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

Reference Scenarios

Deliverable 1.1

Grant Agreement Number: 101119643
Project Acronym: MiFuture
Project Title: ultra-massive MIMO for future cell-free heterogeneous networks
Call: HORIZON-MSCA-2022-DN-01
Type of action: HORIZON TMA MSCA Doctoral Networks - Industrial Doctorates
Granting authority: European Research Executive Agency
Project start date: 01/01/2024

VERSION DETAILS	
Original Delivery Date:	31/12/2024
Actual Delivery Date:	31/12/2024
Version:	V1.0
Number of Pages:	61
Status:	Draft
Dissemination level[1]:	PU

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DOCUMENT HISTORY			
Version	**Date**	**Responsible**	**Description**
V0.2	20/12/2024	Lucía de Miguel	First draft of the document

DELIVERY REVIEWS			
Version	**Date**	**Reviewed by**	**Conclusion[2]**
V1.0	8/01/2025	Ana Garcia Armada Akshay Jain	Minor modifications
V1.1	05/02/2025	Supervisory Board	Accepted

[1] PU = Public, SEN = Sensitive

[2] e.g. Accepted, Develop, Modify, Re-edit, Update

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Executive Summary

This document is a comprehensive report about Reference Scenarios on the MiFuture project, which focuses on optimizing the performance and developing ultra-massive MIMO for future cell-free heterogeneous networks. The project is funded by the European Research Executive Agency under the Horizon-MSCA-2022-DN-01 call and involves multiple beneficiaries and partners, including universities and companies across Europe, previously specified.

The traffic handled by mobile communications is estimated to grow at an annual rate of around 55 percent in 2020– 2030, reaching 607 Exabytes (EB) in 2025 and 5,016 EB in 2030. With 5G presumably reaching its limits by 2030, a collective effort to define and set up the new 6G in the next 10 years is demanded.

Advancing towards 6G means, among other challenges, providing Terabit per second Data Rate ubiquitously. To achieve this purpose, the required increase of the spectral efficiency (from 30 b/s/Hz in 5G to 100 b/s/Hz in 6G) will only be possible with an evolution of massive multiple input – multiple output (MIMO), the technique that has provided the unprecedented spectral efficiency of 5G, towards ultra-massive MIMO (UmMIMO), in order to go far beyond current massive MIMO deployments. This evolution should also take advantage of other advances in the radio access network (RAN). In particular, the new open radio access networks (ORAN) paradigm is enabling the mobile network architecture with enhanced flexibility in the design of the RAN, allowing decentralized and collaborative processing, a feature that will facilitate network densification. We envisage scenarios where users may be able to connect to a multiplicity of access points (AP), being served by cell-free architectures, where the boundary of traditional cells is removed for a seamless coverage and quality of service.

However, 6G and UmMIMO development will face a important number of challenges: One of the key challenges is related to the need that newly arising services, as digital twins, have to accurately map the environment. These services will require the new RAN to offer a combination of communications, positioning and sensing, which are services that traditionally have been offered using different networks and techniques. It is refered as communications networks on one hand and radar and navigation on the other. Therefore, synergies between these services are to be strengthened; Equally important are the latency, reliability and data rate requirements of emerging massively data-intensive use cases and applications (such as multiway virtual meeting with holographic projection, virtual and augmented reality, teleportation, remote surgery, etc.), which are clearly beyond the capacity of existing systems. And there is also the need to ensure that the exponential increase of services does not directly translate into higher energy consumption levels, with the subsequent negative environmental impact.

To accomplish the challenges that advancing towards 6G needs facing the stated evolution of mobile communications relies on the combination of several complementary advances at the physical layer (PHY), medium access control (MAC) level (technological challenges) with

those required at the network protocols and architectures (architectural challenges), since there is no one-size-fits-all for such a number of diverse scenarios and requirements. Of the several needed advances, MiFuture focuses mainly on the lower layers. **It** emphasizes a holistic and cross-layer strategy, leveraging native AI as a fundamental tool to reduce complexity and enhance feasibility. This approach aims to ensure practical implementation and scalability, fostering continuous improvement and adaptive network management.

The document outlines several innovative use cases for future networks, including digital twins, multiway virtual meetings with holographic projection, virtual and augmented reality, and teleportation and remote surgery. These use cases illustrate the potential of future networks to transform various industries and enhance user experiences. It also discusses the reference architecture for future networks, including standardization efforts by 3GPP and the O-RAN Alliance, the benefits and challenges of cloudification, and the importance of automation in achieving fully autonomous networks. The document finishes with the reference scenarios classified as Macro (dense-urban), where it emphasizes innovations in spectrum utilization, AI integration, and network design to meet the performance demands of 6G; Small Cells, low-powered cellular radio access nodes that provide coverage for smaller areas to fill coverage gaps, especially in densely populated urban environment and Non-Terrestrial Networks (NTN) , with GEO, MEO, LEO satellites and airborne (Unmanned Aircraft Systems), providing alternative backhaul solutions, supporting disaster relief operations, and enhancing maritime safety.

These reference scenarios illustrate the potential of future 6G networks to transform various industries and enhance user experiences through advanced communication technologies and innovative applications.

