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D2.1. – INITIAL DEFINITION OF SCENARIOS, USE CASES AND SERVICE REQUIREMENTS FOR IN-X SUBNETWORKS

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V0.9	28/08/2023	Basuki Priyanto	Further minor refinements

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ABBREVIATIONS

2G	Second-Generation
3G	3rd Generation
3GPP	3rd Generation Partnership Project
4G	4th Generation
5G	5th Generation
5G-ACIA	5G Alliance for Connected Industries and Automation
6G	6th Generation
AD	Autonomous Driving
ADAS	Advanced Driver Assistance Systems
AGV	Autonomous Guided Vehicle
AI	Artificial Intelligence
AMR	Autonomous Mobile Robot
AP	Access Point
AR	Augmented Reality
CAN	Controller Area Network
CAN FD	CAN Full Duplex
CAV	Connected and Automated Vehicles
CCU	Connectivity Control Unit
CRT	Cathode Ray Tube
DL	Downlink
DoF	Degree of Freedom
DUT	Device Under Test
D2D	Device to Device
E/E	Electrical/Electronic
ECU	Electronic Control Unit
EV	Electric Vehicles
HMI	Human-Machine Interface
HPCU	High-Performance Computing Unit
IIoT	Industrial Internet of Things
IPU	Image Processing Unit
IT	Information Technology
KPI	Key Performance Indicator
KVI	Key Value Indicators
LED	Light Emitting Diode
LCD	Liquid Christal Display
LIN	Local Interconnect Network
MCS	Modulation and Coding Scheme
ML	Machine Learning
MNOs	Mobile Network Operators

MOST	Media Oriented Systems Transport
O&AM	Operation & Administration Maintenance
OT	Operational Technology
OTA	Over The Air updates
PLC	Programmable Logic Controller
PMI	Precoding Matrix Indicator
RRM	Radio Resource Management
SMS	Short Message/Messaging Service
SDGs	Sustainability Development Goals
TC	Technology Component
TM	Transmission Mode
TPMS	Tire Pressure Monitoring Systems
TSN	Time Sensitive Networking
UE	User Equipment
UL	Uplink
URLLC	Ultra-Reliable Low Latency Communication
VR	Virtual Reality
XR	Extended Reality

EXECUTIVE SUMMARY

This report is the first deliverable of the 6G-SHINE work package (WP2) and provides the initial definition of scenarios, use cases, and service requirements for various types of subnetwork categories. Three subnetwork categories are considered in 6G-SHINE, namely the consumer, industrial, and in-vehicle subnetwork categories. These three categories are defined to ensure that suitable and unique use cases are explored for short-range communications.

For the consumer subnetworks, the identified use cases include Immersive Education, Indoor Interactive Gaming, Virtual Content Production of Live Music, and Augmented Reality (AR) Navigation. These diverse use cases aim at supporting enhanced and immersive user experience. High data-rates and low latency are the Key Performance Indicators (KPIs) for these use cases.

In industrial subnetworks, the use cases are represented using a bottom-up approach, starting from the subnetwork in a single entity to a complex subnetwork with multiple entities. The use cases identified in this category are Robot control, Unit Test Cell, Visual Inspection Cell, Subnet Coexistence in Factory Hall, and Subnetwork Segmentation and Management. These use cases are defined with the objective to maintain the automation process in the manufacturing production line for optimal operation. The network traffic characteristics of these use cases mandate low data rates with ultra-low latency. Many connected devices are expected to be deployed and resulting in high network traffic in certain conditions.

In the in-vehicle subnetwork category, the representation of the use cases also follows a similar bottom-up approach similar to as the industrial subnetworks case. The identified use cases are Wireless Zone ECU, Collaborative Wireless Zone ECU, Inter-Subnetwork Coordination, and Virtual ECU. The objective of realizing these use cases is to design 6G-native in-vehicle wireless subnetworks that are capable of providing dependable service levels like wired networks. These use cases are characterized by multiple network traffic flows with varying requirements, demanding deterministic network performance (ultra-low bounded latency and high reliability).

A principle set of KPIs for the aforementioned use cases in the three subnetwork categories has been designated at the outset and would be revisited at different stages of the project as the work evolves to safeguard their compatibility with the use cases. The purpose of these KPIs is to ensure that the required services of a use case can be supported. It is noteworthy that that some of the KPI requirements may not be fully supported through the existing technology. However, it is expected that the research and development under different technical components of the project would finally allow the application of these KPIs to the identified use cases. In connection to this, the mapping of 6G-SHINE technology components (TCs) to the use-cases in each subnetwork category is provided. In the context of social, economic, and environmental sustainability, the Key Value Indicators (KVIs) associated with the identified uses cases are also investigated to understand the societal impact of the research undertaken in this project.

This deliverable is part of WP2 and will be used as the reference for other activities across the involved WPs of the project. Within WP2, we will also characterize radio propagation at different frequency bands and explore network architectures for in-X subnetworks of the selected use case. The TCs development in other WPs will also be based on one or more of the selected use cases defined in this deliverable.

Additionally, this document will be continuously evolved by proving further refinements on use cases, scenario, requirements, and potentially new KPI/KVI. This will be reported in the next deliverable (D2.2).

1 INTRODUCTION

6G-SHINE is one of the European Union 6G projects under the 6G-SNS Stream B (research for revolutionary technology advancement toward 6G) framework. This report is the first deliverable of 6G-SHINE's WP2. The scope of WP2 focuses on defining scenarios, use cases, and requirements. This report presents a set of initial use cases including their descriptions, KPIs, and KVIs for the consumer, industrial, and in-vehicle subnetworks defined in 6G-SHINE. The selected use cases identified in this report will be used for further work on WP2 and other WPs, particularly in the development of TCs and PoCs.

1.1 Objective of The Document

This report covers the initial work for the definition of relevant scenarios, assumptions, and use cases for the subnetworks along with KPI requirements. The objective of this report is to initially define numerous use cases including the descriptions, operation flows, and pre/post conditions covering consumer, industrial, and in-vehicle subnetwork categories. The initial KPI and KVI related to the use cases are stipulated. Finally, the potential mapping of the 6G-SHINE TCs to the use cases in each subnetwork category is also identified.

1.2 Structure of The Document

This report is organized as follows. Chapter 1 provides the introduction, including the objectives and the methodology for defining the use cases, KPIs, and KVIs. Chapter 2, 3, and 4 describe numerous use cases in the consumer, industrial, and in-vehicle subnetwork categories, respectively. In each chapter, we elaborate the respective background, and the KVIs for the given category. Each use case is thoroughly covered with high-level descriptions, pre- and post-condition aspects, operation flow, and KPIs. In addition, each of these chapters is concluded by describing how the TCs in 6G-SHINE could address the challenges in the respective category. Chapter 5 summarizes the report by highlighting the essential aspects of the use cases across different categories, such as the deployment scenario, KPIs, KVIs, in purview of 6G-SHINE TCs. Finally, Chapter 6 concludes this deliverable by outline the potential next steps to further enhance and improve the use case definitions and their requirements.

1.3 Methodology

1.3.1 Defining Use Cases

Figure 1 illustrates the focus of the 6G-SHINE project. The subnetworks are intended to replace traditional cabled media for demanding use cases, and feature the following main characteristics:

- Short range (below 10 meters) low-power cells meant to offer localized connectivity by offloading larger networks with demanding services.
- Support services with rigorous requirements in terms of latency, reliability, and data rates.
- Consist of one or more AP(s) with integrated edge processing capabilities and a potentially large number of cost-effective and potentially computationally constrained devices with limited form factor, such as sensors/actuators.
- Support the stand-alone operation in case the connection with an umbrella 6G network is not available or it is not needed.

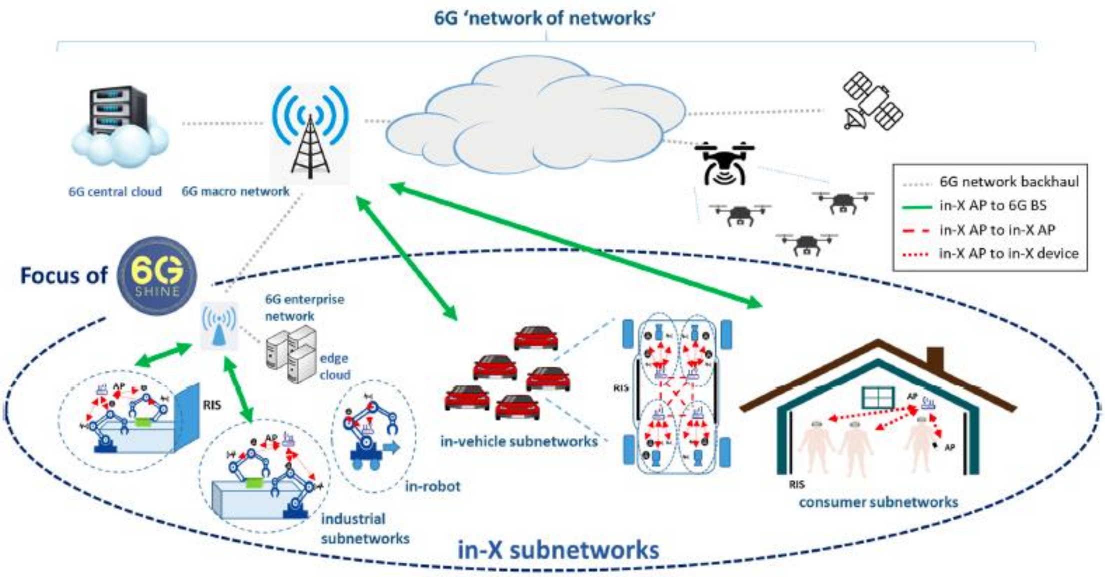

Figure 1. Illustration of 6G-SHINE project in supporting various use cases

Based on the above stated characteristics, various use cases can be defined to address the need in the future. In order to ensure that diverse use cases are identified for 6G deployments, we defined the use cases for the following three subnetwork categories.

- Consumer
- Industrial
- In-vehicle

1.3.2 Definition of Key Performance Indicators

Key Performance Indicators (KPIs) refer to the measurable metrics that are used to assess and evaluate the performance and effectiveness of various aspects of the communication system. These KPIs provide insights into the overall efficiency and quality of infrastructure, services and operations provided by the communication system. In this project, we consider the traditional set of KPIs that are well established by the standardization bodies, such as 3GPP. For instance, transmission (packet/bit) error rate, spectral efficiency, data rate, latency, and reliability.

In addition to the conventional KPIs, we also consider other potential KPIs that could be relevant to 6G-SHINE. These additional KPIs may not only be required for evaluating the performance of a wireless links but also for the optimal operation of subnetworks in 6G-SHINE. For example, system capacity (e.g., the supported number of simultaneous connected devices without compromising each wireless link), power consumption, signalling overhead, computational complexity, and possible distribution/transfer of computation within a subnetwork.

The conventional or standard KPIs that are widely considered for evaluating wireless communication systems are briefly described below. These KPIs are also adopted in 6G SHINE. The additional KPIs depending on the use cases are described in the subsequent sections under different subnetwork categories.

- Communication service availability: Percentage value of the amount of time the end-to-end communication service is delivered according to a specified QoS, divided by the amount of time the system is expected to deliver the end-to-end service [1].

- Communication service reliability: Ability of the communication service to perform as required for a given time interval, under given conditions [2].
- End-to-End latency: The time that it takes to transfer a given piece of information from a source to a destination, measured at the communication interface, from the moment it is transmitted by the source to the moment it is successfully received at the destination [1].
- Survival time: The time that an application consuming a communication service may continue without an anticipated message [1]
- Transfer interval: Time difference between two consecutive transfers of application data from an application via the service interface to 3GPP system [2].
- User experienced data rate: The minimum data rate required to achieve a sufficient quality experience, except for scenario for broadcast like services where the given value is the maximum that is needed [1].
- Clock Synchronicity: The maximum allowed time offset within the fully synchronised system between UE clocks [2].
- Packet Delay Budget (PDB): is a limited time budget for a packet to be transmitted over the air from a gNB to a UE [3].
- Latency: time delay between the initiation of a data transfer or command and its actual reception or execution.
- Bandwidth: capacity of the network to transmit data over a specific period.
- Data rate (Speed): rate at which data is transmitted from one point to another within the network. It is closely related to the concept of bandwidth, but it specifically emphasizes the actual data transfer rate rather than the overall capacity.
- Reliability: percentage of packets successfully delivered within the time/latency constraint required by the target service or domain function out of all the packets transmitted [1].
- Determinism: ability to guarantee that data is delivered within specific time constraints.
- Control loop time (or control cycle time): time interval between consecutive updates or iterations of a control system. In industrial and automotive applications, this represents the frequency at which the control system processes sensor data, computes the appropriate response, and sends commands to actuators.

1.3.3 Definition of Key Value Indicators

The key values (KVs) within 6G-SHINE are initially defined based on the work described in [4]. Firstly, the United Nations have developed the 2030 Agenda for Sustainable Development where the 17 sustainability development goals (SDGs) have been defined and shown in Figure 2 [5].

Figure 2. The 17 UN Sustainability Development Goals (SDGs) (figure taken and simplified from [5])

Furthermore, the Stockholm Resilience Centre has grouped those development goals and visualized them as shown in Figure 3 [6]. Here, these groups are associated with the key value (KV) to be addressed in this project, named as economic sustainability, social sustainability, and environmental sustainability.

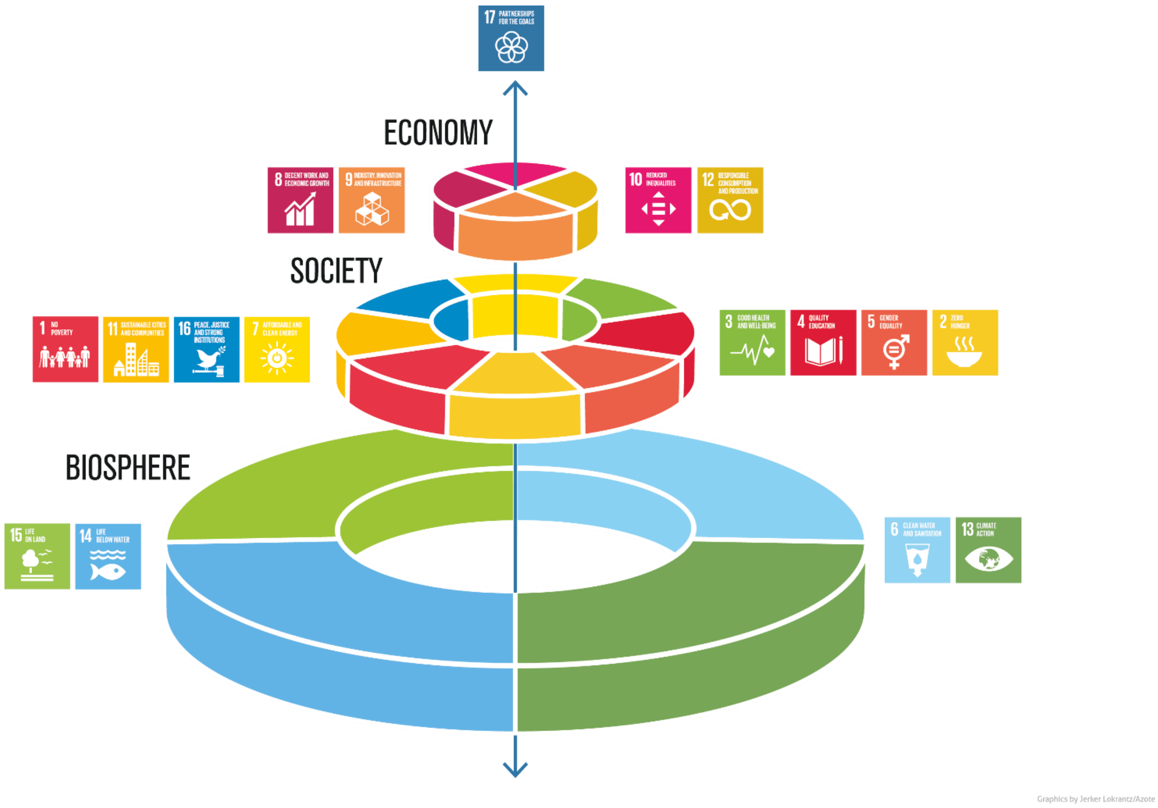

Figure 3. The 17 SDGs grouped by Stockholm Resilience Centre (figure taken from [6])

Subsequently, the indicator for each KVs above will be derived further for each use cases category as described in Section 1.3.1. The identified KVI should be able to measure the impacts of the new generation wireless technologies developed in this project on both qualitative and/or quantitative evaluation. The KV(s) is intangible, but we foresee to have a direct or indirect impact on human society. The assessment towards KVI is important to ensure that the SDGs by United Nation can be fulfilled.

2 CONSUMER SUBNETWORKS CATEGORY

2.1 STATUS QUO ON CONSUMER NETWORKS

Wireless telecommunication (practically telephony) started as a business application with a low adoption rate in the last century because of the prohibitive cost compared to wireline communication. This changed considerably with the introduction of second-generation (2G) technology. A virtuous cycle was sparked by the transition from analogue national to digital regional or global standards, allowing higher adoption rates, larger production volumes, and consequently lower unit costs, enabled by the assignment of additional spectrum that could be used more efficiently, thanks to advanced digital processing technology. This allowed consumers to afford wireless services and in turn, increased the addressable market. After the turn of the century, 3G, and subsequently 4G and 5G technology perpetuated that trend and introduced the support of mobile data services on top of telephony and SMS. The new device category of smartphones leveraged data services, i.e., connectivity to support various web-based services, i.e., take advantage of ever-increasing information that is available on the web. Subsequently specific apps targeting mobile users were developed, that were tailored both to the capabilities (but also limitations) of smartphones and to the specific needs of consumers on the go, wherever they were.

Immersive media were boosted by the transition from bulky Cathode-Ray Tubes (CRTs) to flat screen LCD and LED monitors. These allowed the presentation of more content at better quality in terms of screen size, number of pixels, frame rate, and resolution. Transfer of video footage to the monitors was again facilitated by the change from analogue to digital technologies. While mobile devices, especially the smartphones, drove large parts of the consumer device business, users who demanded the highest performance had to be aware of mobile device constraints (size, energy, complexity, data rate, and latency). The top end of the consumer market, motivated by gaming, strived for ever higher performing setups of computers, networks, and displays for a gaming experience that is as realistic and immersive as possible. While for education multimedia content has been used since a long time, from traditional films over PC based towards the laptop or tablet-based media, it was by no means the sector that was progressing technologies fastest.

2.2 EVOLUTION TRENDS

Apart from the general advancements in all of the above-mentioned technologies, there is desirable to make immersive media experiences available to a broader market, gradually expanding from specialized high-end setups (i.e., primarily for business users or most advanced early adopters and gamers).

Wireless connectivity provides free movement and enables experiencing media on the go. This is particularly useful if several devices (displays, cameras, and sensors, for one or multiple users) are involved to provide data (including video) wirelessly at optimized power consumption.

There is an evolving segment addressing the use of smartphones for a growing set of use cases, at least those allowed by the limited capabilities (screen size, resolution, connectivity, and processing power). An example of such a use case is the display of prospective purchases in the consumers home environment; even simple setups, e.g., using a cardboard-based VR set or a smartphone, allow overlaying the desired product into a display of the local scenery to give a rough impression whether an intended purchase would fit. Gaming applications also soon emerged, as well as immersive performances for entertainment, displaying human performers or animated avatars.

Already today wireless technologies provide instantaneous information for various applications covering anything from pure entertainment up to business-critical information: The spread of smartphones and tablets has brought a variety of information sources to everybody's fingertips. Immersive technologies will make it effortless to access any information, more generally any perceivable content. A natural audio-visual experience will delight end-users who will perceive no constraints from latency, resolution, space, or time. While such technology is not yet widely utilized, we can see an emergence of XR headsets. Future device capabilities will be expected to favour this proliferation, progressing from initial simple concepts to more advanced devices supporting more challenging use cases.

2.3 Benefits and Challenges of Consumer Subnetworks

Providing users the freedom to move around and enabling them to enjoy services wherever they want or need is a strong benefit of wireless networks. This applies both to small-scale scenarios, e.g., within a building or a vehicle, and to large-scale scenarios where users may roam freely within the umbrella network. Several use cases use more than one device either per user or per user group which can naturally form subnetworks or even hierarchical subnetworks within subnetworks within the enclosing network. 6G-SHINE is expected to investigate and develop schemes that will allow running multiple connections amongst the deployed devices, supporting the individual needs of all these devices and their respective interactions with other devices and services running within the same or adjacent sets of subnetworks.

Ideally, wireless networks should be able to support all perceivable use cases. However, as wireless spectrum resources are shared and scarce, there is a limit regarding how tightly they can be reused, and achieving consistent wireless performance will always be challenging. Therefore, it will be essential to develop schemes that may allow to adjust the available capacity by assigning optimal resources to a set of subnetworks that support the specific needs of all the devices and the respective use cases. 6G-SHINE will contribute to this goal by developing and investigating technology components for such schemes. The specific technology components to address the requirements of individual use cases are identified in the respective chapters.

2.4 KVIs of Consumer Subnetworks

The use cases in consumer subnetworks are introduced with the motivation to advance the KVIs as described in Section 1.3.3. On social sustainability aspects, the new use cases, such as immersive gaming and education may enhance the user experience and also realize Digital Inclusion, i.e., to be part of a world where you can meet your peers from around the world in a digital environment, have fun and make new friends, etc. For education, it will affect the individual members of the community and the society in its entirety. Advancements in the education sector in terms of enabling the teachers to educate efficiently through digital tools and students to learn and grasp subjects intuitively and interactively will provide significant rewards, both commercially, intellectually, and emotionally.

