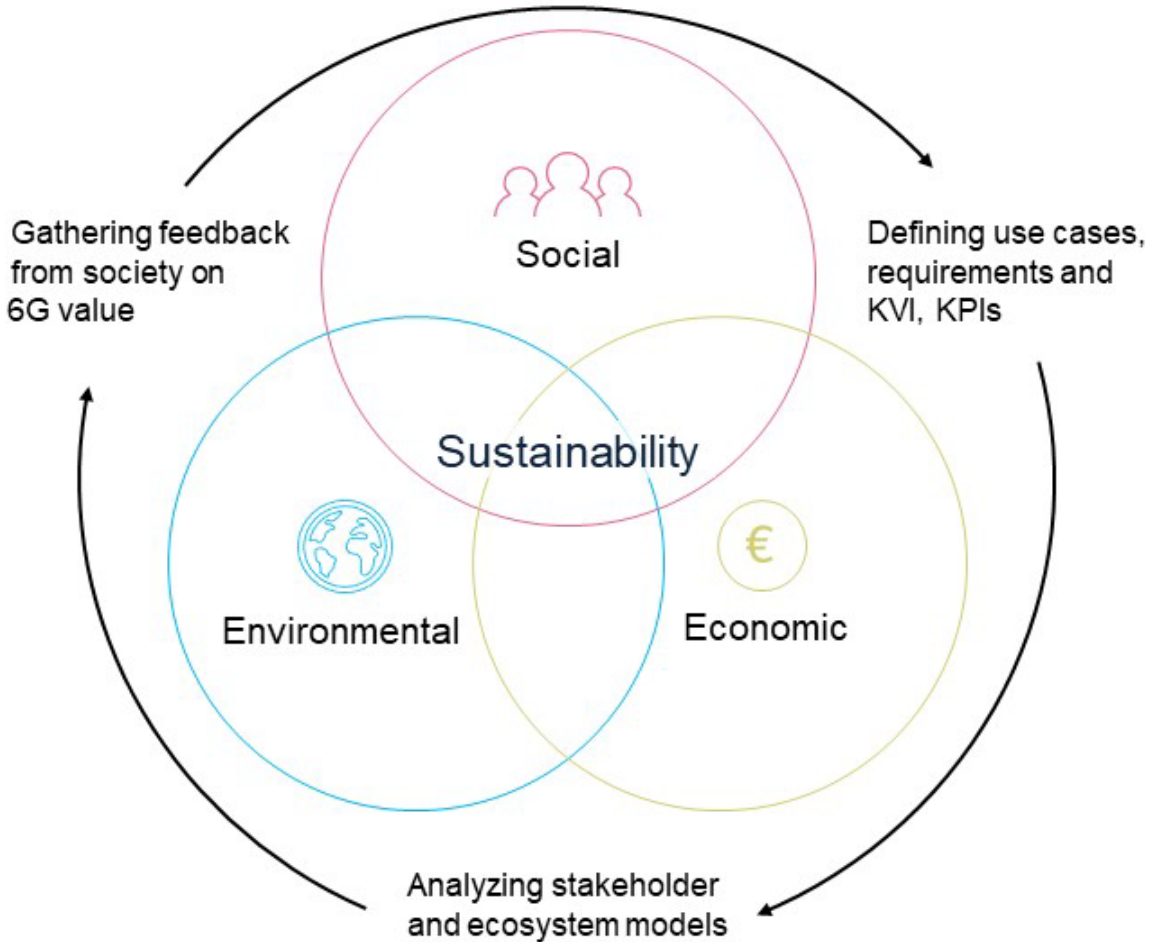
Objective 4 – WP3, 4, 6
Network sensing, compute, and AI novel digital services

Objective 5 – WP2, 3, 5, 6
Efficient network realization, implementation, and management

6G harmonisation

Objective 6 – WP7
Impact creation towards a global & holistic 6G era

WP1 6G Value and Requirements



Task 1.1 – Environmental Sustainability

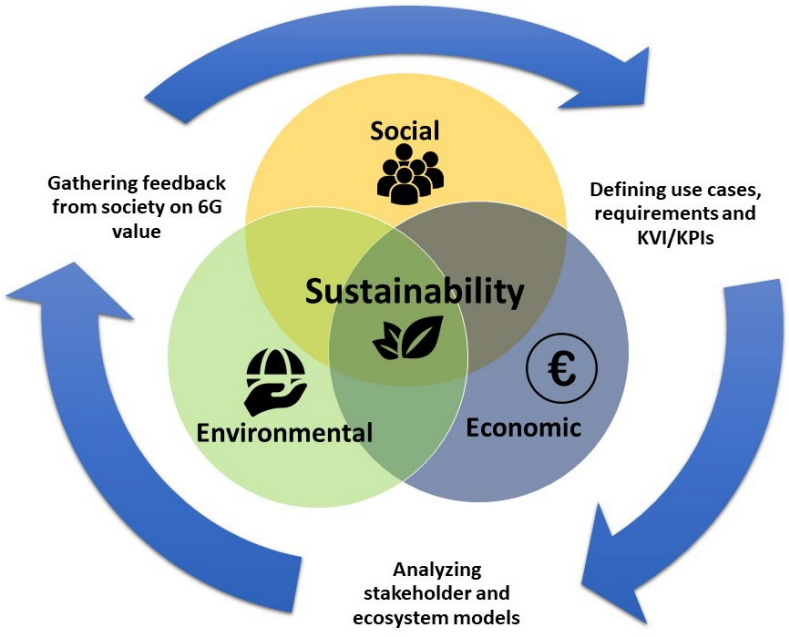
Objectives

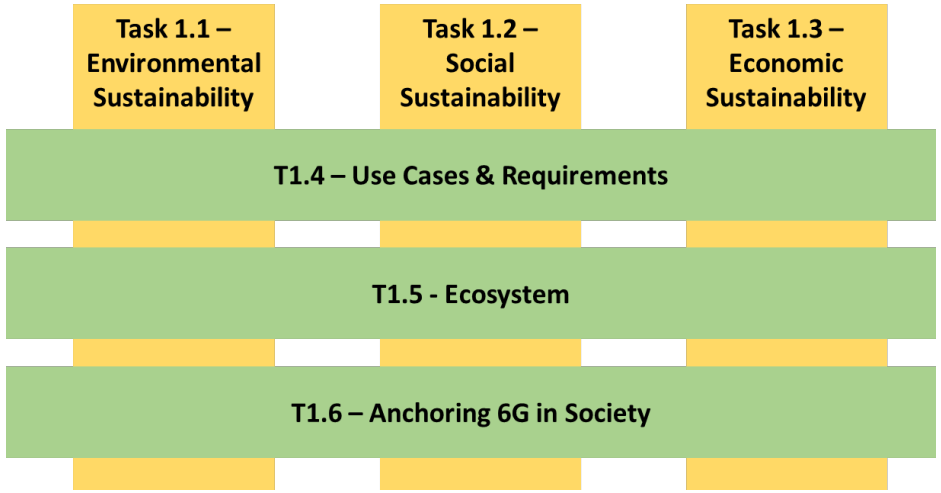
Sustainable 6G

- Improving energy efficiency and total energy consumption (network and device side)
- Improving materials efficiency and circularity
- Evaluation from a system and life cycle perspective, using environmental metrics

