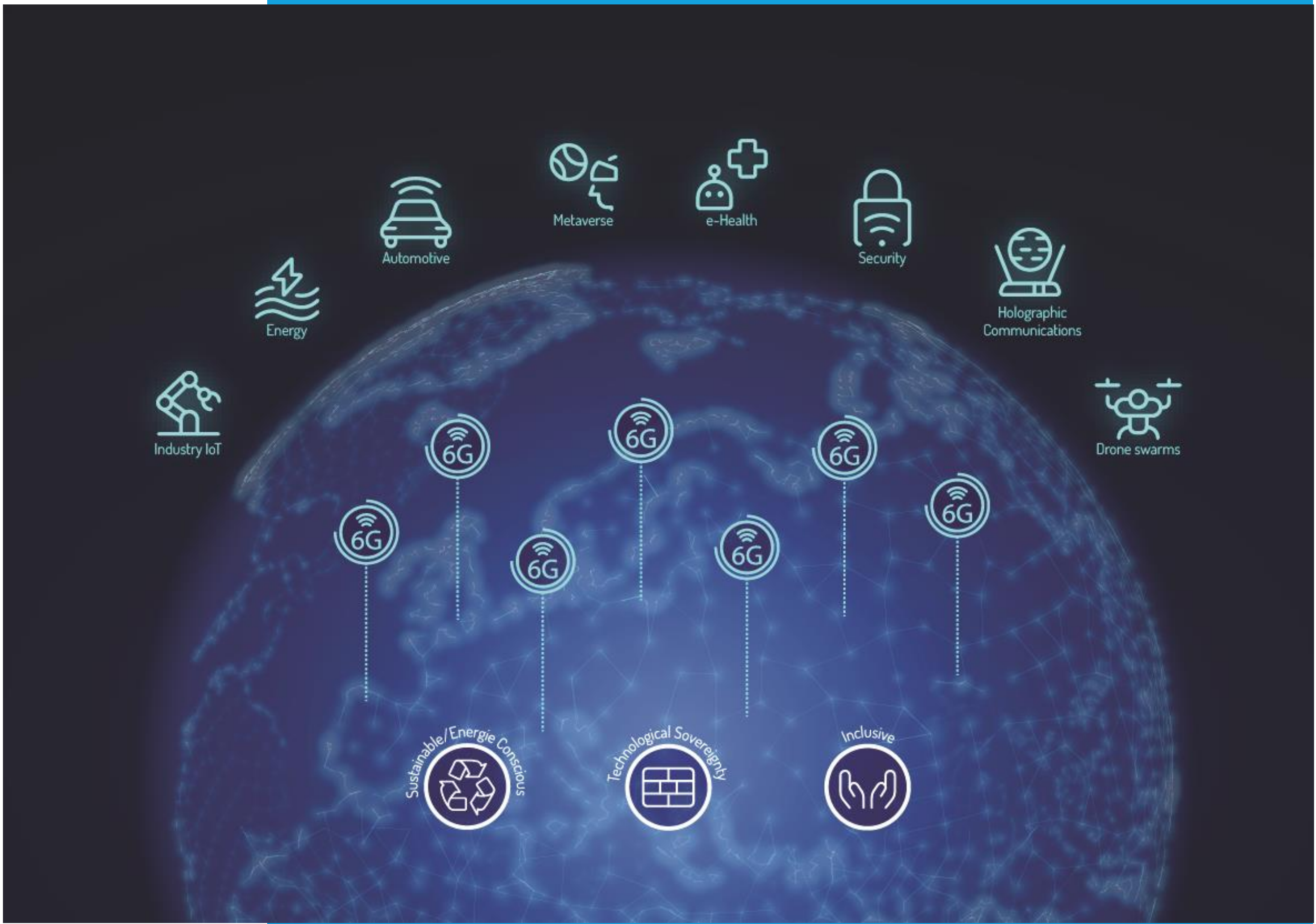
6G Smart Networks and Services Industry Association (6G-IA)

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## Position paper

# RESEARCH PRIORITIES ON WIRELESS COMMUNICATION TECHNOLOGIES AND SIGNAL PROCESSING

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# 1. INTRODUCTION

The SNS initiative is currently in the middle point of its lifespan. To date, there have been already three calls for proposals specifically covering wireless communication technologies and signal processing topics, mainly under Stream B Strand 2 and partially under Strand 3 topics. As a result of the first two phases of the SNS, several ongoing projects[1][2] are already covering multiple technological domains aiming at realizing the 6G vision. These include, among others reconfigurable meta-surfaces, AI-based channel modelling, cell-free/ultra-massive/distributed MIMO, waveform design, hardware co-design, integrated sensing and communications, energy efficiency, Open RAN, semantic communication, wireless edge caching and EMF exposure. A few more projects will be added after the resolution of the third SNS phase call for proposals. For the subsequent phases of SNS, updates of the strategy are required to identify the underpinning technological needs related to the wireless communications and RAN evolution in the light of global developments in this domain.

As in the case of previous generations of cellular-based networks, wireless communications technologies and signal processing are once again called to play a pivotal role to provide cutting edge innovations in highly complex 6G use cases, addressing emerging business requirements, technology trends and the foreseen standardization roadmap. In the context of EU-led research and innovation actions, technology sovereignty -especially in the microelectronics sector-, sustainability and societal requirements are also key factors that need to be considered in future research directions. Towards this end, further synergies and collaboration among different EU funding instruments and stakeholders could be considered and anticipated (e.g., SNS, Eureka, IPCEI's, Chips JU etc.) to develop specific underpinning wireless communication technologies.