Contents

1 Challenges of the Future Networks

Designing future 6G systems involves considering various deployment options, network interfaces, and intent-based autonomy. Simplifying the architecture to limit the number of options can help in the smooth introduction of 6G. One of the key challenges is balancing emergent and intentional architecture. Agile architecture emphasizes collaboration and continuous improvement, which can be difficult to achieve in large systems where upfront design is traditionally used.

Future networks face a myriad of challenges across architectural, technological, and social domains. Architecturally, systems need to adapt to open standards, ensure ubiquitous coverage, and integrate AI natively into their operations. Technologically, ultra-massive MIMO, reconfigurability, and advanced sensing and positioning technologies are at the forefront of innovation. Socially, the focus is on enhancing energy efficiency, achieving high data rates, optimizing spectrum utilization, and ensuring high reliability.

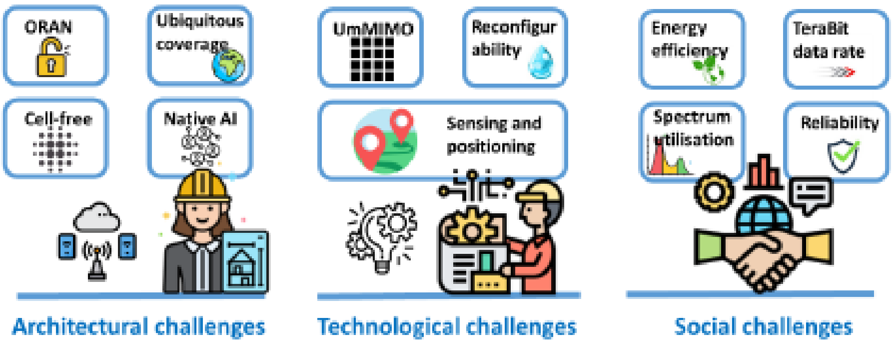

Figure 1:Some of the challenges of future networks

Source: MiFuture Grant Agreement

The current landscape of network research and development is rich with advancements in channel models, hardware and software architectures, and innovative techniques for channel estimation and tracking. Efficient scheduling and resource management, positioning and sensing with ultra-massive MIMO, and the integration of joint communications and sensing are key areas of focus. Additionally, the implementation of artificial intelligence and machine learning continues to drive significant improvements in network performance and capabilities.

The MiFuture development approach emphasizes a holistic and cross-layer strategy, leveraging native AI as a fundamental tool to reduce complexity and enhance feasibility. This approach aims to ensure practical implementation and scalability, fostering continuous improvement and adaptive network management.

Several innovative use cases illustrate the potential of future networks. Digital twins facilitate seamless interaction between the physical and digital worlds, while multiway virtual meetings with holographic projection promise immersive communication experiences. Virtual and augmented reality applications are set to transform various industries, and advanced communication technologies enable groundbreaking developments in teleportation and remote surgery.

1.1 Architectural Challenges

1.1.1 Open Radio Access Network (O-RAN)

Open Radio Access Network (O-RAN) is an innovative architecture that promotes flexibility and interoperability by disaggregation of network functions and supporting multi-vendor environments. Despite its advantages, O-RAN introduces several challenges that need to be addressed. The O-RAN architecture introduces several challenges across four main categories [Abd2022]:

- **End-to-End Security**: O-RANs flexibility and multi-vendor support increase security risks, including misconfiguration, inadequate encryption, and vulnerabilities from open-source software.
- **Deterministic Latency**: Managing latency is complicated by open interfaces and multi-vendor environments. The O-RAN architecture relies on the eCPRI model for delay management, but non-compliant systems can disrupt timing processes.
- **PHY Layer Real-Time Control**: The Near-Real-Time RIC (Near-RT RIC) enhances control but struggles with PHY layer processes due to its timescale. A sub-millisecond Real-Time RIC (RT RIC) is proposed to manage these tasks using AI, while addressing challenges such as computational power and signaling overhead.
- **Testing of AI-Driven O-RAN Functionalities**: AI-driven xApps improve network intelligence but can cause instability if not properly tested. Rigorous testing and validation are essential to ensure AI algorithms handle data variations and maintain performance.

1.1.2 Ubiquitous Coverage

Current communication services are predominantly terrestrial, leaving remote areas and special scenarios without coverage. To achieve ubiquitous global coverage, 6G technology aims to integrate various communication networks, including satellite communications, unmanned aerial vehicle (UAV) communications, terrestrial ultra-dense networks, maritime communications, underwater communications, and underground communications [Sae2019]. This integration will enable seamless three-dimensional (3D) ubiquitous coverage and connectivity, providing a wide range of communication services across different environments [Wan2023].

Despite its potential, the development of space-air-ground-sea integrated networks faces numerous theoretical and engineering challenges. Key issues include [Wan2023]:

- **Communication Channels**: Diverse frequency bands and scenarios complicate channel measurement and modelling. Integrating unique channel characteristics from satellites, UAVs, ocean, and ground scenarios into a comprehensive channel model is essential.

