ultra-massive MIMO for future cell-free heterogeneous networks - **MiFuture**

KPIs and Requirements

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Executive Summary

The MiFuture project aims to develop a comprehensive 6G wireless communication system that not only delivers higher data rates and lower latency but also adheres to essential design principles and sustainability pillars. The project adopts ten key design principles: service support and exposure, automation and optimization, network flexibility, scalability, resilience and availability, security and privacy, cloud-optimized interfaces, function separation, network simplification, and sustainability. These principles, derived from other SNS-JU projects such as EU 6G flagship Hexa-X-II, ensure that the 6G system, and specifically the 6G Radio Access Networks (RAN), provides high performance and significant value to all stakeholders, including vendors, operators, and end-users.

To evaluate the technological concepts and enablers within the MiFuture project, the focus is on Key Performance Indicators (KPIs) and Key Value Indicators (KVIs). KPIs measure the technical performance of the system, such as throughput, latency, energy consumption, spectral efficiency, coverage, positioning accuracy, and localization accuracy. KVIs, on the other hand, assess the broader value and impact of 6G on society, the economy, and the environment, including total cost of ownership, energy consumption, enhanced coverage, lower downtimes, and security and privacy.

The project addresses specific use cases, including digital twins, multiway virtual meetings with holographic projection, virtual and augmented reality, and teleportation and remote surgery. Each use case has detailed KPI, KVI, and technical requirements, emphasizing the importance of AI/ML, sensing, positioning, security, low latency, and high bandwidth. For instance, digital twins require end-to-end latency in the order of milliseconds, reliability of 99.99999%, and high positioning accuracy. Similarly, holographic projections in virtual meetings demand end-to-end latency of less than 10 ms for split rendering and high bandwidth to ensure seamless and immersive experiences.

Overall, the MiFuture project sets a clear path towards a future where 6G technologies enhance connectivity, drive innovation, and promote sustainability. By integrating advanced technological enablers and adhering to sustainability principles, the project aims to create a 6G system that meets the high-performance demands of modern applications while contributing positively to society.

Contents

1 6G Design Principles and Sustainability

The next generation of wireless communications technologies need to not only provision higher data rates and lower latency, as in previous generations [DAL20], but they also need to adhere to certain design principles that provision their utility for a multitude of use cases as mentioned in [MIF25-D11][HEX223-D12] as well as the associated sustainability pillars [HEX223-D12]. In this chapter, the 6G design principles and the sustainability by design concepts a briefly summarized, which will act as the guiding principle for the project and subsequently the broader scientific community.

1.1 Design Principles

The main 6G architecture design principles, based on those discussed in [HEX223-D21], are as follows:

1. Service Support and Exposure: Enable efficient integration of 6G digital services and expose capabilities to end-to-end applications, enhancing features such as low latency, predictive performance, and compute offloading.

2. Automation and Optimization: Implement full automation using distributed AI/ML agents for network and service management, emphasizing observability, analytics, and intent-based management across multiple domains.

3. Network Flexibility: Adapt to various network topologies and scenarios, supporting digital inclusion and allowing runtime addition of services without disrupting existing ones.

4. Scalability: Design for scalability across different network sizes and deployments, from small to large-scale, utilizing shared cloud platforms and supporting multi-stakeholder deployments.

5. Resilience and Availability: Ensure high resilience through control and user plane separation, resilient mobility solutions, and subnetwork interconnectivity to eliminate single points of failure.

6. Security and Privacy: Address current and future security threats proactively, incorporating fundamental security measures and supporting various levels of privacy and anonymity for future services.

7. Cloud-Optimized Interfaces: Design network interfaces for cloud-native environments, emphasizing service separation for reusability and easy integration.

8. Function Separation: Implement bounded contexts for network functions with API-based dependencies, enabling independent development and efficient scaling.

9. Network Simplification: Streamline architecture to reduce complexity, minimize configuration parameters, and accelerate innovation and market deployment.

10. Sustainability: Justify environmental impact with clear benefits, enable power-saving features for unused functions, and promote modular design for easier upgrades and repairs to extend system lifespan.