Furthermore, in the realm of 6G, the RAN needs to continue evolving to support highly distributed edge applications and services by seemingly integrating frictionless AI and machine learning solutions, by exposing data through open APIs, by adopting cloud computing principles and by providing innovating signal processing technologies with integrated sensing and agile management of interference and spectrum resources.

This report summarises the outputs and recommendations of the Wireless Communications and Signal Processing Workshop organised by the 6G IA in April 2024. This was part of a series of workshops aimed at bringing together key industrial and academic stakeholders, DG-CNECT, the SNS JU Office, and other associations. Other areas covered in these series of workshops Include Cloud Computing, Security, Microelectronics, NTN and Photonics. It is important to highlight that, as a follow-up of the Microelectronics workshop, a position paper[3] has already been produced, summarising and highlighting the key research areas of interest. In addition to confirming/outlining the strategic orientations for the next three years, this report also aims to identify the European priorities where R&I is needed, and plan how SNS

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[1] https://cordis.europa.eu/search?q=contenttype%3D%27project%27%20AND%20programme%2Fcode%3D%27HORIZON-JU-SNS-2022-STREAM-B-01-02%27&p=1&num=10&srt=/project/contentUpdateDate:decreasing

[2] https://cordis.europa.eu/search?q=contenttype%3D%27project%27%20AND%20programme%2Fcode%3D%27HORIZON-JU-SNS-2023-STREAM-B-01-02%27&p=1&num=10&srt=/project/contentUpdateDate:decreasing

[3] https://6g-ia.eu/wp-content/uploads/2024/02/6g-ia-position-paper_microelectronics-final.pdf

solutions can be deployed targeting higher TRLs compared to the previous phases and also playing an integral role to the standardization roadmap.

# 2. CURRENT STATUS

**IMT-2030 framework**

IMT-2030 is expected to support the following technology trends and enablers[4]:

- An **AI-native new air interface** to enhance the performance of radio interface functions and automate intelligent networking services (e.g., intelligent data perception, supply of on-demand intelligence -AI as a Service-) including on-demand uplink/sidelink-centric, deep edge, and distributed machine learning.
- **Integrated sensing and communication** functions to enable innovative services and applications with higher sensing accuracy, while guaranteeing performance benefits in terms of cost, size and power consumption.
- **Computing and data services** able to process data at the network edge tackling real-time responses and control loops, low data transport costs and high energy efficiency.
- **Device-to-device wireless communication** with extremely high throughput, and/or ultra-accurate relative positioning and/or low-latency would be an important communication paradigm for IMT-2030.
- **A mixture of different frequency bands** will be leveraged featuring larger bandwidths and higher operating frequencies. Spectrum utilization can be further optimised by employing different technologies to manage resources (e.g., advanced carrier aggregation, distributed cell deployments, spectrum sharing technologies).
- **Energy efficiency** and low power consumption will be paramount both for the user device and at network level by adopting technologies like energy harvesting and on-demand access among others.
- Effectively combine **real-time communications** with extremely low latency, highly accurate time and frequency information for proactive and in-time radio access.
- **Security and resilience** to guarantee the entire cycle of sensitive information exchange. This will imply the adoption of distributed ledger technologies, federated learning, and quantum technology with respect to the RAN and physical-layer security technologies.

The IMT-2030 system is foreseen to extend and support the technology trends described above, while also providing a framework towards a sustainable digital transformation. Towards this end, IMT-2030 is expected to be built on overarching aspects that will form a common basis for all usage scenarios. These design principles include, but are not limited to, **sustainability**, **security and resilience**, **connecting the unconnected** for providing universal and affordable access to all users, and **ubiquitous intelligence** for improving overall system performance (Figure 1). IMT-2030 is also expected to help making a reality the goals for increased environmental, societal and economic sustainability, supporting the Climate

[4] https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2160-0-202311-I!!PDF-E.pdf

Change mandates of the Paris Agreement (United Nations Framework Convention). The usage scenarios of IMT-2030 are envisaged to be built on top of those defined in IMT-2020 (i.e. eMBB, URLLC, and mMTC) featuring broader and evolved capabilities. The IMT-2030 is also envisaged to feature new usage scenarios described in the following **i) Immersive Communication** whose goal will be to extend the enhanced Mobile Broadband (eMBB) mode of IMT-2020 and cover use cases with interactive immersive experience; **ii) Hyper Reliable and Low-Latency Communication** that will expand the Ultra-Reliable and Low-Latency Communication (URLLC) concept of IMT-2020 and cover use cases that are expected to have even more stringent requirements on reliability and latency; **iii) Massive Communication** aiming to extend the massive Machine Type Communication (mMTC) mode of IMT-2020, supporting the connection of a massive number of devices or sensors; **iv) Ubiquitous Connectivity** able to enhance connectivity through interworking with other systems; **v) Artificial Intelligence and Communication** aiming to support distributed computing and AI applications across the edge compute continuum and the creation of digital twins among others; **vi) Integrated Sensing and Communication** providing new applications and services that require sensing capabilities based on wide area multi-dimensional sensing.

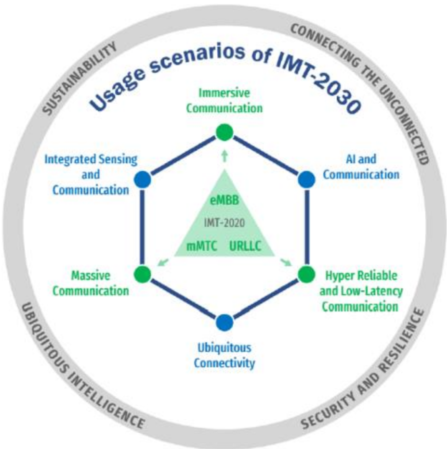


*Figure 1: The "Wheel diagram", Recommendation ITU-R M.2160*

It is important to highlight that the Hyper Reliable and Low-Latency Communication, Massive Communication and Immersive Communication usage scenarios are expected to have more stringent and simultaneous KPIs.