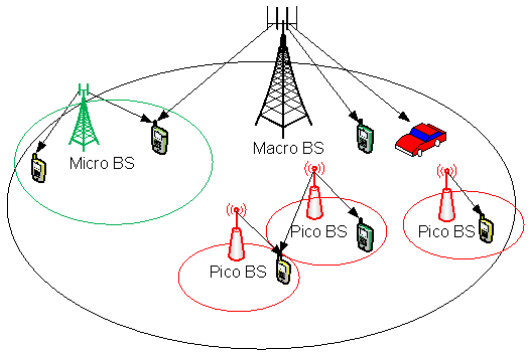
6G for sustainability

- Propose guidelines, recommendaitons and good practices
- Evaluate potential CO2 reductions (and other environmental impacts)





Sustainable 6G Design: Energy Minimization under Service Constraints in mm-wave Multi-AP Cooperation

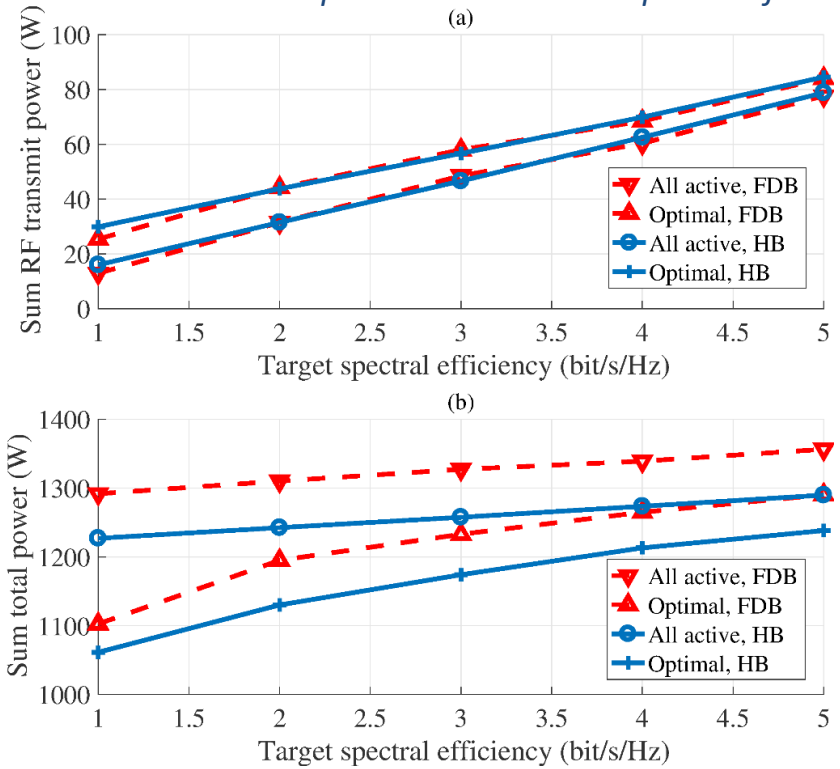


- Multiple base stations (BSs) jointly serving users to mitigate blocking and load balancing in dense mm-wave networks (standalone mm-wave BSs/ non-standalone, macro-BS assisted)
- Derive (close to) optimal fully digital- (FDB) and hybrid beamforming (HB) schemes.
- Minimize sum power *subject to per-user spectral efficiency constraints* and per BS peak power constraints, considering both hardware and RF transmit power of sleep mode capable BSs.

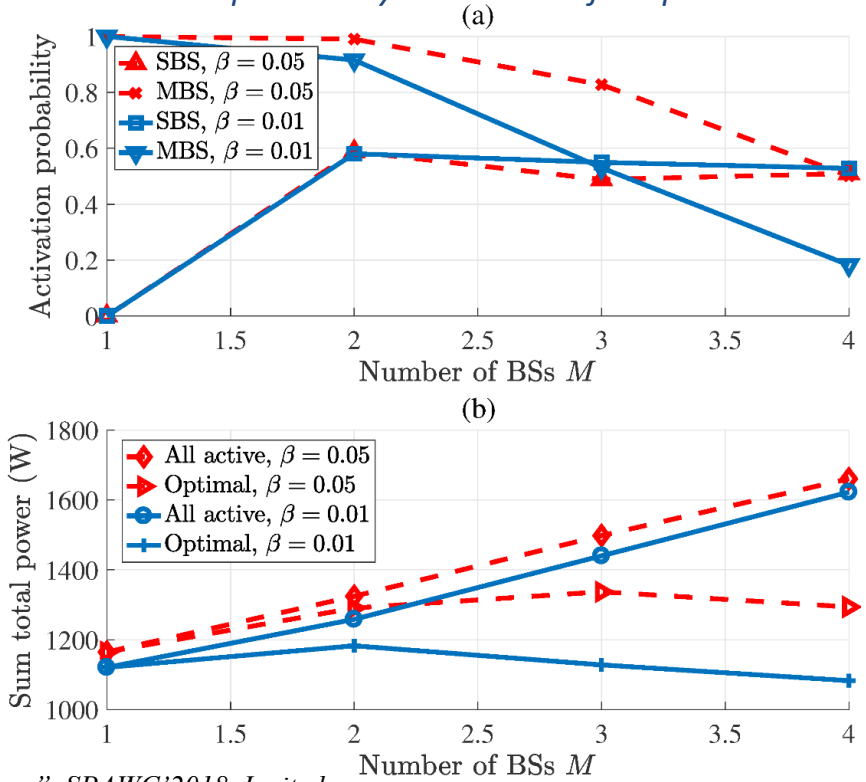
Jointly optimize
- Precoding
- Load balancing
- BS operation mode

To minimize network energy efficiency.

