WHITE PAPER

6G-SHINE: ADVANCING CORE TECHNOLOGIES FOR IN-X SUBNETWORKS

OCTOBER 2025

DOI: 10.5281/zenodo.17338153

URL: https://doi.org/10.5281/zenodo.17338153

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The 6G-SHINE project set out to design the foundational technology components that will enable the next generation of *in-X subnetworks*—short-range, low-power radio cells operating at the very edge of the 6G “network of networks.” These subnetworks are envisioned to provide pervasive wireless coverage with unprecedented performance requirements. They should be able to operate independently, much like ad hoc networks, with the advantages of seamless integration into the broader 6G system, which can support spectrum and computational resource management, authentication and authorization, traffic policy enforcement, and data offloading.

The project advanced research across multiple technical domains, including the physical layer, medium access control, radio resource management, and network architecture. The ambition was to create a portfolio of innovations that can transform in-X subnetworks from concept into reality. This involved not only developing mechanisms for local communication but also establishing how such subnetworks can be efficiently managed, secured, and interconnected with the wider 6G framework.

Through this work, 6G-SHINE has laid the groundwork for future wireless systems in which groups of devices can form intelligent, autonomous, and highly efficient subnetworks operations. These advances open the door to new applications in consumer, industrial, and vehicular domains, where local connectivity, robustness, and responsiveness are critical.

This whitepaper is based on the 6G-SHINE project deliverables and presents a concise overview of the main innovation developed in the project.

Acknowledgement

This whitepaper is based on the deliverables of the 6G-SHINE project (Horizon Europe Grant Agreement No. 101095738), publicly available in the project website. This project is funded by the European Union. Views and opinions expressed here are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Health and Digital Executive Agency. Neither the European Union nor granting agency can be held responsible for them.

ABBREVIATIONS

Abbreviation	**Meaning**
3GPP	3rd Generation Partnership Project
AI	Artificial Intelligence
AR	Augmented reality
BLER	Block Error Rate
CN	Core Network
CSI	Channel State Information
DNN	Deep Neural Networks
ECU	Electronic Control Unit
GDRA	Gradient Descent-based Resource Allocation
GNN	Graph Neural Networks
GW	Gateway Role
HC	Element with High Capabilities
HPCU	High Processing Control Unit
ISAC	Integrated Sensing and Communication
LC	Element with Low Capabilities
LOS	Line-of-Sight
LSTM	Long Short-Term Memory
MAC	Medium Access Control
ML	Machine Learning
NLOS	Non Line-of-Sight
O-RAN	Open Radio Access Network
OFF	Compute Offloading
PoC	Proof-of-Concept
PPO	Proximal Policy Optimization
RAN	Radio Access Network
RIS	Reconfigurable Intelligent Surface
RRM	Radio Resource Management
SL	Sidelink
SN	In-X Wireless Subnetwork
SNE	Subnetwork Element
SNM	Subnetwork Management
SNR	Signal-to-noise ratio
TRL	Technology Readiness Level
UE	User Equipment
URLLC	Ultra-reliable Low Latency Communication
VAA	Vehicle Access Area
XR	Extended Reality

1. INTRODUCTION

The 6G Short range extreme communication IN Entities (6G-SHINE) project, funded under the SNS Work Programme Phase 1 Stream B, targets the design of core technology components for wireless in-X subnetworks—short-range, low-power radio cells deployed at the very edge of the 6G “network of networks.” These subnetworks aim to deliver pervasive wireless coverage while meeting unprecedented performance requirements. They should be able to operate independently similarly to ad hoc networks, while benefitting from connection with the 6G parent network, that can ease management of spectrum and computational resources, authentication / authorization, policy enforcement for traffic to/from devices in the subnetwork, traffic offloading.

6G-SHINE advanced research in the physical layer, medium access control, radio resource management, and network architecture, with the ambition of assembling a portfolio of technology components that can turn in-X subnetworks from concept into reality.

The project brought together a consortium of 12 partners: Aalborg University (Denmark), CNIT (Italy), Universidad Miguel Hernández de Elche (Spain), Apple (Germany), Sony (Sweden), Bosch (Germany), Interdigital (UK), Fraunhofer IIS (Germany), imec (Belgium), Keysight (Finland), Nokia (Denmark), and Cogninn (Greece).

In this whitepaper, we present a concise overview of the innovative ideas and concepts developed in the project.

Section 2 presents the main use cases envisioned for in-X subnetworks, covering the consumer, industrial, and in-vehicle domains, along with the main architectural enablers.

Section 3 summarizes the radio channel characterization activities run in the project, covering diverse use cases and frequency bands.

The developed physical layer and medium access control enablers are presented in section 4, while section 5 focuses on radio resource management research.

Section 6 presents our research outcome for the management of traffic, spectrum and computational resources. The realized PoCs are presented in section 7. Finally, Section 8 provides concluding remarks, and an outlook for future activities.

All project deliverables are available on the project website (6gshine.eu), with references provided throughout this whitepaper to link the innovations presented to their corresponding deliverables. For a comprehensive description of the innovations, the reader can refer to the project deliverables.

2. USE CASES FOR IN-X SUBNETWORKS

In-X subnetworks are short-range, low power radio cells to be installed in entities such as robots, production modules, vehicles, and classrooms, to deliver highly localized and high-performance connectivity. We have identified 13 relevant use cases for in-X subnetworks, covering the consumer, industrial and in-vehicle domains. The use cases, pictorially depicted in Figure 1, 2 and 3, have extensively been described in deliverable D2.2, along with their performance requirements, and are summarized in Table 1.