**Key enabling technologies**

A first approach to identify the key enabling RAN technologies was carried out in the context of the 6G IA position paper "Key strategies for 6G smart network and services"[5] and also in the Deliverable D2.4 "Enabling Radio Technologies and Roadmap towards 6G"[6] of the project HEXA-X. Figure 2 provides a mapping of the identified RAN technologies with their requirements and KPIs[7]. For instance, radio interference management topic is mapped to the

[5] https://6g-ia.eu/wp-content/uploads/2023/10/6g-ia-position-paper_2023_final.pdf

[6] https://hexa-x.eu/wp-content/uploads/2023/06/Hexa-X_D2.4.pdf

[7] https://bscw.5g-ppp.eu/pub/bscw.cgi/d516614/SRIA%202022%20Technical%20Annex%20Published.pdf

energy efficiency, spectral efficiency, peak data rate, air traffic capacity, coverage, reliability and connection density KPIs. The rest of the identified radio technologies are optical wireless communications, mmWave and THz communications, massive MIMO and intelligent reconfigurable surfaces, waveform design and numerology, coding and modulation, multiple access and full duplex, massive random access, integrated sensing and communication and physical layer security. AI/ML provisions is considered a vertical topic that targets every and each one of the other RAN technologies.

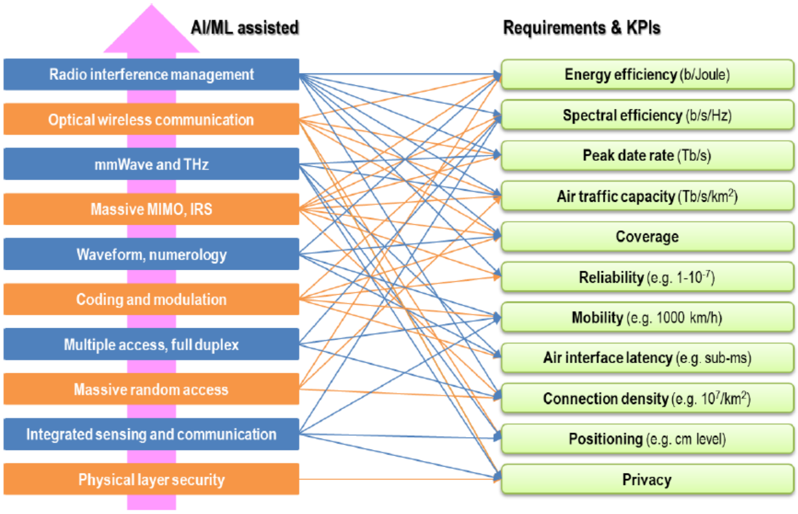


*Figure 2:: Radio Technologies Contributing to 6G requirements/KPIs*

**6G RAN and sustainability**

6G networks will have to consider a number of environmental, social and economic aspects, aligned with the United Nation Sustainability Development Goals (UN SDGs)[8]. Sustainability mainly relates to SDG11 for sustainable cities and communities and SDG13 for climate action, given the fact that high energy efficiency is directly translated to lower CO2 emissions. Even if the current contribution of the ICT sector to the total carbon footprint of the society is limited (estimated to 1.4%[9] of overall global emissions), the increasing digitalization of services and applications will directly imply the densification of the network to increase the capacity and the increase of the total number of end devices that are fabricated. This in turn could lead to an increase of the overall emissions unless energy efficiency principles are natively applied in the related ecosystem. Towards this end, the ITU, GSMA, GESI and SBTi have jointly developed strategies to reduce the environmental footprint of the ICT sector by 50% between 2015 and 2030 in support of the Paris agreement. Likewise, in the "Mobile Net Zero 2024" report from GSMA[10], a total of 53 mobile network operators have committed to reach net-zero emissions by 2050. In this respect, it is important to highlight that, in a GSMA study[11] analysing

[8] https://www.un.org/sustainabledevelopment/sustainable-development-goals/

[9] https://www.itu.int/rec/T-REC-L.1470-202001-I/en

[10] https://www.gsma.com/betterfuture/wp-content/uploads/2024/02/Mobile-Net-Zero-2024-State-of-the-Industry-on-Climate-Action.pdf

[11] https://data.gsmaintelligence.com/api-web/v2/research-file-download?id=60621137&file=300621-Going-Green-efficiency-mobile.pdf

31 networks of different operators, it was calculated that as high as 73% of the energy of the participating operators is consumed in the radio access network, while the network core (13%), owned data centres (9%) and other operations (5%) account for the rest. This trend is only expected to consolidate with the the deployment of 5G networks. The challenge of reducing the energy footprint in 6G RAN opens the door to research and innovation opportunities in the field of wireless communication technologies and signal processing, to help reducing the carbon footprint and thus contribute towards achieving the environmental, economic and social sustainability goals set by the UN SDGs and European Commission.

**Wireless communication technologies and signal processing in 6G use cases**

Wireless Communication Technologies and signal processing will be key to support a whole new range of 6G use cases that will push performance and operational sustainability to whole new limits. For instance, NGMN [12] envisions use cases on Enhanced Human Communication (e.g., XR immersive holographic telepresence communication, intelligent interaction and sharing of sensation, skills and thoughts), Enhanced Machine Communication (e.g., robot network fabric, interacting cobots), Enabling Services (e.g., 3D hyper-accurate positioning, localization and tracking, interactive mapping, automatic detection, recognition and inspection) and Network Evolution (e.g., native trusted AI, coverage expansion). In all these Use Cases a fabric of evolved and novel RAN technologies needs to be put in place to tackle the challenges derived by the combined extreme KPIs.