On economic sustainability aspects, the new use cases in consumer subnetworks will create new services, features and business opportunities, to support the consumer electronics industry and system providers. Furthermore, the willingness to pay for an added value/increased user experience is a revenue opportunity for both mobile network operators (MNOs), for being able to offer high-end subscriptions, and system providers (e.g., gaming/education providers), for being able to generate a more immersive experience based on increased network capacity.

On environmental sustainability aspects, the least we can expect a significant reduction in energy consumption and carbon footprint. Digital Inclusion would enable users to interact virtually, regardless of geographic location. Hence, it reduces the carbon footprint by reasonably lowering the need for business traveling. The design of the consumer subnetworks use cases in their entirety is expected to reduce overall energy consumption.

2.5 Consumer Subnetworks use cases

In the following, the relevant identified use cases for consumer subnetworks are described.

2.5.1 Immersive Education

2.5.1.1 Description

Education is a decisive task of society that crucially determines its future success. Immersive Education aims at enhancing the interactive experience of a group of students and teacher(s) for knowledge exchange, leveraging media content, and related technologies. It allows to enhance the students' experiences beyond an ordinary classroom. This will also help them to understand the course content more easily and intuitively so they can apply the classroom concepts in the practical world. As every student has a different learning style, providing a rich XR experience with various diverse stimuli will give the students a better chance to learn consistently. This not only fosters a healthy interaction amongst students in the classroom, but also aids a better integration of virtual students.

While education is primarily taking place in dedicated venues (classrooms), the concepts can be extended to field excursions, e.g., to historic sites, museums, industry venues and others, as well as on the go. The media to be shared include telepresence type of footage to allow interactive participation of remote students (or teachers). However, an important aspect is also to provide tutorial footage allowing an almost "hands on" experience for the students, ideally offering options for (virtual) interaction providing a "learning by doing" experience.

The immersive education use case can be further divided into a subset of use cases to serve distinct applications as there will not be a single application scenario covering all the related aspects. These applications will also differ depending on the devices that will be utilized. While it would be easier to implement use cases using dedicated and specialized devices, the option should be provided to use generic devices (that may be available to the students anyhow). This however requires dealing with a heterogeneous set of devices, both from student interaction and communication capabilities stand point. Such heterogeneity will have to be supported by the subnetwork architecture and the protocols.

The strict latency requirements, the geographical area of communication, potential computation offloading, and the fact that the capabilities of devices may vary from simple displays over XR devices up to fully immersive holographic devices equipped with tactile sensors and actuators, requires more independent and hierarchical subnetworks.

There are many options for providing a functional split between the subnetwork devices and the content server, which may also include additional content and compute servers in proximity to groups of pupils. These servers belonging to the corresponding subnetworks close to the end devices can greatly offload the computational burden from the end devices and thus allow inclusive scenarios with a set of diverse devices.

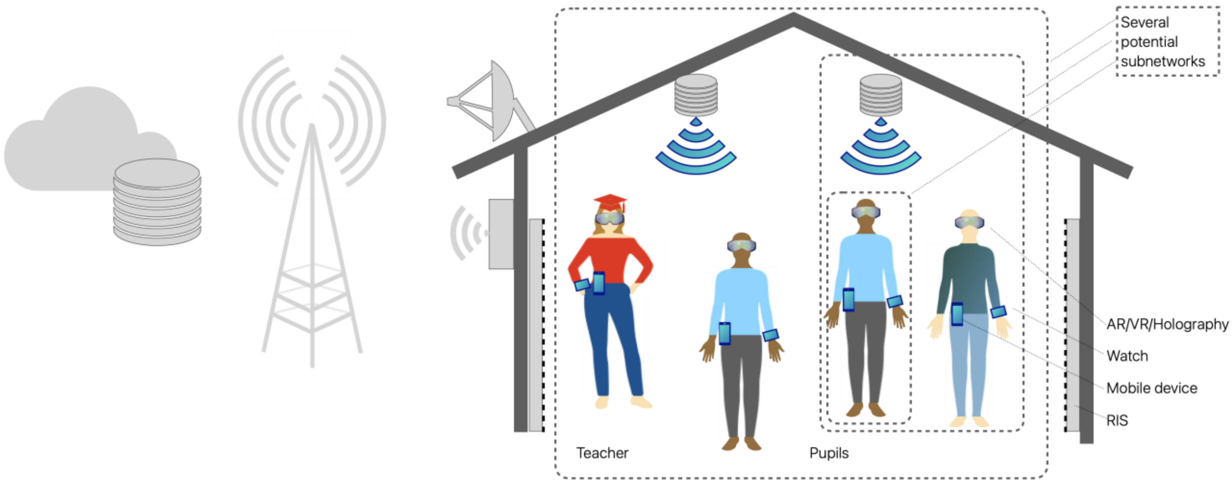

Figure 4. Illustration of immersive education showing some potential hierarchical subnetworks (adapted from [7])

2.5.1.2 Pre-condition(s)

Students (or pupils) have gathered in the classroom (or lecture hall) and have their devices ready. Optionally, some of the pupils or the teacher may join in remotely from another location (tele-education).

Devices may typically be XR devices, but optionally there could also be more advanced or less advanced devices ranging from ordinary screens or tablets (or cardboard-style smartphone holders, improvising XR displays) up to holographic displays serving individual students or sets of students. The teacher has a similar device but with extended capabilities allowing to steer the lesson, supervise pupils' actions and provide dedicated support and feedback.

The footage has been made available in the local subnetworks, i.e., ideally within the classroom. Apart from the media content the provisioning of computational offloading, e.g., for animating the footage or offloading of AI/ML tasks may be beneficial to support a broad range of individual devices.

2.5.1.3 Operation Flow

The flow of operation can be described as follows:

1. Pupils have connected their devices to the local AP and are thus connected to the server hosting the session, either directly or indirectly via intermediate servers or access points within the subnetwork. The teacher has selected a session and is ready to launch and steer it.

2. Media content regarding the lesson is streamed from the respective local AP to the pupils' devices. The teacher can steer i.e., modify the lesson, provide additional explanations, and highlight interesting aspects. Typically, the pupils can also interact with the content and provide hints, such as, pointing at specific questions, which will be visible to the teacher and the other pupils, when enabled by the teacher. Consequently, there is not only a stream of data from the local AP to the devices, but also in the other direction and between devices (potentially via the local AP).
3. Pupils may explore the subject on their own, looking at different aspects of the scene and exercising different details, either individually or in groups. During this stage, the experience of different sets of pupils may diverge due to their individual interests and learning pace.
4. Eventually, the session is wrapped up and finally terminated or replaced by a subsequent lesson by the teacher.

2.5.1.4 Post-condition(s)

Each pupil has experienced an immersive education session and gained insight on the taught subjects, tailored to the user device, and adapted to the individual experience level. The teacher was able to assess pupils' paces, interact with them, and steer the session accordingly.

2.5.1.5 Challenges to the 6G system

The main challenges are:

- To support the necessary connectivity for a suitable immersive education experience to a set of users, either within the same classroom or distributed over a wider area. Particularly the real-time nature that requires a low delay to provide instantaneous response upon user interactions will be challenging. The locality and density of devices communication at a low latency scale may require more local communication managed locally within the respective subnetworks.

- Offloading of the computational efforts from the devices towards an AP or server is a promising technology enabling slim user devices. Unfortunately, this comes at the cost of increased communication load and more strict latency requirements to provide properly pre-processed footage at the right time to the respective devices. There are various strategies available for the local compute vs. communication trade-off. As a general rule, the better the communication the higher the potential for computational offloading and consequently lower complexity and power consumption on the user devices. Accordingly, there is no fixed set of KPIs that enable the use case, but any improvement of the communication KPIs can be leveraged in favour of supporting slim devices and extended device battery longevity.

- Heterogeneity in the devices may necessitate different approaches for the individual devices with tailored trade-offs between computation and communication. To select the proper split of streams for individual and joint footage, the 6G system and the application should be able to determine and adapt to the possible aggregate communication rates for optimal selection of the individual media encoding schemes.

The above challenges may not be able to be fulfilled by the existing 5G technology. We consider the following selected technology components (TCs) shown in Table 1 are highly relevant for this use case.

Table 1: Selected Key TCs for Immersive Education Use Case

Technology component (TC)	**Explanation**
TC1. In-X data traffic models	General aid for developing a concept
TC2. Channel models for in-X scenarios	General aid for developing a concept
TC3. Sub-THz system models	Sub-THz transmissions are a promising technology to provide ample capacity for multiple users closely localized and enable short frame durations to support ultra-low latency and high reliability in suitable propagation environments.
TC4. Ultra-short transmissions with extreme reliability	Small latency enables more options for offloading within the subnetwork, while this use case may not require extreme reliability.
TC5. Analog/hybrid beamforming/beamfocusing	Enable optimized communication with individual devices or groups of devices within the coverage area of a particular subnetwork
TC7. RIS enhancements	Enable steering of beams towards individual users within a room
TC8. Intra-subnetwork macro-diversity	E.g., to achieve reliability for low latency
TC9. Flexible/full duplex scheduler	Depending on the selected offloading scheme for UL and DL related processing, there may be both significant uplink and downlink traffic, which is the scenario benefitting most from flexible/full duplex scheduling options
TC10. Predictive scheduler	Prediction helps optimize compute vs. communication trade-off
TC11. Latency-aware access in the unlicensed spectrum	Optimized latency in unlicensed spectrum enables more options for offloading within the subnetwork
TC13. Distributed/hybrid radio resource management.	E.g., distributed within the subnetwork
TC15. Hybrid management of traffic, spectrum and computational resources	There is a trade-off between communication and compute when deciding about offloading strategies for the provisioning of multimedia content, e.g., rendering. To find the optimum setting and to maintain it despite variations in connectivity and compute demand requires an integrated approach to scheduling and resource management.
TC16. Coordination of operations among subnetworks in the same entity	If multiple subnetworks within a location e.g., the classroom serve the users, potentially via multiple local or edge servers, and considering that the subnetwork may be built from a hierarchy of personal subnetworks that aggregate each user's set of devices, this will be very relevant

2.5.1.6 KPI Aspects & Requirements

XR immersive education will have certain network traffic characteristics, in particular, considering the interactions of multiple pupils and provisioning a suitable footage from a server. For the latter, the 3GPP TR 26.928 on "Extended Reality (XR) in 5G (Release 18)" quotes a wide variety of KPIs depending on the selected compute architecture split [8]. Required latencies are ranging from several 10s of milliseconds down to a few milliseconds, and data rates from few Mbps up to multiple Gbps. Typically, at least the high-end values cannot be achieved for 5G networks, when required for several devices within a constrained area. We expect that advanced communication schemes within subnetworks to be developed within 6G-SHINE will allow to reach such challenging requirements and benefit from device offloading, enabling the utilization of lean devices. Well-coordinated subnetworks will ease signal processing for all the involved devices by mitigating intra subnetwork interference. Basically, the better the communication the less effort for local compute is required. Multiple pupils often view highly correlated content, consequently, precomputing and distributing pre-processed content via broadcast or multicast towards multiple devices allows to benefit the reduced device complexity for multiple devices.

Data rate

Data rate estimates will need to include peak data rate, and typical data rate, both for individual devices and for multiple devices as immersive education is typically a multi-user scenario.

Latency

Considering end-to-end latency, we may need to not only consider communication latency (including retransmissions when necessary), but also the latency for distributed processing that is required both at the end devices and the server and potentially intermediate servers or supporting devices. Note that the configuration of dynamic subnetworks may also contribute to latency. Consequently, this aspect should be investigated and optimized suitably.

Synchronization

Different users' experiences and reactions need to be processed in a well synchronized way to allow a coordinated and responsive immersive experience of multiple users.

Maximum Number of Users

The number of pupils to be supported needs to cover the respective class. Depending on local situations this may be from the low tens of pupils for a typical classroom up to thousands of pupils in specific cases of large lecture halls. Potentially, for fully distributed scenarios linking pupils from multiple sites to a teaching session, the number may be even higher, but this may be considered a specific variant of the use case.

Summary of KPI

- Extremely high data-rates in both downlink and uplink direction, depending on scenario up to and even exceeding 1Gbps in UL and DL.
- Low end-to-end latency in UL and DL latency in the order of 10 ms depending on specific scenario.
- Full-service continuity through support for cooperative technologies such as D2D, mesh, and multi-connectivity.

2.5.2 Indoor Interactive Gaming

2.5.2.1 Description

This use case is about XR interactive gaming in an indoor environment where one or more players play in a controlled environment. A controlled environment is a place equipped with some equipment to facilitate the XR interactive gaming. For example, various sensors have been placed in certain strategic location, the access point and its antennas are placed in optimal location, and a high-end edge cloud server is located or attached together with the AP. A controlled environment is likely an indoor area / a room dedicated for this use case. Figure 5 illustrates the scenario of indoor interactive gaming within a subnetwork. Here, there are two game players, each of them is wearing various types of devices:

- VR headsets
- small sensor devices attached to the body.

The indoor environment is equipped with many static sensor devices which are scattered around the room. These sensors are used to obtain user(s) poses / orientations and then later to be used for the XR scene generation. All those sensor devices can communicate locally to an AP within a subnetwork. There is also an edge server that can be built-in to the AP or separately.

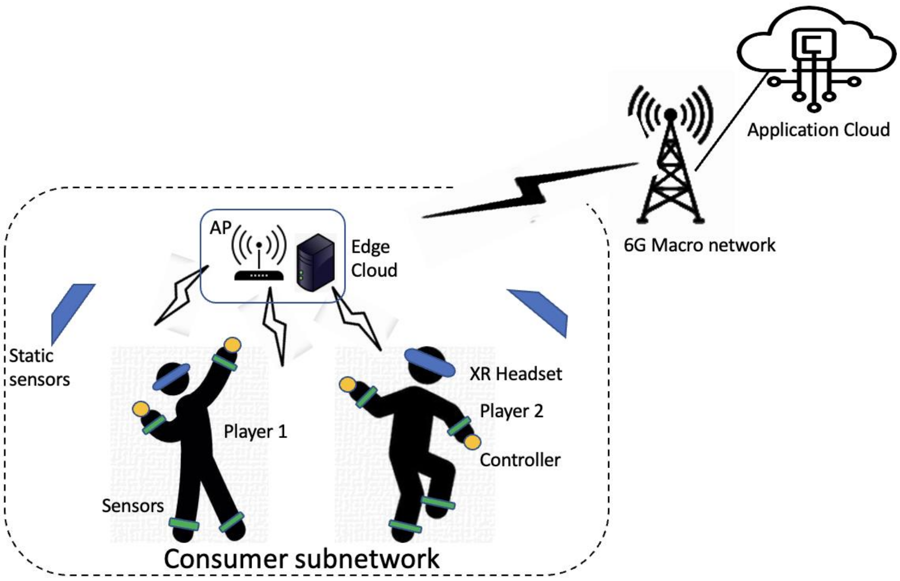

Figure 5. Illustration of indoor interactive gaming within a subnetwork

The game, obtained from the application cloud server, is preloaded into the edge server. The edge server provides the XR scene to the VR headsets based on the input from the camera attached to the VR headsets and various sensors (e.g., in the VR headsets, attached in the room, and attached to the users). The XR scene is produced in the edge server so that it will minimize the computation process in the VR headsets itself. This process is known as split-rendering operation.

In order to provide immersive XR experience, the edge server could provide input to the device attached to the users so that the game player experiences sensation of the game in a form of, for example, vibration, heating. This sensation inputs shall be synchronized with the XR scene delivered to the game player. Furthermore, the XR experiences (e.g., XR scene, sensation) shall also be synchronized among all the game players.

2.5.2.2 Pre-condition(s)

Game participants are wearing the VR headsets and are equipped with sensors which are attached to their bodies.

The indoor environment is equipped with an AP which is connected to the 6G macro network, then to edge cloud server. In addition, certain rooms within the indoor environment are equipped with static sensors.

2.5.2.3 Operation Flow

The flow of operations events can be described as follows:

1. The game player(s) select the game from the application server and downloads it to the edge server.
2. The edge server provides the XR scene to the game player(s) (e.g., the VR headsets attached to the game player(s)).
3. The sensors, including camera attached to the VR headsets provide the input to the edge server. Those sensors detect the head movements and also capture the image surrounding the game player.
4. The sensors attached to the game player (e.g., sensors in hands, legs) detect the body movements and send the output to the edge server.
5. The sensors in the room also detect the player(s) movement and send the output to the edge server.
6. Based on 3), 4), 5), the edge server processes the XR scene and provides the XR scene to the game player (step 2 above).

2.5.2.4 Post-condition(s)

Each game participant is wearing VR glasses that provide full immersive experiences during game playing. The light weight of the glasses guaranties that players can wear them during the duration of the game session and feel comfortable.

2.5.2.5 Challenges to the 6G system

The XR interactive gaming as described above requires massive communication links between the sensors and the edge server, XR scene processing, and the transmission of XR scene from the edge server to VR headsets and devices attached to the users. All of these operations shall be executed in a very limited time in order to provide a high quality XR experience. The main challenges are:

- To provide various sensors outputs from multiple nodes in a synchronized manner
- To provide extreme low latency and high reliability communications
- To provide high data rate communication (i.e., providing XR scene to the users)

The above challenges may not be fulfilled by the existing 5G technology. A 6G system with subnetwork operation is expected to overcome those challenges. A subnetwork that is operated within a close proximity (less than 10 meters) can ensure extreme low latency and high reliability communications, particularly for high data rates communications. The usage of reconfigurable intelligence surface (RIS) is expected to have an important role in increasing the performance of radio communications. The RIS panel(s) can be strategically placed in certain location of an indoor XR gaming area.

The following highly-relevant technology components (TCs) are considered for this use case. Other TCs can still be relevant and are shown in section 2.6.

Table 2: Selected Key TCs for Indoor Interactive Gaming Use Case

Technology component (TC)	**Explanation**
TC3. Sub-THz system models	Indoor gaming, especially in small room, makes it feasible to operate the wireless communications with sub-THz frequency in order to provide high data rate and ultra-low latency communications.
TC4. Ultra-short transmissions with extreme reliability	Ultra-low latency with high reliability improves the user experience.
TC5. Analog/hybrid beamforming/beamfocusing	Enable optimized communication with individual devices or groups of devices within the coverage area of a particular subnetwork
TC7. RIS enhancements	Enable reflecting radio signals towards individual users within a room
TC15. Hybrid management of traffic, spectrum, and computational resources	Enable the efficient resource allocation and distributing the computational resources in various nodes.

2.5.2.6 KPI Aspects & Requirements

XR interactive gaming may have certain network traffic characteristics. For example, the sensors' output from the user(s) and static sensor(s) in an indoor gaming area as the input for XR scene process. In another example, the video, audio, sensors' output generated at the edge server transmitted to the user as part of the generated XR scene.

1. The sensors for the XR scene generation.
   Typically, low data rate, mixture of periodic and aperiodic transmission. There can be multiple sensors for such XR scene generation. These can be the sensor(s) that is statically placed in a specific location(s) or attach to the user(s).
2. XR scene video
   High quality (wide view with 8K video quality), high data rates, payload size may vary a lot. Need to identify the peak data rate (massive scene changes)
3. XR scene audio
   High quality audio, but it is expected the same audio quality as we have today (e.g., in 5G)
4. XR scene actuators to create immersive experience.
   Typically, low data rate, mixture of periodic and aperiodic transmission. Multiple actuator(s) can be placed either static in certain location (e.g., to blow the wind) or attach to the user(s) (e.g., to feel the warm, punch).

The following are the potential key performance indicators (KPI) of interactive indoor gaming use case:

Data rate

We need to anticipate the required data rate to support the use case, including peak data rate, and average data rate. Peak data-rate can happen when there is a sudden scene-change during the game. The entire video frame containing the main object and its background must be refreshed and transmitted.

Latency

We can firstly consider end-to-end latency. However, we need to break-down between communication latency and processing latency which may occur in various levels (lower / upper layer) and nodes (e.g., terminal, Access Point (AP), base-station, core network node, etc).

Synchronization

Simultaneous transmission within a limited time window from the end-user needs to be supported. The user is expected to transmit video frame (captured from the camera(s)), audio (from microphone(s)), and sensors.

Maximum Number of Users

The number of users that can be supported and satisfied with the XR experience. This may include the number of user(s) connected to an AP and the number of user(s) connected to a 6G base-station.

The requirements to support the use case can be defined based on the above KPIs. For the existing 5G system, 3GPP has performed a study and identified the traffic model parameters for cloud gaming (CG) use case which is relevant to this use case [3]. It has been identified that for the video streaming, the default packet rate is 60 frame per seconds (fps), the average data rate is 30 Mbps. For the motion/control of the user, the packet rate is 250 fps with the average data rate of 0.2 Mbps. For the audio/data, the average data rate is 1.12 Mbps. As for the latency, a parameter, called as packet delay budget (PDB) is used. The PDB is 15 ms. For the 6G use cases, we consider the requirements are expected to be much more stringent to fulfil the service requirements of this use case. Particularly, to support high quality video and supporting more concurrent users. High quality video (e.g., Ultra High-Definition Video, 4K/8K quality) is required to have better user experience. For synchronization, such as the synchronization from multiple devices are expected to be less than 10 micro-seconds [9]. The exact requirements for this use case are still under investigation.