Table 1 6G-SHINE in-X subnetworks use cases

No	Title	Short Descriptions
C-1	Immersive Education	Immersive Education aims to enhance the interactive experience for a group of students and teacher(s) for knowledge exchange, leveraging media content and related technologies (e.g., XR devices).
C-2	Indoor Interactive Games	XR interactive gaming in an indoor environment where one or more players play in a place where it has been equipped and pre-loaded with some equipment to facilitate the XR interactive gaming.
C-3	Virtual Live Production	One or more performers that can be located in different geographical areas produce 3D video content that can be live-broadcasted or uploaded to social media.
C-4	AR Navigation	AR navigation powered by AI/ML concierge based on user input, including the information around the user. The output is provided to the user via an AR device.
I-1	Robot Control	The wireless control of robot operations, such as the control of multi-axis robots for leveraging the degrees of freedom offered by potential movement directions the robot can accomplish.
I-2	Unit Test Cell	To perform quality assurance tasks of product parts in the manufacturing process, as well as of devices used in the manufacturing process.
I-3	Visual Inspection Cell	A visual inspection cell performs quality assurance in the manufacturing process through video feeds. The video feeds are processed, and quality control is performed, by eventually outputting commands to actuators in case actions are to be taken for improving operation quality.
I-4	Subnet Co-existence in Factory Hall	Tasks distributions among a swarm of smaller, specialized robots. Each robot is configured to perform a specific function. Working in concert, these robotic swarms can assemble intricate products
I-5	Subnetwork Segmentation and Management	Combination of all the other industrial use cases with a focus on the security and management aspects, particularly on functional requirements.

V-1	Wireless Zone ECU: in-vehicle wireless subnetwork zone	In-vehicle zone wireless subnetwork that is utilized by some sensors and actuators located in this zone to connect wirelessly to the zone Electronic Control Unit (ECU) that manages and controls them. The sensors and actuators that are wirelessly connected to the zone ECU are equipped with a 6G-capable wireless communication interface that replaces their former wired communication interface.
V-2	Collaborative Wireless Zone ECUs: Functions across multiple in-vehicle zones	This use case covers automotive systems and applications that require (or benefit from) collaboration or offloading between functions, sensors and actuators located at different zones of the considered 6G-SHINE reference in-vehicle E/E architecture, via a High Processing Control Unit (HPCU).
V-3	Inter-subnetwork Coordination: Collaboration/interference/RRM between subnetworks in intra/inter-vehicle communications	Two cases of subnetwork coordination on RRM/interference handling where the sub-networks can be within the same vehicle (Intra-vehicular) or in some other vehicle(s) (Inter-vehicular).
V-4	Virtual ECU: In-vehicle sensor data and functions processing at the 6G network edge	Integrating the in-vehicle network with the 6G parent network, to seamlessly extend the in-vehicle embedded compute capabilities to the edge/cloud.

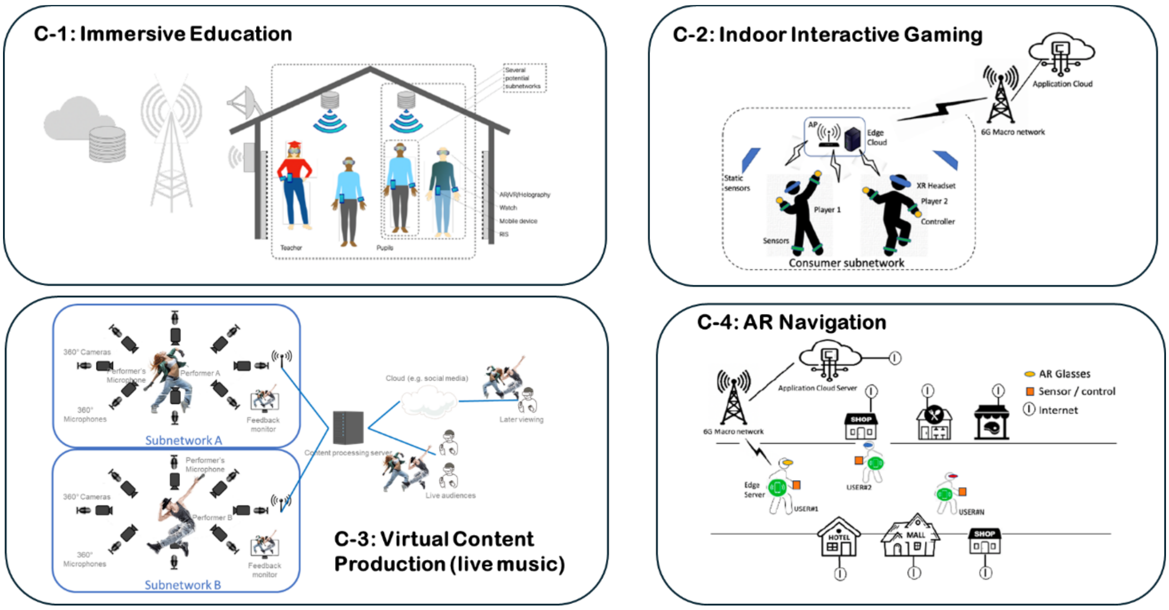

Figure 1. Use cases for consumer subnetworks.

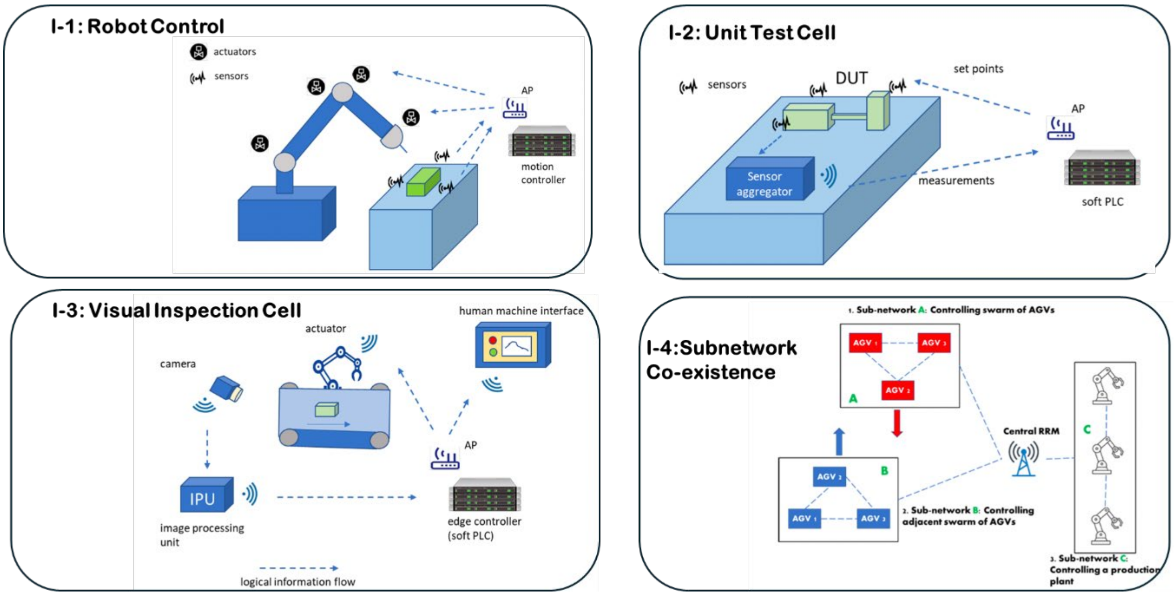

Figure 2. Use cases for industrial subnetworks.