- **Network Architecture and Protocols**: Designing a safe and efficient network architecture that integrates diverse communication systems is crucial. This includes developing efficient, secure, and anonymous authentication protocols, as well as innovative mobility management solutions to ensure seamless transitions between different network types.

    - **Resource Allocation and Routing**: High mobility and dynamic network topology in integrated networks necessitate advanced network protocols, resource allocation strategies, and routing methods.

    - **Energy Efficiency and Maintenance**: Ensuring energy efficiency across all network nodes is critical for the overall efficiency of 5G and 6G networks. This involves managing power consumption, optimizing load distribution, and balancing performance improvements with cost considerations. In high-value areas, 6G coverage needs to further improve energy efficiency and user experience, while in low-value areas, it is important to reduce coverage costs. Effective energy management is essential to support the high demands of ubiquitous coverage and maintain network reliability.
    - **Intelligent Technologies**: Utilizing artificial intelligence (AI) and deep learning (DL) to optimize network architecture and enhance overall performance remains a significant challenge due to the need for robust data collection and processing capabilities, high energy consumption, privacy and data security concerns, and the complexity of integrating AI across diverse environments and conditions.

By addressing these challenges, the vision of a fully integrated space-air-ground-sea communication network for 6G can be realized, providing reliable and comprehensive global coverage.

1.1.3 Cell-Free Massive MIMO Systems

Ultra-dense Cell-Free Massive MIMO (CF-MMIMO) is a key technology for 6G, addressing the need for ubiquitous connectivity and high data traffic. It involves numerous Access Points (APs) distributed over a wide area, serving many users simultaneously. This system combines Ultra-Dense Networks (UDNs), massive MIMO, and network MIMO (CoMP-JT), providing high spectral and energy efficiency.

Despite its potential, ultra-dense CF-MMIMO faces several challenges [Ngo2024]:

- **Network Density**: Ensuring multiple APs cover each user is essential for the cell-free paradigm.

- **Interference Management**: Effective interference reduction through beamforming and AP cooperation is crucial to avoid “densification collapse”.

- **Deployment Scenarios**: Various scenarios impact performance, requiring sophisticated interference reduction techniques.
- **Quantitative Metrics**: In ultra-dense networks, SINR approaches SIR, making noise power negligible compared to interference.

Addressing these challenges will enhance data rates and reliability, ensuring robust 6G networks.

1.1.4 AI-Native Network

AI-native networks integrate artificial intelligence (AI) and machine learning (ML) from the outset to address complex challenges in modern and future Wi-Fi networks. These technologies enhance network performance and manage complexity, providing solutions that traditional methods cannot.

The development includes a roadmap, key challenges, standardization efforts, and major enablers, showcasing AI/ML's potential at various adoption stages [Wil2024].

The implementation of AI-native networks presents several significant challenges:

- **Backward Compatibility**: Ensuring AI/ML features work alongside legacy devices is crucial. This requires thorough testing and possibly new certification procedures to prevent disruption. Alternatively, new frequency bands could be allocated for AI/ML protocols, though this involves regulatory bodies.
- **Computational Demands**: AI/ML methods are computationally intensive, leading to increased power consumption and the need for significant computational and communication resources. Hardware-constrained devices may require enhanced capabilities or external computational support, such as cloud services.
- **Continuous Development**: ML models need constant updates and monitoring to maintain performance. This requires flexible deployment options and standardized interfaces to allow easy updates and integration of new models.
- **Interoperability**: The diversity of ML solutions can cause conflicts and fairness issues, particularly in channel access. Standardizing the operation boundaries for AI/ML and ensuring compliance with spectrum regulations is essential to maintain interoperability and fair access.
- **General Concerns**: AI/ML raises broader issues related to security, privacy, explainability, and ethics. The rapid advancement of AI outpaces regulatory measures, potentially leading to misuse and security vulnerabilities. Ensuring data privacy and secure handling of sensitive information is critical, especially with the increasing use of AI/ML in networking.

1.2 Technological Challenges

1.2.1 Ultra Massive MIMO at high frequencies

Terahertz (THz)-band communications are being hailed as a pivotal technology to meet the surging demands for wireless data traffic in 6G networks. Despite their potential, several challenges, such as significant propagation losses and power constraints leading to limited communication ranges, must be overcome. Ultramassive multiple-input, multiple-output (UM-MIMO) antenna systems have emerged as a viable solution to these issues, enhancing system capacity and extending communication distances [Fai2020].

However, there are some challenges that need to be addressed:

- **Propagation Losses**: High propagation losses at THz frequencies limit communication distances.
- **Power Limitations**: Power constraints make it difficult to achieve long-range communication.
- **Blockage**: Small wavelengths are easily blocked by obstacles and particles.
- **Doppler Effect**: Severe Doppler spread in multipath scenarios at THz frequencies.
- **Environmental Factors**: Requires robust solutions to maintain communication quality in varying

1.2.2 Reconfigurability

Reconfigurability in Ultra Massive MIMO is defined as the ability of antennas to dynamically adjust their frequency, radiation pattern, and polarization to meet varying operational requirements. This flexibility is crucial for modern applications such as cognitive radio, MIMO systems, and 5G networks. However, achieving effective reconfigurability presents several technological challenges [Tan2023]:

- **Integration of Reconfiguration Elements**: Complexity in integrating switches (e.g., PIN diodes, varactor diodes, RF MEMS) and ensuring mechanical stability, especially in flexible antennas.
- **Performance Trade-offs**: Balancing reconfigurability with efficiency, gain, and bandwidth. Maintaining wide bandwidth and proper impedance matching.
- **Complexity and Cost**: Increased design complexity and higher manufacturing costs.
- **Environmental Sensitivity**: Reliability under varying temperature, humidity, and mechanical stress.
- **Energy Consumption**: Higher power requirements due to active components.
- **Scalability**: Challenges in scaling for large deployments while ensuring consistent performance.
- **Control and Reliability**: Developing reliable control mechanisms and ensuring long-term reliability.