A different grouping and lineup of use cases is proposed of the O-RAN Alliance[13] which focus among others on new public safety and government applications, specialized vertical industry sectors, real-time analytics, resilience by design, sensory and brain experiences, AI/ML in every part of the network, extreme edge or edge-centric networks and 6G spectrum towards sub terahertz. All these use cases underpin the importance of softwarization and disaggregation of the RAN, the need to expose data through open APIs and the need to efficiently manage new spectrum.

The Next G Alliance[14] is similarly focusing on networked-enabled robotic and autonomous systems (e.g., online cooperative operation among a group of service robots, Field Robots for Hazardous Environments), multi-sensory extended reality (e.g., immersive gaming/entertainment, mixed reality co-design, mixed reality telepresence), distributed sensing and communications (e.g., Remote Data Collection, Public Safety Applications) and personalised user experiences.

**3GPP standardization roadmap**

Regarding the 6G RAN standardization roadmap there was a first 6G timeline discussion in RAN#101 (September 2023), which was triggered by the ITU-R WP5D liaison in RP-23151[15]. High-level considerations for 6G timeline were discussed in RAN#102 (December’2023), resulting in

[12] https://www.ngmn.org/wp-content/uploads/NGMN-6G-Use-Cases-and-Analysis.pdf

[13] https://mediastorage.o-ran.org/ngrg-rr/nGRG-RR-2023-01-O-RAN-Towards-6G-v1_3.pdf

[14] https://nextgalliance.org/white_papers/6g-applications-and-use-cases/

[15] http://www.3gpp.org/ftp/tsg_ran/TSG_RAN/TSGR_101/Docs/RP-231518.zip

the endorsed way forward in RP-233985[16]. Additional considerations for the 6G timeline were discussed in RAN#103 (March 2024), resulting in the endorsed way forward in RP-240823[17].

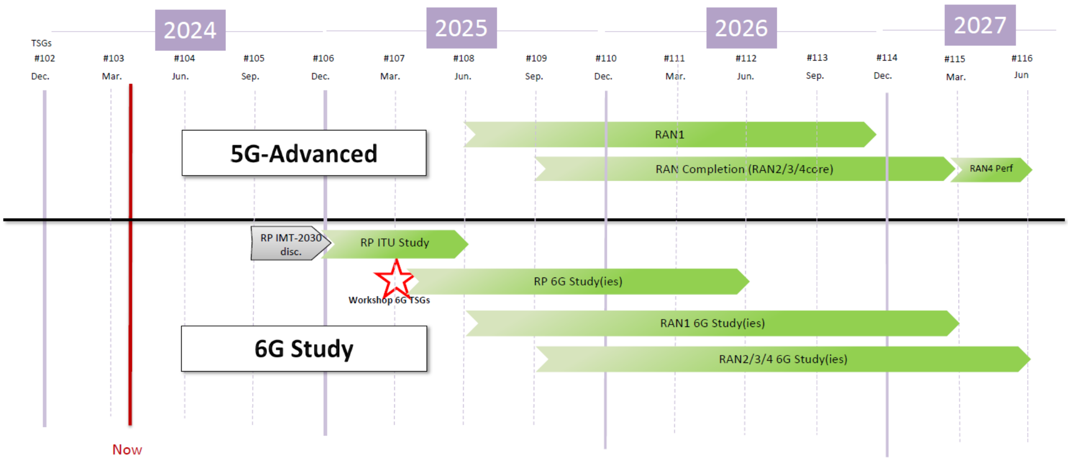


*Figure 3: Illustration of 3GPP RAN Rel 20 Timeline*

The first 3GPP Technical Specification Group (TSG)-wide 6G workshop will take place on March 10th–11th 2025, before the planned Rel-19 RAN1 functional freeze (June 2025). The IMT-2030 discussion is expected to take place in RAN from September to December 2024. The RAN Working Group in Rel-20 will cover the 6G study item (SI) for RAN1 starting from the 3rd quarter 2025 until the 1st quarter 2027 and for RAN2/3/4 starting from the 4th quarter 2025 until the 2nd quarter 2027. The IMT-2030 submission and normative work for 6G in 3GPP are expected to start from Release 21. The latter is expected to produce the first set of 3GPP 6G technical specifications, and will be the release for IMT-2030 submission before 2030. Release 21 is expected to be delivered with a single drop (i.e., a single code freeze) and its timeline is to be decided no later than June 2026. Given the 3GPP timeline depicted in Figure 3 it is clear the priority to start the standardization of the RAN within 2025, a fact that implies a prompt engagement of the key industry players and related stakeholders.

**SNS funding, synergies and opportunities**

Wireless communication technologies and signal processing are considered a cornerstone for making reality the 6G vision, a fact that is affirmed by the amount of funding allocated to the Stream B strand 2 projects in the first 3 phases of SNS programme, as detailed in the following:

- Call 1 (2022): 30 M€
  - 6GTandem: "A Dual-frequency Distributed MIMO Approach for Future 6G Applications"
  - CENTRIC: "Towards an AI-native, user-centric air interface for 6G networks"
  - TIMES: "THz Industrial Mesh Networks in Smart Sensing and Propagation Environments"

[16] http://www.3gpp.org/ftp/tsg_ran/TSG_RAN/TSGR_102/Docs/RP-233985.zip
[17] http://www.3gpp.org/ftp/tsg_ran/TSG_RAN/TSGR_103/Docs/RP-240823.zip