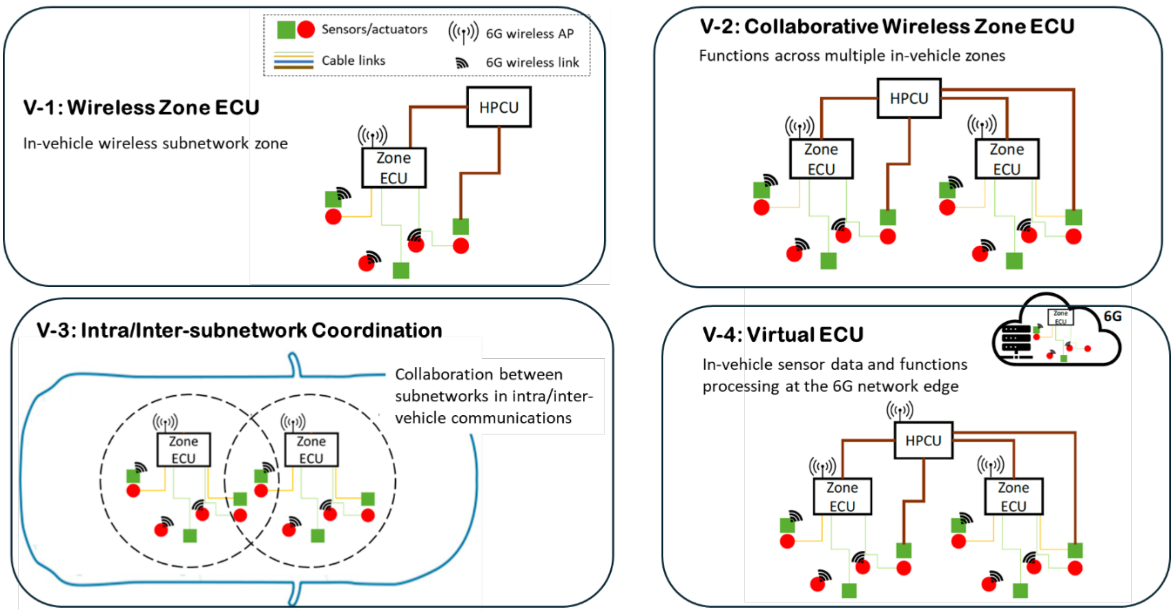

Figure 3. Use cases for in-vehicle subnetworks.

Consumer Subnetworks:

Use cases in consumer subnetworks typically demand high data rates and low latency. Computation offloading is commonly employed, particularly for video rendering and AI/ML data processing. A baseline level of reliability is essential to minimize retransmissions, which could otherwise increase latency. These scenarios involve a diverse set of KPIs across different links—such as one or more high-throughput data streams (e.g., uplink/downlink video frames) accompanied by multiple low-rate sensor data streams. Additionally, synchronization among multiple media streams—including video, audio, and sensor data—is often required. Meeting the simultaneous demands of high throughput (up to 6.37 Gbps), low latency, and high reliability presents significant technical challenges.

Industrial Subnetworks:

Industrial use cases generally prioritize ultra-low latency and high reliability. Certain scenarios require communication cycles below 100 µs. Although the data rates per device are typically low, the number of connected devices per access point (AP) can be high. Furthermore, multiple APs may need to operate concurrently, necessitating a well-designed network architecture to support stringent latency requirements and enable potential computation offloading between nodes. It is worth noting that industrial use cases involving video feeds may also require relatively high data rates—up to approximately 50 Mbps.

In-Vehicle Subnetworks:

In-vehicle use cases place a strong emphasis on extreme reliability, with some scenarios demanding up to 99.9% reliability. These deployments often involve a mix of medium-rate links—such as those carrying image or video data from cameras—and low-rate links related to interactions with various sensors and actuators.

The use cases defined within the 6G-SHINE framework are expected to contribute meaningfully to key value indicators (KVIs) related to social, environmental, and economic sustainability.

Social sustainability is addressed through enhancements in user experience, ensuring that future connectivity services deliver greater inclusivity, accessibility, and quality of life compared to existing technologies.

Environmental sustainability is pursued through targeted reductions in carbon emissions, including both carbon dioxide and methane, alongside a decrease in overall energy consumption across network operations and end-user applications.

Economic sustainability is addressed through different mechanisms depending on the subnetwork context. In industrial subnetworks, the focus is on improving production efficiency, thereby enhancing competitiveness and resource utilization. In in-vehicle subnetworks, economic benefits stem from the extension of vehicle lifecycles and the promotion of circular economy principles. In consumer subnetworks, economic sustainability is supported by enabling new digital services in sectors such as education and gaming, potentially unlocking new markets and innovation opportunities.

Across all use cases, low-latency and reliable communications are identified as foundational enablers of these sustainability objectives. In addition, high data rates are recognized as essential in specific scenarios, particularly within consumer subnetworks, to support advanced multimedia applications and real-time interactivity.

Related deliverable: D2.1, “Initial definition of scenarios, use cases and service requirements for in-X subnetworks” , D2.2, “Refined definition of scenarios, use cases and service requirements for in- X subnetworks”.

2.1 Architectural enablers

In-X subnetworks, along with their integration in the 6G network of networks, represent a major architectural innovation in the wireless communication landscape. In-X subnetworks are specialized networks designed to provide localized, high-performance connectivity within a defined entity or environment. These networks operate over short ranges—typically under 10 meters—and are generally low-power, making them well-suited for offloading demanding services from larger networks. Their primary purpose is to deliver highly localized connectivity through compact, efficient network cells.