- **Material Limitations: Limitations of materials used, requiring advanced materials for better performance.**

1.2.3 Sensing & Positioning

Positioning systems face several significant challenges and research opportunities [Far2022]:

- **Noise and Obstacles**: The presence of obstacles and noise can cause signal distraction, fading, and reflection, leading to multipath effects. Solutions include removing environmental noise and obstacles, and using filters like median, Kalman, and particle filters to reduce noise.
- **Energy Efficiency**: Balancing energy consumption with accuracy and performance is crucial. Solutions include using low-power nodes, outsourcing tasks to servers, and employing lightweight algorithms to save energy.
- **Cost**: High costs are associated with equipment, infrastructure, and maintenance. Affordable options like Bluetooth and Wi-Fi can help reduce hardware costs.
- **Security and Privacy**: Ensuring the security and privacy of location data is critical. Threats include database corruption, RF interference, and malicious nodes. Lightweight algorithms can help detect and mitigate these threats.
- **Lack of Standard and Interoperability**: The absence of comprehensive standards hinders interoperability. Developing middleware for interaction between heterogeneous components and creating a central platform with all communication technologies can address this issue.

Addressing these challenges is essential for advancing positioning systems and their applications.

1.3 Social Challenges

1.3.1 Energy Efficiency

The push towards next-generation wireless networks brings significant environmental and social challenges. As the industry strives for sustainability, several key issues must be addressed to balance the growing demand for mobile traffic and the environmental impact of energy consumption [Ene2023].

- **Vast Mobile Traffic**: The exponential growth in mobile traffic, including machine-to-machine (M2M) traffic, necessitates efficient management to limit power usage while meeting demands.
- **Environmental Impact of Energy Consumption**: Cellular networks consumed approximately 150 TWh of electric power in 2022, equating to roughly $25 billion annually. This significant energy usage has both financial and environmental impacts.
- **Energy Efficiency in 5G**: While 5G is more energy-efficient per bit compared to previous generations, the power required for massive MIMO antennas and maintaining multiple generations of infrastructure increases overall energy usage.

- **Intelligent Management of Legacy Equipment**: Effective management of legacy equipment, traffic routing, and network orchestration is essential to avoid increased power consumption when deploying new technologies.
- **Virtualization and Disaggregation**: These trends offer potential gains in energy efficiency, but only with thoughtful implementation. Combining dedicated hardware and cloud resources optimally is necessary to achieve energy efficiency.
- **Lack of Energy Efficiency Standards**: The absence of comprehensive standards makes it difficult to measure and track energy flow, impacting the effectiveness of efficiency improvements.

Addressing these challenges is crucial for ensuring the sustainability and efficiency of future wireless networks.

1.3.2 Terabit Data Rate

As we move towards achieving terabit data rates in wireless communication, several social challenges emerge. These challenges are not only technological but also have significant social implications that need to be addressed to ensure equitable and sustainable development [Ron2008].

- **Digital Divide**: The rapid advancement in wireless communication technologies may widen the digital divide, leaving behind regions and communities that lack access to these cutting-edge technologies. Ensuring that all populations benefit from these advancements is crucial.
- **Privacy Concerns**: With higher data rates and more connected devices, there are increased concerns about the privacy and security of user data. Protecting personal information and ensuring data security are paramount.
- **Economic Disparities**: The cost of deploying and maintaining advanced wireless networks can be high, potentially exacerbating economic disparities between different regions and countries. Affordable access to high-speed internet is essential for inclusive growth.
- **Environmental Impact**: The energy consumption associated with maintaining high-capacity networks can have significant environmental impacts, necessitating sustainable practices and technologies. Reducing the carbon footprint of these networks is a key challenge.
- **Infrastructure Development**: Building the necessary infrastructure to support terabit data rates can be challenging, especially in rural or underdeveloped areas. Ensuring widespread and reliable connectivity is essential for social and economic development.
- **Regulatory and Policy Issues**: Ensuring that regulations and policies keep pace with technological advancements to address issues such as spectrum allocation, data privacy, and security is critical. Effective governance frameworks are needed to manage these challenges.