These design principles provision the broader guardrails towards developing a 6G system that provisions not only performance but also value to all the stakeholders, i.e., vendors, operators and end-customers.

1.2 Sustainability by Design

One of the main objectives for 6G system design is to adhere to the three sustainability pillars, i.e., social, environmental and economical sustainability [HEX224-D23]. To do so, a shift in how the 6G enablers are selected will be required. Consequently, multiple research efforts have outlined the requirement to consider not just performance-based criteria for selecting technological enablers, but also the extent to which the selection satisfies the three sustainability pillars [HEX224-D23]. To this end, given that in the MiFuture project the focus is on the radio access network (RAN) components, the sustainability pillars and the performance indicators will be considered whenever required to create technological enablers that adhere to sustainability by design principles. Concretely, the enablers under consideration will be challenged and optimized whenever required so that sustainability criteria are always considered as part of the design objective. For more details on sustainability pillars and 6G design, we refer the reader to [HEX223-D11, HEX224-D12, HEX224-D23, 6GIA, VZ].

2 Key Performance Indicators and Key Value Indicators

The various technological concepts and enablers being investigated within the MiFuture project will be examined not just from the lens of performance but also from the aspect of generating value for the stakeholders. Hence, tangible indicator metrics in the form of Key Performance Indicators (KPIs) and Key Value Indicators (KVIs) have been considered in this project. Sections 2.1 and 2.2 present the formal definition of KPIs and KVIs. Additionally, a set of RAN specific KPIs and KVIs, which is not an exhaustive list, have been introduced.

2.1 Key Performance Indicator

KPIs focus on the technical performance of 6G. Specifically, they are quantifiable metrics used to measure the technical performance of a system, network, or technology. Their objective nature helps to evaluate how well a system is functioning.

2.1.1 RAN Specific KPIs

Given that the technological enablers being explored within the MiFuture relate directly to the RAN, in this sub-section the KPIs specific to RAN have been briefly presented.

A. <u>Throughput</u>
   This KPI measures the rate at which data is successfully transmitted over the network. It is typically expressed in bits per second (bps) and indicates the network's capacity to handle data traffic. Higher throughput means better network performance and user experience.
B. <u>Latency</u>
   Latency refers to the time it takes for data to travel from the source to the destination across the network. It is usually measured in milliseconds (ms). Lower latency is crucial for real-time applications such as voice calls, video conferencing, and online gaming, as it ensures minimal delay in communication.
C. <u>Energy Consumption</u>
   This KPI tracks the amount of energy used by the radio access network components, including base stations and antennas. It is an important metric for assessing the network's energy efficiency and sustainability. Lower energy consumption can lead to reduced operational costs and a smaller environmental footprint.
D. <u>Spectral Efficiency</u>
   Spectral efficiency measures how effectively the available spectrum is utilized to transmit data. It is expressed in bits per second per hertz (bps/Hz). Higher spectral efficiency indicates that the network can deliver more data within a given bandwidth, improving overall network capacity and performance.
E. <u>Coverage</u>
   Coverage refers to the geographical area where the radio access network provides reliable service. It is a critical KPI for ensuring that users have access to network services across

different locations, including urban, suburban, and rural areas. Good coverage ensures that users can stay connected wherever they are.

F. Positioning Accuracy
This KPI measures the precision with which the network can determine the location of a device. It is important for applications that rely on accurate location information, such as navigation, emergency services, and location-based services. Higher positioning accuracy ensures better service quality for these applications.

G. Sensing Accuracy
This KPI measures the precision with which the network can detect and measure the location and orientation of surrounding objects (eg clutter and other static or moving objects that surround the mobile of interest)

Commented [S(1]: what about Sensing accuracy? I woud also add Sensing accuracy, with the following description: this KPI measures the precision with which the network can detect and measure the location and orientation of surrounding objects (eg clutter and other static or moving objects that surround the mobile of interest)

2.2 Key Value Indicator

KVIs focus on the broader value and impact of 6G on society, the economy, and the environment. Concretely, these are higher-level metrics that go beyond technical performance and reflect the societal, economic, or sustainability impact of a technology. Thus, they help in assessing the value and impact of 6G beyond just technical measurements.