An In-X subnetwork may include one or more High-Capability (HC) or Low-Capability (LC) nodes, with HCs often featuring integrated edge processing capabilities. These are complemented by a potentially large number of cost-effective, resource-constrained devices with compact form factors, such as sensors and actuators, collectively referred to as Subnetwork Elements (SNEs).

In-X subnetworks are capable of operating independently in the event of intermittent or lost connectivity to the overarching 6G network, ensuring continued service in stand-alone mode. When connected, the parent 6G infrastructure orchestrates the subnetwork's operations to maximize efficiency and coordination. Non-standalone subnetworks, by contrast, remain continuously dependent on the 6G umbrella network.

Moreover, In-X subnetworks support hierarchical and multi-tiered architectures by allowing nesting—where a subnetwork can host one or more smaller-scale subnetworks. This nesting capability enhances scalability, enables localized optimization, and supports flexible deployment models across diverse use cases.

The following main roles have been defined:

Gateway (GW) Role:

An element assigned the gateway role is responsible for managing data traffic routing both within a single subnetwork and across multiple subnetworks. In certain scenarios, it may function as a relay either within the same subnetwork (intra-SN) or between different subnetworks (inter-SN), and can also serve as the access point to the parent 6G network.

Compute Offloading (OFF) Role:

An element with the compute offloading role leverages its processing capabilities to coordinate the offloading of applications and/or network functions from source nodes to target nodes. It may act as a provider (or donor) of computational resources to other elements within the same subnetwork or across different subnetworks. Additionally, such an element may interface with the 6G Network Compute Node to facilitate distributed computing operations.

Radio Resource Management (RRM) Role:

An element performing the radio resource management role oversees the allocation and optimization of radio resources for one or more elements within a subnetwork. Various RRM schemes may be employed, including centralized, hybrid, or fully distributed approaches. The RRM role may also encompass advanced functions such as interference and jamming mitigation, coordination of Reconfigurable Intelligent Surfaces (RIS), and the management of both licensed and unlicensed spectrum, including support for spectrum sharing.

Subnetwork Management (SNM) Role:

An element with subnetwork management capabilities is tasked with overseeing the operational integrity of the subnetwork. This includes functions such as device authentication, mobility management (e.g., handover procedures), time synchronization (e.g., acting as a master clock), and continuous monitoring of network performance metrics.

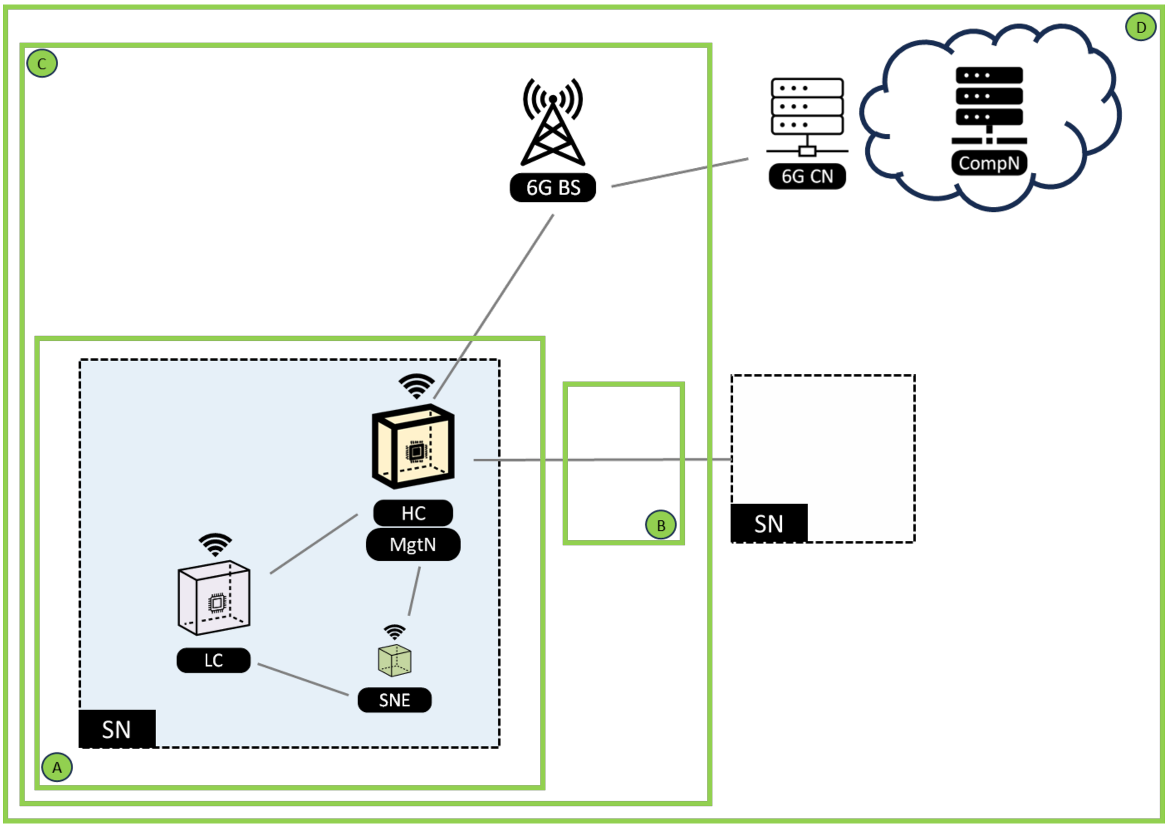

Figure 4. 6G-SHINE architectural blueprint.

The architectural enhancements defined in 6G-SHINE, reflect the following clusters (pictorially depicted in Figure 4):

A. Intra-Subnetwork Management:

This cluster encompasses all functional enhancements necessary for managing an individual subnetwork. It includes core capabilities such as authentication, node and node group management, routing, tunneling, virtual connection provisioning, assignment of compute roles, AI/ML integration, and radio resource allocation. These functions collectively form the foundation for enabling and sustaining the autonomous operation of subnetworks.

B. Inter-Subnetwork Management:

This cluster focuses on the control mechanisms required to ensure connectivity, operability, and seamless service continuity across multiple subnetworks. It also addresses the enablers for distributed computing across subnetworks, supporting collaborative processing and resource sharing.