Sum RF transmit power and sum total power of all BSs

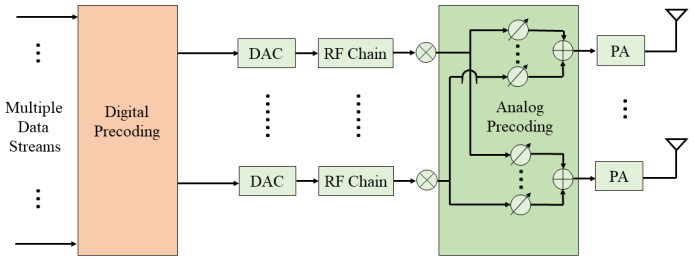


BS activation probability vs number of cooperative BSs



- *[1] C. Fang, B. Makki, J. Li, T. Svensson, "Coordinated Hybrid Precoding for Energy-efficient Millimeter Wave Systems", SPAWC'2018. Invited paper.*
- *[2] C. Fang, B. Makki, J. Li, T. Svensson, "Hybrid Precoding in Cooperative Millimeter Wave Networks," in IEEE Transactions on Wireless Communications, vol. 20, no. 8, pp. 5373-5388, Aug. 2021.*

Power Consumption Model



Total power consumption P_m of BS m

$$P_m = \begin{cases} \eta'_m P_m^{\text{tx}} + P_m^{\text{hw}}, & \text{active}, \\ a P_m^{\text{hw}}, & P_m^{\text{tx}} = 0, \ \text{silent}, \end{cases} \quad \eta'_m = \frac{1}{\eta_m(1-\Delta_m)},$$

η_m power amplifier efficiency

Δ_m power loss factor accounting for losses in non-transmission related parts (such as power supply loss and active cooling)

$a \in [0,1]$ silent mode scalar (value depends on degree of HW deactivation during silent mode)

$$P_m^{\text{tx}} = \sum_{k=1}^{K} ||\mathbf{w}_{k,m}||^2$$

RF transmit power

$$P_m^{\text{hw}} = \frac{N_m^{\text{PS}} P_{\text{PS}} + L_m \left(P_{\text{DAC}} + P_{\text{RF}}\right)}{1 - \Delta_m}$$

L_m: Number of RF chains at BS m

N_m^{PS}: Number of phase shifters at BS m for the beamforming architecture

P_{PS}; P_{DAC}; P_{RF}: power consumption of the phase shifters, DACs and RF chains, respectively

Model used in the following optimization problem [2].

$$\mathcal{P}: \min_{\{\mathbf{R}_m, \mathbf{d}_{k,m}\}} \sum_{m=1}^{M} b_m P_m$$

$$\text{s.t.} \quad \Gamma_k \geq \tau_k, \qquad \forall k$$

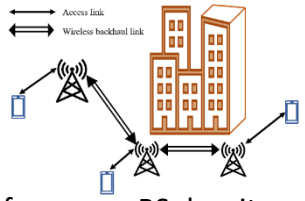
$$\sum_{k=1}^{K} ||\mathbf{R}_m \mathbf{d}_{k,m}||^2 \leq P_{\max,m}, \qquad \forall m$$

$$\left|\mathbf{R}_m^{(i,j)}\right| = \frac{1}{\sqrt{N_m L_m}}, \qquad \forall m, i, j, \qquad \text{for FHP},$$

$$\mathbf{R}_m = \text{diag}[\hat{\mathbf{r}}_{1,m}, \cdots, \hat{\mathbf{r}}_{L_m,m}], \quad \left|\hat{\mathbf{r}}_{i,m}^{(j)}\right| = 1/\sqrt{N_m}, \qquad \forall m, j, \qquad \text{for PHP}.$$

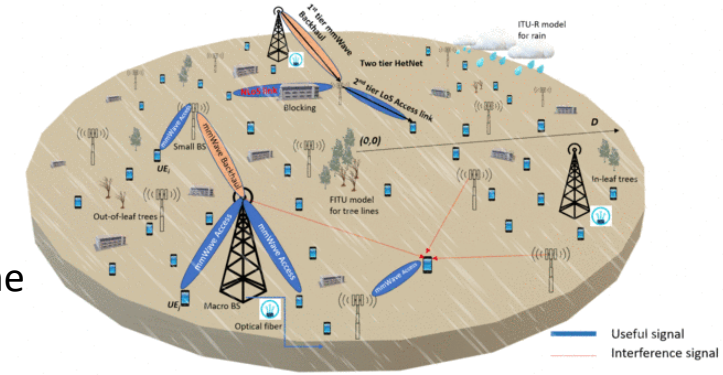
[2] C. Fang, B. Makki, J. Li, T. Svensson, "Hybrid Precoding in Cooperative Millimeter Wave Networks," in IEEE Transactions on Wireless Communications, vol. 20, no. 8, pp. 5373-5388, Aug. 2021.

Sustainable 6G Design: Integrated Access and Backhaul (IAB)



Arguments for IAB

- Network resources flexibility
- Network cost reduction
- Time-to-market reduction
- Controlled interference also in the backhaul/fronthaul



System model

Node/BS Distribution

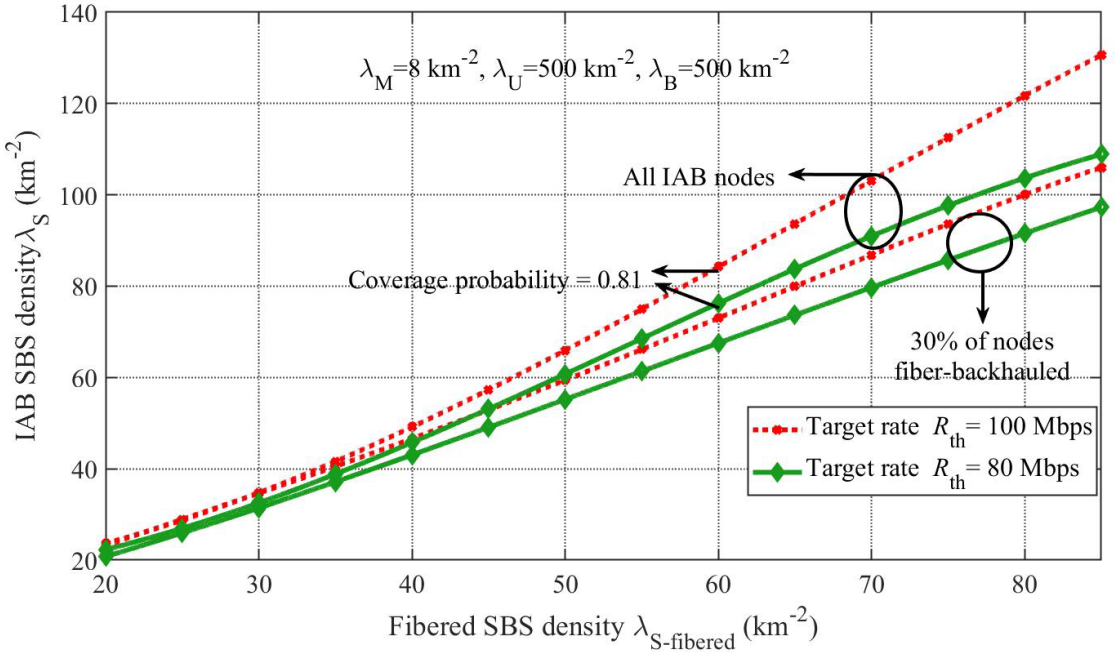
- Finite homogeneous poisson point processes (FHPPP) for macro BS density (λ_M), small BS density (λ_S), blockers (λ_B) and users (λ_U).
- Two-tier HetNet on a circular plane