1.3.3 Spectrum Utilization

The social challenges of spectrum utilization primarily stem from the need to balance various interests and values associated with the use of radio frequency spectrum, which is a finite and valuable resource. Here are some key social challenges [Inc2015]:

- **Equity and Access**: Ensuring equitable access to spectrum for different stakeholders, including public and private sectors, is critical. There may be disparities in access for smaller companies or rural communities compared to larger corporations or urban areas, potentially exacerbating digital divides.
- **Externalities**: Spectrum utilization often generates external costs or benefits that are not reflected in market prices. For example, interference from one service can negatively impact others, affecting non-users (e.g., TV viewers affected by mobile signals). These externalities complicate decision-making as they can lead to under- or over-utilization of spectrum.
- **Broader Social Value**: Beyond economic considerations, spectrum usage can impact social goods such as democracy, public safety, cultural diversity, and social cohesion. Incorporating these broader social values into spectrum allocation decisions poses a significant challenge, as they are often difficult to quantify.
- **Public Interest vs. Commercial Value**: There is often a tension between maximizing commercial value through spectrum auctions and ensuring that spectrum is used in the public interest (e.g., for public broadcasting, emergency services, or community-based networks). Finding a balance that satisfies both interests is challenging.
- **Changing Technologies and Needs**: The rapid evolution of technology (e.g., the rise of IoT, 5G) leads to changing demands for spectrum. Policymakers must anticipate future needs while managing current allocations, which can lead to conflicts over resource allocation and usage.
- **Regulatory and Administrative Challenges**: Effective governance of spectrum utilization requires robust regulatory frameworks that can adapt to technological advancements and changing social needs. Ensuring transparency and accountability in spectrum management is crucial to maintain public trust.
- **Stakeholder Engagement**: Effective spectrum management often requires engaging a diverse range of stakeholders, including industry players, government agencies, community groups, and the public. Balancing these interests and facilitating meaningful participation can be complex.
- **Environmental Considerations**: The environmental impact of spectrum utilization, particularly in terms of energy consumption for wireless infrastructure, is a growing concern. Ensuring that spectrum policies contribute to sustainability is an emerging challenge.

1.3.4 Reliability

Providing reliable wireless connectivity in rural areas presents a unique set of challenges driven by geographical, infrastructural, economic, and technological factors. Difficult terrain such as mountains, forests, and vast open spaces can impede wireless signal propagation. Unlike urban environments, rural regions may have large areas with little to no infrastructure, making it challenging to provide consistent coverage. The lack of existing telecommunications infrastructure is a significant barrier, as many rural areas lack basic infrastructure like roads, electricity, and wired internet. This makes the deployment of wireless networks more challenging and expensive. Lower population densities in rural areas translate to fewer potential customers for wireless service providers, making it difficult to justify the high costs associated with deploying and maintaining wireless networks. Additionally, the economic conditions in rural areas often mean that residents may have less disposable income to spend on advanced wireless services, further reducing the financial incentive for providers to invest in these areas. Technological limitations also play a significant role, as many rural areas rely on outdated technologies that are not equipped to handle modern data demands, resulting in slower speeds and unreliable connections. Regulatory and policy challenges add another layer of complexity, as inconsistent policies across regions can create confusion and delays in the deployment of wireless networks. Despite these challenges, innovative solutions and collaborative efforts are emerging to bridge the gap and bring reliable wireless services to underserved rural areas [Cha2024].

2 State of the Art

2.1 Channel Models

Recent advancements in channel modeling focus on integrating quasi-static and dynamic components to enhance accuracy and reduce overhead. For instance, the Environment-Aware Channel Estimation method combines prior information from a channel knowledge map (CKM) with dynamic sensing data to improve channel estimation [Wuq2024]. Additionally, the spatial channel model (SCM) is used for realistic modeling of the environment, capturing the spatial characteristics of the channel [Kim2021].

2.2 Channel Estimation and Tracking

State-of-the-art techniques in channel estimation and tracking employ various advanced methods to improve performance in dynamic environments. Notable approaches include:

- **Environment-Aware Channel Estimation**: Integrates CKM and dynamic sensing information to enhance accuracy and reduce overhead [Wuq2024].
- **Non-uniform Pilot Pattern Design for** multiple-input-multiple-output (MIMO)-orthogonal frequency-division multiplexing (**OFDM**) Systems: Utilizes compressed sensing (CS) algorithms and cyclic difference set (CDS) to design pilot patterns that minimize interference and overhead.
- **Channel Estimation for** Massive MIMO-orthogonal time frequency space (**OTFS**) Systems: Proposes a two-step CS-based method for asymmetrical architectures, initially estimating direction of arrival (DoA) parameters using the proximal gradient descent (PGM) method, followed by delay, Doppler, and channel coefficient estimation [Che2023].
- **Nonlinear Kalman Filter-Based Robust Channel Estimation**: Employs extended Kalman filter (EKF) and unscented Kalman filter (UKF) algorithms to model time-varying channels and reduce error propagation in high mobility OFDM systems [Lia2021].
- **Massive MIMO Channel Prediction**: Compares Kalman filter (KF) and machine learning predictors, using Yule-Walker equations for autoregressive (AR) coefficient estimation and a combination of linear minimum mean square error (LMMSE) pre-coding and multi-layer perceptron (MLP) for machine learning-based prediction [Kim2021].

These methods collectively enhance the accuracy, reduce the overhead, and adapt to the high mobility scenarios in modern wireless communication systems.