C. Parent 6G Network Management – Radio Access Network (RAN) Level:

This cluster comprises the necessary enablers to integrate subnetworks within the RAN domain of the parent 6G network. While many of the functionalities addressed in clusters

A and B have implications at the RAN level, particular emphasis is placed here on AI/ML-driven management and ensuring interoperability with O-RAN architectures.

D. Parent 6G Network Management – Core Network (CN) Level:

This cluster focuses on the integration of subnetworks within the 6G Core Network. In addition to aspects from clusters A and B that impact the CN domain, this cluster prioritizes enablers for integrated sensing and ISAC capabilities, edge-cloud fabric support for compute services, bidirectional compute offloading between subnetworks and the CN, management of non-3GPP subnetworks, and AI/ML services provisioning for subnetwork support.

Related deliverable: D2.4 "In-X subnetwork architectures and integration into 6G 'networks of networks'"

3. IN-X SHORT-RANGE RADIO CHANNEL CHARACTERIZATION

6G-SHINE has done significant experimental work for characterizing the short-range radio channel characterization of in-X subnetworks, with particular emphasis on those scenarios disregarded by industry and academia.

The measurement campaign was primarily conducted in industrial and vehicular environments using a Vector Network Analyzer (VNA)-based channel sounding system, covering a wide spectrum of frequencies ranging from sub-6 GHz to sub-terahertz (sub-THz). Complementary measurements were also carried out to assess short-range propagation in an outdoor campus setting and to investigate human-body shadowing effects in the D-band. In addition, a fully automated system was developed for three-dimensional characterization of Reconfigurable Intelligent Surface (RIS) re-radiation, along with a diagnostic procedure designed to evaluate the impact of faulty RIS elements on overall system performance. Particular attention was given to emerging frequency bands considered critical for the 6G ecosystem, especially FR3 and sub-THz bands.

In the industrial context, various measurement scenarios were analyzed: (1) spatial map acquisition in both Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions using omnidirectional antennas; (2) short-range measurements conducted in proximity to a robotic arm and along a production line; and (3) Vehicle Access Area (VAA) and large-scale VAA assessments aimed at comprehensive channel characterization. From a channel modeling perspective, spatial maps in industrial environments were rigorously analyzed, extracting key parameters such as path loss, delay spread, and Rician K-factor. The measured delay spreads were consistent with the median values predicted by reference 3GPP models. However, Rician K-factors were generally low—typically not exceeding 10 dB—even under LOS conditions. This suggests that, in industrial settings, the LOS component does not dominate the channel response due to the presence of several strong multipath contributions.

In the vehicular domain, measurements were performed under diverse conditions—including in-cabin, engine bay, LOS, obstructed-LOS (O-LOS), and outdoor-to-indoor scenarios. The results revealed rich scattering behavior and low attenuation due to internal components across a broad frequency range, thereby supporting the feasibility of in-vehicle subnetworks operating in low-frequency (FR1), mmWave (FR2), and 8–12 GHz (FR3) bands. In these ranges, radio channels exhibited similar characteristics. In contrast, sub-THz frequencies demonstrated sparser channels due to stronger propagation losses and the use of highly directional antennas.

Outdoor-to-indoor measurements were specifically conducted at 8–12 GHz (FR3 mid-band) and in the D-band (sub-THz). The analysis of signal penetration through various vehicle components indicated that inter-vehicle communication is feasible in the FR3 band, aided by diffraction around metallic obstructions. However, at sub-THz frequencies, penetration through the vehicle body is largely inhibited, with windows representing the only viable propagation path, due to the high attenuation and poor penetration properties of these bands.

Overall, these findings provide key insights for the design of vehicular subnetworks. They highlight both the potential for reliable inter-vehicle communication at certain frequencies and the opportunity to exploit high-frequency signal confinement for interference mitigation and subnetwork isolation across vehicles.

Related deliverable: D2.3 “Radio propagation characteristics for in-X subnetworks”.

4. PHYSICAL LAYER AND MEDIUM ACCESS CONTROL ENABLERS

By exploring concrete subnetwork configurations across consumer, industrial, and vehicular domains, 6G-SHINE has demonstrated how its advanced PHY and MAC solutions can meet demanding KPIs related to throughput, latency, reliability, scalability, determinism, and synchronization—surpassing the capabilities of current wireless technologies. Figure 5 clusters the PHY and MAC methods developed in the project in terms of their expected short-, medium- and long-term impact.

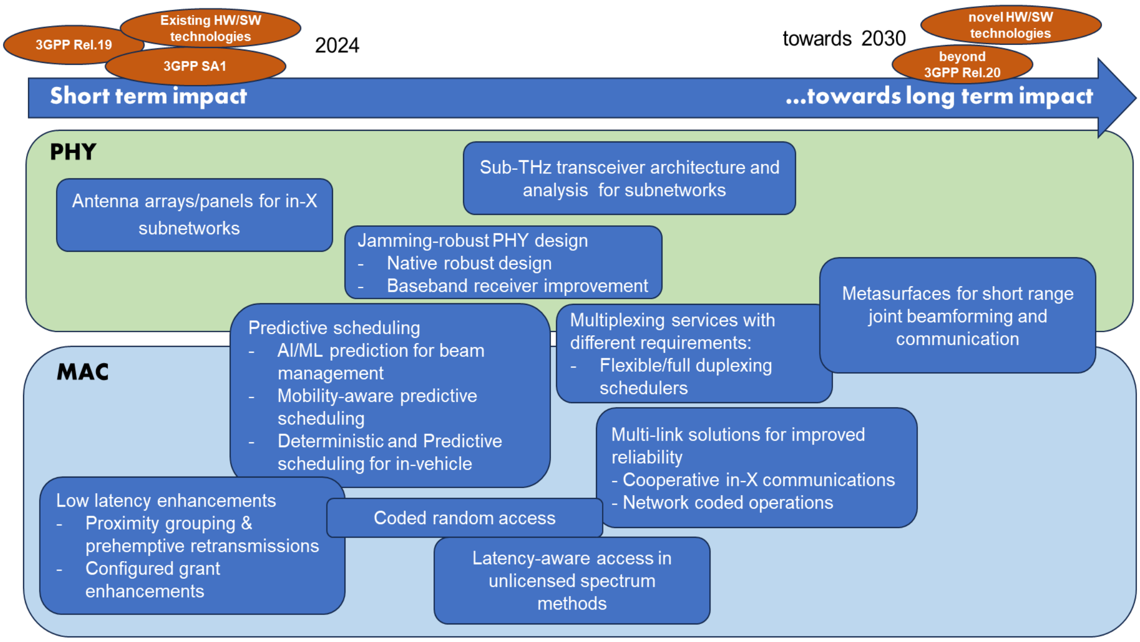

Figure 5. 6G-SHINE PHY and MAC innovations.