2.2.1 RAN Specific KVIs

Some of the KVIs that relate to the RAN, but may also be utilized for network-wide assessment of value generation [HEX224-D23, HEX223-D12], are as follows:

A. Total Cost of Ownership
It encompasses all costs associated with deploying, operating, and maintaining the RAN infrastructure over its lifecycle. It includes capital expenditures (CAPEX) for equipment and infrastructure, as well as operational expenditures (OPEX) for maintenance, energy, and staffing. Lower TCO indicates a more cost-effective, and hence, economically sustainable network solution.

B. Energy Consumption
This KVI measures the amount of energy used by the RAN components, such as base stations and antennas. Efficient energy consumption is crucial for reducing operational costs and minimizing the environmental impact of the network. Lower energy consumption translates to higher energy efficiency and environmental sustainability.

C. Enhanced Coverage
This assesses the extent and quality of the geographical area that the RAN can effectively serve. Enhanced coverage ensures that users have reliable access to network services across various locations, including urban, suburban, and rural areas. It is vital for providing ubiquitous connectivity and improved user experience, thus translating to improvement in digital inclusion.

D. Lower downtimes
This KVI tracks the amount of time the RAN is unavailable or experiencing service interruptions. Lower downtimes indicate higher network reliability and availability, which are

critical for maintaining continuous service and minimizing disruptions for users, and hence, also improving trustworthiness of the system.

E. Security and privacy

This evaluates the measures in place to protect the RAN from unauthorized access, cyber threats, and data breaches. It also includes safeguarding user data and ensuring privacy. Furthermore, it includes ensuring explainability for decisions generated by AI/ML method. Strong security and privacy measures are essential for maintaining user trust and complying with regulatory requirements.

3 Use cases and Requirements

With 6G, we are entering an era of unprecedented data rates and throughput, enabling novel use cases and enhancing existing ones through precise sensing, positioning, and cloud-based computations within an intelligent, scalable network. The primary goal is to seamlessly integrate the physical and digital worlds, offering immersive user experiences and industry-wide sustainable solutions through insightful data analysis. This technology facilitates applications ranging from virtual gaming to UAV-based emergency response and rescue operations. Real-time monitoring and solution provision will significantly reduce maintenance costs and prevent hazardous situations. Hence, in this chapter a summary of the use cases presented in [MIF25-D11] and their corresponding KPI, KVI and technical requirements have been presented.

3.1 Digital Twins and the Seamless Interaction of the Physical and the Digital Worlds

Digital Twins (DT) represent the digital counterparts of real-world objects, capturing their characteristics, properties, and dynamics throughout their lifecycle. Utilizing sensors to gather real-time data, DTs process this information mathematically, considering the physical properties of the objects. This real-time input helps mitigate potential issues through continuous monitoring. For instance, in localization, DTs can provide real-time data for automated driving and flying taxis, ensuring safe navigation in dense environments. Similarly, a farmer can use a DT model of farmland to monitor critical parameters and prevent crop damage. Integrating Machine Learning (ML) with DTs allows simulation of future scenarios, aiding in crisis mitigation and fostering sustainable solutions. This interaction relies on reliable wireless sensing, accurate localization, and real-time data processing from embedded sensors, extending information beyond immediate surroundings through network intelligence.

3.1.1 KPI Requirements

The KPI requirements for the digital twin use case, as shown in Hexa-X-II project [HEX223-D12], as follows:

- **End-to-End latency**: It should be in the order of milliseconds
- **Reliability**: It should be 99.99999% for real-time digital twins, while non-real time digital twins can have lower reliability.
- **User Experienced data rate**: The user experienced data rate expectation will be less than 100 Mb/s
- **Connection density**: Typically around 1-10 devices/m^2 is considered
- **Coverage**: A coverage of 99.99% is expected
- **Mobility**: Mobility support of less than 100 Km/h is expected
- **Location accuracy**: Positioning accuracy of less than or equal to 10 m is expected to enrich DT model

- **Sensing and AI/ML capabilities:** It will be important to have these capabilities to enrich the digital twin model as well as the digital twin can itself influence AI/ML models, if any.