    - TERA6G: "TERAhertz integrated systems enabling 6G Terabit-per-second ultra-massive MIMO wireless networks"
    - TERRAMETA: "TERahertz ReconfigurAble METAsurfaces for ultra-high rate wireless communications"
- Call 2 (2023): 24 M€
    - 6G-MUSICAL: "6G-Multiband Wireless and Optical Signalling for Integrated Communications, Sensing and Localization"
    - INSTICT: "Joint Sensing and Communications for Future Interactive, Immersive, and Intelligent Connectivity Beyond Communications"
    - 6G-SENSES: "SEamless integratioN of efficient 6G wireleSs tEchnologies for communication and Sensing"
    - iSEE-6G: "Integrated SEnsing, Energy and communication for 6G networks"
    - 6G-DISAC: "6G for Distributed Intelligent Sensing and Communication"
    - 6G-GOALS: "6G Goal-Oriented AI-enabled Learning and Semantic Communication Networks"
- Call 3 (2024): 16 M€
    - 2 projects (foreseen)

Complementarily, the wireless communication technologies and signal processing area is also part of HEXA-X project saga, with a more system-oriented perspective. Also, it is worth mentioning that there are also 3 more projects funded under the Stream B strand 5 on Microelectronics-based solutions for 6G networks:

- 6G-REFERENCE: "6G haRdware Enablers For cEll fRee cohErENt Communications & sEnsing"
- TeraGreen: "Towards Energy-Efficient Tbps Wireless Links"
- FirstTo6G: "Fourier-Domain TRx solutions enabling widespread realisation of 6G"

Finally, it is worth mentioning that RAN technologies including AI/ML have a great potential for collaboration with other regions such as USA, Japan and South Korea (SNS calls already included in phase 2 and 3).

Given this panorama and fact that the SNS JU is middle way through its lifespan it is important to define the areas of wireless communication technologies and signal processing that a shift could be applied to higher TRLs in order to target the first release of 6G and also contemplate the focus areas for longer term research (i.e., for future releases and for exploratory topics beyond 6G).

# 3. TOPICS FOR CONSIDERATION

To help the discussions, a list of potential topics was included in the invitation letter sent to workshop participants. This indicative list, which was compiled from the NetworldEurope SRIA and then used as the basis for the SNS SRIA, was meant to be a mere starting point for discussions. This list, which was organized into four distinctive areas, included the following topics:

a) **Technologies and system aspects:**
- 6G RAN System, including all topics e.g., interference management, massive MIMO/RIS, waveform design, full-duplex, modulation and coding, non-orthogonal multiple access/massive random access, etc.
- Cell-free networks.
- System perspective/support of multiple frequencies.
- Energy efficiency and powerful energy management system.
- Evolutive/modular architecture and system design - lifetime maximisation.
- Integrated access/backhaul, evolution of fronthaul.
- Open RAN.

b) **Spectrum-related aspects:**
- Terahertz communication, mmWave, upper-mid band.
- Further improvements to 6GHz and below (e.g., spectral and energy efficiency).
- Efficient multi-RAT dynamic spectrum sharing.

c) **Hardware development aspects:**
- Front-end modules.
- JCAS and positioning.

d) **AI/ML-related aspects:**
- Integrated AI in support of wireless communications (beyond RIC).
- AI-native networks.
- Intent-based management.
- Joint communication and compute (JCAC) in support of distributed AI over the wireless channel.

Prior to the meeting, all participants prepared and shared a presentation of up to five slides about their proposed strategic orientations for this domain. From them, they derived the needed technological developments, together with an identification of their maturity level. Specifically, workshop participants were required to identify (i) the top topics of importance for their organization along with the current TRL levels; (ii) the expected timeline for each topic (short, medium, long) for the foreseen TRL after the completion of the R&I activities; (iii) synergies with other instruments/programmes; and (iv) topics that are currently missing for 6G, that is, not already covered by SNS. Workshop participants included key players from the telecommunications industry (mobile network operators, equipment vendors, research centres and academia). Besides, other players from the microelectronics sector were invited too, to identify further synergies in this domain. The interested reader is referred to Annex 2 for details.

| Nr. | Topic | Sub-topics |
|---|---|---|
| 1 | MIMO, Massive MIMO, and MIMO evolutions | Massive MIMO technology for indoor coverage<br>Extremely large arrays<br>(massive) MIMO evolutions |
| 2 | Efficient support of mmWave and sub-THz communications | Efficient support of mmW/sub-THz band for specific deployment.<br>Beyond mmW: operation in sub-THz and THz frequency bands |
| 3 | AI & Semantic communications | Framework for native AI<br>AI/ML for PHY, MAC and resource optimization in RANs<br>Semantic communications<br>Conflict detection and resolution, predictive management.<br>Distributed and centralized learning<br>Exploitation of Generative AI<br>Trustworthy AI, safe and explainable AI.<br>AI for reduced power consumption, trafic management, coding,..<br>Vision-assisted communications for improved radio/network efficiency<br>AI-assisted multi-user and massive-MIMO Systems<br>Protocol Learning & Learning Networks |
| 4 | Spectrum sharing and RAN co-existence | Spectrum sharing and coexistence mechanisms to enable 6G in 7-15GHz<br>Spectrum sharing and re-use for sustainability<br>Overcoming limitations of variable numerology (coexistence)<br>Dynamic spectrum sharing between 5G and 6G<br>Spectrum sharing with satellite, radar, other terrestrial, UWB |
| 5 | Open RAN | AI/ML powered automation and optimisation, programmability<br>Programmable networks and API native<br>Automation and disaggregation in the RAN segment<br>Exposure of network capabilities<br>Micro-orchestration of RAN functions<br>Open RAN architectures |