In the consumer domain, the indoor interactive gaming scenario illustrates the need for massive bandwidth and ultra-low-latency synchronization to enable immersive XR experiences. The combination of outside-in tracking, local rendering, and actuator control within a confined subnetwork imposes stringent performance requirements. 6G-SHINE addresses these challenges through sub-THz communications, enabling 8K–24K video streaming with power consumption below 1W at the headset, while achieving ~2× lower complexity at the device side and ensuring high reliability (BLER < 10^{-6}).

In industrial settings, wireless robot control poses some of the strictest demands, including communication cycles below 100 μs, jitter under 1 μs, and ultra-low BLER. 6G-SHINE introduces novel technologies—such as metasurfaces to shift part of the processing directly to the electromagnetic (EM) domain (self-conjugating metasurfaces and dynamic scattering arrays), jamming-resilient PHY, proximity grouping, predictive scheduling, coded random access, and network-coded cooperation—that not only match but often exceed the performance of wired systems like EtherCAT. Results include ~10× latency reduction, ~20× improvement in latency metrics in unlicensed bands, BLER <10^{-6} (down to 10^{-7} in relaxed settings), and ~4× improvement in spectral efficiency, along with significant power savings through EM-native processing and cooperative mechanisms. These techniques ensure robust subnetwork operation even under interference and jamming conditions.

In the vehicular domain, the Virtual (Wireless) ECU use case marks a shift toward fully wireless in-vehicle networks, replacing traditional harnesses with high-capacity 6G wireless subnetworks. Required KPIs include latencies under 1 ms, data rates ranging from 2 Mbps to Gbps, and highly reliable, deterministic communications. 6G-SHINE meets these targets through deterministic and predictive traffic scheduling and flexible duplexing. These approaches deliver up to 18× improvements in communication reliability, ~7× enhancements in scalability, and up to 2× more efficient resource utilization compared to state-of-the-art techniques.

Beyond these use-case-specific advancements, several core PHY and MAC innovations developed within 6G-SHINE have broader applicability:

- Antenna arrays with reciprocity-based beam alignment improve throughput by 50% to 100% over conventional wide-beam transmit schemes.
- Full and flexible duplexing allows for ~10× latency reduction and up to ~8× spectral efficiency gains over 5G benchmarks.
- Low-latency, reliable unlicensed spectrum access techniques achieve 2–3× lower packet drop rates across a wide SNR range compared to existing solutions.
- Interference-resilient, scalable access protocols enable dense subnetwork deployments in constrained or unlicensed spectrum.
- Predictive mechanisms, including Long Short-Term Memory (LSTM)-based schedulers and proximity-aware retransmissions, improve responsiveness and resource efficiency.
- Hardware-native innovations—such as metasurfaces and sub-THz transceivers—provide performance levels beyond the reach of conventional digital architectures.

Together, these results illustrate the potential of 6G-SHINE's subnetwork-centric approach to meet and exceed the ambitious targets set for next-generation wireless systems.

Besides the enhancements mentioned above, Reconfigurable Intelligent Surfaces (RIS) have emerged as a promising technology to address key challenges in subnetworks, including energy efficiency, latency, implementation complexity, and communication reliability. However, deploying RIS in subnetwork scenarios also introduces non-trivial challenges, such as the lack of physically consistent models, high signaling overhead, configuration complexity and latency, and the risk of uncontrolled interference—both within a subnetwork and across neighboring ones, especially in uncoordinated environments.

6G-SHINE tackled these issues through advances at the modeling, technology, and algorithmic levels. More accurate RIS models were developed, rooted in multi-port theory, enabling offline RIS optimization based on statistical channel knowledge. This approach significantly reduces the overhead required for channel state information, by up to a factor of N, where N is the number of RIS elements. In parallel, macroscopic ray-based models were created and validated through extensive measurements.

On the technological side, innovative RIS architectures were introduced, including non-diagonal RISs that offer enhanced flexibility in interference mitigation and support the formation of broad beams. Such capabilities proved essential in use cases like indoor interactive gaming, where non-diagonal RISs enabled 20–30 dB interference reduction compared to conventional configurations. Similarly, wide-beam RIS designs were critical to supporting dense subnetwork deployments (e.g., 20 nodes) in factory environments.

To further improve performance, optimization strategies were proposed to minimize power consumption while preserving required data rates in networks comprising multiple RISs and subnetwork elements. These approaches demonstrated power savings of 5–60 dB in dense industrial subnetwork scenarios compared to setups without RIS support.

Additional innovations included novel packet coding schemes that exploit RIS presence to enhance communication reliability. For example, in visual inspection tasks in industrial environments, the proposed flexible packet coding led to a ~10× improvement in spectral efficiency.

Unexpected yet impactful outcomes also emerged during the RIS-focused research activities. Specifically, when used with Ultra wide-band (UWB) signals, RISs were found to exhibit a double beamforming effect. Rather than posing a limitation, this effect was harnessed by redesigning the RIS architecture to manage up to five times the bandwidth compared to conventional RISs, opening new opportunities, particularly for consumer applications.

Related deliverables: D3.1 "Preliminary results on PHY and MAC enablers for in-X subnetworks", D3.2 "RIS technologies and models for in-X subnetworks", D3.3 "Recommended PHY and MAC enablers for in-X subnetworks", D3.4 "RIS Management strategies for in-X subnetworks".

5. RADIO RESOURCE MANAGEMENT

Subnetworks can spontaneously become very dense, such as those installed in robots, production modules, and vehicles. Interference is therefore a major challenge to be dealing with in order to support the demanding requirements of dense subnetworks.

Significant progress has been achieved in advancing reliability, scalability, low latency, spectral efficiency, and resilience to interference through a unified suite of centralized, distributed, and goal-oriented radio resource management (RRM) solutions developed within the 6G-SHINE project. Figure 6 presents a pictorial depiction of the RRM context for dense in-X subnetworks.