2.5.3 Virtual content production of live music

2.5.3.1 Descriptions

This use case is about virtual content production of live music. Performers produce 3D video content that can be live or uploaded to social media. Performers in different locations perform live together. To create 3D video content, multiple professional cameras (e.g., 4K cameras) and multiple microphones are used in each indoor room (e.g., live studio) where one performer performs. Audience in different places far from the live studio (e.g., their home) can view content at different angles of the production by using XR device. Figure 6 illustrates the scenario of virtual content production of live music supported by a subnetwork. This illustration shows two performers, and each performer is in a different live studio. In the live studio, 360° cameras and 360° microphones are installed and connected wirelessly in the subnetwork. Video and audio data from 360° cameras and 360° microphones are sent to content processing server. Content processing server creates 3D video content. To enable performers to act in a well synchronized way, the content processing server sends feedback function (e.g., feedback via monitor and earphone) to each performer via monitor and earphone. The feedback video and audio data, that shows and hears their own performance, is used for checking their synchronized performance in real time. The content processing server sends the 3D video contents to remote live audiences or uploads 3D video contents to cloud servers (e.g., social media) for later viewing. The post-processed 3D will show one or multiple of the performers video.

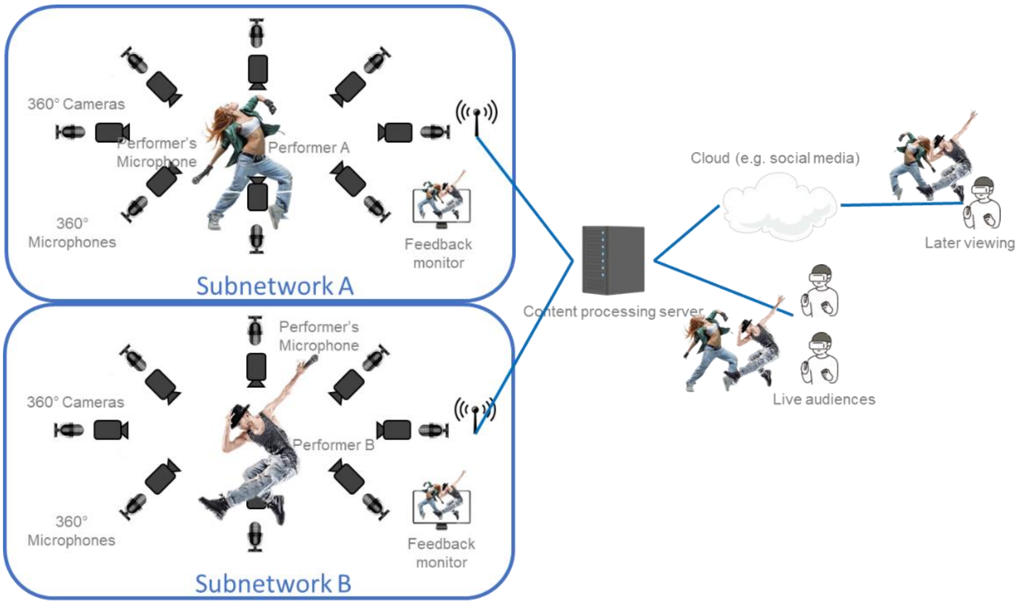

Figure 6. Overall Description of Content Production of Live Music

2.5.3.2 Pre-condition(s)

Multiple professional cameras and multiple microphones are installed in a live studio where performer(s) will perform and are connected wirelessly with the respective subnetworks. The performer(s) in different geographical location is(are) equipped with similar installations.

2.5.3.3 Operation Flow

The operation flow of this use case is described as follows:

1. The performer(s) starts to perform their live music (i.e., singing, dancing) in the live studio.
2. Multiple professional cameras and microphones record video and audio of their performance.
3. The multiple professional cameras and microphones send these data (video and audio) to content processing server.
4. The content processing server creates 3D video content that performer(s) performs in the live studio.
5. The content processing server sends the feedback data to each feedback function (monitor and earphone).
6. The content processing server broadcasts the 3D live video contents to live audiences or uploads to cloud servers for later viewing.

2.5.3.4 Post-condition(s)

1. The audiences can have immersive experience of remote live music in different places.
2. The performers can perform in different places.
3. The operator of live music can easily set up the environment of live music since the system is operated wirelessly. Wiring installations (and possible removal) can be avoided.

2.5.3.5 Challenges to the 6G system

To provide immersive experience of live music, extremely high data rate is required to send video data from multiple professional cameras to the content processing server. In addition, to enable synchronized performance, low latency feedback to each performer is necessary.

It is difficult to meet the above requirements by using the existing 5G. A 6G system with subnetwork is designed to meet the requirement of this use case as the 6G system will support ultra-high data rate with extreme low latency.

The following highly-relevant technology components (TCs) are considered for this use case. Other TCs can still be relevant and are shown in section 2.6.

Table 3: Selected Key TCs for Virtual Content Production Use Case

Technology component (TC)	**Explanation**
TC3. Sub-THz system models	To provide ultra-high data rate, operation with extremely wide bandwidth would be required. Sub-THz would be one of options to easily allocate such wider bandwidth.
TC4. Ultra-short transmissions with extreme reliability	Ultra-low latency with high reliability improves the user experience.
TC5. Analog/hybrid beamforming/beamfocusing	Along with operation with extremely wide bandwidth, advanced beamforming/beamfocusing technology would be beneficial to improve spectrum efficiency. Analog/hybrid beamforming/beamfocusing using massive antennas and/or multiple transmission/reception points would contribute to achieve ultra-high data rate.
TC7. RIS enhancements	Since this use case is mainly indoor and in a stationary place, the reconfigurable intelligent surface (RIS) would be an attractive technology to achieve ultra-high data rate. RIS could be useful for deploying multiple transmission/reception point (TRP) operation with lower cost.
TC9. Flexible/full duplex scheduler	Flexible/full duplex scheduler on TDD band would be beneficial for extreme low latency operation. By using a flexible/full duplex scheduler, high priority packets could be transmitted anytime even when the resource is occupied by a low priority packet on a different link.

2.5.3.6 KPI Aspects & Requirements

This use case requires combination of high data rate and low latency. The network traffic model analysis is quite similar as described in Section 2.5.2.6. We consider this use case is similar to Augmented Reality (AR) as identified in [3]. However, high quality video is expected to improve the user experience, especially the user experience at the audience. In [3], It has been identified that for the uplink video streaming, the default packet rate is 60 frame per seconds (fps), and the average data rate is 10 Mbps. For the motion/control of the user, the packet rate is 250 fps with the average data rate of 0.2 Mbps. For the audio/data, the average data rate is 1.12 Mbps. Lastly, for the uplink latency, the Packet Delay Budget (PDB) is 30 ms.

We consider the following initial requirements in order to fulfil the service requirement of this use case:

Data rate

- UL 4K performance video streaming: [30-60] Mbps per camera
- DL feedback of live video content: [30-60] Mbps

Latency (from UL streaming to DL feedback)

- Audio latency (Mouth-to ear latency): < 4 ms
- Video latency: < [20] ms

Synchronization

- Each of the multiple cameras and microphones need to be synchronized. For the synchronization, such as the synchronization from multiple devices are expected to be less than 10 micro-seconds [9].

2.5.4 Augmented Reality (AR) Navigation

2.5.4.1 Descriptions

This use case considers augmented reality (AR) navigation powered by Artificial Intelligence/Machine Learning (AI/ML) concierge and operated typically in an urban city scenario. The AR device via the glasses provides the augmented reality image containing the information that could be useful to the user. The AR device may also be equipped with sensors, microphone, camera, speaker, and communication module. In principle, the AR device is a tool to gather the input, transfer the input to a server (processing node), receiving the post-process data (information) from the server, and provide the information to the user (via AR glasses, speaker). An AI/ML server is used to assist the user by providing the user's desired information based on various input to the server. In practice, this operation is inspired by the usage of an AI/ML tool where the user asks a question, and the answer is later provided by the AI/ML tool itself. In our case, the user may have interactive communication so that she/he provides the enquiry and receives the intended information, such as the best location and best route to the destination. In terms of usage, it can be illustrated in the following examples:

- When the user walks around a pedestrian street full of stores/restaurants, the user may ask via AR glasses concierge to find any interesting location based on user's need, such as the availability of nearby good restaurant. The AR will immediately provide the navigation information, such as the way and direction to go to the destination. At the same time, reservation can also be performed by concierge.
- In another example, the user meets a person and wanted to know a bit more information (e.g., names, occupation, hobby, etc). The AR device collects the information via its camera and/or microphone of the surrounding environment, such as a public space. Eventually the user may receive the intended information in the AR device (e.g., via glass and/or speaker).
- In another example, the user walks on the pedestrian street. The user may retrieve information around the pedestrian street in his/her AR device. The information could be the information

related to the shops or restaurants that is matched with the user preferences. It could also be generic information, such as the interesting item(s) or promotion(s) in a specific shop or restaurant. Here, the information retrieved by the user is controlled by the movement of the user itself. The AR system at the user is expected to support 6 Degree of Freedom (DoF) operation so that the movement of AR device (e.g., attached in the user's head), controllers and body movement in the space are all tracked.

This use case is illustrated in Figure 7. There can be multiple users equipped with AR devices on a pedestrian street. In addition to AR device, the user has a smartphone which could act as edge server and a local AP connected to the AR device and user's controller / sensors node(s). Furthermore, each shop/restaurant has a set information describing the shop/restaurant itself. The information can be the items inside the shop/restaurant, promotion information, etc. This information can be stored in a website or any kind of information database that can be accessed from the internet. For example, the application, such as in the cloud, can obtain such information. A form of subnetwork is established by having an AP that can reside in a smart phone and the AP is connected to the user's devices, such as AR device, sensor(s) and controller(s). Furthermore, the AP maintains connection to the application cloud server via 6G Macro network.

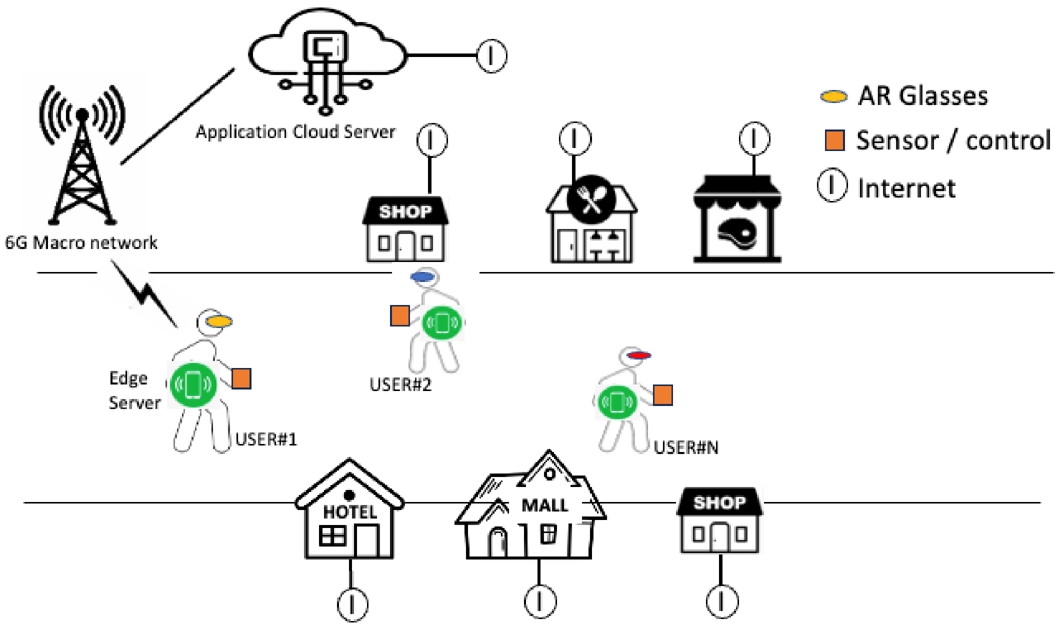

Figure 7. Illustration of AR Navigation

2.5.4.2 Pre-condition(s)

The application cloud server or in this case the AI/ML server is connected to 6G macro network so that it can be reached by the user smart phone. The user smart phone also supports an AP functionality so that it can connect to the devices belong to the users (e.g., AR device, sensor(s), controller(s)). The shop / restaurant has provided its information (e.g., products, items, sale/promotion) that can be accessible via internet / application.

2.5.4.3 Operation Flow

The operation flow of this use case can be described as follows:

1. Initialization / Information collection:
    a. The user triggers the operation by collecting the input within a certain duration of time, such as voice (e.g., question), image(s), user's body, AR headset direction). The input collection can be aperiodic, triggered by the user explicitly, e.g., press a button, or implicitly (e.g., body movements). For example, the input could be the user's preference, the user mentioned and captured by the microphone and/or the user stares in certain direction and this is captured by the camera.
2. Processing of the information:
    a. The collected information is transmitted to the AP via a local connection and post-processed in the edge cloud server residing in the AP. The edge-server transmits the post-processed information to the cloud application server.
    b. The cloud application server further post processes the user's input and tries to link and match it with the data from e.g., the shop/restaurant.
3. Providing the output to the user:
    a. The cloud application server transmits the output, basically the information that is expected to be matched with the user's request. The information is transmitted to the user's AP and further transmitted to the edge-server.
    b. The edge-server post-processes the input, particularly to provide the representative information to the AR glasses display and/or the speaker residing at the AR glass.

2.5.4.4 Post-condition(s)

The user receives the intended information in the AR device based on the input that the user has provided to the system. The input can be in a form of voice (e.g., questions) and image (screen capture). The output is mostly displayed to the glass of AR device. The amount of information can also be selectively shown based on the priority level and/or user's gesture or body movements.

2.5.4.5 Challenges to the 6G system

In this use case, it is expected that the user receives accurate information with relatively low latency based on the user's input. The delay in receiving the requested information reduces the user experience. Furthermore, it is expected that multiple users use the system simultaneously in the same place / area. Hence, we foresee the following one or the combinations of challenges that must be fulfilled in 6G system:

- The ability to collect input from multiple sources (i.e., various sensors, speakers, camera, etc) simultaneously at the user side, where the timing of collecting information should be aligned when received at the local AI/ML server (edge-server) (e.g., within a limited time window). The usage of time stamp can also facilitate this operation.
- The ability to collect the information, process the information, and provide the output in timely manner, i.e., with a low latency. The information processing can be both at the edge-server and cloud application server.
- The ability of handling interference / jamming by the system as the system is operated in uncontrolled environment (i.e., public space) where there can be other users with the same system or other systems that may be operated in the same spectrum.

- Operating the system in an efficient manner so that the user devices are supported in a relatively small form factor and with reasonable battery life.

In order to address the above challenges, we consider the following technical components (TCs) are highly relevant for this use case. Other TCs can still be relevant and are shown in section 2.6.

Table 4: Selected Key TCs for Augmented Reality (AR) Navigation

Technology component (TC)	**Explanation**
TC09. Flexible / full duplex scheduler	To support low power transmission from sensors or other devices to the AP. The AP is collocated at the device / wireless terminal carried by the user.
TC10. Predictive scheduler	The user may receive periodic and/or scheduled information. Hence, a predictive scheduler could be facilitated to optimize resource allocation and ensure information with low latency requirements can be provided in time.
TC11. Latency-aware access in the unlicensed spectrum	The system is operated as a personal subnetwork to be used in a public space in which it can be deployed in unlicensed spectrum. Considering latency is an important aspect, a latency-aware access for a system in the unlicensed spectrum could be beneficial.
TC14. Jamming detection and mitigation	The system is expected to be operated in an uncontrolled environment (e.g., public space). Hence, the presence of jamming (e.g., due to the operation of other system or explicit jammer(s) should be able to be detected and mitigated to ensure the operation of the use case.
TC15. Hybrid management of traffic, spectrum and computational resources	We expect there is a split operation / processing of AI/ML in the application server in the cloud and edge server. Distributed / hybrid resource management could facilitate the split operation of AI/ML function so that efficient radio resources and computation resources can be achieved.

2.5.4.6 KPI Aspects

This use case has certain subnetwork traffic characteristics covering the uplink and downlink transmission from the devices to the AP and vice-versa, respectively. The uplink transmission is mostly the input from the user collected from the microphone, camera, and sensors. The downlink transmission is the output to the user such that the information in response to the user's enquire(s). We have identified the following key traffic characteristics:

1. Uplink video/image transmission
   This is uplink transmission from the user. It could be a snapshot of video / image. The data rate expected should be medium as it does not require super high-quality video / image transmission. However, the periodicity can be frequent, and it may depend on the body movement of the user.
2. Voice / gesture / sensor transmission

This could be an event triggered transmission. On the other hand, the sensor's outputs in obtaining the body movement should be rapidly transmitted.

3. Downlink video/audio/text streaming
   This is the downlink transmission to the user, typically the information to be displayed in the glasses of AR device. The quality of the image/video may not be the most important aspect. The important aspect is the latency of the information so that the information can be provided at the right time.

Based on the above key traffic characteristics, we consider the KPI is quite similar as the KPI identified in Section 2.5.2.6. In terms of the requirements, we can also refer to the Augmented Reality (AR) as described in Section 2.5.3.6. However, the video transmission quality can be lower as the ultimate goal of this use case is to provide the relevant information to the user. The latency from providing the information (e.g., uplink video transmission), processing information, and post-processing information (e.g., display to the user) are the main requirements of this use case. For synchronization, such as the synchronization from multiple devices (e.g., camera, microphone, sensors) are expected to be less than 10 micro-seconds [9].

2.6 6G Challenges and 6G-SHINE Technology Components Related to Consumer Subnetwork

The use cases of consumer subnetwork as described above show stringent requirements in order to satisfy the user experience. In most of the cases, high data rates, low latency and high reliability requirements are required, particularly to provide immersive experience using VR and AR glasses. In order to fulfil these 6G challenges, the list of relevant 6G-SHINE technology components is listed in Table 5.

Table 5: Technical Components (TCs) Addressing the Consumer subnetwork Use Case Challenges

Technology component (TC)	**Use cases**	**Explanation**
TC1. In-X data traffic models	All consumer use cases	General aid for developing a concept
TC2. Channel models for in-X scenarios	All consumer use cases	General aid for developing a concept
TC3. Sub-THz system models	- Indoor Interactive Gaming - Immersive Education - Virtual Content Production	Sub-THz transmissions are a promising technology to provide ample capacity for multiple users closely localized and enable short frame durations to support ultra-low latency and high reliability in suitable propagation environments.
TC4. Ultra-short transmissions with extreme reliability	All consumer use cases	Small latency enables more options for offloading within the subnetwork. However, consumer use cases may not require extreme reliability
TC5. Analog/hybrid beamforming/beamfocusing	- Immersive Education - Indoor Interactive Gaming - Virtual Content Production	Enable optimized communication with individual devices or groups of devices within the coverage area of a particular subnetwork
TC6. Jamming-aware native PHY design	AR Navigation	Navigation in an open space prone to possible jamming.

TC7. RIS enhancements	- Immersive Education - Indoor Interactive Gaming - Virtual Content Production	Enable steering of beams towards individual users within a room
TC8. Intra-subnetwork macro-diversity	Immersive Education	e.g., to achieve reliability for low latency
TC9. Flexible/full duplex scheduler	All consumer use cases	Depending on the selected offloading scheme for UL and DL related processing, there may be both significant uplink and downlink traffic, which is the scenario benefitting most from flexible/full duplex scheduling options
TC10. Predictive scheduler	All consumer use cases	Prediction helps optimize compute vs. communication trade-off
TC11. Latency-aware access in the unlicensed spectrum	All consumer use cases	Optimized latency in unlicensed spectrum enables more options for offloading within the subnetwork
TC12. Centralized radio resource management	All consumer use cases	Optimized resource allocation depending on the deployment scenarios.
TC13. Distributed/hybrid radio resource management.	All consumer use cases	e.g., distributed within the subnetwork
TC14. Jamming detection and mitigation	AR Navigation	Navigation in an open space prone to possible jamming.
TC15. Hybrid management of traffic, spectrum and computational resources	All consumer use cases	There is a trade-off between communication and compute when deciding about offloading strategies for the provisioning of multimedia content, e.g., rendering. To find the optimum setting and to maintain it despite variations in connectivity and compute demand requires an integrated approach to scheduling and resource management.
TC16. Coordination of operations among subnetworks in the same entity	All consumer use cases	If multiple subnetworks (e.g., within the classroom) serve the users, potentially via multiple local or edge servers, and considering that the subnetwork may be built from a hierarchy of personal subnetworks that aggregate each user's set of devices, this will be very relevant

3 INDUSTRIAL SUBNETWORKS CATEGORY

With s. 6G-SHINE will research technology enablers for enhancing latency and reliability of wireless communications, leveraging specific in-X deployment characteristics. We present in this Section the current status quo, and an overview of use cases for short-range industrial communications, where in-X subnetworks can be a fundamental enabler. In the presentation of use cases, we use a bottom-up approach, starting with use cases where subnetworks are installed in single entities like robots and production modules, and then introducing subnetworks formed by robot swarms, and factory asset management.

3.1 STATUS QUO ON INDUSTRIAL NETWORKS

Industry 4.0 envisions a transformative progression of industrial manufacturing systems, blending cyber-physical systems, Industrial Internet of Things (IIoT), and cloud computing technologies. This evolutionary step necessitates a seamless interconnection of individuals, machines, and computational resources within manufacturing workflows. Fundamental to this new paradigm is the ability to gather and utilize data to reconcile the physical and digital worlds, thus enabling the development of new revenue channels and cost efficiencies. The challenge here lies in addressing diverse connectivity requirements pertaining to reliability, low latency, and capacity.

Currently, industrial networks feature an array of wired-oriented solutions such as Ethernet-based networks and field buses. In tandem, the IEEE 802.1 TSN task group is crafting standards to enhance the Ethernet networking model to ensure deterministic streaming services. The IEC/IEEE 60802 is also developing the TSN profile for industrial automation. In contrast, wireless systems have yet to become popular due to concerns over the reliability and performance of industrial-grade deterministic communication [10], and some parts of the ecosystem still remain to become mature, too. As a result, wireless networks currently have a limited footprint, extending only into areas of factory process automation and other noncritical applications. The wireless communication sector gained a clearer understanding of the integration scenarios and reliable communication requirements of industrial use cases only recently. The 3rd Generation Partnership Project (3GPP) and 5G-ACIA, along with the close collaboration between wireless communication and industrial sectors, have led to the development of industry-specific, time-sensitive, ultra-reliable, and massive-connectivity features in 5G networks [2], [12], [18], potentially paving the way towards the future 6G.