2.3 Hardware and Software architectures

Hardware-software codesign integrates both hardware and software components to optimize system performance, particularly in resource-constrained environments like IoT and embedded systems. Key techniques in this approach include feature selection, which reduces model complexity and computational costs by selecting important features for machine learning models, and parallel processing, which utilizes the parallel processing capabilities of hardware, such as FPGAs, to accelerate computational tasks [Liu2024].

FPGAs play a crucial role in this process due to their high efficiency and low power consumption, making them ideal for real-time processing tasks. Their reconfigurability allows for flexibility and adaptability in various applications. The codesign approach involves implementing critical algorithms on FPGAs to leverage their speed and parallelism, while the software component handles tasks like data preprocessing and feature extraction, optimizing the overall system performance. Integration of hardware acceleration with software flexibility achieves efficient and accurate processing [Liu2024].

Implementation of hardware-software codesign uses platforms like Xilinx Vivado for hardware design and Xilinx Vitis for software development. The effectiveness of this approach is demonstrated through practical applications and datasets. The advantages of hardware-software codesign include resource efficiency, reducing computational costs and power consumption, making it suitable for small, resource-limited devices, and enhanced performance, providing a robust solution for real-time applications [Liu2024].

In conclusion, hardware-software codesign offers a powerful approach to optimize system performance by combining the strengths of both hardware and software, making it ideal for applications requiring high efficiency and real-time processing [Liu2024].

2.4 Scheduling and Resource Management

The rise of fifth-generation (5G) technology has enabled diverse services, with Internet of Things (IoT) devices playing a crucial role. Device-to-device (D2D) communication enhances power efficiency, spectrum utilization, and computational resources but faces challenges like limited battery capacity and the need for timely updates. Key performance indicators (KPIs) such as the age of information (AoI) are critical for maintaining information freshness [Par2024].

Recent advancements focus on improving data rates, energy efficiency, and overall network performance [Par2024]:

- **Energy Harvesting (EH)**: Techniques like simultaneous wireless information and power transmission (SWIPT) and EH-based scheduling improve energy efficiency.
- **Optimization Methods**: Approaches such as mixed-integer nonlinear programming (MINLP), particle swarm optimization (PSO), and federated learning (FL) enhance data rates and reduce energy consumption.
- **Machine Learning (ML)**: Multi-agent deep reinforcement learning (MADRL) and deep Q-networks (DQN) optimize resource allocation, reduce latency, and improve energy efficiency.

These advancements highlight the state-of-the-art in D2D network management, addressing key challenges effectively.

2.5 Positioning and Sensing with Ultra-Massive MIMO

Next-generation wireless communication, particularly 6G, aims to enhance mobile broadband and real-time experiences, introducing new use cases like spatial perception and immersive platforms. Ultra-massive MIMO (UM-MIMO) technology is crucial for achieving higher spectral efficiency and improved throughput, latency, and coverage. Utilizing millimeter-wave (mmWave) and terahertz (THz) bands, UM-MIMO systems offer substantial bandwidth and high transmission rates, with dense antenna packing to compensate for path loss [Gao2024].

Challenges such as the Hybrid Far- and Near-Field Beam-Squint (HFBS) effect arise due to increased antennas and bandwidth, necessitating new signal processing paradigms. Despite these challenges, UM-MIMO systems provide enhanced delay and angle resolution, making them suitable for applications like target localization, radar sensing, SLAM, and integrated sensing and communication (ISAC) [Gao2024].

Hybrid beamforming architectures and compressive sensing (CS) techniques are employed for cost-effective channel estimation, though they face issues like energy dispersion and reduced sparsity. Solutions include subarray piecewise approximation and higher-dimensional projection matrices, albeit with increased computational complexity [Gao2024].

Future 6G systems are expected to support ultra-high accuracy localization, tracking, imaging, mapping, and enhanced human sensing. Recent research focuses on joint localization and location-aware beamforming, integrated uplink channel estimation, and network-level cooperative ISAC to improve sensing accuracy and system performance [Gao2024].

2.6 Joint Communications and Sensing

Integrated Sensing and Communication (ISAC) systems combine radar sensing and communication, making them ideal for applications like intelligent transportation and smart factories. They achieve high data rates, low latency, and precise sensing by leveraging synergies between radar and communication technologies [Wei2024].

A key component of ISAC systems is the radar channel model, essential for understanding radar signal propagation and performance evaluation. Traditional communication standards lack detailed radar modeling, which is addressed by incorporating radar cross-section (RCS) characteristics using deterministic and statistical methods [Wei2024].

Clutter modeling is also crucial, with various methods predicting the RCS characteristics of clutter sources. ISAC systems use these models to integrate communication and radar functionalities, establishing two-way multipath channels for sensing [Wei2024].

Key differences between communication and radar channels include transceiver locations, application scenarios, and channel fading. Research in ISAC channel modeling includes deterministic and statistical methods, measurement platforms, and correlation studies, aiming to improve accuracy and reliability [Wei2024].

Future research will focus on enhancing radar channel models, integrating advanced measurement techniques, and improving the precision of ISAC systems [Wei2024].