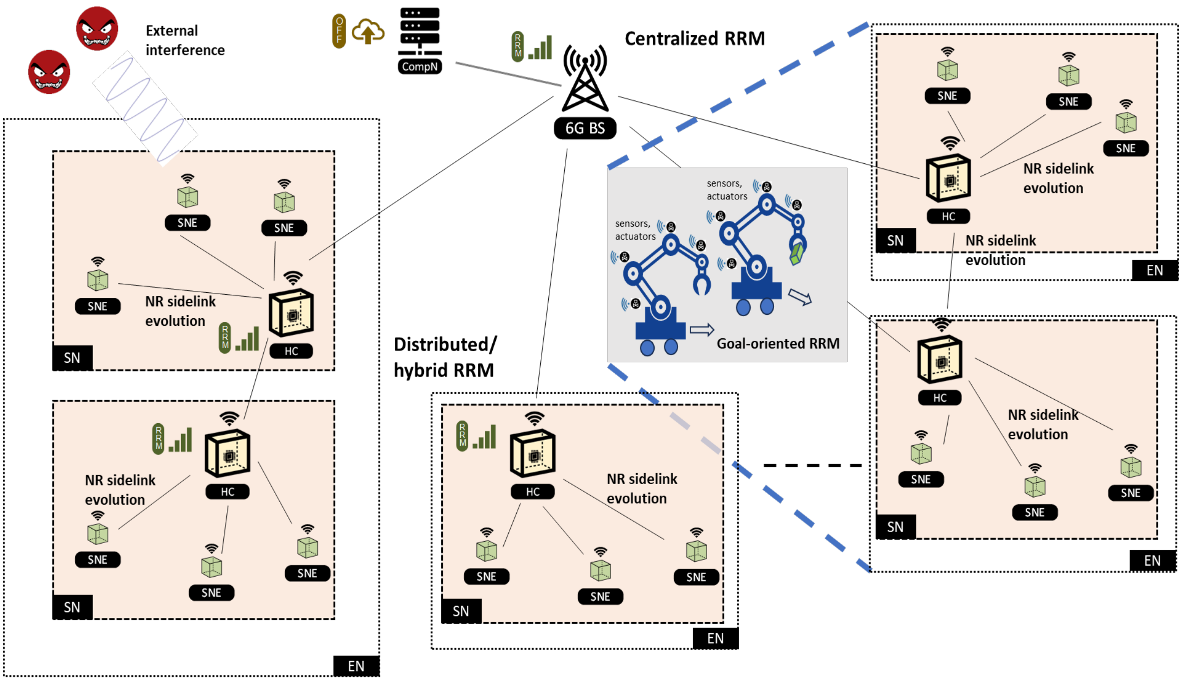

Figure 6. Radio resource management in dense in-X subnetworks.

Centralized solutions rely on the presence of RRM capabilities at the 6G parent network. Subnetworks report periodically their experienced channel conditions to the parent network, that can perform decisions on the radio resources they should use locally. Approaches based on deep neural networks (DNN) allow to reduce the computational burden with respect to iterative heuristics in the execution phase, provided that the DNN has been previously trained in the environment of interest. To mitigate the effects of outdated channel state information (CSI) due to subnetwork mobility, and combining spatio-temporal attention-based LSTM prediction with a robust deep neural network (DNN)-based resource allocation scheme. Under realistic CSI delays (e.g., 4-samples lag), this method outperformed state-of-the-art approaches, delivering 53% higher minimum spectral efficiency than systems without prediction and 94% higher than those using standard LSTM predictors. These results were validated in extremely dense scenarios—up to 25,000 subnetworks per km^2—supporting the project's goal of scaling 10× beyond current 5G ultra-dense deployments.

A complementary distributed RRM solution tailored to subnetworks that are not in the coverage area of a parent network, based on Graph Neural Networks (GNNs), enables autonomous power control in environments where centralized coordination is not feasible. This approach improved spectral efficiency by ~7% in uniform settings and up to 13.16% in heterogeneous channel conditions over equal power allocation baselines, while leveraging practical over-the-air message exchanges compatible with existing 3GPP systems.

For mission-critical applications in industrial automation, a goal-oriented RRM strategy was introduced, co-optimizing network quality and application-level metrics such as robot mission completion time. Using a Proximal Policy Optimization (PPO) reinforcement learning algorithm for mobility control, the system increased the likelihood of meeting stringent URLLC targets—achieving 20% higher probability of sustaining the same BLER under a 0.5 ms latency constraint compared to baseline approaches.

In light of the rising relevance of unlicensed and hybrid spectrum use, 6G-SHINE developed techniques to enable dense subnetwork operation in such environments. Semi-static channel access methods were shown to support up to 10× more XR sessions than conventional dynamic schemes. When combined with licensed-assisted operation, an additional 67% increase in supported subnetworks was achieved. Further capacity gains—up to 40%—were realized by mitigating in-band emissions through improvements in device front-end design and spectrum coordination strategies.

To address the pervasive issue of external interference, a dual-pronged strategy was employed: robust resource allocation and resilient receiver design. A Gradient Descent-based Resource Allocation (GDRA) algorithm limited spectral efficiency degradation to just 9.7%, outperforming existing benchmarks that saw losses exceeding 13%. On the receiver side, low-complexity likelihood ratio approximation techniques were developed to ensure reliable decoding even under impulsive noise and jamming, with dynamic adaptation to real-time channel conditions and minimal processing burden.

Together, these innovations demonstrate the feasibility of deploying dense, autonomous, and interference-resilient subnetworks across diverse domains—including industrial, consumer, and vehicular settings. The RRM solutions developed not only exceed current performance benchmarks but also provide a robust foundation for enabling dynamic and scalable 6G network architectures.

Related deliverables: D4.1 “Preliminary results on the management of radio resources in subnetworks in the presence of legitimate and malicious interferers”, D4.3 “Final results on the management of radio resources in subnetworks in the presence of legitimate and malicious interferers”.

6. MANAGEMENT OF TRAFFIC, SPECTRUM AND COMPUTATIONAL RESOURCES

Recent developments have addressed the management of traffic, computation, and spectrum resources both among subnetworks within the same domain and between subnetworks and the broader 6G infrastructure. These advancements have built upon earlier architectural frameworks to define a comprehensive operational model for subnetworks, prioritizing user privacy, autonomy, and reduced dependency on the central network.