3.2 SWARM PRODUCTION AS A TREND AND THE ROLE OF 6G SUBNETWORKS

Achieving comprehensive connectivity throughout the entire value chain necessitates a pragmatic integration of wireless solutions with diverse manufacturing use cases. Wireless technologies can help eliminate cables, thereby speeding up the reconfiguration of production facilities and reducing the cost of deployment. Moreover, they can enable new industrial use cases that require full mobility support [10]. The imperative for enhanced wireless systems stems from two major trends.

1. Dynamic network customization:
   There is a need for swiftly reconfigurable and modular production lines, or 'swarm' production, to scale capacity, speed, and control in response to evolving manufacturing demands [10]-[11]. Current production lines are typically statically configured due to the expense and complexity of cable management. Wireless connectivity can deliver the required flexibility, but this complicates radio resource allocation and network management.

2. Mobility and collaboration:
   Support for mobile objects such as AGVs, robots, and control panels and their collaboration in flexible/modular manufacturing is key to automating repetitive, labor-intensive, and costly tasks. Such mobility and collaboration-oriented use cases require robust wireless connectivity to ensure fail-safe operation.

Understanding current and envisioned use cases specific to certain scenarios and their communication requirements can lead to the optimization of integrated wireless solutions. By supporting full mobility and replacing cables, wireless automation holds transformative potential for industrial production systems.

The manufacturing sector is rapidly evolving towards creating highly adaptable infrastructure, primed to cater to the increasing demand for customized products. This adaptability can be best achieved by embracing the concept of swarm production [11]. Characterized by decentralized, non-linear production workflows, swarm production relies on Autonomous Mobile Robots (AMRs) to transport products between diverse manufacturing stations dispersed throughout the factory floor. Implementing such an adaptable, intelligent production system necessitates the amalgamation of various technology components, including cloud-computing, 6G communications equipped with Ultra-Reliable Low-Latency Communications (URLLC) capabilities, robotics, autonomous systems, and highly accurate localization systems.

However, transitioning from traditional production models to swarm production is a complex process. It is useful here to refer to the evolutionary roadmap for the production process suggested in [11], where the transition pathway from traditional manufacturing systems to swarm production is segmented into four progressive stages, predominantly focusing on (1) removing cables, (2) usage of cloud-based soft Programmable Logic Controllers (PLCs), (3) cloud robotics, and (4) transitioning product carriers into small mobile robots (swarm production).

6G subnetworks can form the backbone of this technological integration [14]. Swarm production inherently requires high levels of reliability, low-latency communication, real-time adaptability, and complex control strategies. The expected features of 6G subnetworks align perfectly with these needs, making them an integral, logical element for facilitating the evolutionary trend towards swarm production.

3.3 Benefits and challenges of industrial subnetworks

Subnetworks are projected to bring significant advancements, including even higher data rates, lower latency, and increased network reliability and efficiency, among others. This could have notable impacts on the manufacturing industry comprising several benefits.

1. Enhanced connectivity:
   6G subnetworks could potentially offer uninterrupted local and short-range connectivity, capable of ensuring extraordinarily high reliability alongside low latency. This advancement is critical for meeting communication requirements previously unattainable through 5G standards, such as high throughput URLLC and loop cycles of 100 microseconds. This paves the way for an array of novel use cases demanding complex and stringent network requirements, thus offering possibilities of applications and services.

2. Distributed computational architecture:
   6G subnetworks could facilitate a new architectural paradigm that strikes a balance between localized processing and cloud computing. This could involve dividing the computational load between subnetworks and edge/cloud servers, optimizing the distribution based on the criticality and latency requirements of different tasks. Critical functionalities demanding ultra-low latency and high reliability, such as real-time process control, could be handled within the subnetwork itself, thereby minimizing delay and potential disruptions. On the other hand, tasks that are less time-sensitive, such as advanced analytics, machine learning model training, or supply chain optimization, could be offloaded to the cloud. This distributed computational model aligns with the vision of 6G as an enabler of a more flexible, responsive, and efficient manufacturing sector, while acknowledging the diverse requirements of different tasks and applications.

3. Replacement of traditional cabled connections:
   This transition unlocks a preliminary level of flexibility, facilitating more straightforward reconfigurations of the production facilities compared to their wired counterparts. Furthermore, removing cables can enhance the flexibility of motion of robot parts, and maintenance, as it is easier to replace wireless components than wired ones.

Despite the promising benefits, there are also challenges with respect to the introduction of subnetworks.

1. Network Management:
   The potential complexity of 6G subnetworks could make network management and radio resource allocation more challenging. In this context, AI can play an important role for enabling sophisticated predictive maintenance strategies and optimization methods.
2. Security:
   With greater connectivity and more sophisticated networks, security threats could be more diverse and challenging to manage. Ensuring the security of data and network operations in a swarm production setting would be crucial.
3. High-precision requirements:
   Swarm production requires high-precision operations, particularly when it comes to real-time control and coordination of machines, where the level of reliability required is in the orders of magnitude higher than in a typical public network 6G subnetworks are expected to support such real time operations, and coordination of tasks.

3.4 KVIs of Industrial Subnetworks

In congruence with the aims of the 6G-SHINE project, our primary objective within the realm of factory automation is to ascertain the social impact and value of 6G subnetworks, placing a strong emphasis on sustainability. The integration of flexible, low-power, and short-range wireless subnetworks within factory automation ecosystems fuels the evolutionary trajectory of manufacturing networks. Such progressive transition from wired to wireless connections within factories yields multiple benefits. It substantially mitigates operational costs and the physical heft of manufacturing machinery, leading to environmental sustainability. Moreover, it bolsters production efficiency, facilitating the production of faster, more affordable, and higher-quality products for society. This transition aligns with the broader global efforts towards achieving a more sustainable future, while also driving significant economic sustainability.

3.5 Industrial Subnetworks use cases

In the following, the relevant identified use cases for industrial subnetwork applications are described.

3.5.1 Robot Control

3.5.1.1 Description

Inspired by [10], a relevant use case for industrial subnetworks is represented by the wireless control of robot operation. Examples can be the control of multi-axis robots for leveraging the degrees of freedom offered by potential movement directions the robot can accomplish; force control; control of moving and rotating parts in printing machines, packaging machines, or machine tools. As observed in [3], the usage of wireless for these applications can ease movements and rotation with respect to wired components, possibly enabling further degrees of freedom in the manufacturing operations. Robot control operations are usually relying on wired industrial technologies such as Profinet IRT or EtherCAT, and are supported by very short communication cycles, down to 50 µs and below, to ensure fast and accurate robot movements. This use case aims at translating such wired communication technologies over wireless, while maintaining cycle times and expected quality of service. A pictorial representation of this use case is shown in Figure 8.

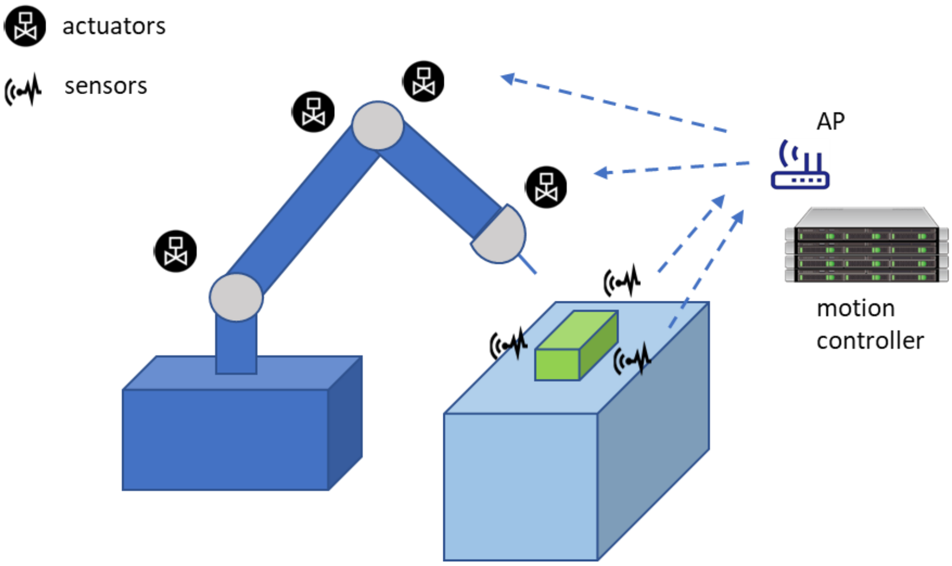

Figure 8. Illustration of the Robot Control Use Case

3.5.1.2 Pre-condition(s)

A robot control system consists of several sensors (e.g., position, rotation, and force sensors), a motion controller, and a number of actuators (e.g., linear actuators and servo drive). Most (or all) sensors and actuators can be connected to a subnetwork AP, which hosts motion controller capabilities. Alternatively, the motion controller is also a device connected to the subnetwork AP. When the machine is on, all devices connect to the subnetwork AP.

3.5.1.3 Operation Flow

The operation flow follows a typical control cycle and can be exemplified as follows.
Sensors are measuring the actual values of the property of interest in the plant and transmit them to the subnetwork AP at periodic, deterministic cycles. Depending on the specific sensor, such cycles can

be in the order of a few ms, down to around 100 µs and below. Packets can be in the order of 200-300 bytes.

In case the AP is equipped with motion controller capabilities, it will process the measurements sent by the sensors and generate a command (e.g., set points) for the actuators. In case the AP is not equipped with motion controller capabilities, it will forward the sensors' measurements to the motion controller device and receives the commands from it. The subnetwork AP transmits the commands to the actuators at a predefined time according to the communication cycle. Actuators perform the command set by the controller.

Note that different cycle times might need to be efficiently multiplexed in a subnetwork, e.g., 10 - 100 ms down to <100 µs.

3.5.1.4 Post-condition(s)

By following the communication cycles without loss of messages, the robot can correctly perform its operational task including the movement/rotation of its parts.

3.5.1.5 KPI Aspects & Potential Requirements

Relevant challenges for supporting this use case are already presented in [2] . These can be summarized as follows. On one hand, the system must be able to support very short communication cycles, in the order of 100 µs or below, with packet size in the order of 200-300 bytes, and a probability of having two consecutive errors < 10^{-6}. On the other, the system must be able to ensure a high level of synchronicity among its parts, e.g., with a jitter below 1 µs, such that measurements reported by the sensors can be time aligned. Additionally, the system must be able to support many sensors and actuators, e.g., in the order of 50.

Besides, there are other relevant challenges. Since not all communication loops may require ~100 µs cycles, the system must be able to efficiently support different communication cycles, e.g., 10-100 ms, in the same air interface. Moreover, sensors and actuators can be mounted over robot parts in motion, with speeds up to 20 m/s. The system should then be able to ensure the expected communication quality with mobile devices (whose motion can, however, be predictable). Since a production line can include many robots performing their dedicated tasks, and each robot can have its dedicated subnetwork, subnetwork density can be very high, therefore generating potentially high levels of mutual interference. Also, it is worth observing that robot control tasks can happen over mobile robots, and therefore the mutual interference levels may vary depending on the mutual robot position.

3.5.2 Unit Test Cell

3.5.2.1 Description

This use case is also inspired by the analysis of data traffic characteristics in relevant industrial use cases based on wired setups [13]. A unit test cell is meant to perform quality assurance tasks of product parts in the manufacturing process, as well as of devices used in the manufacturing process. For example, it can be used for providing calibration and tolerance figures for actuators to be used in a factory, to make sure they comply with predefined requirements during execution.

3.5.2.2 Pre-condition(s)

A unit test cell, as depicted in Figure 9, can consist of a test rig where the device to be tested (e.g., an actuator) is placed, and several sensors are meant for assuring its quality. The device can be activated by a soft PLC according to a specified control sequence. The sensors continuously measure the performance of the actuator and report the measurements to the soft PLC. Once the test sequence is finished, the results collected by the soft PLC are reported to a factory common database. We assume a wireless subnetwork consisting of an AP co-located with the soft PLC. The DUT, and the sensors, are connected to the subnetwork AP, i.e., one connection per sensor. Another option consists of having a sensor aggregator connected via fieldbus with all sensors that aggregate all the measurements to be reported to the soft PLC.

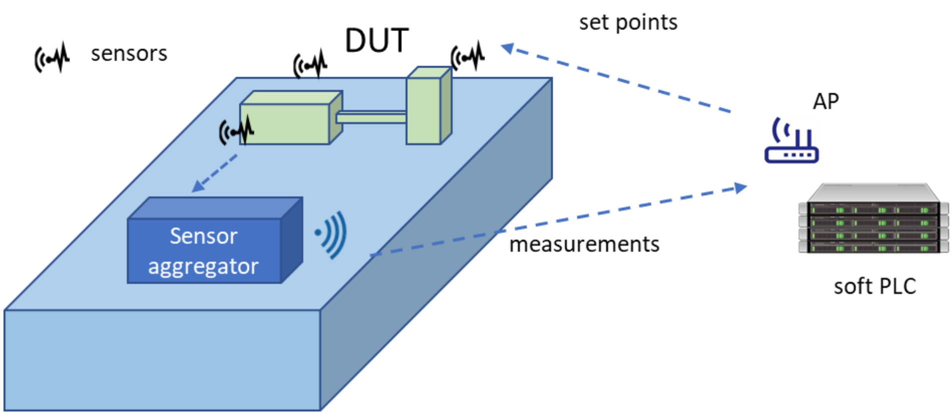

Figure 9. Illustration of the Unit Test Cell Use Case

3.5.2.3 Operation Flow

Once the device to be tested is placed on the test rig, the operation flow is the following:

1. The soft PLC generates a sequence of operations to be performed by the DUT and transmits the sequence to the subnetwork AP.
2. The subnetwork AP forwards the sequence of operations to the DUT.
3. The DUT performs the operations in the list and the sensors are measuring continuously the parameters of interest.
4. In case each sensor is equipped with wireless capabilities, they will transmit their measurements to the subnetwork AP. Such measurements can be transmitted in a periodic or aperiodic fashion. In the presence of a sensor aggregator, these measurements are first collected and then transmitted by the sensor aggregator to the subnetwork AP.
5. The subnetwork AP forwards the measurements to the soft PLC, that stores them. These measurements are utilized to assess the quality of the DUT performance.

Note that in case the soft PLC is co-located with the subnetwork AP, it can communicate directly with the device under test and receive measurements from the actuators.

3.5.2.4 Post-condition(s)

At the end of the test sequence, the soft PLC has received relevant quality measurements (e.g., tolerance and accuracy figures from an actuator as the DUT. It can then forward these measurements to a factory common database. This may happen over a wireless system other than a 6G subnetwork.

3.5.2.5 KPI Aspects & Potential Requirements

The main challenge to the 6G system of the presented use case is the need to transmit sensor measurements to the soft PLC with very low latency and low jitter. It is important indeed that the measurements from the multiple sensors are time aligned to calculate properly the performance figures at the soft PLC. This might be particularly challenging in the case where the sensors are transmitting individually their measurements to the subnetwork AP, rather than relying on a sensor aggregator.

- The system must be able to support cycle times (below 1 ms), with packet sizes in the order of 100 bytes, and the probability of having two consecutive errors < 10^{-6}.
- Short cycle time must be kept also in case sensor information is aggregated, and therefore transmitted as a single message by the sensor aggregator. Since measurements should be timely aggregated for generating commands to the actuators, a high level of synchronicity with < 1 µs errors is required. The system should also support more relaxed cycles, e.g., 10-100 ms, using same air interface.
- Besides periodic traffic, aperiodic traffic with potentially short interarrival times, below 100 µs, is to be supported. Up to 20 sensors are to be served.
- Besides, it should support periodic traffic with packet interarrival times below 100 µs.
- The soft PLC should also be interfaced with an external database, for reporting periodically the measurements.

3.5.3 Visual Inspection Cell

3.5.3.1 Description

This use case is also inspired by our analysis of data traffic characteristics in relevant industrial scenarios [13]. A visual inspection cell performs quality assurance in the manufacturing process using 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.

3.5.3.2 Pre-condition(s)

A visual inspection cell, as it is illustrated in Figure 10, can be installed in proximity to a conveyor belt that transports parts for assembly tasks over multiple production modules. It consists of a camera (or multiple cameras) pointed at a specific portion of the conveyor belt, an image processing unit (IPU), a soft PLC, and an actuator, which takes care of performing quality control actions. The cell can also include a HMI device, for general monitoring purposes. The HMI can eventually attach and detach from the visual inspection cell during runtime operations, without the need of interrupting the operations. We assume the camera, IPU, actuator, and HMI device to be connected wirelessly to a subnetwork AP. In a possible implementation, the AP is co-located with an edge processing server performing the soft PLC control tasks. In another implementation, the soft PLC is another device connected to the subnetwork AP. Similarly, the IPU can eventually be co-located with the camera or connected to it via a wired connection. In this case, the camera and the IPU represent a single device from the subnetwork point of view.

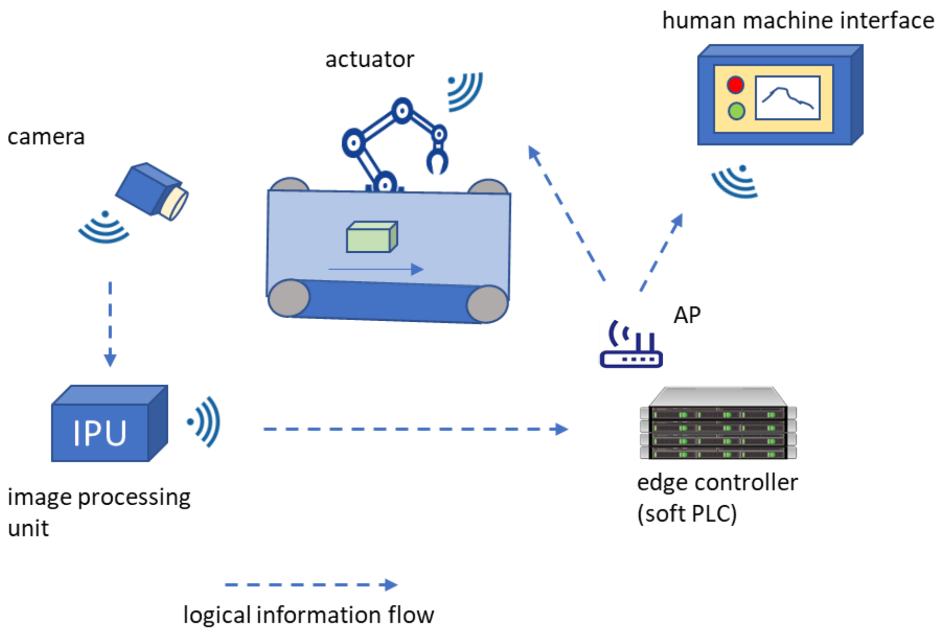

Figure 10. Illustration of the Visual Inspection Cell Use Case

3.5.3.3 Operation Flow

Let us consider first the case where all the devices (camera, IPU, soft PLC, actuator, and HMI) are wirelessly connected to the subnetwork AP. The operational flow is then the following:

1. The camera streams video of the production items passing over the conveyor belts to the subnetwork AP.
2. The subnetwork AP transmits the video to the IPU device.
3. The IPU device performs quality control tasks by comparing the received video with a collection of images of correctly assembled products, for the sake of detecting possible discrepancies. In case discrepancies are found, the IPU issues a message meant for the soft PLC and transmits it to the subnetwork AP.
4. The subnetwork AP receives the message for the IPU, and forwards it to the soft PLC.
5. The soft PLC processes the message received and outputs a command for the robots in the assembly line by sending a command to the actuator controllers. For example, in case the product is deemed to be faulty, it will instruct the robots in the production line to remove it from the conveyor belt or to re-direct it to a different production line. In case the product fulfills the quality specification, it can be forwarded to the next manufacturing cell.
6. During the process, the soft PLC can transmit status updates on the actions taken to the subnetwork AP.
7. The subnetwork AP transmits the status updates to the HMI, in case this is connected to the network, for general monitoring purposes.

The above-described operation flow may be simplified in case some of the devices are co-located or wired-connected, e.g., camera with IPU, subnetwork AP with soft PLC, as the corresponding wireless communication link can be removed from the process. Also, the operation flow presented above subsumes a star topology where all transmissions are directed to the subnetwork APs. One may explore the possibility of enabling direct communication among devices, configured by the AP itself. For example, the camera can stream the video feeds directly to the IPU rather than to the subnetwork AP.

3.5.3.4 Post-condition(s)

As a result of the visual inspection cell operation, quality of production is ensured in a timely and efficient manner since eventual faulty parts are promptly removed from the production pipeline or corrected via further manufacturing process.

3.5.3.5 KPI Aspects & Potential Requirements

The successful execution of the visual inspection cell operation poses significant challenges to 6G subnetwork operations. From our early measurements in a cabled setup for visual inspection, the packet inter-arrival time of certain communication links, e.g., between soft PLC and HMI can be significantly shorter than 1 ms and therefore beyond the 5G capabilities. The system must then be able to support aperiodic traffic with packet interarrival times in the order of 100 µs, with packet sizes in the order of 100 bytes, and packet error rate < 10^{-6}.

In case all devices are communicating via the subnetwork AP, this should be able to efficiently multiplex different traffic types. The video feeds transmitted by the camera(s) to the IPU require large data rates (e.g., ~80 Mbps per camera in the case of 4K videos). Conversely, the communication between IPU and soft PLC, as well as between soft PLC and actuator, requires low data rates but may require very low latency and high reliability as in the above point, to ensure that potentially faulty products are not removed from the production line.