Blocking model

- Germ grain model
- OpenStreetMap 3D

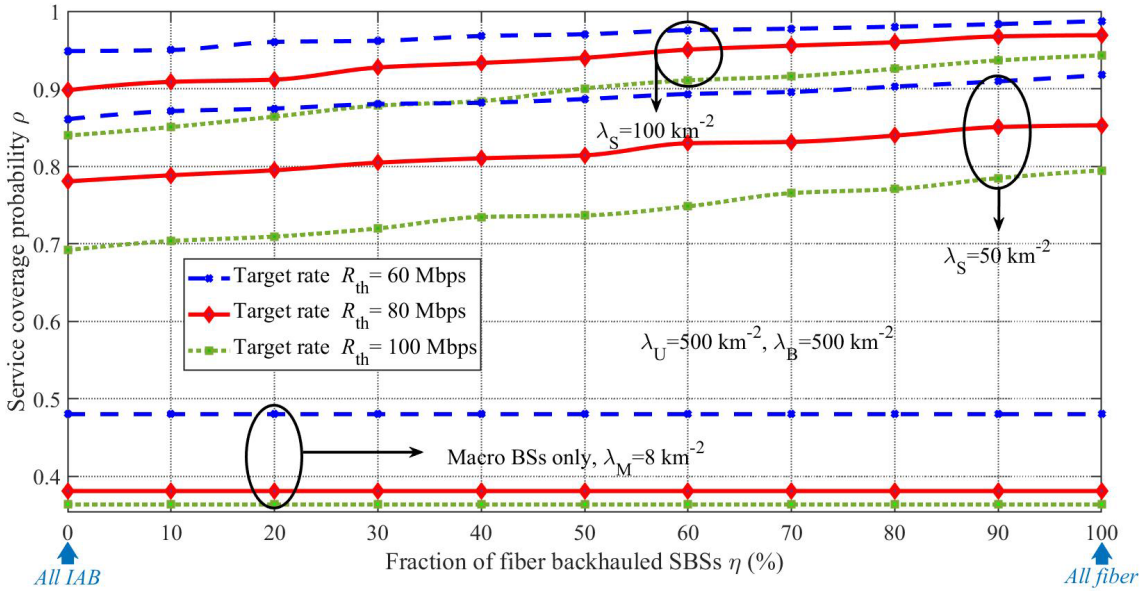
Rain model: ITU-R Rec 8.38-3

IAB nodes density providing same coverage probability as fiber-backhauling



- Simulation parameters: (α_{LOS} ; α_{NLOS} = (2; 3), blocker lengths l_B = 5 m, f_c = 28 GHz, bandwidth= 1 GHz and P_{MBS}; P_{SBS}; P_{UE} = (40; 24; 0) dBm.

Service coverage probability as a function of percentage of fiber-backhauled SBSs

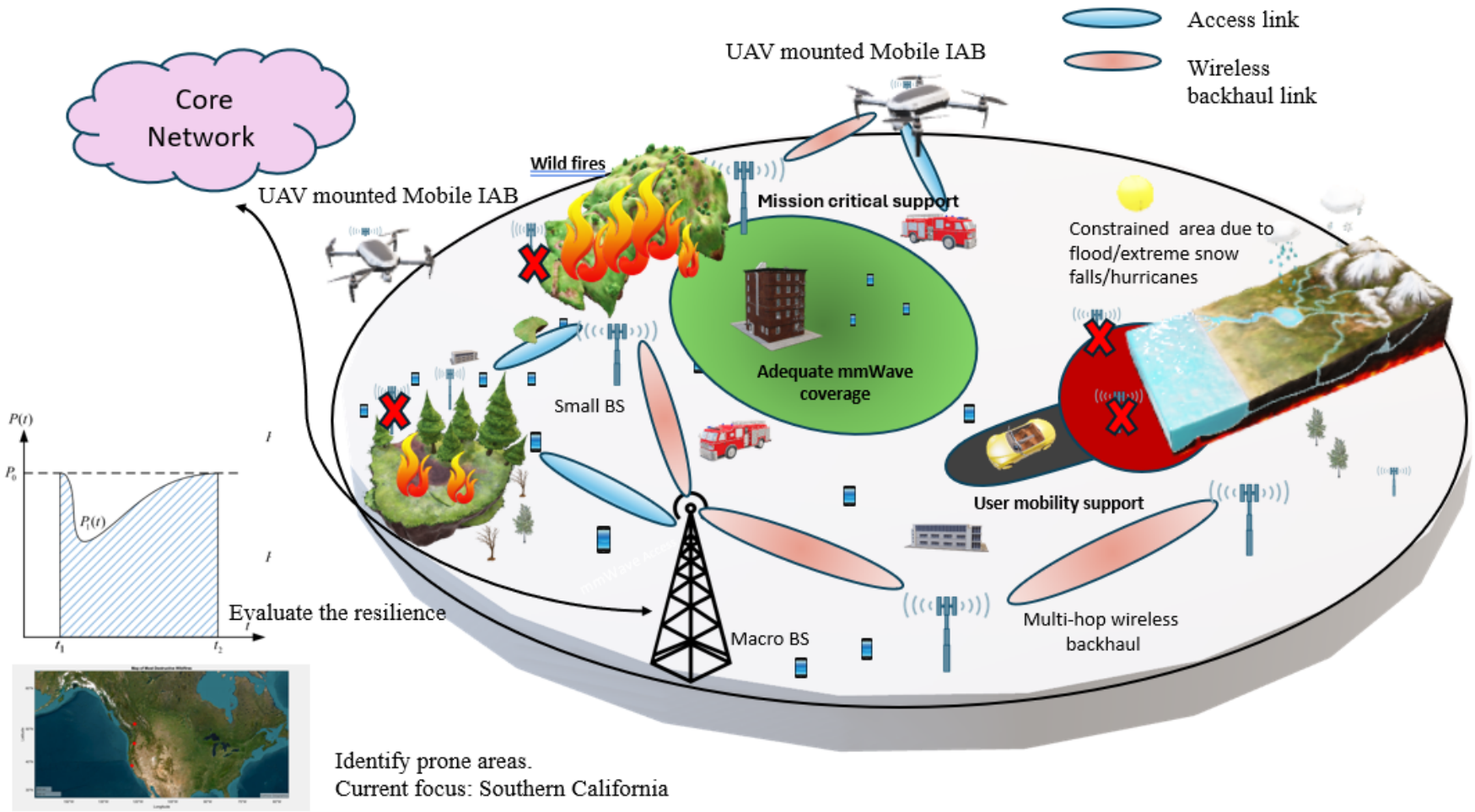


- Simulation parameters: (α_{LOS} ; α_{NLOS}) = (2; 3), blocker lengths l_B = 5 m, f_c = 28 GHz, bandwidth= 1 GHz and P_{MBS}; P_{SBS}; P_{UE} = (40; 24; 0) dBm.