A new category of user equipment has been introduced, with tailored enhancements in configuration, security, and data multiplexing. A decentralized authentication framework supports direct device-to-device interactions, minimizing reliance on core network functions. Subnetwork formation, registration, and mobility management have been further refined through distributed control and user-plane functions, with added support for local IP routing. To optimize control plane operations, especially for tasks like location updates, offloading strategies were proposed. Subnetworks were also enabled to coordinate with neighboring subnetworks, supporting predictive mobility and coordinated measurement functions, ultimately improving individual user performance.

The challenges of handling multi-modal data—especially relevant in consumer applications—were also addressed. Two methods were developed to align data packets across interrelated flows, either by enriching packet headers for device-side synchronization or by introducing a management-side controller that handles scheduling and alignment. These methods enhance quality of service even for locally-contained traffic. Improvements in uplink scheduling were also proposed, enabling more efficient resource use by the parent network.

In computation offloading, the framework now supports both local and decentralized approaches across subnetworks. Methods for selecting compute nodes and managing the association between operational and computational entities have been formalized. To support this shift, the quality of service framework was expanded to incorporate computing-specific requirements and constraints, with new parameters and procedures introduced for supporting computation-aware service levels.

In vehicular applications—where topologies are relatively static, but reliability requirements are extremely stringent—novel deterministic task offloading and resource allocation schemes were proposed. These prioritize task deadlines rather than mere latency minimization, allowing for better workload distribution across IoT-edge-cloud architectures. This improves scalability and performance in safety-critical systems. Further enhancements for in-vehicle networks include deterministic task scheduling schemes tailored for zonal electronic/electric architectures, enabling reliable service levels even under increasing computational demands.

For immersive XR applications, a compute- and network-aware traffic steering framework was introduced. It dynamically selects optimal service instances and manages mobility-aware service anchoring and migration, ensuring seamless execution in heterogeneous and resource-constrained environments, thereby enhancing both user experience and quality of service.

Finally, research on dynamic spectrum sharing compared regulatory policies across major global regions, evaluated existing sharing mechanisms, and highlighted emerging trends. A flexible spectrum access protocol was developed to allow dynamic allocation of licensed resources to subnetworks based on real-time traffic demands, using the concept of dynamic resource pools to enhance spectral efficiency and responsiveness.

Related deliverables: D4.2 "Preliminary results on the management of traffic, computational and spectrum resources among subnetworks in the same entity, and between subnetworks and 6G network", D4.4 " Final results on the management of traffic, computational and spectrum resources among subnetworks in the same entity, and between subnetworks and 6G network".

7. DEVELOPED PROOF-OF-CONCEPTS

A selected set of technologies developed within the project were demonstrated through proof-of-concepts (PoCs) in laboratory facilities. Since 6G-SHINE is a low technology readiness level (TRL) project, it was out of our scope to develop a fully integrated prototype of an in-X subnetwork. Instead, the focus was on showcasing specific technology components, selected on the basis of their promised performance and feasibility of implementation within the project time.

The demonstrated PoCs are the following:

1. **Low-latency channel emulator** – Validates short-range channel modeling for vehicular, industrial, and consumer applications, significantly improving the latency performance of the PROPSIM channel emulator in capturing short-range channel effects.
2. **Latency-aware MAC access** – Demonstrates improved coexistence in shared bands, providing deterministic medium access for latency-sensitive applications, with little to no penalization of best-effort traffic.
3. **Jamming-resilient PHY** – Shows how an enhanced scheduler and decoder can maintain robust performance under both wideband and narrowband jamming conditions.
4. **Intra-subnetwork macro-diversity** – Uses network coding and cooperative mechanisms to improve reliability and latency in industrial subnetworks.
5. **Centralized RRM** – Introduces dynamic resource allocation mechanisms for interference mitigation in vehicular and industrial environments.
6. **Centralized/distributed interference management** – Demonstrates AI-driven, decentralized techniques to optimize transmission power and channel usage in subnetworks operating over overlapping resources.
7. **Jamming detection via anomaly detection** – Presents anomaly detection solutions capable of recognizing malicious jammers and thereby triggering appropriate mitigation techniques in subnetworks.

These PoCs confirmed that the technologies developed in the project can deliver performance gains comparable to those observed in theoretical and simulation studies, while accounting for the constraints of the laboratory environment and the underlying hardware and software.

Related deliverables: D5.2 "First implementation and evaluation of PoCs", D5.3 "Second implementation and evaluation of PoCs, final results".

8. OUTLOOK

The 6G-SHINE project has significantly advanced the vision of in-X subnetworks, short-range low-power cells at the very edge of the 6G "network of networks." Scientifically, the project has contributed new models, architectures, and methods across the physical, MAC, and resource management layers. These results are the building blocks for making in-X subnetworks (and their integration with a 6G parent network) a solid reality in the figure wireless landscape, and form a foundation for future research on resilient, efficient, and intelligent short-range wireless systems.

From an industrial and economic perspective, 6G-SHINE has already left a tangible mark on the standardization landscape. The project introduced the subnetwork concept in 3GPP, contributed to ETSI ISAC, and delivered inputs to IEEE and ETSI RIS and THz groups. In particular, our proposed in-vehicle subnetwork use case has been already captured on 3GPP TR 22.870 "Study on 6G Use Cases and Service Requirements", section 11.10. This early engagement ensures that the technologies and use cases explored in 6G-SHINE can influence global standards at the very moment when 6G discussions are consolidating. The consortium also generated substantial intellectual property and initiated collaborations that strengthen Europe's industrial competitiveness in wireless technologies.

Societally, the project promotes a sustainable and human-centric approach to 6G, with localized processing for privacy and safety, reduced cabling for greener deployments, and support for new applications in education, industry, and mobility. Beyond its technical outcomes, 6G-SHINE has also contributed to the broader SNS and 6G-IA vision activities, ensuring that the project's innovations are visible and aligned with Europe's strategic ambitions.

In summary, 6G-SHINE has positioned in-X subnetworks as a credible building block of 6G, bridging low-TRL research with standardization and paving the way for their industrial and societal uptake.