2.7 Artificial Intelligence and Machine Learning

The evolution of wireless networks has seen significant innovations, with 6G poised to bring a paradigm shift beyond 5G's capabilities. Key technologies for 6G include semantic communications for context-aware networks, integration of non-terrestrial networks for global coverage, and free space optical links to bridge the digital divide. Integrated sensing and communications (ISAC) will enhance network quality, while high-frequency spectrum, reconfigurable intelligent surfaces (RIS), and extremely large antenna arrays (ELAA) will improve connection density and efficiency. Holographic communication will enable advanced applications like IoT and the metaverse [Cel2024].

The complexity of 6G networks necessitates the use of machine learning (ML) and artificial intelligence (AI). While discriminative AI (DAI) models are useful, generative AI (GenAI) offers significant potential for data augmentation and anomaly detection, driven by recent advancements in large language models [Cel2024].

3 MiFuture Development Approach

To have an immersive experience of the use-cases, and to make it feasible to the masses a cross-layer and holistic approach is necessary while having AI in the driving seat. Figure 1 accurately depicts the service requirements for the use cases we discussed. This section discusses our approach to cater for these service requirements.

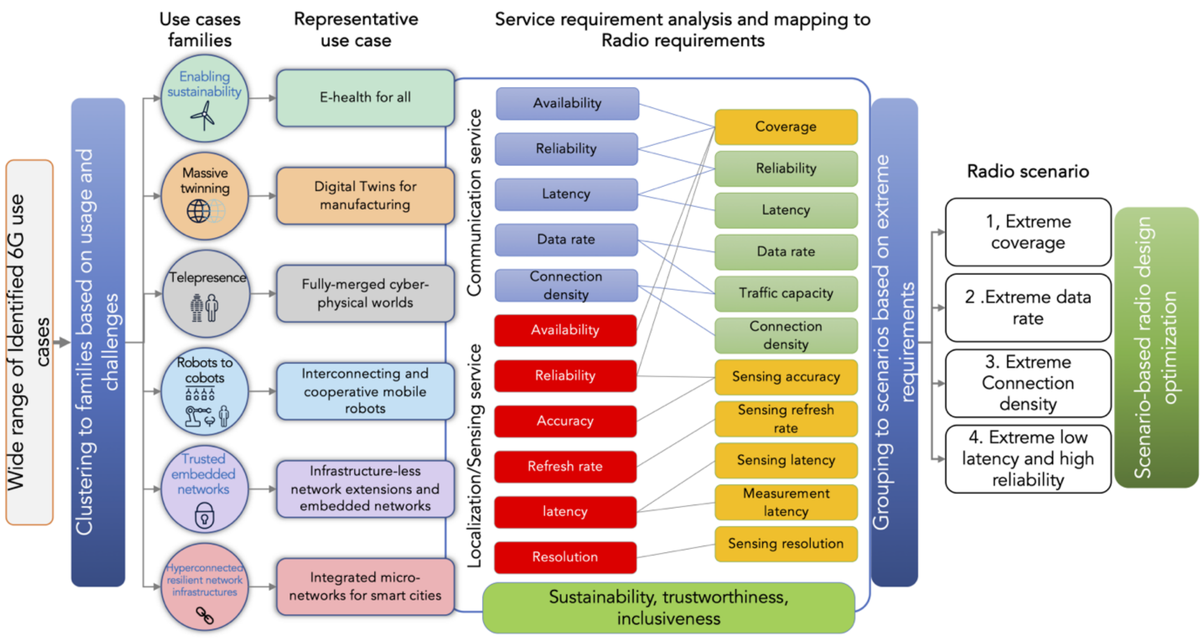

Figure 2: Service Requirements

Source: [Sal2024]

3.1 Holistic

A holistic approach means seeing the use case involving the whole system and its impact on the system rather than on an individual. For MI Future the development plan for the Holistic Approach is to:

- We are trying to be efficient with our spectrum utilisation by increasing the data throughput through optimization to provide a sustainable solution decreasing the energy efficiency in the new Ultra-Massive MIMO world.
- The idea is to increase the sensing and localization accuracy which will benefit verticals and not just one sector in a way that it can reconfigure itself to suit the needs of the application.
- The approach is to create a seamless interaction with the real and the digital world enabling a more personalized experience with the help of machine learning to sense the environment and communicate simultaneously providing valuable feedback.

- Along with increasing the efficiency, joint positioning and communication we are also working on the safety-related issues by also considering the non-connected objects in the system environment.

3.2 Cross-layer

A cross-layer approach means sharing information between the layers. 6G is going to be the first network that has sensing capabilities, thus sharing information between layers becomes a critical part. If AI is utilized with joint communication and sensing, the resource allocation can be done in a way that only part of the spectrum is dedicated to a particular task and the computation can be done near to the device reducing latency. [Sal2024]

If the need of the application is to have more resources the physical layer can be re-configured according to the feedback from the application and the computational resources it requires. This can be useful in the use-cases like Holographic meeting and virtual online gaming. a simple figure showing how a cross-layer approach can be integrated with the help of AI is depicted in Figure 3.