| | | |
|---|---|---|
| 6 | Optical-wireless convergence | Radio/optical convergence |
| 7 | Network as a sensor and positioning | JCAS, ISAC and (multi-functional) RIS<br>Network-wide ISAC<br>UE & environment sensing capabilities for improved RRM (eg. beam management)<br>Sensing capabilities with low impact on capacity & radio performance<br>Privacy preserving and surveillance resistant sensing architectures and solutions.<br>High accuracy 3D positioning in high-end UE or for critical usage<br>Ultra low cost positioning for sensors and IoT devices<br>Positioning: real-time 3D/6D imaging, object classification, and technologies for ultra-accurate large-scale synchronization |
| 8 | Multi-processor SoC/accelerators, flexible HW architectures | Flexible HW / SW architecture – modular HW acceleration<br>Agile use of function accelerators at the 6G compute continuum<br>Multi-stakeholder and multi-hardware heterogeneous resource mgment.<br>Communication-compute-control co-design<br>New requirements and expectations on confidential computing solutions.<br>RAN sillicon: photonics, network as a sensor & new processor architectures<br>Energy efficient ASIC technology<br>Radio on glass for wireless backhaul |
| 9 | Integration with NTN | Seamless NTN / TN integration<br>Integration of NTN and TN networks (including mobility-centric design) |
| 10 | Security / privacy | PHY-level spoofing issues<br>Preserving privacy.<br>Air interface security mechanisms: secure scheduling, covert channels |
| 11 | Physical layer technologies for enhanced spectral efficiency | Energy-efficient new waveform design (Low PAPR, low complexity processing)<br>RAN coordination (multi-TRP)<br>CP-OFDM compatible evolution for 6G in NR-Band<br>New duplex principles, UE relaying, specific UL modulation and coding.<br>Self synchronizing modulation and waveform<br>Asynchronous multiple access: NOMA, advanced interference cancellation, full duplex.<br>Energy efficient implementation of key algorithm (FEC, channel estimation)<br>Coding and caching for over-the-air computing in the network edge<br>Improved low layer signalling in 6G Air Interface<br>Waveform design and source-channel codes for short packet trainsmission |
| 12 | Cloud architectures (liaison) | Cloud continuum and network intelligence distribution from sensors / UE to cloud |
| 13 | RF technologies for FR3 implementation | - |
| 14 | Sustainability | Framework for energy efficiency<br>Complete energy usage monitoring and associated optimisation<br>Energy effcient training |

*Table 1: Research topics identified during the wireless workshop in Brussels.*

Based on the received contributions, the discussions held during the workshop, and further analysis and grouping, a total of 14 research topics were identified. These topics are listed in Table 1 above. For a better understanding of their scope, each topic comes with several subtopics as per the interests of workshop participants. A number of comments and considerations are in-line:

- As Table 1 illustrates, not all the 14 identified topics received the same number of contributions. Most popular **topics with a broad consensus** revolve around **MIMO/Massive MIMO/MIMO evolutions (T-1); AI & Semantic communications (T-3); Spectrum sharing and RAN co-existence (T-4); Open RAN (T-5); Network as a sensor and positioning (T-7); Multi-processor SoC/accelerators; flexible HW architectures (T-8); Physical layer technologies for enhanced spectral efficiency (T-11).** Besides, those general topics are also in line with the majority of the "Top 2 priorities" that each participant was asked to identify during the workshop. It is thus proposed to focus in priorities on these topics that have stimulated a higher number of contributions.
- Topic T-14, **Sustainability (in its various flavours), was also identified as a priority** by several workshop participants. Given the large contribution of radio access networks to the overall energy consumption of wireless networks (see Section 2), this should be regarded **as a horizontal aspect** to be addressed by the other topics/priorities to the largest extent possible.
- In many cases, the topics identified are broad in nature (e.g., Physical layer technologies for enhanced spectral efficiency). To date several calls have been launched and substantial funding committed to this research area (and other). In the sequel, **particular attention should be paid to the identification of (i) gaps** in the existing project portfolio; **(ii) topics which have reached a higher maturity level** but still requiring a TRL boost prior to being fed into the standards-related activities to kickstart in 2025; **(iii) longer term topics of a more exploratory nature** and/or meant for later releases of 6G.
- It is also of utmost importance the identification of the suitable frequency bands for operation. For example, despite the large interest that sub-THz, THz and mmW communication raised in the first calls of the SNS R&I WorkProgramme (and latest calls of the 5G-PPP), the support of the big industry players participating in the workshop seems to be more limited now, at least in the short term. On the contrary, **several companies expressed their interest in conducting research activities in the upper mid-band (FR3)** given the inherent cost vs. spectral efficiency trade-offs, and their suitability for technologies such as JCAS/ISAC and u/m/MIMO evolutions.
- Particular attention should be paid to the **impact of new waveform designs and backwards compatibility with existing CP-OFDM waveforms**. Whereas new waveform designs can help enhance spectral efficiency and/or enable sensing operations, the associated cost-benefit trade-offs should be investigated with respect to legacy waveforms, in particular in the lower (legacy) frequency bands.
- Clearly, **several subtopics under multi-processor SoC/accelerators and flexible HW architectures go well beyond the scope of SNS** (e.g., RAN silicon, energy-efficient ASIC technology). Whereas SNS projects are likely to leverage and/or integrate those technologies, their development falls under the umbrella of the Chips JU. Also, RF Technologies for FR3 implementation (T-13) seems to be in close alignment with or at least closer to the SRIA of the Chips JU

- The **attention received by other topics** such as Optical-Wireless Convergence (T-6), Integration with NTN (T-9), Security/privacy (T-10), Cloud Architectures (T12) **is clearly lower. Besides, those topics exhibit synergies and/or are partially under the umbrella of other workshops** in this series. Concerning NTN in particular, network integration aspects go beyond the scope of the radio interface. Therefore, they should preferably be part of the priorities defined in the NTN workshop. Concerning Security/privacy (T-10), physical layer aspects, secure scheduling or covert channels could be addressed here, if room. Privacy and higher layer aspects would probably be more aligned wtih or part of the outcomes/priorities of the security workshop. Finally, for cloud architectures, a liason is mostly envisaged here to guarantee a valid system perspective for the technologies being developed for RAN networks.
- As for the topic **Efficient support of mmWave and sub-THz communications** (T-2), this could well be developed **in the context of the so called Front End Module** intiative of the SNS R&I workprogramme.