3.1.2 KVI Requirements

The KVI requirements for the digital twin use case are as follows:

- Energy efficiency: Reduce power consumption for 6G RAN functions as compared to 5G RAN functions, where possible
- Network Reliability: Identify coverage holes, traffic bursts, edge cases for ML, etc
- Coverage and Economic viability: Improved network planning to improve user experience, and reduce operator CAPEX

Note that, the aforementioned KVIs should be measured with respect to 5G baselines.

3.1.3 Technical Requirements

The main technical requirements for digital twins use case are:

1. Data collection: This is the foundational step in creating and maintaining digital twins. It involves gathering real-time data from various sources such as sensors, IoT devices, and existing databases. This data can include environmental conditions, operational parameters, and physical states of assets. The accuracy and frequency of data collection are critical to ensure the digital twin accurately reflects the real-world counterpart.
2. Data security and privacy: Ensuring data security and privacy is paramount in digital twin implementations. This involves protecting sensitive data from unauthorized access, breaches, and cyber-attacks. Measures such as encryption, secure data transmission protocols, access controls, and compliance with data protection regulations (e.g., GDPR) are essential to safeguard the integrity and confidentiality of the data.
3. Low latency: This is crucial for real-time digital twin applications where instantaneous data processing and response are required. This is particularly important in scenarios like industrial automation, autonomous vehicles, and smart cities, where delays can lead to inefficiencies or safety risks. Achieving low latency involves optimizing network infrastructure and leveraging edge computing to process data closer to the source.
4. High bandwidth: It is necessary to handle the large volumes of data generated by digital twins, especially in environments with numerous sensors and high-resolution data streams (e.g., video feeds, 3D models). Sufficient bandwidth ensures that data can be transmitted quickly and reliably between the physical and digital worlds, enabling seamless updates and interactions.
5. High positioning accuracy: This is is essential for digital twins that rely on precise location data, such as in logistics, manufacturing, and construction. Accurate positioning allows for detailed mapping and tracking of assets, ensuring that the digital twin accurately represents the spatial relationships and movements of its physical counterpart. Technologies like GPS, RTLS, and advanced sensor fusion contribute to achieving high positioning accuracy.

6. AI/ML: Artificial Intelligence (AI) and Machine Learning (ML) play a critical role in digital twins by enabling advanced data analysis, predictive modeling, and automation. AI/ML algorithms can process vast amounts of data to identify patterns, predict future states, and optimize operations. These technologies enhance the digital twin's capability to simulate scenarios, perform diagnostics, and recommend actions, thereby improving efficiency and reducing downtime.

3.2 Multiway Virtual Meeting with Holographic Projection

The shift to remote work and virtual meetings has highlighted the need for a more immersive presence. Holographic projections in virtual meetings address this by capturing 3D visual and audio information through multiple sensors, transmitting it, and reconstructing it as holograms. This technology can create a realistic presence, enhanced by haptic sensors, but requires improved Quality of Service (QoS) and complex edge computing with minimal latency for real-time 3D data encoding and rendering. With proper 6G protocols, immersive holographic calls could become a reality. Current AR devices use SLAM (simultaneous localization and mapping) to map surroundings and anchor content, providing an immersive experience by viewing holograms from different angles.

3.2.1 KPI Requirements

The KPI requirements for the holographic project use case, based on the immersive experience use case in Hexa-X-II project [HEX223-D12], is as follows:

- **End-to-End latency**: It should be less than 10 ms for split rendering, less than 50 ms for voice and less than 150 ms for collaboration
- **Reliability**: It should be 99.9%-99.999% depending on service and data stream.
- **User Experienced data rate**: The user experienced data rate expectation will be less than 250 Mb/s
- **Area traffic capacity**: Typically less than 250 $Mb/s/m^2$ is considered
- **Mobility**: Seamless handover with mobility support for pedestrian users is expected
- **Location accuracy**: Positioning accuracy of less than or equal to 10 m is expected
- **Sensing and AI/ML capabilities:** It will be essential to have sensing and AI/ML capabilities

3.2.2 KVI Requirements

The KVI requirements for the holographic projection use case are as follows:

- Security and Privacy: Increased levels of security and privacy of user data due to physical perception and sharing of information
- Network Reliability: Reduced network outages, lower latency and ability to combat with varying bit-pipe conditions such as TCP slow start, etc.
- Economic viability: The service should be affordable for a wide range of consumers and not just high income consumers

Note that, the aforementioned KVIs should be measured with respect to 5G baselines.