The system should be able to dynamically add and remove the HMI devices without affecting the current runtime operations of the visual inspection cell, e.g., without adding any additional delay. Communication with the HMI device is best-effort traffic, in the order of 10 Mbps.

Table 6 summarizes the main requirements of the three presented use cases, referring to subnetworks installed in a single entity.

Table 6: summarizes the main requirements of the three use cases in the Industrial category

Use case	Purpose	Requirements
Robot control	Control of moving and rotating parts in printing machines, force control, packaging machines, or machine tool	- Packet size: 200-300 bytes - Communication cycles down to <100 µs - Jitter < 1µs - Probability of two consecutive errors < 10^{-6} - Up to 50 sensors/actuators - Device speed up tp 20 m/s
Unit test cell	Quality assurance tasks of product parts in the manufacturing process	- Packet size: ~100 bytes - Communication cycles down to <1 ms - Aperiodic traffic with packet interarrival time < 100 µs - Jitter < 1µs - Probability of two consecutive errors < 10^{-6} - Up to 20 sensors
Visual inspection cell	Quality assurance in the manufacturing process by means of video feeds	- Packet size: ~100 bytes - Packet interarrival time can be < 100 µs - Low latency traffic to be multiplexed with high data rate traffic due to video feeds (~80 Mbps per camera)

		- Possibility of adding new devices (HMI) during execution without affecting performance

3.5.4 Subnetworks Swarms: Subnetwork Co-existence in Factory Hall

3.5.4.1 Description

In many manufacturing processes, particularly those in the electronics or automotive sector, tasks can be distributed among a swarm of smaller, specialized robots. Each robot is configured to perform a specific function or a series of functions. Working in unison, these robotic swarms can assemble intricate products with an expected level of efficiency that may surpass conventional assembly lines. Critical to this coordinated operation and the targeted increased efficiency is the concept of collaborative problem-solving. In this model, each robot not only performs its individual tasks but also shares information with the other robots in the swarm. This real-time data sharing ensures a seamless workflow and allows the swarm to tackle complex problems that would be challenging for a single robot or a human operator to address.

To meet the stringent communication requirements intrinsic to swarm operation, the role of 6G subnetworks becomes crucial. In this use case, the concept of subnetworks is to be applied at a higher level than the previous use cases hierarchically, as it refers to a swarm of connected robots.

In the context of a manufacturing scenarios as illustrated in Figure 11, multiple co-existing subnetworks play a pivotal role. They maintain reliable and efficient communication and control among various AGV formations (robot swarms) and production lines.

These subnetworks need to manage potential challenges related to spectrum sharing, interference management, and resource allocation. These factors, if not properly managed, could lead to a degradation in the control system's performance. To tackle this, each sub-network might include a device capable of receiving command guidelines from a parent network, thus enabling smooth RRM among adjacent subnetworks.

Research is underway to develop strategies to achieve 100 µs loop cycles with reliability levels ranging from 10^{-6} to 10^{-9} for control in-X traffic [18]. Additionally, it aims to ensure the support of Gbit/s link throughput with 5 - 10 ms average latency for best-effort traffic, as outlined by the 3GPP TS 22.261 use cases for cyber-physical systems [1].

Further challenges lie in devising control system strategies that align with the operation of the subnetwork. For example, the process may be further optimized when joint control and network design is pursued [17], in order to ensure the seamless integration of 6G communication technology with swarm robotics.

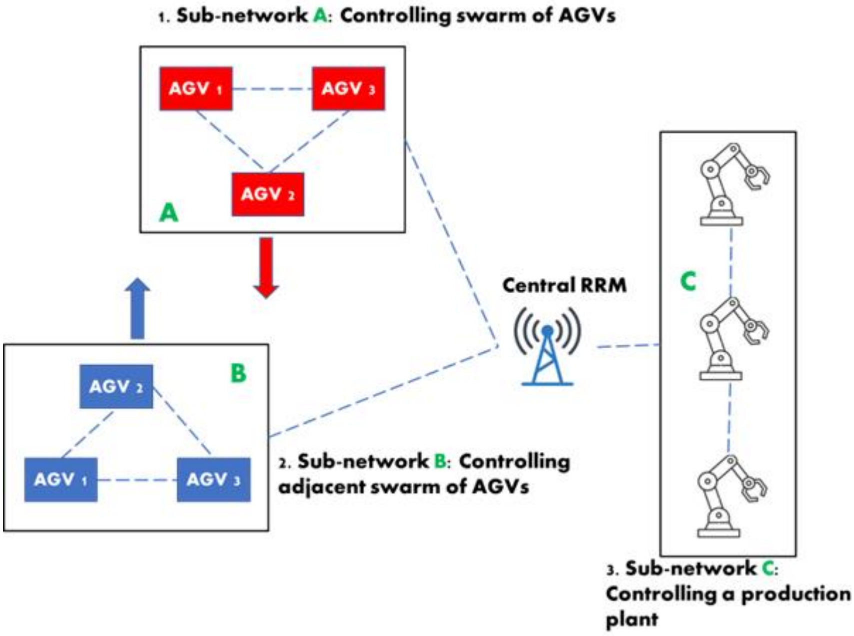

Figure 11. Illustration of the Subnetwork Co-existence in Factory Hall Use Case

3.5.4.2 Pre-condition(s)

The industrial environment/setup is comprised of a heterogeneous assortment of robotic systems, each engineered to execute distinctive manufacturing operations. Discrete control entities, such as Programmable Logic Controllers (PLCs), are implemented either entirely or partially within the confines of an edge infrastructure, which in this case is given by a nearby devices with high compute capacity empowered with edge capability, as illustrated in Figure 12. In this case, critical traffic, such as sensor and control information, are exchanged between the devices, instituting a localized, short-range subnetwork that leverages the edge computing capabilities inherent in a selected device within this subnetwork.

The 6G Network (e.g., enterprise base station or gNodeB) is responsible to handle radio resource management (RRM) when adjacent subnetworks must co-exist, either in a static or a mobility scenario.

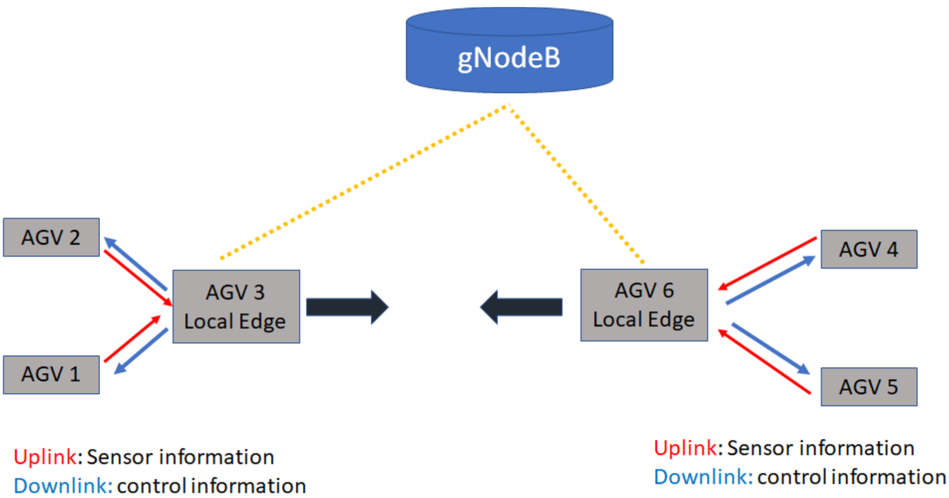

Figure 12. Example of a pre-condition for the co-existence of two adjacent sub-networks.

3.5.4.3 Operation Flow

Considering a set of robots, the flow of operations is described as follows:

1. Initially, each robot in the set identifies itself to device 3 (the edge-capable device) in the star topology subnetwork. These identifications could be through unique IDs or signatures that each robot carries.
2. The robots (devices 0, 1,... N) will constantly send sensor information like camera data, Lidar readings, temperature, etc., to device 3 using their assigned frequency bands. This data exchange could be carried out using advanced communication protocols to ensure efficient and reliable data transfer.
3. After receiving the sensor information, device 3, equipped with PLC capabilities, processes it internally to determine the required control functions. This may involve sophisticated algorithms that consider different robot functions and their states, environmental parameters, etc.
4. Device 3 then sends back the computed control information to each respective robot, thus closing the control loop. The data sent back can include motion control data, task assignments, error corrections, etc.
5. Upon receiving the control loop data, each robot applies the received control instructions to its actuators and executes the corresponding commands. The execution could involve various tasks such as moving, picking, aligning, etc.
6. The edge-capable device (device 3) must also actively manage potential interference within the subnetwork to ensure the smooth functioning of the closed-loop connection. This could involve advanced interference management techniques like adaptive beamforming, dynamic spectrum access, etc.
7. In scenarios where another set of robots (a different subnetwork) enters the wireless collision domain of the subnetwork, the management of inter subnetwork interference is handled by the corresponding 6G network gNodeB, to which the edge-capable device is attached. This could involve coordination strategies such as network slicing, flexible duplex, dynamic spectrum allocation, etc.
8. It would also be important to have a monitoring and updating mechanism in place. Device 3, along with the gNodeB, should continuously monitor the network performance, robot functioning, and other relevant parameters. Based on this, regular updates and adjustments can be carried out to ensure optimal performance and efficient resource utilization.
9. In a swarm-production environment, robots may exhibit emergent behaviour based on their interactions. Device 3, as the edge-capable node, should have protocols and algorithms to identify, analyse, and manage such behaviours to prevent any disruption or inefficiency.
10. Considering the critical role device 3 plays, it might be worthwhile to have a backup or redundancy mechanism in place. In the event of a failure or issue with device 3, a secondary device could take over the control and management functions to prevent disruption to the operations.

3.5.4.4 Post-condition(s)

Upon the completion of the use case, each robot within the subnetwork is expected to execute control tasks correctly in accordance with defined KPIs, including efficiency metrics, task execution accuracy, and safety norms adherence. Transmission errors are kept to a minimum, ensuring high data integrity, while advanced error detection and correction techniques are in place for efficient recovery. The methodology also aims to reduce costs substantially by consolidating Programmable Logic Controllers (PLCs) within edge devices, thereby reducing hardware, maintenance, and upgrade costs. Moreover, this approach significantly enhances operational flexibility by allowing dynamic task assignment based on real-time requirements and quick adaptations to changes in manufacturing priorities. The system design ensures scalability to accommodate additional robots or new subnetworks and reliability for maintaining high production uptime. Security measures are integral to protect against potential cyber threats, ensuring robust protocols to guard against unauthorized access, data breaches, or interference with control functions.

3.5.4.5 KPI Aspects & Potential Requirements

The proposed use case hinges on ensuring ultra-high reliability and low latency communication, alongside the need for high throughput. This combination, referred to as high-throughput URLLC (Ultra-Reliable Low Latency Communications), is a highly anticipated aspect of 6G networks. It presents a considerable challenge due to the stringent requirements and the unprecedented levels of performance required. The scenario becomes even more complex due to its ultra-dense nature, characterized by multiple intra- and inter sub-networks in proximity. This necessitates robust and synchronized interference management strategies to ensure seamless communication. The same degree of sophistication is needed for resource allocation, where resources must be dynamically and efficiently allocated to ensure optimal network performance. Furthermore, the system must exhibit real-time adaptability to accommodate changes in production needs, robot behaviours, or network conditions. This necessitates the design of adaptive control strategies that seamlessly align with network operations, a task that could potentially require an approach to joint control and network design. These challenges underline the complexity of deploying 6G in an industrial setting and highlight the need for advanced solutions and strategies.

For this use case, various KPIs are relevant, such as communication service availability, communication service reliability, end-to-end latency, survival time, transfer interval, and user experienced data rate, as described in Section 1.3.2.

Service performance requirements:

The system must be able to support the following main KPI requirements:

- Communication service availability with a minimum target value of 99.999%
- Communication service reliability with a mean time between failures around 10 years.
- Maximum end-to-end latency less than the transfer interval value of the applications.
- User experienced data rate of at least 10 Mbits/s
- Transfer Interval of 100 µs with minimal jitter (± 0.5 µs)
- Survival time of 100 µs
- Up to 20 UEs simultaneously supported

3.5.5 Subnetwork Segmentation and Management

3.5.5.1 Description

Information technology (IT) and operational technology (OT) infrastructure can be complex, and one needs to adhere to strict IT security requirements to prevent the adverse impact of attackers and misuse. In principle, the IT infrastructure security is realized through horizontal and vertical segmentation, or, in other words, through defence by depth and security zones [16].

Vertical segmentation, or defence by depth, is realized by multiple security layers starting from the Internet (unprotected) to multiple manufacturing layers to the segment related to elements requiring the highest security standards, e.g., a production machine. The smallest entity or zone can be related to one manufacturing cell or a single robot, which themselves are comprised of several components such as a PLC, and sensors and actuators. In addition to vertical segmentation, horizontal segmentation provides isolation between different parts of the factory or production IT environment, i.e., in the physical and logical sense, that do not depend on each other in very short time cycles and can, therefore, communicate through dedicated services that operate at higher zones. Zones can comprise different machines of separate value streams, entire production lines, or segments that provide services to multiple machines in lower zones (at lower security layers).

Through the combination of defence by depth and zones, many different IT architectures can be implemented and usually they are specifically tailored to the type of production or manufacturing. Moreover, conduits are realized to allow well-defined communication only between pre-defined nodes to enable communication between zones only for a certain purpose, further adding to the complexity of the IT infrastructure.

The concept of segmentation with zones and conduits needs to be considered during the design, setup and management of subnetworks. This holds especially true in the context of swarm production, where different manufacturing machines perform ad-hoc actions to achieve a certain, temporary production goal. In such a case, zones may be reconfigured dynamically, which includes managing the assets and their segments, like adding a component to a segment and removing it from another one, or managing and configuring the segments themselves.

In this regard, this use case can be comprised of all other use cases, while it focuses on the security and management aspects on a higher abstraction layer, in particular at functional requirements rather than performance requirements compared to the other use cases.

3.5.5.2 Pre-condition(s)

There is a certain target factory layout with a physical and logical plan of factory assets incl. sensors, actuators, robots, PLCs, machines, etc. A subset of these assets needs to be put together in the form of a subnetwork as they will jointly perform a production target along a value chain.

3.5.5.3 Operation Flow

1. A user creates a new instance of a new subnetwork and configures it.
2. A user adds 3GPP-based assets to the subnetwork and configures the communication relationships for each pair in this group as well as between these assets and other assets outside of this subnetwork through another external tool with appropriate APIs.
3. A user adds non-3GPP assets to the subnetwork and configures the communication relationships. This could be a special case, in which the asset has no cellular connectivity but

used a different non-3GPP access technology to establish communication links. This could include WLAN, Ethernet and others, and might involve corresponding inter-working functions.
4. A user adds a soft PLC as a software instance on a compute node to the subnetwork.
5. A user activates the subnetwork so that all necessary network functions are instantiated, e.g., at the subnetwork AP.

3.5.5.4 Post-condition(s)

The subnetwork and all assets are fully operational, and all security requirements are fulfilled.

3.5.5.5 KPI Aspects & Potential Requirements

The challenges for the design and manageability of subnetworks in the context of manufacturing IT security and factory asset management can be summarized as

1. Flexibility of the subnetwork architecture:
   The subnetwork architecture should be flexible enough to realize any possible setup of a combined horizontal and vertical segmentation with intra- and inter-subnetwork communication and where also non-3GPP end devices are supported.
2. Performance:
   Sufficient wireless performance (see other industrial use cases) for temporary communication with a certain purpose between nodes in different zones / subnetworks (whitelisting) needs to be ensured while security and isolation is guaranteed at the same time.
3. Manageability:
   Due to the potentially very large number of subnetworks in a factory, managing them can become complex and expensive. Appropriate management and exposure functionalities need to be provided.

From the operation flows and challenges above, industrial subnetworks need to fulfil several functional requirements. First and foremost, the overall system shall enable easy and efficient manageability of subnetwork membership of nodes within and across subnetworks, also by third parties incl. the user (factory personnel), which includes adding, configuring, and removing of nodes and subnetworks. This necessitates exposure of node and subnetwork management functionalities towards an OA&M and third-party applications, as well as manageability (enabling and disabling) of intra- and inter-subnetwork communication relationships on a per-node/group basis, with the possibility to also realize nested subnetworks.

Regarding security, secondary authentication support is required, which ideally should be subnetwork specific. Security for insecure IT end devices with limited encryption capabilities is important, as many sensors and actuators have very limited capabilities for application-level security.

Due to the flexibility requirements of future industrial networks, multi-subnetwork membership of a node and the integration of non-3GPP nodes, such as nodes that are connected via Ethernet or WLAN, into a subnetwork, i.e., integration with respective interworking functions, become important. Furthermore, servers and compute nodes (SW instances) as parts of a subnetwork should be supported, while network functions should be instantiated efficiently per subnetwork, i.e., efficient usage of resources for these network functions, e.g., at the subnetwork AP.

3.6 Possible Industrial Sub-Categories

As highlighted already in Section 3.1, the different use cases follow a somewhat hierarchical order, in which the terms 'In-X entity' and 'device' have different meanings. Table 7 gives an overview of the hierarchical levels in the form of industrial sub-categories according to the (semi-)static vs. dynamic formation of subnetworks and small vs. large spatial footprints.

Table 7: Hierarchical Setup of Industrial Sub-Categories and Use Cases

Industrial sub-category	**Communication area (up to)**	**In-X entity**	**Device/Node Examples**	**Use Cases**
A – Static setup / Small footprint	Extreme short-range, e.g., within 2 m x 2 m x 2 m	Robot, machine, or production cell	Sensors, actuators, PLCs	Robot control, Unit test cell
B – Dynamic setup / Small footprint	Between the areas of sub-categories A and C	Machine or production cell	Sensors, actuators, PLCs, HMIs, cameras	Visual inspection cell
C – Dynamic setup / Large footprint	10 m x 10 m x 5 m (per subnetwork)	AGV group, production line, material/asset supermarket	AGVs, robots	Robot swarms
D – Managemen t / Static and dynamic setups	25 m x 10 m x 5 m (per segment), with nested subnetworks, e.g., production cells	Production line (e.g., with 20 production cells), factory network segment (e.g., with up to 10 production lines)	Sensors, actuators, PLCs, HMIs, cameras, AGVs, robots, machines	Factory asset management

3.7 6G Challenges and 6G-SHINE Technology Components Related to Industrial Subnetwork

We have seen that industrial use cases impose very stringent requirements on industrial subnetworks, which include KPIs targeting extremely low latency, cycle times and transfer intervals, as well as very high reliability. In addition, the broad variety of in-X entities (see Table 7), ranging from small-footprint robots to highly dynamic formations of AGV or robot swarms to entire production lines, necessitates architectural and management capabilities far beyond what exists in current wireless networks.

The following 6G-SHINE's Technology components (TCs) (see Table 8) are identified as relevant to address the above challenges.

Table 8: Technical Components (TCs) Addressing the Use Case Challenges

Technology component (TC)	**Use cases**	**Explanation**

TC1. In-X data traffic models	Robot control, Unit test cell, Visual inspection cell	Traffic models can be derived based on previous experience and new measurements in industrial lab facilities.
TC2. Channel models for in-X scenarios	Robot control, Visual inspection cell, Robot swarms	Channel models will be derived upon measurement campaigns in industrial lab facilities. Also measurements for RIS will be performed.
TC3. Sub-THz system models	Robot control, Visual inspection cell	Developed sub-THz system models can be applied for providing reliable low latency links in line of sight conditions.
TC4. Ultra-short transmissions with extreme reliability	Robot control, Unit test cell	Support of fast communication cycles (with duration below 100 µs) require physical layer enhancements beyond 5G
TC5. Analog/hybrid beamforming/beamfocusing	Robot control, Unit test cell, Visual inspection cell	This TC can be used in case antenna arrays can be installed in the plant to control robot parts. It might be more suited at high frequencies (e.g., sub-THz) as small factor arrays are possible.
TC6. Jamming-aware native PHY design	Robot control	Relevant for critical control operations – including life-critical operations- which cannot be interrupted
TC7. RIS enhancements	Robot control, Unit test cell, Visual inspection cell, Robot swarms	Relevant in case a RIS can be installed in proximity of robots and machineries, to control propagation environment and counteract blockage effects
TC8. Intra-subnetwork macro-diversity	Robot control, Unit test cell, Visual inspection cell, Robot swarms	Relevant for those subnetworks featuring multiple Aps that can be used for providing redundant radio link for enhancing reliability
TC9. Flexible/full duplex scheduler	Robot control, Unit test cell, Visual inspection cell	Relevant for subnetworks supporting different traffic types, e.g. control loops with different cycle duration, or multiplexing of low data rate traffic (e.g. control loops with small packets), with high data rate video feeds
TC10. Predictive scheduler	Robot control, Unit test cell, Visual inspection cell	Relevant for control applications featuring traffic with a predictive pattern. The usage of predictive schedulers allows for improved promptness, and reduces signalling overhead
TC11. Latency-aware access in the unlicensed spectrum	Robot control, Unit test cell, Visual inspection cell, Robot swarms	Relevant for unlicensed spectrum operations, when services with deterministic latencies are to be supported (e.g., control loop)
TC12. Centralized radio resource management	Robot control, Visual inspection cell, Factory asset management	Relevant for industrial subnetworks in the coverage area of a 6G enterprise network, that are able to signal to the enterprise network information on the locally experienced channel quality and interference levels.
TC13. Distributed/hybrid radio resource management.	Robot control, Visual inspection cell	Relevant for those subnetworks with sporadic or no connection with an enterprise network.