For the topics identified in the workshop, a time-plan was discussed as well. This includes the **classification as short-term, mid-term and long-term priorities**, accounting for e.g., future calls for projects to be launched in 2025/2026/2027 respectively, with projects starting one year later in all cases. Potential synergies wtih other funding instruments were also discussed. Major findings are summarized in Table 2 below.

| Nr. | Topic | Short (2025) | Medium (2026) | Long (2027) | Specific/Synergy |
|---|---|---|---|---|---|
| 1 | MIMO, Massive MIMO, and MIMO evolutions | x | | | SNS |
| 2 | Efficient support of mmWave and sub-THz communications | | x | | SNS, CJU |
| 3 | AI & Semantic communications | x | x | | SNS |
| 4 | Spectrum sharing and RAN co-existence | x | | | SNS |
| 5 | Open RAN | x | | | SNS |
| 6 | Optical-wireless convergence | | | x | SNS, Photonics 21 |
| 7 | Network as a sensor and positioning | | x | x | SNS, CJU |
| 8 | Multi-processor SoC/accelerators, flexible HW architectures | x | x | | SNS, CJU, EuroHPC JU |
| 9 | Integration with NTN | | | x | SNS, ESA |
| 10 | Security / privacy | x | | | SNS |
| 11 | Physical layer technologies for enhanced spectral efficiency | x | | | SNS |
| 12 | Cloud architectures (liaison) | x | x | | SNS, Cluster 4, CIS IPCEI |
| 13 | RF technologies for FR3 implementation | x | | | CJU |
| 14 | Sustainability | x | x | x | SNS, CJU |

*Table 2: Research topics identified during the wireless workshop in Brussels.*

Short term topics include areas which are considered particularly mature and or deemed particularly relevant for the initial stages of the standardization process. Mid-term priorities, on the contrary, account for areas where technology is not yet mature, or where topics are currently under development in active SNS projects at lower TRL. Still, for short and mid-term topics further research might also be needed at later stages according to the evolution of the state of the art, Finally, long term priorities are topics of a more exploratory nature and/or not considered critical for the initial standardization steps of radio access networks. In some cases, several boxes have been checked since topical areas are broad in nature and the corresponding timeframes of each subtopic may differ. Likewise, there can be different needs for cross-domain collaboration for the different subtopics within a given topic. In T-8 for instance, the multi-stakeholder, co-design and new requirements areas may require a broader cross-domain collaboration. On the contrary, modular HW acceleration, energy efficient ASIC and radio-on-glass tend to be more single-domain.

# 4. POSSIBLE WAY FORWARD

Table 2 reveals that virtually all the proposed research topics fall under the umbrella of the SNS. However, some of the areas identified are more aligned with other streams of the SNS JU R&I programme. Besides, it also evidences that a number of synergies with sister JUs (Chips JU, EuroHPC JU), and related initiatives (IPCEI) exist.

In the light of the discussions maintained during the workshop, in upcoming calls of the SNS R&I Workprogramme priority should be preferably given to topics which are technologically relevant, and exhibit a broad consensus, namely,

- MIMO/Massive MIMO/MIMO evolutions (T-1)
- AI & Semantic communications (T-3)
- Spectrum sharing and RAN co-existence (T-4)
- Open RAN (T-5)
- Network as a sensor and positioning (T-7)
- Multi-processor SoC/accelerators; flexible HW architectures (T-8)
- Physical layer technologies for enhanced spectral efficiency (T-11)
- Sustainability (T-14), as a horizontal aspect.

In doing so, particular attention should be paid to the gap analysis in the current project portfolio, and to the corresponding TRL levels of such technologies. It is also worth mentioning that several subtopics listed under multi-processor SoC/accelerators and flexible HW architectures go well beyond the scope of the SNS JU. This includes for instance, the development of RAN silicon or energy-efficient ASIC developments, or the development of hardware acceleration platforms themselves for the 6G compute continuum, which are mostly to be integrated/used by SNS projects. Currently, SNS' Front-End Module (FEM) initiative, which is aimed at establishing synergies with the Chips JU, does not cover those aspects. Therefore, one possible way forward would be to address those developments as part of the Chips JU efforts, for instance in relation with its cross-sectional technology 2.1 (Edge Computing and Embedded Artificial Intelligence) in the ECS Strategic Research and Innovation Agenda 2024. On the contrary, Efficient support of mmWave and sub-THz communications (T-02) and RF technologies for FR3 implementation (T-13) could make a better fit into the FEM initiative or, alternatively, in selected parts of the CJU Workprgramme in relation with e.g., its cross-sectional technology 2.2 (Connectivity) in the ECS SRIA.

As for the topics that received less attention in this workshop, namely,

- Optical-Wireless Convergence (T-6)
- Integration with NTN (T-9)
- Security/privacy (T-10)

- Cloud Architectures (liaison) (T12)

there exist clear synergies with other parts of the SNS Workprogramme beyond the wireless technologies and signal processing area that should be explored. Likewise, synergies could also be sought with Photonics 21, ESA, Cluster 4 (Connected–Collaborative –Computing initiative 3C) and the existing CIS IPCEI initiative.