3.2.3 Technical Requirements

The main technical requirements for holographic projection use case are:

1. AI/ML (Artificial Intelligence/Machine Learning): It is crucial for optimizing the rendering and transmission of holographic content. AI/ML algorithms can enhance image processing, predict user movements for more responsive interactions, and optimize network resources to ensure smooth and realistic holographic experiences. These technologies also enable real-time adjustments and improvements in holographic displays, making the experience more immersive and interactive.
2. Sensing: This is essential for capturing the environment and user interactions accurately. High-precision sensors can detect user movements, gestures, and the surrounding environment to enable real-time interaction with holographic projections. This includes the use of cameras, LiDAR, and other sensors alongside 6G to create a detailed map of the physical space, ensuring that holographic content is correctly positioned and responsive to user actions.
3. Positioning: It ensures that holographic projections are accurately placed within the physical environment. High-precision positioning, i.e., 6G which aims to provide centimeter-level accuracy, maintains the correct spatial relationship between the holographic content and the real world. This is critical for applications like augmented reality (AR) where the holograms need to interact seamlessly with physical objects.
4. Security and Privacy: This is paramount to protect the integrity of holographic data and user information. Robust encryption methods, secure data transmission protocols, and privacy-preserving AI techniques are necessary to prevent unauthorized access and ensure that sensitive information is protected. This includes safeguarding the data captured by sensors and ensuring that user interactions remain confidential.
5. Low Latency: It is critical for real-time holographic interactions. Latency needs to be minimized to ensure that there is no noticeable delay between user actions and the corresponding holographic response. This is particularly important for applications like telepresence, gaming, and remote collaboration, where any lag can disrupt the immersive experience. Achieving low latency requires advanced network infrastructure and optimized data processing techniques.
6. High Bandwidth: It is required to transmit the large amounts of data involved in high-resolution holographic projections. Holographic content, especially when it involves 3D models and real-time video, demands significant data throughput to maintain quality and responsiveness. High bandwidth ensures that the holographic content is delivered smoothly and without interruption, providing a seamless user experience.

3.3 Virtual and Augmented Reality

Virtual Reality (VR) immerses users in a completely virtual world, while Augmented Reality (AR) overlays virtual elements onto the real world. With 5G, AR has advanced significantly in gaming and education, exemplified by games like Pokemon Go, which uses accurate tracking and localization to place virtual elements in real-world environments. VR can enhance learning experiences in museums by providing virtual storytelling. The primary challenges for AR and VR are latency and high-resolution streaming requirements. With 6G, AI as a service, higher data rates, and precise localization will offer more personalized and seamless experiences, integrating virtual and real worlds effortlessly.

3.3.1 KPI Requirements

The KPI requirements for the VR and AR use case, based on the immersive experience use case in Hexa-X-II project [HEX223-D12], is as follows:

- **End-to-End latency**: It should be less than 10 ms for split rendering, less than 50 ms for voice and less than 150 ms for collaboration
- **Reliability**: It should be 99.9%-99.999% depending on service and data stream.
- **User Experienced data rate**: The user experienced data rate expectation will be less than 250 Mb/s
- **Area traffic capacity**: Typically, less than 250 Mb/s/m^2 is considered
- **Mobility**: Seamless handover with mobility support for pedestrian users is expected
- **Location accuracy**: Positioning accuracy of less than or equal to 10 m is expected
- **Sensing and AI/ML capabilities:** It will be essential to have sensing and AI/ML capabilities

3.3.2 KVI Requirements

The KVI requirements for the AR and VR use case are as follows:

- Security and Privacy: Increased levels of security and privacy of user data due to physical perception and sharing of information
- Network Reliability: Reduced network outages, lower latency and ability to combat with varying bit-pipe conditions such as TCP slow start, etc.
- Economic viability: The service should be affordable for a wide range of consumers and not just high-income consumers

Note that, the KVIs should be measured with respect to 5G baselines.