C. Madapatha, B. Makki, C. Fang, O. Teyeb, E. Dahlman, M. S. Alouini, T. Svensson, "On Integrated Access and Backhaul Networks: Current Status and Potentials", IEEE Open Journal of the Communications Society (OJ-COMS), vol. 1, pp. 1374-1389, 2020.
C. Madapatha, B. Makki, A. Muhammad, E. Dahlman, M.S. Alouini, T. Svensson, "On Topology Optimization and Routing in Integrated Access and Backhaul Networks: A Genetic Algorithm-based Approach", IEEE Open Journal of the Communications Society, vol. 2, pp. 2273-2291, 2021.

Sustainable 6G Design: Resilience and Hazard Alerts

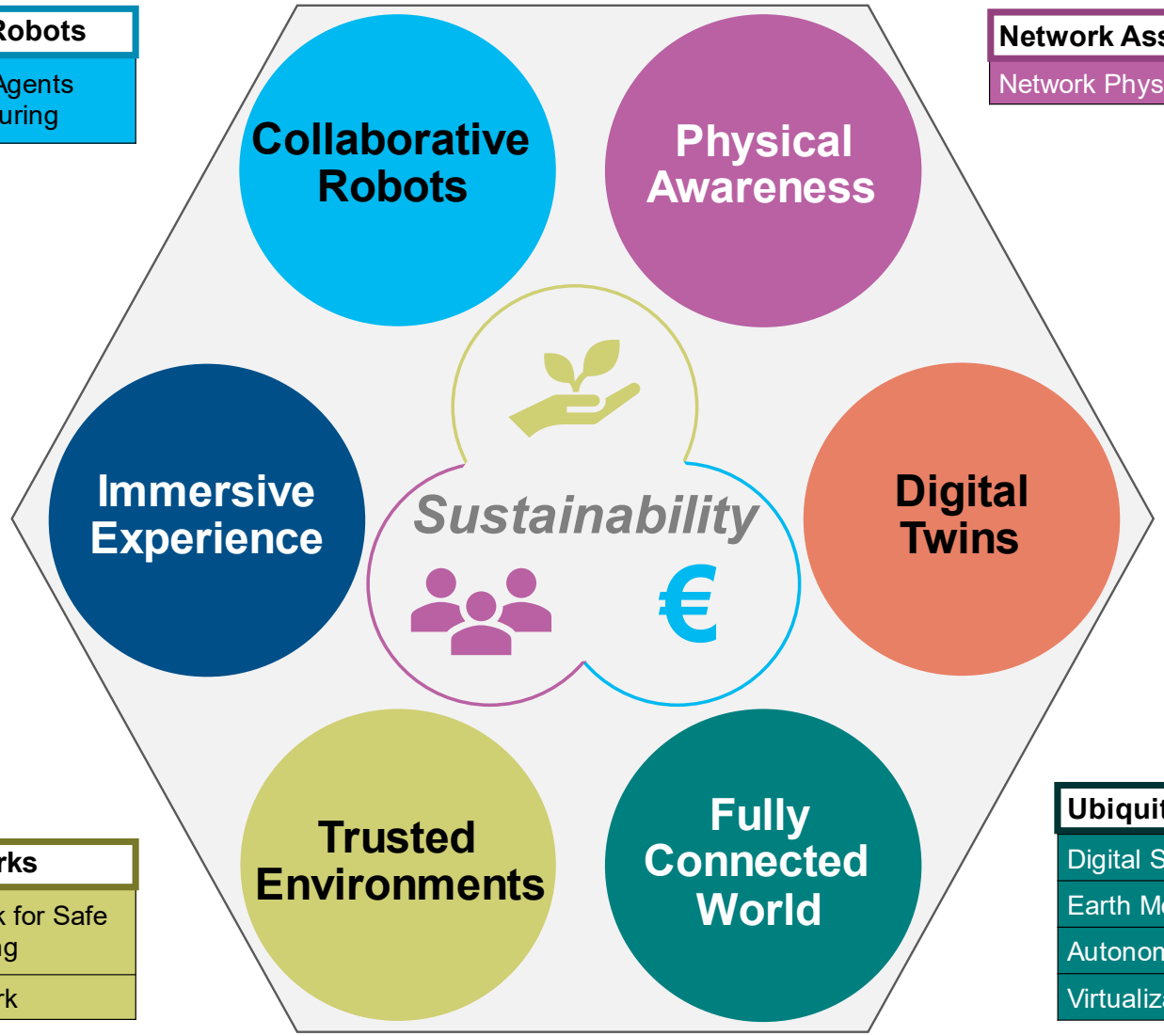
Future network resilience: Conceptual framework



Hexa-X-II Use Case Families

Cooperating Mobile Robots
- Autonomous Embodied Agents Within Flexible Manufacturing

Network Assisted Mobility
- Network Physical Data Exposure



Seamless Immersive Reality
- Immersive Education
- Immersive Gaming
- Live and Interactive Immersive Content Creation