# 5. ANNEX 1: COMPLETE LIST OF TOPICS

1. MIMO, Massive MIMO, and MIMO evolutions
2. Efficient support of mmWave and sub-THz communications
3. AI & Semantic communications
4. Spectrum sharing and RAN co-existence
5. Open RAN
6. Optical-wireless convergence
7. Network as a sensor and positioning
8. Multi-processor SoC/accelerators, flexible HW architectures
9. Integration with NTN
10. Security / privacy
11. Physical layer technologies for enhanced spectral efficiency
12. Cloud architectures (liaison)
13. RF technologies for FR3 implementation
14. Sustainability

# 6. ANNEX 2: LIST OF PARTICIPANTS TO THE WORKSHOP ON WIRELESS COMMUNICATIONS AND SIGNAL PROCESSING

| *Surname* | *Name* | *Company / Institute / University* |
|---|---|---|
| Albares Bueno | Javier | SNS-JU |
| Alonso | Jesús | i2CAT |
| Antón-Haro | Carles | CTTC |
| Barani | Bernard | 6G-IA |
| Bartzoudis | Nikolaos | CTTC |
| Bayou | Remy | DG-CNECT |
| Boldi | Mauro | TIM |
| Charalambides | Marinos | SNS-JU |
| Delsing | Jerker | Inside IA/LTU |
| Dieudonne | Mikael | Keysight |
| Fallgren | Mikael | Ericsson |
| Fitori | Erzsebet | SNS-JU |
| Fournogerakis | Pavlos | SNS-JU |
| García | Aitor | Vodafone |
| Kaloxylos | Alex | 6G-IA |
| Knopp | Raymond | Eurecom |
| Lentini Graziano | Roberta | TIM |
| Pirmagomedov | Rustam | Nokia |
| Pyrovolakis | Odysseas | SNS-JU |
| Roda Neve | Cesar | SOITEC |
| Schwoerer | Jean | Orange |
| Xu | Wen | Huawei |

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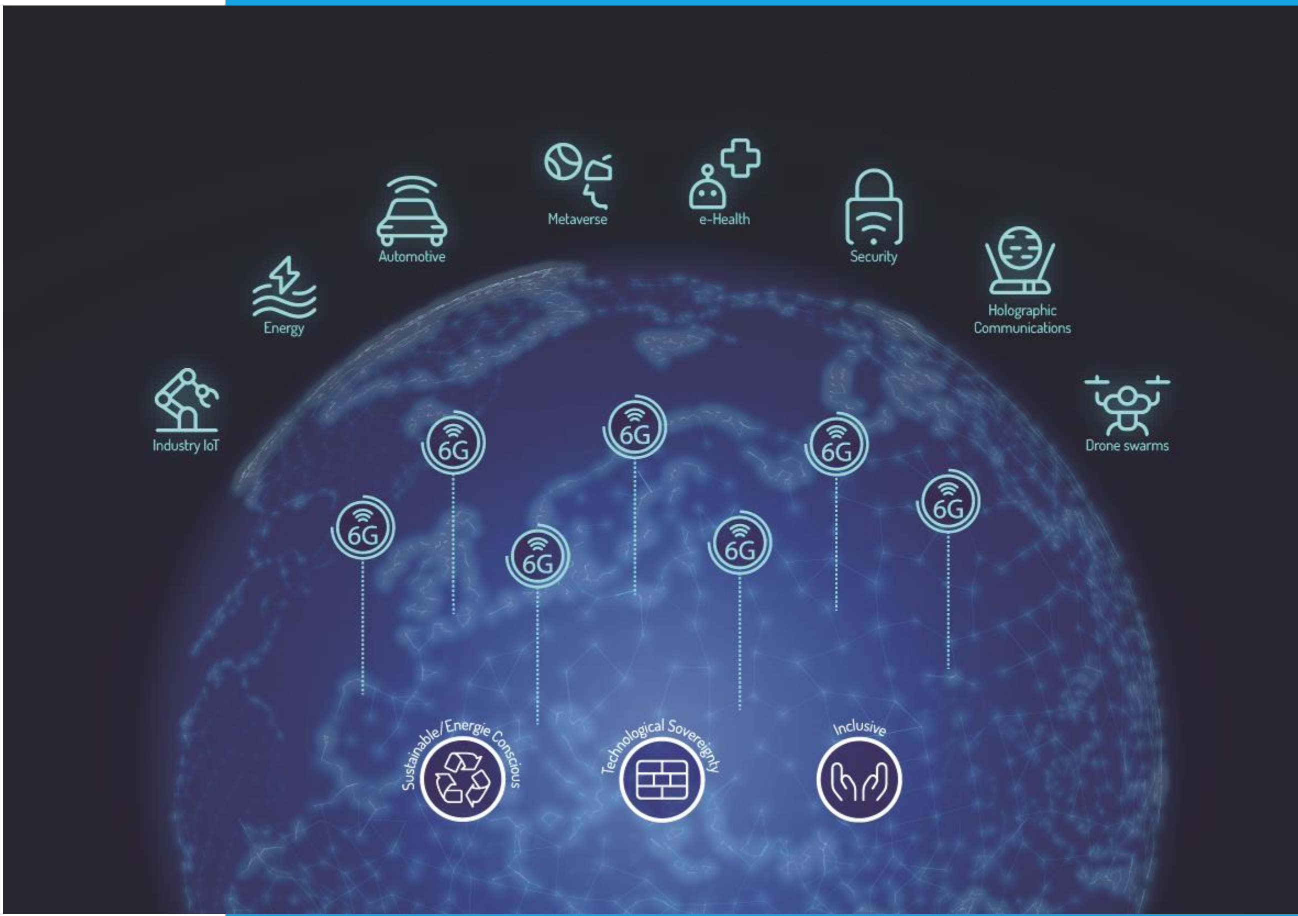


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