3.3.3 Technical Requirements

The main technical requirements for AR and VR use case are:

1. AI/ML (Artificial Intelligence/Machine Learning): It is essential for enhancing AR and VR experiences. AI/ML algorithms can improve image recognition, object detection, and scene understanding, making interactions more intuitive and responsive. In VR, AI can create more realistic virtual environments and characters, while in AR, it can provide context-aware information and real-time object tracking, enhancing the overall user experience.
2. Sensing: This is essential for capturing user movements and environmental data accurately. In VR, sensors such as gyroscopes, accelerometers, and motion trackers are used to detect head and body movements, ensuring that the virtual environment responds accurately to

user actions. In AR, sensors like cameras, LiDAR, and depth sensors capture the physical environment, allowing digital content to be seamlessly overlaid onto the real world.

3. Positioning: It ensures that AR and VR content is accurately placed and aligned with the physical world or virtual environment. In VR, accurate positioning helps maintain the user's orientation and movement within the virtual space. In AR, 6G with its precise location data, will enable digital content to be correctly positioned relative to the user's surroundings.
4. Security and Privacy: These are crucial to protect user data and ensure safe interactions in AR and VR environments. Robust encryption methods, secure data transmission protocols, and privacy-preserving AI techniques are necessary to prevent unauthorized access and data breaches. This includes safeguarding personal data captured by sensors and ensuring that user interactions remain confidential and secure.
5. Low Latency: It is vital for real-time interactions in AR and VR. Any delay between user actions and system responses can disrupt the immersive experience and cause issues like motion sickness in VR. Achieving low latency requires advanced network infrastructure, optimized data processing, and edge computing to minimize the time it takes for data to travel between the user and the system.
6. High Bandwidth: It is required to handle the large amounts of data involved in high-resolution AR and VR experiences. This includes transmitting detailed 3D models, high-definition video, and real-time interactive content. High bandwidth ensures that AR and VR content is delivered smoothly and without interruption, providing a seamless and immersive user experience.

3.4 Teleportation and Remote Surgery

Teleoperation, or remote surgery, allows doctors to perform operations from a distance using high-end cameras and robotic arms, offering greater precision than manual surgery. This application is particularly beneficial in rural and remote areas with limited medical facilities, enabling patients to access specialized care without traveling. Haptic sensors play a crucial role in analyzing tissue textures, requiring networks with very low latency to process complex calculations and provide effective feedback to surgeons. The feasibility of remote surgery depends on the distance from the remote doctor, as latency increases with distance.

3.4.1 KPI Requirements

The KPI requirements for the Teleportation and remote surgery use case, based on the Human-centric services use case in Hexa-X-II project [HEX223-D12], is as follows:

- **End-to-End latency**: It should be less than 250 ms
- **Reliability**: It should be 99.9%-99.99999%.
- **Connection density**: Typically less than 1-10 devices/m^2 is considered
- **Mobility**: Seamless handover with mobility support for pedestrian users or slow moving vehicles is expected
- **Location accuracy**: Positioning accuracy of less than or equal to 0.1 m is expected

- **Sensing and AI/ML capabilities:** It will be essential to have sensing and AI/ML capabilities

3.4.2 KVI Requirements

The KVI requirements for the Teleportation and remote surgery use case are as follows:

- Security and Privacy: Increased levels of security and privacy of user data due to physical perception and sharing of information
- Network Reliability: Reduced network outages, lower latency and ability to combat with varying bit-pipe conditions such as TCP slow start, etc.
- Economic viability: The service should be affordable for a wide range of consumers and not just high-income consumers

Note that, the KVIs should be measured with respect to 5G baselines.