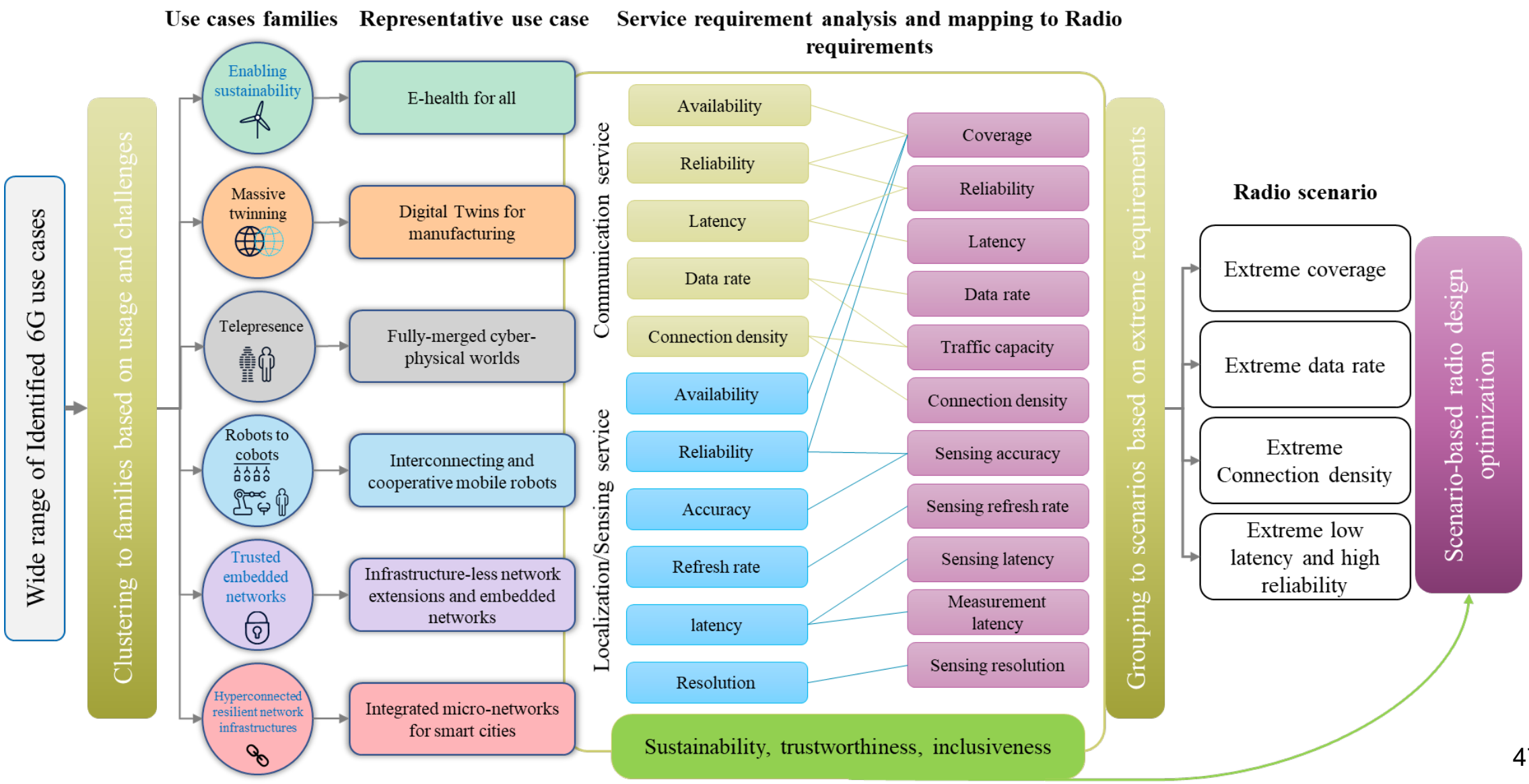
Realtime Digital Twins
- Cloud Continuum
- Smart Maintenance
- Digital Twins (Building Model)

Human-Centric Networks
- Industrial Sensors Network for Safe Production & Manufacturing
- Wireless In-Vehicle Network

Ubiquitous Network
- Digital Sobriety and Enhanced Awareness
- Earth Monitor, Sustainable Food Production
- Autonomous Supply Chain
- Virtualization of Device Functionalities

Hexa-X-II Use Cases with Highlighted Representative Use Cases

Selected use cases and defined radio scenarios

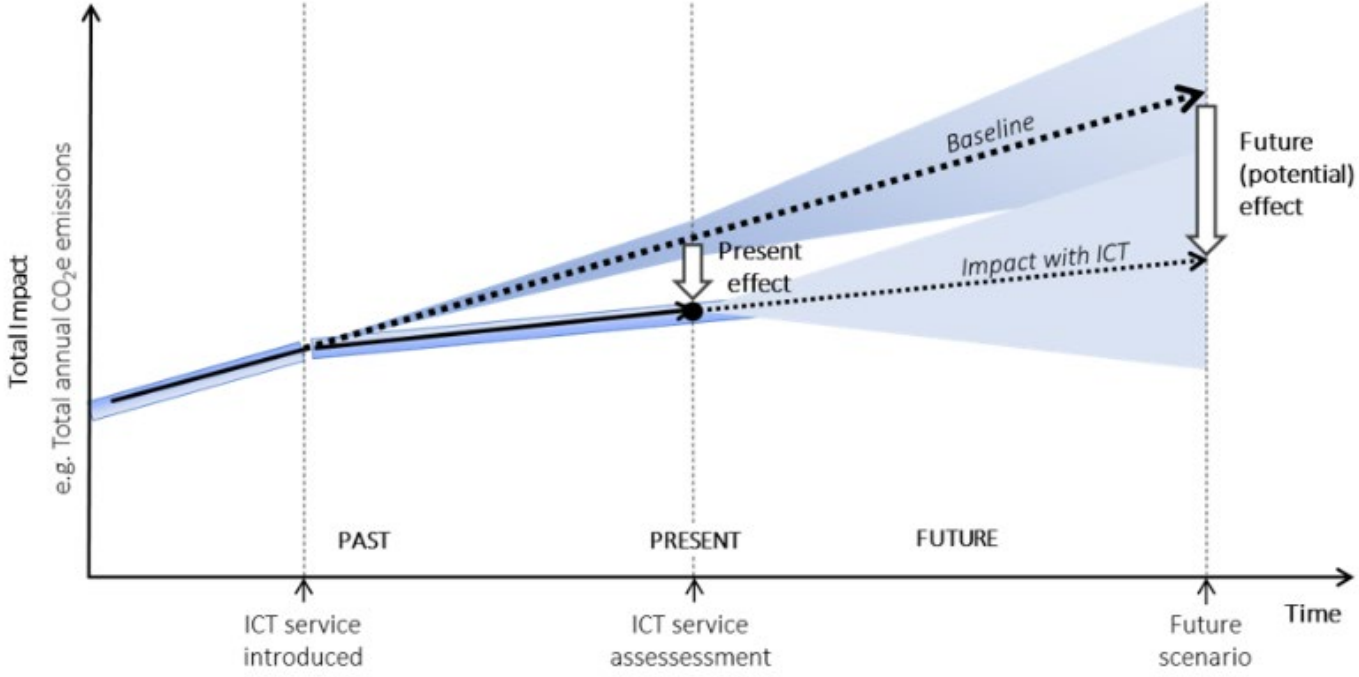


Assessing the Enablement Effect

To **assess** the reduction of emissions permitted by an ICT solution, two scenarios considered:

1. the reference scenario, or the **baseline**, emissions without the ICT/6G solution in place
2. the ICT/6G scenario, where the emissions are those occurring in a scenario with the ICT/6G solution