TC14. Jamming detection and mitigation	Robot control	Relevant for critical control operations – including life-critical operations, that cannot be interrupted.
TC15. Hybrid management of traffic, spectrum and computational resources	Visual inspection cell, Robot swarms	Relevant for subnetworks handling diverse traffic types, where the non-critical traffic can eventually be offloaded to an edge cloud or central cloud server
TC16. Coordination of operations among subnetworks in the same entity	Subnetwork Segmentation and Management	Relevant for architecture and the overarching management and coordination of multiple, nested, subnetworks in a factory environment.

4 IN-VEHICLE SUBNETWORKS CATEGORY

In-vehicle networks are necessary to exchange data between sensors, actuators, control units, and computing systems. Due to the critical timing, reliability, and safety requirements of automotive functions and services, in-vehicle communications nowadays mostly rely on cable links. Cabled communications entail careful planning and an increase in the weight of vehicles. The shift towards software-based Connected and Automated Vehicles (CAV) and Electric Vehicles (EV) increases interactions between in-vehicle functions and places higher demands on in-vehicle networks that should be able to support increasing levels of reconfigurability in software-defined vehicles. Adapting cabled-based in-vehicle networks to meet evolving needs might be challenging since cable harness is designed with specific configurations and limited flexibility, making it harder to accommodate new needs. Replacing cables with in-vehicle wireless links could facilitate the evolution of in-vehicle networks and enable the incorporation of new functionalities through the vehicle's lifespan, in addition to reducing the vehicle's weight and reducing fuel or battery consumption. However, this must be done without compromising the automotive service levels, and in particular reliability and safety.

6G-SHINE focuses on designing and developing key technology components for short-range, flexible, and low-power subnetworks that could be implemented in vehicles to facilitate a transition towards more pervasive in-vehicle wireless networks. 6G-SHINE solutions will also benefit from their integration into the 6G 'network of networks, enabling seamless connection to the cloud. In this context, this section identifies use cases and scenarios of interest where wireless links can be employed for communication between in-vehicle elements (sensors, actuators, and control and computing units) and 6G network elements (edge, cloud). The selection of use cases is technology-oriented given the large timespan of development of vehicular platforms and the objective to provide a comprehensive set of options for future flexible in-vehicle network designs.

4.1 STATUS QUO ON IN-VEHICLE NETWORKS AND E/E ARCHITECTURES

In-vehicle networks and Electrical/Electronic (E/E) architectures that connect sensors and actuators with ECUs are evolving from flat or distributed CAN-based networks to hierarchical networks [19][20][21] (see Figure 13). Traditional E/E architectures incorporate one ECU for each in-vehicle electronic function with a very specific control task, and a direct interconnection among them (see Figure 14.a). This approach requires new ECUs and interconnections when new sensors or actuators are required. However, the large increase of electronic functions introduced in vehicles to support driver assistance systems challenges the scalability of traditional E/E architectures.

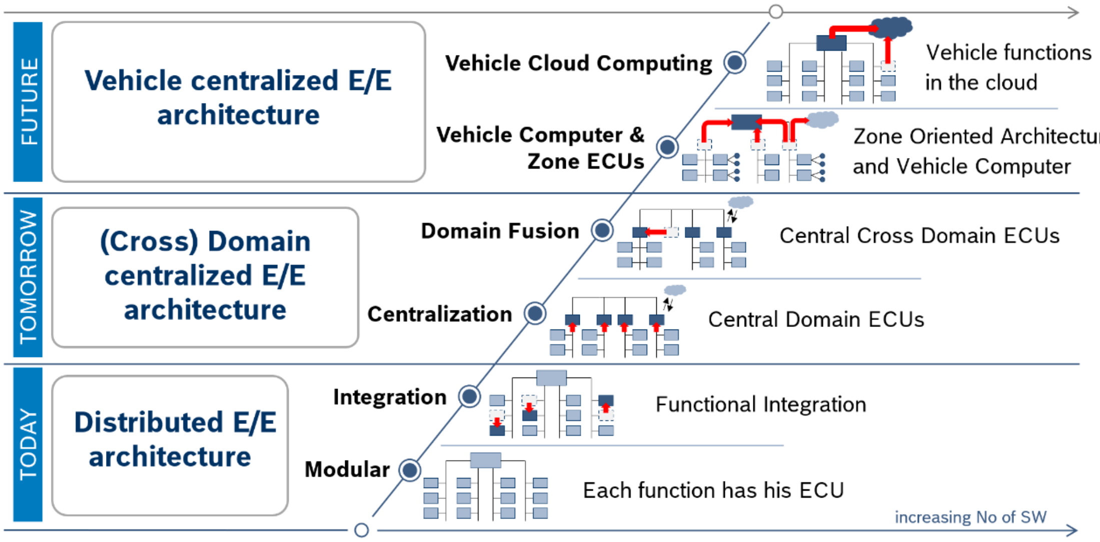

Figure 13. Evolutionary Trends in E/E Architecture Development (figure taken from [22])

4.2 In-vehicle evolutionary trends

A first evolution of in-vehicle networks includes domain-based E/E architectures (see Figure 14.b) and it is motivated by the growing number of automotive applications that require interconnecting functions with increasing demands. High bandwidth data flows and lower and deterministic latency requirements (see Integration and Centralization in Figure 13) are typically required from relevant applications. In domain-based E/E architectures, ECUs group sensors and actuators based on functionalities or domains (e.g., infotainment, powertrain, assisted driving, etc.). This logical definition of the E/E architecture simplifies the design of ECUs and in-vehicle networks that need only to handle the traffic and address the requirements of one domain.

In the domain-based E/E architecture, the interconnections between sensors and actuators that are in different physical locations of the vehicle are managed by domain-specific technologies such as CAN, FlexRay, Local Interconnect Network (LIN), Media Oriented Systems Transport (MOST), or Automotive Ethernet, attending to the specific requirements of each domain. As a result, different cables need to be routed through the vehicle to interconnect all the sensors and actuators of each domain. In addition, the domain-based E/E architecture relies on cross-domain communication via a central gateway/controller to interconnect domains and the functionalities they support. The disassociation between the logical/functional and physical distribution of sensors and actuators within the in-vehicle network is the main drawback of the domain-based E/E architecture. This challenges the scalability of domain-based E/E architectures from the architecture and topology (and cable cost) point of view considering the increasing number of sensors and actuators that are to be integrated into in-vehicle networks with the softwarization of vehicles and the gradual introduction of AD functions.

AD will not only challenge the design of future E/E architectures but also the in-vehicle networking and communication infrastructure required to simultaneously support control loop applications with strong real-time and bounded requirements, applications with higher bandwidth demands but relaxed timing constraints (e.g., software updates or multimedia streaming) and AD functions supported by high-resolution sensors requiring high data rates, and strict reliability and timing.

"Zonal network" E/E architectures (see Figure 14.c) represent an alternative evolution to increase efficiency while the complexity and functionalities of vehicles expand as we progress to AD. Zonal E/E architectures group embedded devices and electronics by physical location rather than logically or per domain (Domain Fusion and evolution towards Zone ECUs in Figure 13). Defining zones within the architecture of the vehicles which have their own ECU or zonal gateway controller increases the flexibility, performance, and scalability compared to the domain-based E/E architecture. ECUs distribution changes from logical functionality or domain to physical zone inside the vehicle, solving the scalability issues identified in domain-based E/E architectures. The zonal E/E architecture locally connects sensors, actuators, and functions to zonal ECUs or gateway controllers that are physically and strategically distributed within the vehicle. This also reduces the cable length compared to the domain-based E/E architecture [23].

The zonal E/E architecture helps in addressing some of the limitations of the domain-based E/E architecture, but it also brings new challenges to overcome. In domain-based E/E architectures, each ECU is only in charge of handling the traffic and requirements of sensors and actuators of one domain. A zone ECU needs to support sensors and actuators that are physically placed in the same area but belong to different functionalities and domains (Domain Fusion). This implies that zonal ECUs need to handle mixed traffic of different functionalities and with different requirements. The evolution towards zonal E/E architectures increases the design complexity of ECUs with the support of heterogeneous and cross-domain functionalities, which are distributed and must be synchronized across several vehicle zones. With the aim to address these challenges, the zonal E/E architecture relies on a high-speed automotive Ethernet backbone to connect zonal ECUs together, as well as to the vehicle's central brain platform/server, that is referred to as HPCU or Vehicle Computer. The HPCU has advanced processing (and Artificial Intelligence) capabilities and is in charge of doing the necessary processing of complex vehicular functions [24].

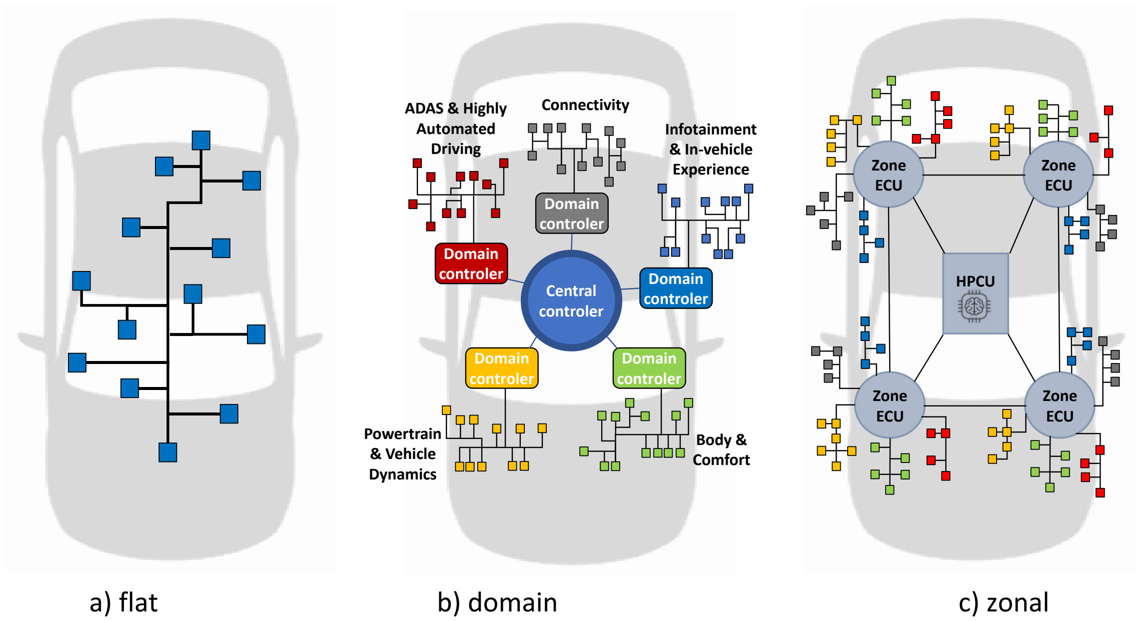

Figure 14. Evolution of vehicular E/E architectures

The evolution of the zonal E/E architecture continues, with a noticeable trend towards a more centralized and zone-oriented E/E architecture [24][25]. This evolution is characterized by the centralization of data streams using a reduced number of HPCUs that are strategically distributed throughout the vehicle. This contrasts with the many individual ECUs that are utilized in former E/E architectures for control and data processing. The centralized, zone-oriented E/E architecture envisions that zonal ECUs perform limited processing for automotive applications or functions. Instead, they collect data generated by sensors and forward them to a central HPCU that does the necessary processing [24]. It is also envisioned that the sensors and actuators have the capability of bypassing the zonal ECUs to directly connect with the HPCU in specific cases. To ensure strict requirements and service levels of automotive applications and functions, the centralized, zone-oriented E/E architecture might rely on a communication network that uses high-speed automotive Ethernet with Time Sensitive Networking (TSN) capabilities [26] for the direct communication between HPCUs and the zonal ECUs, sensors, and actuators.

This evolutionary architecture also considers the integration with the cellular network for over-the-air updates [27] and the offloading of complex functions to the cloud (Vehicle Cloud Computing in Figure 13). In this case, a CCU acts as a gateway between the in-vehicle network and the cellular network unifying the high-processing and AI capabilities on both ends.

4.3 6G-SHINE REFERENCE IN-VEHICLE FRAMEWORK

The description of the 6G-SHINE's in-vehicle use cases provided below takes as a reference the in-vehicle architecture evolutionary trends described in Section 4.2, which are characterized by a centralized, zone-oriented E/E architecture. Without loss of generality, Figure 15 captures a logical representation of such centralized, zone-oriented E/E architecture. Note that this logical representation does not represent a specific zone of the vehicle where the sensors/actuators, zonal ECUs and HPCU are located. It is also not limited by the number of elements (sensors/actuators, zonal ECUs, HPCU) represented in the figure. In addition, Figure 15 does not provide intentionally a complete view of the in-vehicle E/E architecture. On the contrary, the logical representation of the centralized, zone-oriented E/E architecture reported in Figure 15 is intentionally left open and general with the aim of not being restricted to a specific vehicle design.

Figure 15 shows that the sensors and actuators can utilize different cabling technologies (e.g., CAN, FlexRay, LIN, MOST, or Automotive Ethernet; represented by different colours) to connect to a zone ECU. The possibility that the sensors and actuators bypass the zone ECU to connect directly to the HPCU is also represented in the reference E/E architecture shown in Figure 15. If this is the case, it is considered that the cable technology utilized for such interconnections is the high-speed automotive Ethernet link (with TSN capabilities) that is also used between the zone ECUs and the HPCU.

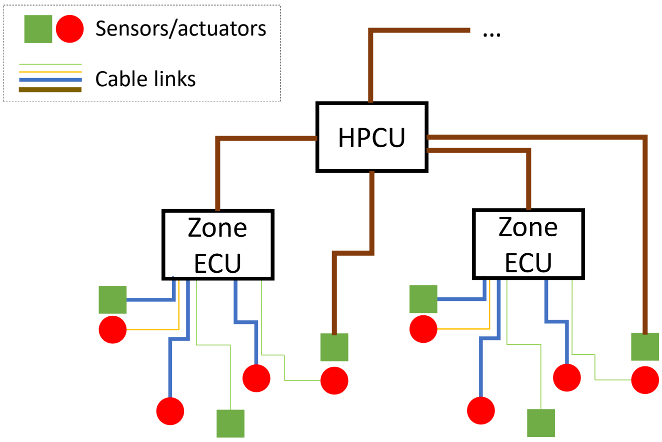

Figure 15. 6G-SHINE reference in-vehicle E/E architecture that captures the evolutionary trends towards centralized, zone-oriented E/E architectures.

4.4 Benefits and challenges of in-vehicle subnetworks

6G-SHINE targets the design of 6G-native in-vehicle wireless subnetworks capable to provide dependable service levels similar to those reached with cables. Despite recent advances in wireless technologies, such as (Beyond) 5G and Wi-Fi 6 developed in 3GPP and IEEE standardizations, respectively, it remains still a significant challenge to deliver wire-equivalent bandwidth and reliable deterministic wireless communications to be used in time-safety critical systems like those implemented inside vehicles.

The 6G-SHINE's in-vehicle subnetworks will also need to efficiently support multiple traffic flows with varying requirements, including deterministic performance which is critical in sustaining AD functionalities, and increasing data rates as AD sensing units (e.g., cameras, lidars, or radars) are integrated into vehicles. To this aim, 6G-SHINE in-vehicle subnetworks will benefit from the native high-processing and AI capabilities available in central controllers or HPCU for their operation and deployment.

In addition, 6G-SHINE in-vehicle subnetworks will benefit from their integration into the 6G network of networks from inception to provide native connections to the cloud. This will foster opportunistic offloading and vehicle-network-cloud cooperation to support advanced functionalities critical for AD and the continuous evolution and advancement of vehicles. These concepts will also be an enabler for a framework for reliable radio resource management supported by the network infrastructure for both, intra- and inter-vehicle subnetwork interference management.

The use of 6G in-vehicle subnetworks will offer the possibility to gradually replace more cabled in-vehicle connections with wireless solutions that are currently limited to those that cannot be reached with cables (e.g., TPMS). This has the potential to reduce the cost and weight of vehicles (increased with the introduction of electric vehicles) and may lower consumption and emissions (e.g., fuel and battery).

In-vehicle subnetworks also target high-reliability designs due to the advancements in autonomous driving and increased integration of sophisticated systems. To achieve this level of reliability, it is essential to utilize redundant connections. 6G-SHINE wireless subnetworks can provide an alternative or complementary solution to address this reliability challenge by providing a combination of redundant in-vehicle wireless and wired connections.

In addition, 6G-SHINE in-vehicle subnetworks will provide additional means to evolve and improve new functionalities over the life of vehicles with the softwarization of vehicles. The introduction of 6G-based in-vehicle subnetworks fuels such evolutions with additional levels of flexibility for in-vehicle connectivity that can overcome potential limitations from cabling planned at the time a vehicle is designed (the lifetime of a vehicle is currently around 12 years).

4.5 KVIs of in-vehicle subnetworks

6G-SHINE aims to assess the social impact and value of the 6G in-vehicle wireless subnetworks across various vertical sector applications, including the automotive industry. Sustainability will be one of our primary concerns. The functionalities and technologies of vehicles are continuously advancing and evolving through the introduction of new connected and automated systems for self-driving and electric vehicles. The adoption of flexible, low-power, and short-range in-vehicle wireless subnetworks will facilitate the update and evolution of in-vehicle networks and architectures, enabling them to adapt to these advancements, thereby extending the lifetime of vehicles and promoting a circular economy (i.e., economic sustainability).

Furthermore, gradually replacing more wired in-vehicle connections with wireless solutions may contribute to reducing the cost and weight of vehicles, as well as to lowering energy consumption (fuel of battery) and CO_2 emissions (i.e., environmental sustainability). In line with the 6G 'network of networks' vision, 6G-SHINE also aims to integrate the in-vehicle subnetworks, which presents new technological opportunities and fosters substantial economic growth and business value. This integration increases flexibility in service provisioning, including the ability to offload complex functions/services to the edge or the cloud and deliver over-the-air updates for device's firmware. By distributing the traffic and computational load between in-vehicle subnetworks and the broader 6G network, optimized resource allocation can be achieved, resulting in an overall reduced energy consumption.

4.6 In-vehicle Subnetworks Use Cases

The following subsections describe the identified in-vehicle use cases. For each use case, we describe the elements that intervene and the automotive functions or services that are represented. We also identify pre-conditions, the operational flow, and post-conditions when the use case is correctly implemented. Finally, we report the main potential key performance indicators and requirements of the use cases.

4.6.1 Wireless Zone ECU: In-vehicle wireless subnetwork zone

4.6.1.1 Description

This technology-oriented use case is aimed at enabling wireless zonal ECUs for the 6G-SHINE's reference, centralized, zone-oriented in-vehicle E/E architecture (see Section 4.3). As it is shown in Figure 16, and without loss of generality, the considered in-vehicle zone is characterized by the presence of sensors and actuators that might support automotive functions and systems from different in-vehicle domains (e.g., ADAS, powertrain, etc.). In the in-vehicle zone, there is also a zone ECU that manages and controls the sensors and actuators that are located in this zone. The zone ECU is connected to the HPCU through the automotive Ethernet (TSN) backbone.

In this context, this use case defines the 6G in-vehicle wireless zone subnetwork that is utilized by some sensors and actuators located in this zone to connect wirelessly to the zone 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. Note that it would also be possible to utilize the wireless interface for high-reliability designs using redundant in-vehicle wireless and wired connections. The zone ECU includes a wireless communication interface and AP capabilities to wirelessly communicate with the sensors and actuators of this in-vehicle wireless zone, and it maintains the wired communication interface(s) that it uses to communicate with the sensors and actuators that are not part of the 6G wireless subnetwork and with the HPCU.

Identifying which cables are replaced by wireless connections will be a critical aspect of this use case. In principle, the 6G in-vehicle zone wireless subnetwork is considered to replace cable links utilized to support demanding and critical information, which justifies the need for a 6G wireless technology. For example, this might be the case of cable links utilized to transfer (raw) sensor data generated by sensors like cameras, radars, or lidars, which are utilized in ADAS-based automotive systems. The introduction of wireless links in in-vehicle networks could also be justified by the necessary flexibility and reliability of in-vehicle networks to adapt to needs demanded by sophisticated systems like AD. Wired connections have been the traditional method for in-vehicle communication due to their stability and robustness. However, the challenge lies in adapting cabled-based networks to keep up with the evolving needs of modern vehicles. By integrating wireless connectivity into the in-vehicle network design, there's an opportunity to increase flexibility and accommodate new technologies more efficiently. Wireless connections can also be introduced for redundancy to increase the in-vehicle network reliability when combined with wired connections.

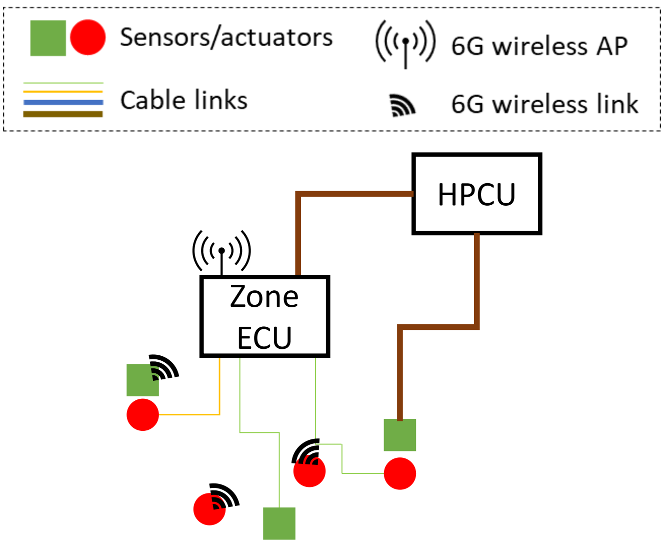

Figure 16. Wireless zone ECU

4.6.1.2 Pre-condition(s)

The 6G-SHINE reference in-vehicle E/E architecture is composed of zonal ECUs located at different zones of the vehicle. These zonal ECUs manage, connect, and control the sensors, actuators, and functions that surround them. The communication networks that connect sensors and actuators with zonal ECUs can be based on different wired technologies, such as CAN, Flex Ray, LIN, MOST, or Automotive Ethernet. The choice of technology depends on the specific requirements of the automotive system or service that is supported by the sensors and actuators in the zone, such as bandwidth/speed, latency, reliability, and determinism.