3.4.3 Technical Requirements

The main technical requirements for the Teleportation and remote surgery use case are as follows:

1. Positioning: 6G networks will provide extremely high precision, often down to the centimeter level, which is crucial for remote surgery. Accurate positioning ensures that robotic surgical instruments can be precisely controlled and manipulated in real-time, mirroring the surgeon's movements exactly. This high level of accuracy is essential to avoid any errors during delicate surgical procedures.
2. Low latency: It is is critical for remote surgery to ensure real-time responsiveness. 6G networks aim to achieve latency as low as 1 millisecond, which is essential for transmitting the surgeon's commands to the robotic instruments without any noticeable delay. This immediate feedback loop is vital for the surgeon to perform precise and timely movements, reducing the risk of complications during surgery.
3. Security and Privacy: These are paramount in remote surgery to protect sensitive patient data and ensure the integrity of the surgical process. 6G networks incorporate advanced encryption methods, secure data transmission protocols, and robust authentication mechanisms to prevent unauthorized access and data breaches. Ensuring the confidentiality and integrity of medical data is crucial to maintain patient trust and comply with regulatory requirements.
4. High bandwidth: It is required to handle the large volumes of data generated during remote surgery, including high-definition video feeds, real-time sensor data, and control signals. 6G networks provide significantly higher data rates compared to previous generations, ensuring that all this information can be transmitted quickly and reliably. High bandwidth ensures that the surgeon has access to clear, real-time visuals and data, which are essential for making informed decisions during surgery.

4 MiFuture Technical Enablers: A bridge to Use case requirements

In this chapter, a mapping of the various research topics, i.e., RAN enablers, being investigated by the Doctoral Candidates (DCs) to the technical requirements and hence, the related KPIs and KVIs of the use cases, as presented in [MIF25-D11], has been presented. This is provided in Table 4.1. This table provides a clear understanding of the impact of different research topics on performance and sustainability of 6G networks.

Table 4.1 Mapping of RAN enablers to Technical Requirements, KPIs and KVIs for Use cases

Use cases	KPIs	KVIs	Technical Requirements	MiFuture RAN enablers
Digital Twins and the Seamless Interaction of the Physical and the Digital Worlds	• **End-to-End latency** order of milliseconds • **Reliability**: 99.99999% • **User Experienced data rate**: < 100 Mb/s • **Connection density**: ~1-10 devices/m^2 • **Coverage**: 99.99% • **Mobility**: Mobility <100 Km/h • **Location accuracy**: <=10 m • **Sensing and AI/ML capabilities:** Yes	• Energy efficiency • Network Reliability • Coverage and Economic viability	1. Data collection 2. Data security and privacy 3. Low latency 4. High bandwidth 5. High positioning accuracy 6 7. AI/ML	Channel estimation and tracking aided by positioning UE aspects of ultra-massive MIMO Positioning and tracking of non-connected objects for vehicular safety with mmW frequencies Joint Positioning and Spatial Resource Allocation for Cell Free Systems Non-coherent approaches for ultra-massive MIMO mm-Wave positioning and sensing for aerial-user applications Clutter characterization and cancelation in MIMO sensing Very low complexity implementations of ultra-massive MIMO Machine learning methods for Cell-free systems in 6G networks