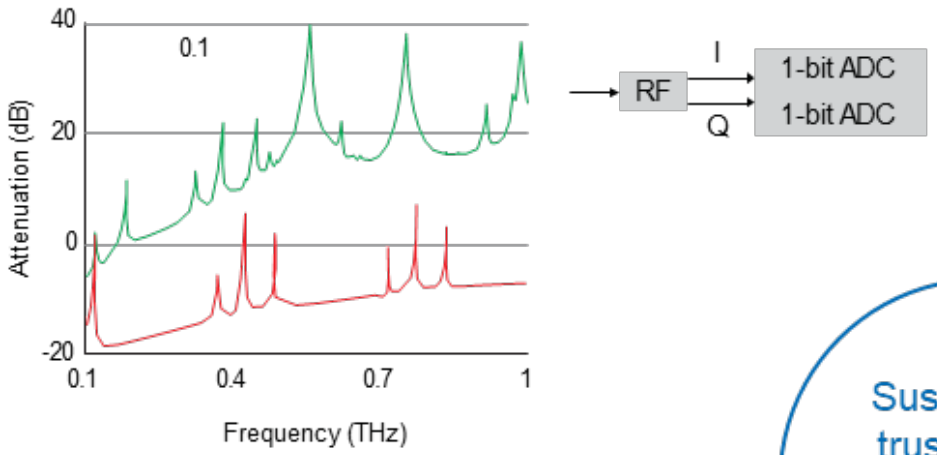
It is noted that the comparison is necessarily hypothetical since the two considered scenarios cannot coexist simultaneously



Based on (Coroamă, Bergmark et al. 2020): *A Methodology for Assessing the Environmental Effects Induced by ICT Services. Part I*, ICT4S 2020, Bristol, UK.

WP4 6G radio evolution & innovation

Towards THz communications

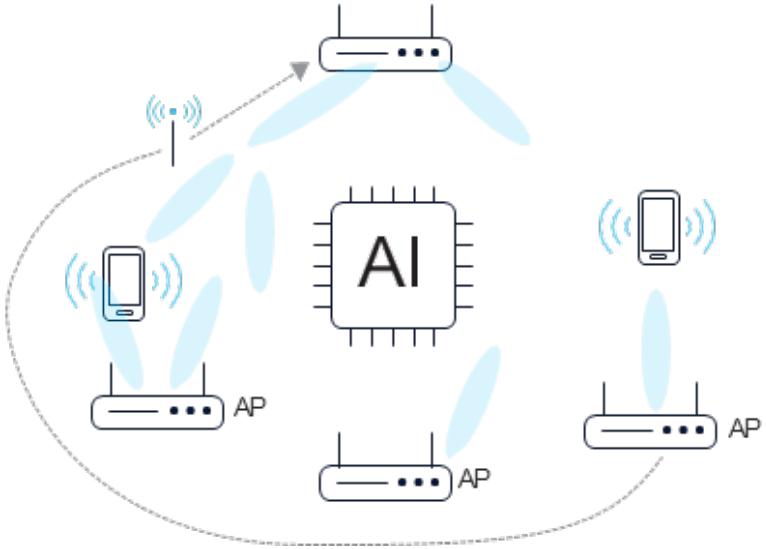


Joint communications and sensing

Sustainable, trustworthy, inclusive and holistic radio design

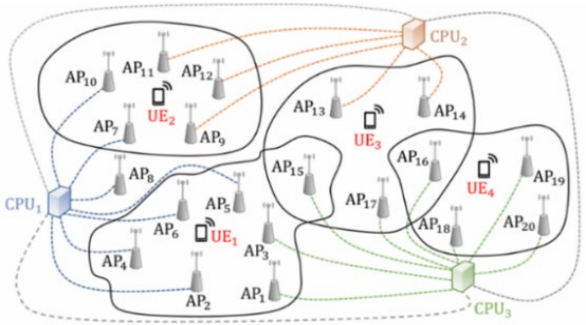
Flexible spectrum access solutions

Intelligent radio air-interface design

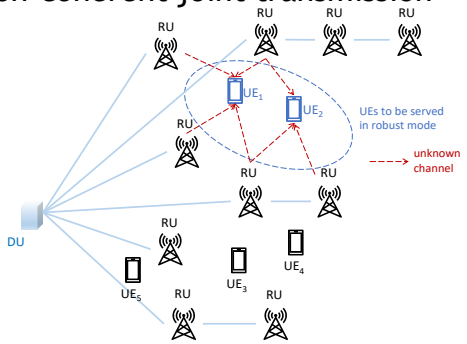


D-MIMO + RIS schemes and architectures

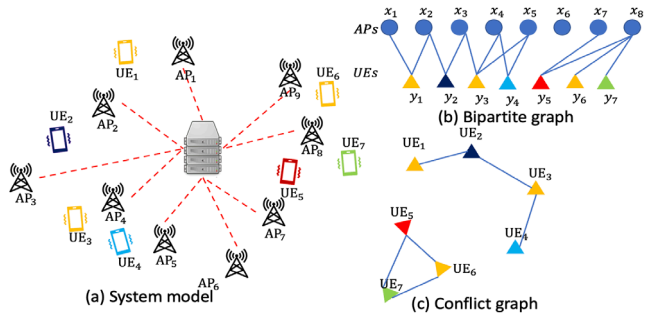
Coherent joint transmission



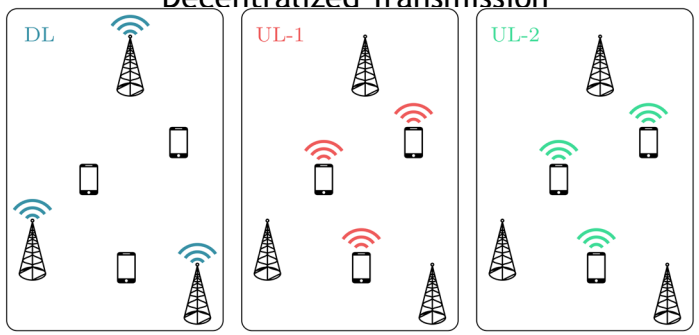
Non-coherent joint transmission



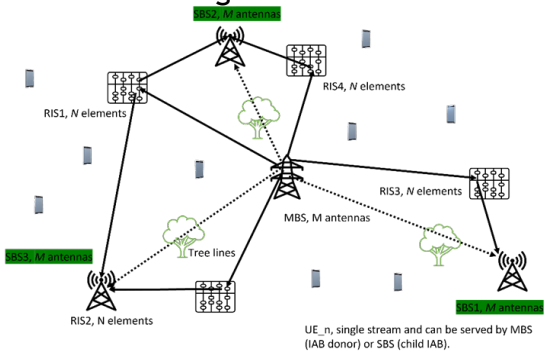
Joint UE / AP selection for scalable



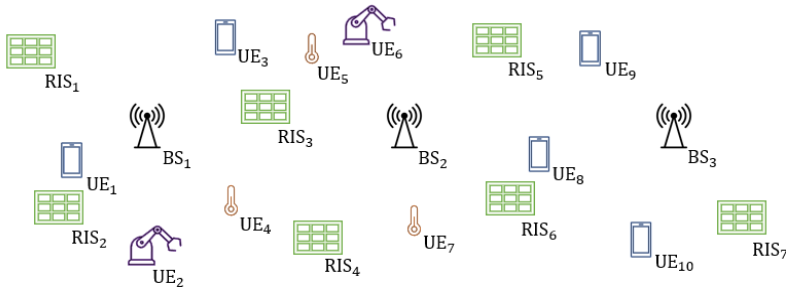
Decentralized Transmission



RIS-assisted integrated access and backhaul



RIS-assisted D-MIMO



KPIs: spectral efficiency, BER, cell capacity, throughput, coverage

KPIs: Energy consumption reduction, reduced cost

- Sustainability: reduced energy consumption
- Inclusiveness: coverage extension
- Trustworthiness: higher reliability