This use case considers that some of the cable links that connect the sensors/actuators to the zone ECU are replaced by wireless connections and that the zone ECU also takes the role of an AP to manage these wireless links. The zone ECU is connected to the HPCU via an automotive Ethernet cable according to the 6G-SHINE reference in-vehicle EE architecture (see Section 4.3). The wireless connections between the sensors/actuators and the zone ECU form a 6G in-vehicle zone wireless subnetwork.

The sensors located in the zone (e.g., cameras, lidars, radars, etc.) capture data from the environment and transmit it via wired or wireless links to the zone ECU. The accuracy/precision and rate at which sensors operate (e.g., image resolution and frames captured per second in cameras, data density in the point clouds logged by lidars, etc.) depend on their specific functions and capabilities. Sensors of the same type could be synchronized and operate at the same rate. However, it is important to note that not all sensors need to operate with the same accuracy and at the same rate. Some sensors, such as cameras or lidars, may generate data at higher rates to capture a more detailed representation of the driving environment, while others, like temperature or pressure sensors, may provide data at a slower rate since they change relatively slowly. In-vehicle synchronization techniques ensure that the data is generated to be effectively utilized by the vehicle's systems for various tasks such as sensing, perception, planning, decision-making, and control.

The wireless zone ECU is responsible for the effective and timely management of the data generated in its zone in order to guarantee the service levels and the successful fulfilment of the associated in-vehicle functions or services when some of the cables have been replaced by wireless links.

Note: This operational flow focuses on the communication between sensors and actuators with the zone ECU. The case in which sensors and actuators can bypass the zone ECU to communicate directly to the HPCU is covered in the later use cases.

4.6.1.3 Operation Flow

The flow of operation events in the in-vehicle zone can be described as follows:

1. The sensors located in the in-vehicle zone generate data at a specific rate and with accuracy according to the automotive system.
2. The data is transmitted from the sensors to the zone ECU using the wired or wireless communication interface and technology of choice based on the requirements of the automotive system they support.
3. The zone ECU might perform certain processing on the received data, with the extent of the processing being dependent on the specific automotive function or service. However, most of

the processing is carried out in the HPCU, following the operation of the centralized, zone-oriented E/E architecture.

4. As a result of 3, the zone ECU might perform one or a combination of the following actions:
    a. Communicate to an actuator located in this zone the resulting action according to the requirements of the automotive system it provides support to.
    b. Forward the received (and processed) data from the sensors to the HPCU according to the requirements of the automotive system.

4.6.1.4 Post-condition(s)

The zone of the 6G-SHINE reference in-vehicle E/E architecture includes sensors and actuators that are equipped with either (or both for redundancy) a wired or wireless communication interface to communicate with an AP-capable wireless zone ECU. The seamless integration and management of the wired and wireless communications between the zone ECU and the sensors/actuators, and between the zone ECU and the HPCU, guarantee the service levels and requirements of the multiple automotive systems and functions supported in the in-vehicle zone.

4.6.1.5 KPI Aspects & Potential Requirements

The defined wireless zone ECU needs to support the multiple and varying traffic characteristics of the supported automotive systems and domain functions. This might include powertrain control, chassis control, body electronics, infotainment systems, ADAS, telematics, autonomous driving, connectivity systems, and HMI, to name a few. Table 9 summarizes the main characteristics of these vehicle's domain functions as well as their associated KPIs. Wired technologies currently used to support the vehicle's domain functions reported in Table 9 include CAN, LIN, Flex Ray, MOST, Automotive Ethernet, TSN, and Radio Frequency. Table 10 shows the main features and KPIs of such wired networking technologies.

In this context, the KPI requirements for the in-vehicle wireless zone subnetworks emerge from the supported automotive systems and domain functions (Table 9) and the service levels reached with the wired networking technologies (Table 10) are to be replaced. In this specific use case, the requirements need to be restricted for the confined data and command traffic generated in a particular zone of the vehicle.

Table 9: KPIs for in-vehicle networks of the vehicle's domain functions [29]

Domain Function	Main Characteristics	KPIs for In-Vehicle Networks
Powertrain Control	Manages engine and transmission operations	Latency: <1 ms Bandwidth: 2Mb/s Reliability: >99.9% Determinism: Yes Control loop time: µs
Chassis Control	Controls vehicle dynamics and handling	Latency: <1 ms Bandwidth: 2 Mb/s Reliability: >99.9% Determinism: Yes Control loop time: µs/ms
Body Electronics	Controls various electrical systems in the vehicle	Latency: <2 ms Bandwidth: 2 Mb/s Reliability: >99%

		Determinism: Yes Control loop time: ms
Infotainment System	Provides entertainment, information, and connectivity	Latency: <1 ms Bandwidth: 1 Gb/s Reliability: >99% Determinism: Yes Control loop time: ms
Advanced Driver Assistance Systems (ADAS)	Enhances driver safety and assists in driving tasks	Latency: <1 ms Bandwidth: 100 Mb/s Reliability: >99% Determinism: Yes Control loop time: ms
Telematics	Enables remote connectivity and vehicle tracking	Latency: <500 ms Bandwidth: 1 Gb/s Reliability: >99% Determinism: Yes
Autonomous Driving	Enables self-driving capabilities	Latency: <1 ms Bandwidth: 10 Gbps Reliability: >99.9% Determinism: Yes Control loop time: ms
Human-Machine Interface (HMI)	Enables interaction between the driver and the vehicle	Latency: <100 ms Bandwidth: 10 Mbps Reliability:>99% uptime Determinism: Yes

Table 10: *KPIs for in-vehicle wired networking technologies [28][29]*

Networking Technology	**Main Features**	**Speed [Mbps]**	**Determinism**	**Vehicle Applications/Domains**
CAN/CAN FD	Robust, low-cost, widely used, multi-master protocol	<= 1 / <= 6	No / Yes under circumstances	All domains Powertrain control, chassis control, body electronics, …
LIN	Low-cost, simple, single-master protocol	< 0.02	Yes	Body and window control, lighting control, Heating Ventilation and AC control, sensors, motors, …
Flex Ray	"High-speed", fault-tolerant (two-channel), deterministic protocol	<= 10	Yes	Drive-by-Wire systems, Brake-by-Wire, active suspension systems, Advanced Safety and Collision Avoidance Systems, Steer-by-Wire, Stability, powertrain
Ethernet 100BASE-TX	Fast Ethernet	100	No	Diagnostic interface
MOST	High-quality multimedia, low-latency protocol	<= 150	Yes	Premium audio systems, infotainment systems Will be phased-out
Automotive Ethernet (10BASE-T1S, 100BASE-T1,	Automotive-specific Ethernet layer 1	10/100/1.000 2,5/5/10.000	No	ADAS ECUs, multimedia systems, Ethernet backbone networks, sensors, …

1000BASE-T1, 2,5/5/10GBASE-T1)	variants/speed grades			
TSN	IEEE Ethernet layer 2+ standards with real-time capabilities	<= 10.000	Yes	Autonomous driving systems, connected car platforms, in-vehicle systems

4.6.2 Collaborative Wireless Zone ECUs: Functions across multiple in-vehicle zones

4.6.2.1 Description

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 (see Section 4.3). Each in-vehicle zone is characterized by the presence of a wireless zone ECU as defined in Section 4.6.1, which integrates sensors and actuators that might support automotive functions and systems of different in-vehicle domains.

This use case considers the scenario represented in Figure 17 in which two wireless zonal ECUs are interconnected via HPCU. The wireless zonal ECUs might utilize wired and wireless communications interfaces to connect with surrounding sensors and actuators, as well as an automotive Ethernet (TSN) connection to the HPCU. Some examples of the automotive functions represented by this use case include, for example, the rear-view camera application that displays the images captured by a rear-facing camera (located at the rear zone of the vehicle) onto the vehicle's dashboard (located at the front of the vehicle), or the lane departure warning application that utilizes front-facing camera images for lane tracking/detection, and warns the driver with visual, audible and/or vibration warning when the vehicle leaves its lane without signalling it. The front-facing camera in the lane departure warning application is located at the front of the vehicle, the lane tracking/detection can be performed at the HPCU (or at the camera itself), and the warnings are sent to the driver zone.

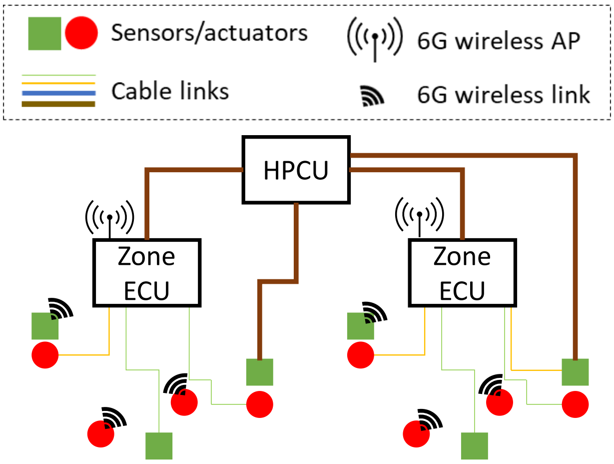

Figure 17. Collaborative wireless zone ECUs.

4.6.2.2 Pre-condition(s)

Based on the 6G-SHINE reference in-vehicle E/E architecture, each wireless zone ECU handles sensors, actuators, and functions of different domains, which are placed in the same physical area. The communication networks that connect sensors and actuators with their wireless zone ECU are based on different wireless and wired technologies depending on the requirements of the supported automotive system or service. Wireless zonal ECUs rely on a high-speed automotive Ethernet backbone network to connect to HPCU with advanced processing capabilities.

This use case covers automotive systems and services that require for their execution the interaction and cooperation between sensors, actuators and processing units located at different in-vehicle zones. For example, the zone ECUs and the HPCU in between the two zones are responsible for managing and processing the data generated by sensors in one zone and producing the corresponding output on time for its execution in actuators located at another zone. The use case also covers scenarios in which automotive systems and services require the processing and computation offloading between in-vehicle zones to guarantee their correct execution.

4.6.2.3 Operation Flow

The flow of operations events in this use case can be described as follows:

1. The sensors located in an in-vehicle zone, or sensors located in different zones, generate (raw) data according to the automotive.
2. The data is transmitted from the sensors to their zone ECU (or directly to the HPCU) using the wired and wireless communication interface and technology of choice based on the requirements of the automotive system they support.
3. When the sensors communicate with the zone ECU, it performs some processing over the received (raw) data while strictly guaranteeing the automotive system and service requirements.
    a. The zone ECU might identify that the execution of the functions and/or the processing of the data needs to be carried out in the HPCU. Then, the zone ECU forwards the received data to the HPCU.
4. The received (and/or processed) data from the sensors at the HPCU (directly or via the zone ECU) is processed or combined/fused.
5. The HPCU sends the post-processing feedback/command/action to the intended actuator managed by a zone ECU located at another zone.

4.6.2.4 Post-condition(s)

The 6G-SHINE reference in-vehicle E/E architecture includes zonal wireless ECUs (as defined in Section 4.3) that communicate between them through a HPCU using an automotive Ethernet backbone connection. The wireless zone ECUs and HPCU seamlessly manage and control the traffic generated by the sensors connected through wireless or wired connections. In this use case, the automotive systems are supported by zone ECUs and HPCU through the collaboration and/or offloading between sensors, actuator, and/or functions located in different in-vehicle zones. The collaboration and offloading between the in-vehicle zones guarantee the service levels of the supported automotive systems.

4.6.2.5 KPI Aspects & Potential Requirements

This use case's KPI requirements also emerge from the automotive functions domain (Table 9) and the cable-based networking technologies (Table 10) that have been utilized traditionally to support them. In this case, the requirements to be considered are those related to automotive functions that necessitate coordination between sensors and actuators situated in various zones of the vehicle.

4.6.3 Inter-subnetwork Coordination: Collaboration between subnetworks in intra/inter-vehicle communications

4.6.3.1 Description

In a fully connected vehicle scenario according to the 6G-SHINE reference in-vehicle E/E architecture, different components communicate with each other through a wireless link. In this environment, the allocation of network resources emerges as a critical factor. This importance is amplified by the demanding nature of automotive application requirements among varying components and the inherent scarcity of network resources. The scenario becomes further challenging when multiple vehicles come into proximity with each other, such as on a busy road. Interference among the wireless subnetworks across these vehicles can potentially degrade the performance of the communication systems within each vehicle.

Consequently, two levels of Radio Resource Management (RRM) become essential:

1. **Intra-vehicular RRM:**
   This optimizes the distribution of network resources among different components of the E/E architecture within a vehicle, ensuring smooth and uninterrupted communication. It also involves managing resources, for example, between different zones or components within the vehicle, as illustrated in Figure 18;
2. **Inter-vehicular RRM**:
   This manages potential interference between adjacent vehicles to prevent any performance degradation. This involves careful resource allocation to mitigate the risk of cross-vehicle interference, which becomes especially important when vehicles are close to each other, as illustrated in Figure 19.

This use case highlights the need for a sophisticated RRM system that can handle both these levels of management efficiently, ensuring optimal performance of the wireless subnetworks in an automotive E/E architecture.

We should note that this use case could be applied concurrently with the other use cases presented for in-vehicle wireless subnetworks.

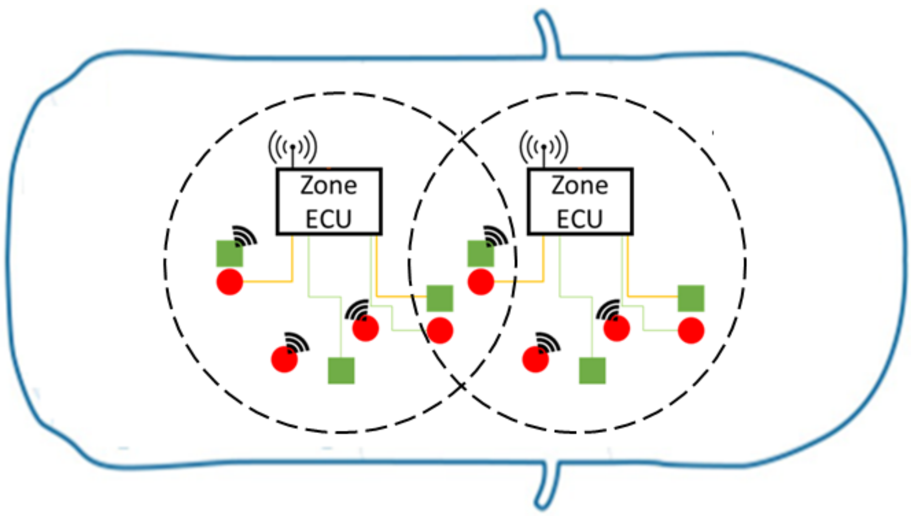

Figure 18. Intra-vehicular RRM within the 6G-SHINE reference E/E Architecture.

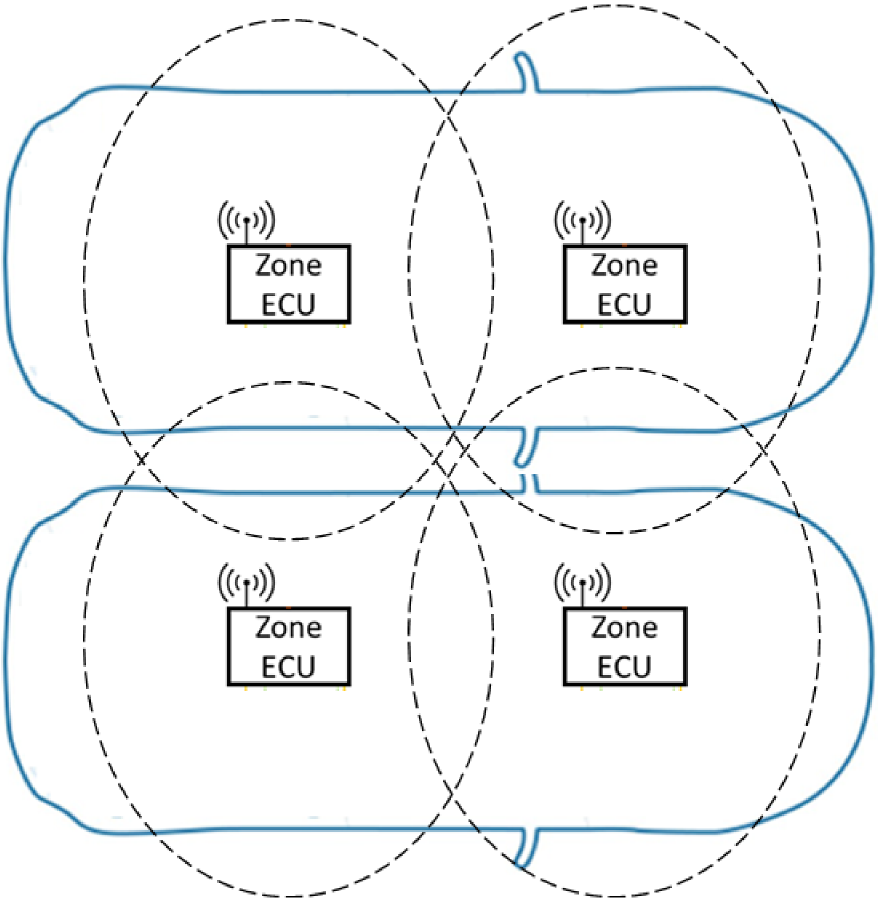

Figure 19. Inter-vehicular RRM between adjacent vehicles.

4.6.3.2 Pre-condition(s)

In this setup, each zone ECU manages sensors, actuators, and other functions within its specific domain, located in the same physical area. The communication networks connecting these sensors and actuators to their respective zone ECUs are based on wired/wireless technology. Each network has a unique set of requirements contingent on the particular automotive system or service they support.

These zone ECUs rely on a high-speed automotive backbone network for connection to HPCU, which provides advanced processing capabilities. This connection could be either wireless or Ethernet-based (or a combination of both for redundancy, see Section 4.4).

Like the ‘Collaborative Wireless Zone ECUs’ use case (see Section 4.6.2), this use case is focused on automotive systems and services that necessitate collaboration and interaction between sensors and actuators located in different in-vehicle zones. However, given the limited wireless network resources available for communication, this use case focuses on the use of these resources which must be meticulously managed.

The zone ECUs and the HPCU positioned between two zones handle the management and processing of data generated by sensors in one zone, producing timely output for actuation in another zone (‘Collaborative Wireless Zone ECUs’ use case in Section 4.6.1). Proper wireless resource management is crucial to ensure that the communication requirements of each entity are successfully met during the vehicle's operation (this use case).

Furthermore, this use case also considers scenarios where adjacent vehicles can cause mutual interference. In such instances, a coordination protocol (either centralized through a 6G parent network or distributed) is necessary to prevent performance degradation. This makes it crucial to develop efficient mechanisms for managing both intra-vehicle and inter-vehicle wireless resources, ensuring optimal performance of the E/E architecture in both single-vehicle and multi-vehicle scenarios.

4.6.3.3 Operation Flow

The sequence of events in this use case is as follows:

1. Sensors within a particular in-vehicle zone generate data, following the specifications of the automotive system they support.
2. This data is wirelessly transmitted from the sensors to the corresponding zone ECU via a wireless communication interface. The choice of wireless resource parameters (such as time/frequency resources, MCS, PMI, TM, etc.) depends on the requirements of the supported automotive system and the need to mitigate potential interference with other entities within the E/E architecture or nearby vehicles.
3. The zone ECU receives and processes the sensor data, generating an actuation command. This command can either be executed locally or sent to another zone ECU for further processing and/or execution. The latter is facilitated via the HPCU using another wireless link.
4. If the command is sent to another zone ECU, the choice of wireless resource parameters to be utilized again depends on the requirements of the application and the need to mitigate potential interference with other entities within the E/E architecture or nearby devices.
5. In scenarios where a nearby vehicle is present, interference management becomes crucial to prevent performance degradation of the wireless connections between the vehicles. This entails implementing a strategy (either centralized or distributed) to manage and minimize interference, thereby ensuring a smooth operation of the wireless links within and between vehicles.

4.6.3.4 Post-condition(s)

Upon successful execution of this use case, the following conditions should hold:

- The zone ECUs and the HPCU operate seamlessly and reliably over wireless connections. Their coordination is critical in managing and processing data within the vehicle's E/E architecture.
- Any potential intra- and inter-vehicle interference is effectively managed, preventing any performance degradation within the E/E architecture. Efficient RRM ensures that wireless resources are optimally allocated, considering the needs of the system and the potential interference from within the vehicle or from nearby vehicles.
- It is assumed that the automotive systems supported by the zone ECUs and HPCU necessitate collaboration among sensors, actuators, and/or functions located in different in-vehicle zones. These collaborations, facilitated by efficient wireless communication and resource management, ensure the service levels of the supported automotive systems are met.
- The integrity of the wireless communication within and between vehicles is maintained, preserving the effectiveness and safety of the overall E/E architecture, even in complex multi-vehicle environments.

4.6.3.5 KPI Aspects & Potential Requirements

Our vision aligns with the KPIs outlined in the Wireless Zone ECU use case (see Section 4.6.1.5). The transition from a traditional networking technology to wireless links must meet specific criteria in terms of speed, distance, and determinism. For achieving this transition, the wireless links must maintain the performance of their wired predecessors. They must offer high-speed connections that support the required distance between components, and ensure deterministic responses, a critical aspect for safety-related automotive applications. Consequently, the implementation of strategic RRM will be key to efficiently managing potential interferences within the wireless network, ensuring optimal performance and system reliability.