Multiway Virtual Meeting with Holographic Projection	• **End-to-End latency:** <10 ms for split rendering, <50 ms for voice and <150 ms for collaboration • **Reliability:** 99.9%-99.999% • **User Experienced data rate:** <250 Mb/s • **Area traffic capacity:** < 250 Mb/s/m2 • **Mobility:** Seamless handover with mobility support for pedestrian users is expected • **Location accuracy:** <= 10 m • **Sensing and AI/ML capabilities:** Yes	• Security and Privacy • Network Reliability • Economic viability	1. AI/ML 2.Sensing 3.Positioning 4. Security and Privacy 5.Low latency 6. High bandwidth	Channel estimation and tracking aided by positioning Waveform design for joint communications and sensing UE aspects of ultra-massive MIMO Joint Positioning and Spatial Resource Allocation for Cell Free Systems Non-coherent approaches for ultra-massive MIMO mm-Wave positioning and sensing for aerial-user applications Very low complexity implementations of ultra-massive MIMO
Virtual and Augmented Reality	• **End-to-End latency:** <10 ms for split rendering, <50 ms for voice and <150 ms for collaboration • **Reliability:** 99.9%-99.999% • **User Experienced data rate:** <250 Mb/s • **Area traffic capacity:** < 250 Mb/s/m2 • **Mobility:** Seamless handover with mobility support for pedestrian users is expected • **Location accuracy:** <= 10 m • **Sensing and AI/ML capabilities:** Yes	• Security and Privacy • Network Reliability • Economic viability	1. AI/ML 2.Sensing 3.Positioning 4. Security and Privacy 5.Low latency 6. High bandwidth	Channel estimation and tracking aided by positioning Waveform design for joint communications and sensing UE aspects of ultra-massive MIMO Positioning and tracking of non-connected objects for vehicular safety with mmW frequencies Joint Positioning and Spatial Resource Allocation for Cell Free Systems Non-coherent approaches for ultra-massive MIMO

				mm-Wave positioning and sensing for aerial-user applications Clutter characterization and cancelation in MIMO sensing Very low complexity implementations of ultra-massive MIMO Machine learning methods for Cell-free systems in 6G networks
Teleportation and Remote Surgery	• **End-to-End latency:** <250 ms • **Reliability:** 99.9%-99.99999% • **Connection density:** < 1-10 devices/m2 • **Mobility:** Seamless handover with mobility support for pedestrian users or slow moving vehicles is expected • **Location accuracy:** <= 0.1 m • **Sensing and AI/ML capabilities:** Yes	• Security and Privacy • Network Reliability • Economic viability	1. Positioning 2. Low latency 3. Security and Privacy 4. High bandwidth	Channel estimation and tracking aided by positioning Joint Positioning and Spatial Resource Allocation for Cell Free Systems Very low complexity implementations of ultra-massive MIMO

Commented [S(2]: I don't see in this table and discissions also the autonomoustransport use case, which is addressed in many DC projects (eg aviation, road transport, etc.)

Commented [AJ3R2]: The use cases are based on D1.1, otherwise we will end up adding many other use cases which have not been listed here or in D1.1.

5 Conclusion

The MiFuture project is poised to revolutionize the landscape of wireless communications by adhering to the foundational principles of 6G design and sustainability. By integrating service support, automation, network flexibility, scalability, resilience, security, cloud-optimized interfaces, function separation, and network simplification, the project aims to deliver a robust and versatile 6G architecture. These principles ensure that the 6G system not only meets the high-performance demands of modern applications but also provides significant value to stakeholders, including vendors, operators, and end-users. Furthermore, the emphasis on sustainability by design underscores the project's commitment to addressing social, environmental, and economic sustainability, ensuring that technological advancements contribute positively to society.

The project's focus on Key Performance Indicators (KPIs) and Key Value Indicators (KVIs) provides a comprehensive framework for evaluating both the technical performance and broader impact of 6G technologies. By addressing specific use cases such as digital twins, multiway virtual meetings with holographic projection, virtual and augmented reality, and teleportation and remote surgery, the MiFuture project demonstrates the potential of 6G to transform various industries. The detailed technical requirements for each use case highlight the critical role of AI/ML, sensing, positioning, security, low latency, and high bandwidth in achieving seamless and immersive user experiences. Overall, the MiFuture project sets a clear path towards a future where 6G technologies enhance connectivity, drive innovation, and promote sustainability.

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7 Acronyms

6G	6^{th} Generation
5G	5^{th} Generation
NR	New Radio
AI	Artificial Intelligence
ML	Machine Learning
KPI	Key Performance Indicators
KVI	Key Value Indicators
DT	Digital Twin
RAN	Radio Access Network
MIMO	Multiple Input Multiple Output
CAPEX	Capital Expenditure
OPEX	Operating Expenditure
TCO	Total Cost of Ownership
Hz	Hertz
Bps	Bits Per Second
AR	Augmented Reality
VR	Virtual Reality
TCP	Transmission Control Protocol
mmW	Millimetre Wave