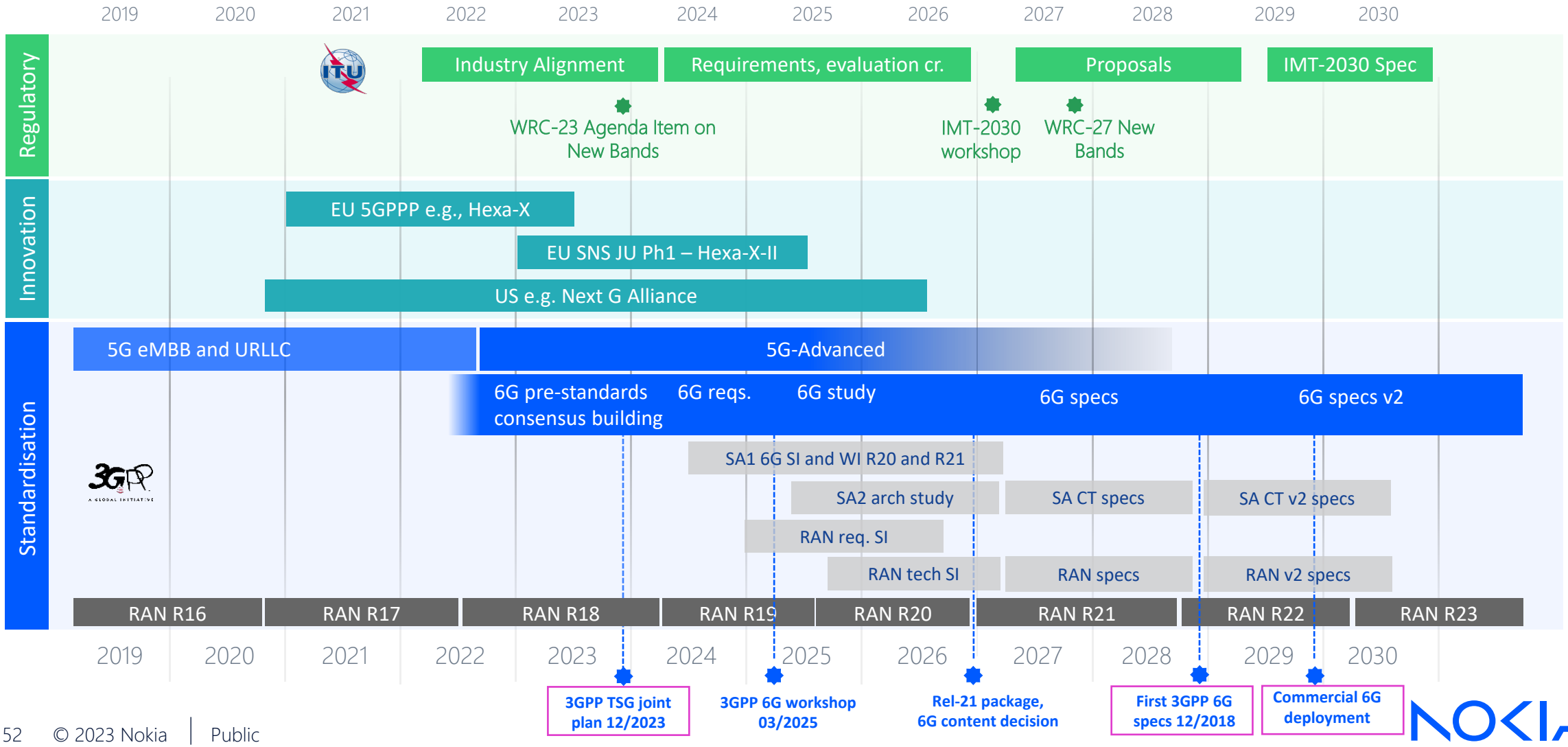
Deliverables

- D3.3 – Initial analysis of architectural enablers and framework • 30/4/2024
- D4.3 – Early results of 6G Radio Key Enablers • 30/4/2024
- D1.3 – Environmental and social view on 6G • 31/3/2024
- D5.3 – Initial design and validation of technologies and architecture of 6G devices and infrastructure • 29/02/2024
- D7.5 – Impact to industry activities, standardisation and regulation – intermediate release • 01/01/2024
- D7.3 – Dissemination, communication, and clustering • 31/12/2023
- D1.2 – 6G use cases and requirements • 30/12/2023
- D2.2 – Foundation of overall 6G system design and preliminary evaluation results • 29/12/2023
- D3.2 – Initial Architectural enablers • 31/10/2023
- D4.2 – Radio Design and Spectrum Access requirements and key enablers for 6G Evolution • 31/10/2023
- D5.2 – Characteristics and classification of 6G device classes • 31/10/2023
- D6.2 – Foundations on 6G Smart Network Management and Orchestration Enablers • 30/10/2023
- D1.1 – Environmental, social, and economical drivers and goals for 6G • 30/06/2023
- D2.1 – Draft foundation for 6G system design • 30/06/2023
- D7.2 – Planning for dissemination, exploitation, standardisation and clustering • 30/04/2023
- D7.1 – Online project presence • 31/01/2023

https://hexa-x-ii.eu/results/

6G success depends on a global unified approach

Different regulatory, innovation, standardization timelines to be brought in harmony



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Take Home Messages

- Scalable and adaptive D-MIMO systems have strong potential
  - both at low (cm/lower mm-wave) and high frequency bands (upper mm-wave)
- RIS technology has potential
  - some remaining challenges
- Convergence of D-MMO and sensing has potential and seems feasible
- (RF) Digital Twinning might be useful for context-aided communications
- Combination of D-MIMO and RIS has potential
- Sustainable 6G Design and 6G for Sustainability

Standardization starting, but still plenty of research to be made!

Thanks for listening!

Questions?