4.6.4 Virtual ECU: In-vehicle sensor data and functions processing at the 6G network edge

4.6.4.1 Description

This use case focuses on integrating the in-vehicle network with the 6G parent network, following the 6G 'network of networks' paradigm. The goal is to seamlessly extend the in-vehicle embedded computing capabilities to the edge/cloud. The connection from the in-vehicle network to the edge/cloud is exploited in this use case to enable opportunistic offload and vehicle-network-cloud cooperation to support advanced in-vehicle automotive functionalities critical for AD and the continuous evolution and advancement of vehicles. This way the edge/cloud would act as a virtual ECU (or HPCU) by elastically extending the computing and processing capabilities of the vehicle using the 6G network. This includes, for instance, the possibility to opportunistically offload to the edge or cloud the processing of the sensor data generated in an area supported by the wireless zone ECU (see Section 4.6.1), and some demanding functions like the machine learning inference. This use case also enables the possibility of data collaboration and machine learning operation based on the data from multiple vehicles.

The integration between the in-vehicle network and the 6G network will also facilitate over-the-air updates (OTA), whose demands will significantly increase with the softwarization of vehicles. It will also provide a framework for reliable management of interference and radio resources between in-vehicle subnetworks supported by the network infrastructure, including the possibility of performing dynamic spectrum sharing between a 6G parent network and in-vehicle subnetworks.

This use case utilizes the high capabilities of the in-vehicle HPCU (and CCU) to act as the bridge between the in-vehicle network and the 6G parent network (see Figure 20). In this use case, we will focus on ensuring that offloading processing and functions from the in-vehicle network to the 6G network do not affect service provisioning (including guaranteed bounded latencies and determinism), even if there are changes in the quality-of-service levels within the 6G parent network.

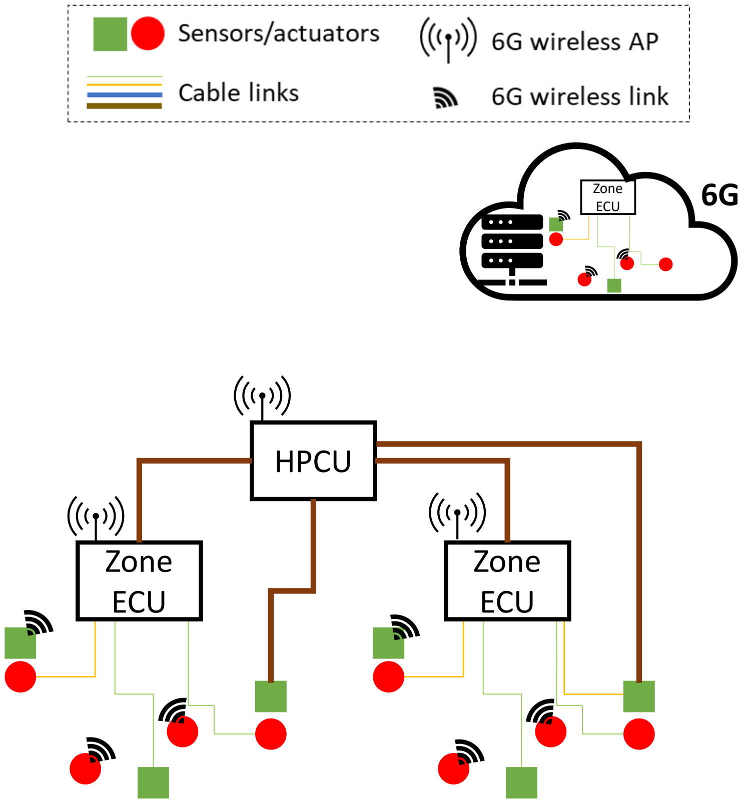

Figure 20. Integration of the 6G in-vehicle network with the 6G parent network.

4.6.4.2 Pre-condition(s)

The 6G-SHINE reference centralized, zone-oriented E/E architecture is network-access oriented. The network access is gained through a CCU –implemented and located closely to the HPCU (and thereby efficiently connected to it)– that acts as a gateway between the in-vehicle network and the 6G parent network. This use case extends the integration with the 6G network to also include the in-vehicle 6G subnetworks. The HPCU performs most of the demanding data and processing functions, and it can proactively or reactively decide to offload (part of) such processing to a computing platform located in the 6G network's cloud/edge.

4.6.4.3 Operation Flow

The flow of operations enabled by the integration between the in-vehicle subnetworks and the 6G parent network include:

1. Sensors located in an in-vehicle zone generate data according to the.
2. The data is transmitted from the sensors to the zone ECU using the wired or wireless communication interface and technology of choice based on the requirements of the automotive system they support.
3. The zone ECU might perform some processing of the data or forward it to the HPCU.
4. The HPCU decides to offload partially or completely the data processing to the edge or cloud computing facilities.
5. The data processing is completed on time and the resulting action, if needed, is implemented by the in-vehicle actuator according to the implemented automotive system.

The operation flow could also be extended for the offloading of critical in-vehicle functions (e.g., machine learning inference) to be implemented at the edge.

4.6.4.4 Post-condition(s)

The 6G-SHINE reference centralized, zone-oriented E/E architecture seamlessly integrates the in-vehicle 6G subnetworks with the 6G parent network. This enables opportunistic and on-demand off-boarding sensor data processing and functions while satisfying the service levels, including deterministic ones, of the supported automotive system.

4.6.4.5 KPI Aspects & Potential Requirements

This use case's requirements still emerge from the automotive functions and domains reported in Table 9 which are currently supported using the wired networking technologies shown in Table 10. However, this use case seeks fulfilling the requirements of these automotive functions and domains despite part of the processing and/or computation, which is traditionally carried out in the vehicle can be offloaded to the edge or cloud. The use case also considers automotive functions that will arise from the integration of the in-vehicle subnetworks within the 6G 'network of networks' (e.g., OTA, digital twining), and whose requirements will need to be supported without compromising the service provisioning in the connectivity continuum subnetwork-edge-cloud.

4.7 6G Challenges and 6G-SHINE Technology Components Related to In-Vehicle Subnetwork

The in-vehicle networks will need to support a growing number of automotive applications with varying requirements that require interconnecting cross-domain functions and collaboration between sensors and actuators physically located in different zones of the vehicle. These are raising demands on in-vehicle networks with high bandwidth data flows and lower and deterministic latency requirements. The demands will significantly increase with the softwarization of vehicles and the gradual introduction of AD functions. This challenges the integration of 6G wireless technologies in vehicles to replace cable-based connections used in time-safety critical automotive systems. The stochastic nature of wireless communications makes it difficult to achieve time-critical and strict service level capabilities (e.g., determinism/TSN) that are interoperable and compatible with wired capabilities.

The evolution of in-vehicle networks is directly related to the rising demands of increasingly sophisticated automotive applications. These applications would require in-vehicle wireless networks capable of handling high-bandwidth data flows and lower, deterministic latency requirements. The ongoing trend of vehicle softwarization and the gradual integration of AD functions are expected to significantly amplify these demands.

The following 6G-SHINE's Technology Components (TCs) are identified as relevant to address the above challenges, see Table 11.

Table 11: Technical Components (TCs) addressing In-Vehicle category use case challenges

Technology component (TC)	Use cases	Explanation
TC1. In-X data traffic models	• Wireless Zone ECU • Collaborative Wireless Zone ECU	In-vehicle data traffic generated by sensors (e.g., camera, lidar, radar, etc.) in a zone and between zones will be collected from an emulation platform for its

		characterization (e.g., spatial-temporal correlations) and for determining its requirements.
TC2. Channel models for in-X scenarios	• Wireless Zone ECU • Collaborative Wireless Zone ECU • Inter-subnetwork Coordination • Virtual ECU	In-vehicle channel model will be derived based on radio propagation measurements inside vehicles. Measurements will also cover propagation from outside to inside the vehicle. The use of RIS could also be covered in the measurement campaign.
TC3. Sub-THz system models	• Wireless Zone ECU • Collaborative Wireless Zone ECU	The in-vehicle subnetwork wireless link can benefit from the high-bandwidth, reliable, and low latency sub-THz communications.
TC4. Ultra-short transmissions with extreme reliability	• Wireless Zone ECU	Critical sensors generating non-predictable traffic composed of short packets require ultra-reliable transmissions.
TC5. Analog/hybrid beamforming/beam-focusing	• Wireless Zone ECU	TC.5 might be necessary to support TC.4
TC6. Jamming-aware native PHY design	• Wireless Zone ECU • Collaborative Wireless Zone ECU • Inter-subnetwork Coordination • Virtual ECU	Native robustness to jamming attacks is needed for life-critical in-vehicle services.
TC7. RIS enhancements	• Wireless Zone ECU • Collaborative Wireless Zone ECU • Inter-subnetwork Coordination	Static smart surfaces deployed within the vehicle can create a favourable propagation condition to reduce interference and improve the links' reliability.
TC8. Intra-subnetwork macro-diversity	• Collaborative Wireless Zone ECU	The possibility that the sensors can connect directly to the HPCU brings some macro diversity possibilities, such that the zone ECU can act as a relay, or provide a redundant radio link to the HPCU.
TC9. Flexible/full duplex scheduler	• Wireless Zone ECU • Collaborative Wireless Zone ECU	Flexible/full duplexing capabilities at the AP or zone ECU are of high relevance to multiplex traffic with different requirements from different automotive systems
TC10. Predictive scheduler	• Wireless Zone ECU • Collaborative Wireless Zone ECU	The localized and predictive nature of the traffic patterns generated and demanded in the in-vehicle zone by sensors/actuators can be exploited to anticipate radio resource requests and program scheduling. Traffic prediction can also be utilized to pre-allocate resources in the communication

		path between subnetworks located at different in-vehicle zones, which can be particularly necessary for use cases and links requiring deterministic service levels.
TC11. Latency-aware access in the unlicensed spectrum	• Wireless Zone ECU • Collaborative Wireless Zone ECU • Inter-subnetwork Coordination	In-vehicle wireless subnetworks might operate using licensed or unlicensed spectrum.
TC12. Centralized radio resource management	• Inter-subnetwork Coordination	The integration of 6G in-vehicle networks with the 6G parent network favours the centralized management of radio resources to prevent intra-/inter-vehicle subnetworks interferences.
TC13. Distributed/hybrid radio resource management	• Inter-subnetwork Coordination	Distributed/hybrid radio resource management schemes will be critical for preventing interference among in-vehicle subnetworks at nearby vehicles, in particular when experiencing partial coverage from a 6G parent network or critical functions that might require short reaction times to prevent interference.
TC14. Jamming detection and mitigation	• Wireless Zone ECU • Collaborative Wireless Zone ECU • Inter-subnetwork Coordination • Virtual ECU	Native robustness to jamming attacks is needed for life-critical in-vehicle services.
TC15. Hybrid management of traffic, spectrum and computational resources	• Virtual ECU	6G-SHINE will explore solutions for efficient and dynamic traffic and computational offload between subnetworks and the larger 6G network.
TC16. Coordination of operations among subnetworks in the same entity	• Collaborative Wireless Zone ECU	Adaptive and efficient coordination mechanisms within and across subnetworks will be designed for dependable service levels in-vehicle networks and offloading computational tasks among HCPUs or ECUs when needed or beneficial.

5 SUMMARY

In the previous chapters, the use cases of each category have been described. This chapter provides the summary of these use cases, including the analysis, particularly the possible relevancy among these use cases and/or categories.

5.1 COLLECTION OF THE USE CASES

We have identified 13 use cases in three categories. The consumer subnetwork category has 4 use cases in which the use cases are representing different purposes and applications, such as education, gaming, and navigation. There are 5 and 4 use cases for the industry and in-vehicle subnetwork categories, respectively. In these categories, the use cases are identified with a different approach than the consumer subnetwork. The use cases are represented using a bottom-up approach, starting from the subnetwork in a single entity or zone to a complex one that consists of multiple entities or zones. The use cases titles and short descriptions are provided in Table 12.

Table 12: Summary of the use cases and short descriptions

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 unison, 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 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.
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.

5.2 Deployment Scenarios

The high-level descriptions of deployment scenarios for the use cases in each category have been described in the previous chapters. The analysis of various deployment scenarios is described in this section. We consider the deployment scenario aspect to be essential, especially for the channel modelling development which can be specifically applied to a deployment scenario. It can also be essential for finding the technical solutions and/or technology component development which can be dependent on a specific deployment scenario or can also be applied (independent) to any deployment scenario.

Firstly, we classify the use cases based on the deployment scenario whether indoor or outdoor, summarized in Figure 21. We identified that some use cases that are typically operated in indoor environments. It can be operated in a small size of indoor environment (for example in a room, or classroom). There can be an AP in a small room communicating with the devices attached to the user(s) or placed in the intended location. The other scenario is the operation in a big hall, such as a factory hall, that is typically applicable to an industry subnetwork. Within a big hall, there can be multiple AP(s) either in the robot itself or located in a strategic location. One AP can be more active than the others depending on the operation around it. Considering it will be deployed in an industrial environment, there could be many metal objects that can increase the non-line of sights (NLOS) components of the radio link.

Furthermore, some other use cases are typically operated in outdoor environments. The operation in an outdoor environment would need to consider the reflection that may occur due to the surrounding objects (e.g., buildings, trees, cars, moving objects, etc). However, there may be a special case for the in-vehicle subnetwork category. The vehicle may be operated in the outdoor environments. However, the communications between AP and the devices can be limited in a vehicle itself (e.g., within the vehicle's metal chassis).

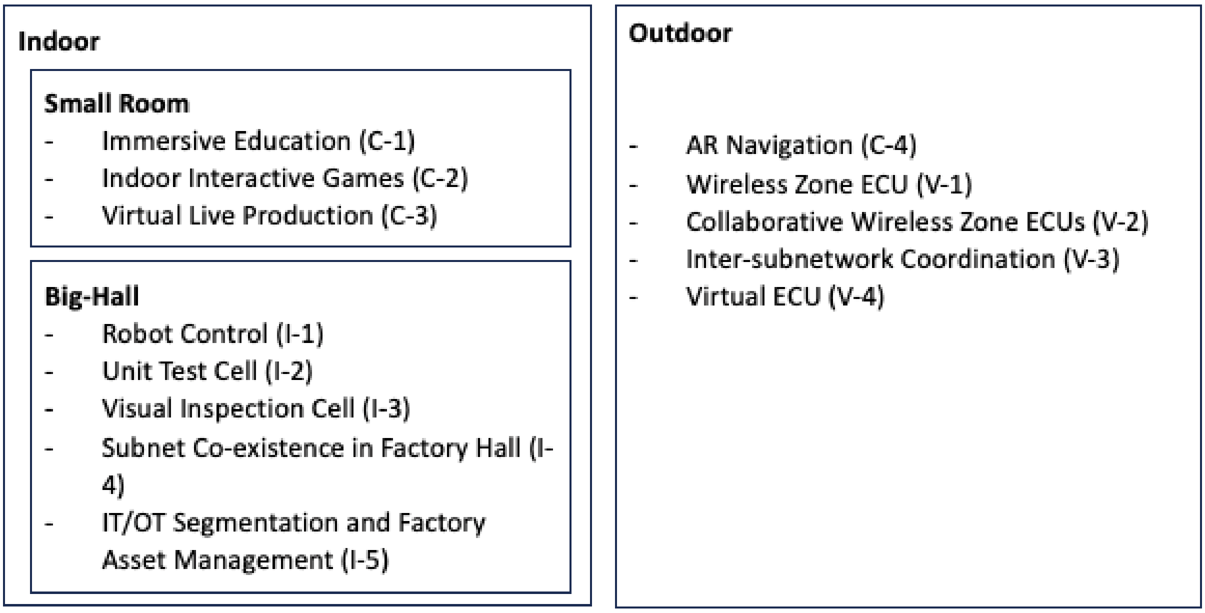

Figure 21. The use cases classification based on deployment scenario indoor/outdoor

Secondly, we also analyse the use cases based on the movement of the device. In this context, the movement of the device is relative to the access point (AP) within a subnetwork that has a maximum range of 10 meters. We have identified the following characteristics:

- Some use cases may have static cases (i.e., zero movement), for example when the sensors are statically placed in a certain location.
- Some use cases have limited movements, particularly when the movement is predictable and within a short distance (up to [4m]).
- Some use cases have dynamic movements, particularly when the movement is unpredictable and within a relatively large distance (up to [10m])

The use case classification based on the movement between AP and devices is illustrated in Figure *22*

Static	Limited Movements	Dynamic Movements
- Wireless Zone ECU (V-1) - Collaborative Wireless Zone ECUs (V-2) - Inter-subnetwork Coordination (V-3) - Virtual ECU (V-4)	- Robot Control (I-1) - Unit Test Cell (I-2) - Visual Inspection Cell (I-3) - AR Navigation (C-4)	- Immersive Education (C-1) - Indoor Interactive Games (C-2) - Virtual Live Production (C-3) - Subnet Co-existence in Factory Hall (I-4)

Figure 22. The use cases classification is based on the movement between AP and devices

Note that in some use cases, it can be a mixture of static, limited movements, and dynamic movements. For example, in indoor interactive games (C-2), there can be some devices with sensor(s) placed in static locations within a room and also some devices (e.g., VR glasses, sensors) attached to the moving users. Furthermore, some use cases may have higher movement than others. Immersive education (C-1) may have lower dynamic movements in comparison to virtual live production (C-3).

5.3 KPI Considerations

We identified the key performance index and its requirements defined in use cases targeting various purposes.

- For the use cases in the consumer subnetwork, the objective is to provide and satisfy user experience. For example, a high data rate and low latency are required to provide an immersive XR experience to the user.
- For the use cases in the industrial subnetwork, the main objective is to maintain the automation process in the production line work as it should and it can be operated in optimal way without interruptions.
- For the use cases in the in-vehicle subnetwork, the functional requirements of the automotive services and functions are mostly to provide safety to the car's users (both driver and passenger(s)). The reliability aspect is utterly important to ensure the system works in all kinds of scenarios.

The identified KPI and its requirements for various use cases have unique characteristics:

- The use cases in consumer subnetworks typically require high data rates and low latency. A certain level of reliability is still needed to minimize possible retransmission which may increase the latency. It has a mixture of KPIs for various links, such as one or more data streams with high data rates (UL/DL video frame) and accompanied by multiple low data rates for sensors. Furthermore, synchronization of multiple streams, such as video, audio, and sensors is required.
- The use cases in the Industrial subnetworks typically require ultra-low latency and high reliability. The data rate is typically low, but it may have a high number of devices connected to an AP. Furthermore, the operation of multiple APs may be needed. Hence, a proper network architecture design is required to ensure the operation of low latency and possible computation offloading from one node to another. Note that use cases where video feeds play a role can also require high data rates.
- The use cases in the In-vehicle subnetwork typically require extreme reliability. The possible multiple links are a mixture of medium data rates (e.g., picture/video captured by camera) and low data rates (e.g., the interactions with sensor(s) and actuator(s)).

5.4 KVI Considerations

The use cases defined in 6G-SHINE assess the key values in the following considerations:

- **Social Sustainability**
  In all use cases, social sustainability is achieved by improving user experience compared to the existing technology. In the consumer subnetworks, the user can educate himself with an immersive experience and participate more actively in the learning session. In the industry and in-vehicle subnetworks, a fully automated system can provide unique ways of operating the equipment.
- **Environmental Sustainability**
  In all use cases, the aim is to reduce carbon footprint (including carbon dioxide and methane) as well as energy consumption. An example of environmental sustainability is the cable replacement with a wireless link which can reduce the usage of cables and reduce the weight of the equipment (vehicle, robot).
- **Economic Sustainability**
  There are several examples of achieving economic sustainability, such as production efficiency improvement in the industry subnetwork category, increasing the vehicle lifetime and circular economy promotion in the in-vehicle subnetwork category, and increasing and creating new services for game and education in the consumer subnetwork category.

5.5 6G-SHINE Technology Components

It has been shown that all the 6G-SHINE technology components can be applied in some of the presented use cases. First of all, TC-1 In-X data traffic models and TC-2 channel model for the in-X scenario can be the starting point for all of the use cases. All use cases require low latency. Hence, TC4 Ultra-short transmission with extreme reliability is needed. Note that the extreme reliability is more crucial for both industry and in-vehicle subnetworks. Some of the use cases may require tailored technology components. For example, the consumer subnetwork deployed in a small room is feasible to be supported with TC3 Sub-THz system models. In another example, the industry subnetwork with multiple subnetworks is expected to require the development of TC16 on Coordination of operations among subnetworks in the same entity. The rest of the examples have been elaborated in the previous chapters.

6 NEXT STEPS

The initial work for the definition of use cases, including the scenarios and assumptions, for the 3 categories considered in 6G-SHINE have been described in this deliverable, along with KPI and KVI aspects. As the continuation of this deliverable (D2.1), we will consolidate the details of use cases, scenarios, and requirements leveraging the input of the advisory board and further insights from our continuous research activities. The potential updates include but are not limited to the overall descriptions of each use case, further considerations on KPIs, particularly on adding specific requirements, further considerations on KVIs, including the possibility of adding new KVIs such as security and trustworthiness, and elaborate the KVI for each use case. Lastly, additional use cases can still be considered depending on our progress.

This deliverable will also be used as a reference to other activities. Within WP2, we will investigate radio propagation characterization and explore network architectures for in-X subnetworks of the selected use cases. The technical components exploration in other WPs (WP3 and WP4) and proof of concept (PoC) development in WP5 will also be based on one or more of the selected use cases defined in this deliverable.

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