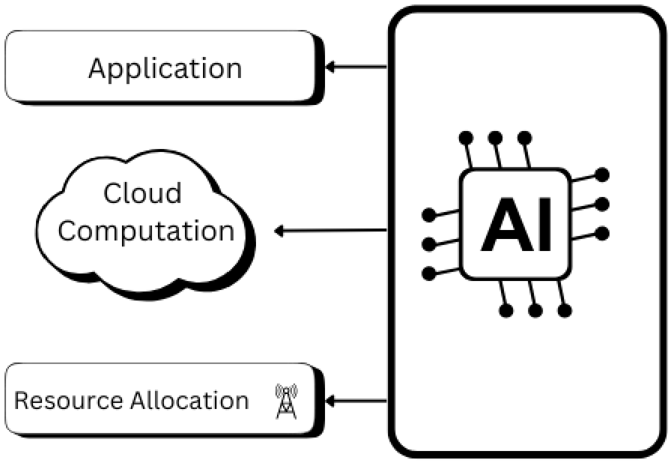

Figure 3: Cross-Layer Approach

With MI Future we are working to improve the joint communication and sensing by trying to know the channel conditions and allocate the power and resources effectively. Also along with cell-free networks and beamforming, we can utilise the spatial resources in a better way giving cross-layer functionality for the network to adapt to real-time situations.

3.3 Native AI as a Tool

Native AI and cross-layer approach go hand in hand. The Native AI is the functionality of the AI to change according to the data it has received and it replaces the static rule-based mechanisms leveraging AI more power to do things and make it more intelligent moving from connected things to connected intelligence. A simple example could be autonomous driving detecting obstacles and making decisions autonomously or a voice-assistant that adapts to the user inputs and gives personalized responses.

To effectively utilize the data from the physical layer, machine learning methods are being tested to enhance the environment-sensing capabilities, which then can provide better channel characteristics. Our approach is to utilize these sensing capabilities and with the help of AI try to communicate the same simultaneously providing accurate and necessary resources and details for the application and improving spectral efficiency. The main challenge is scaling the AI in a cell-free network considering the high computation it requires to be done on the cloud and provide it to the application with very low latency.

3.4 Reduced Complexity

The main challenge with using Native AI and cross-layer approaches is the scalability as the system gets too complex. Our approach is to investigate the problem from the grassroots and try to find the most optimal solution in a way the complexity is reduced to a minimum and the system becomes scalable for future development.

As 6G will unify the experiences across all the verticals, the challenge is to reduce the function overhead in the network while maintaining the same functionality reducing the complexity of the core network.

Doing this would also help to design the networks in a more sustainable manner and would also cut down the time to market. The approach is to have as much as possible simpler algorithms that would do the required task effectively. Again, for doing this, using the network in an intelligent form is important which makes all the other approaches necessary.

The graph by Fraunhofer FOKUS (Figure 4) shows how with 6G core network we would reduce the complexity compared to 5G core network.

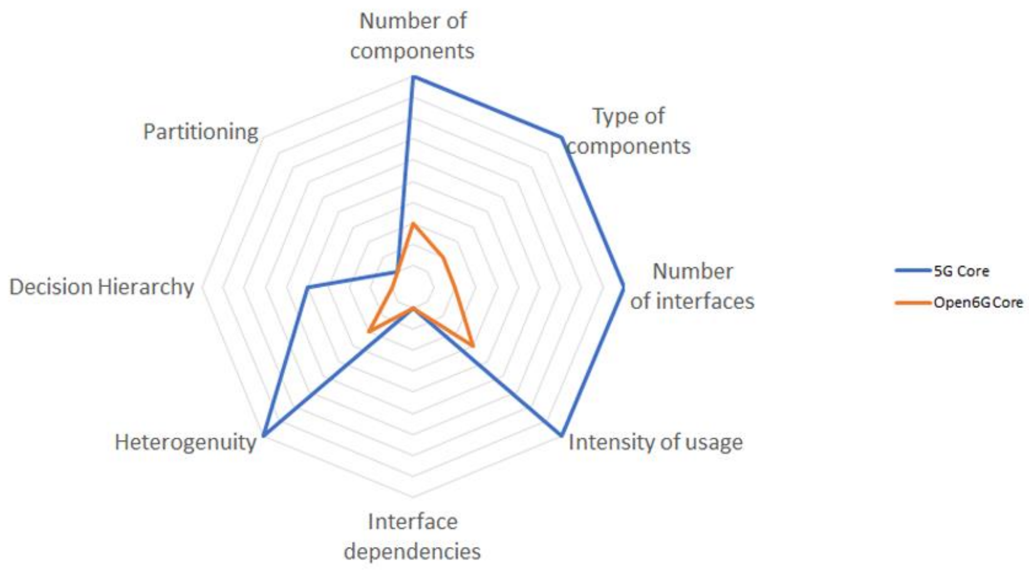

Figure 3: Reduced Complexity for 6G Core

Source: Fraunhofer FOKUS [Cor2022]

3.5 Feasibility

Our approach is to make the use cases as feasible as possible with the help of the approaches mentioned above and at the same time provide a sustainable solution. Use cases like Digital Twins and AR are much more feasible in terms of data throughput and resource requirements, but holographic projections and teleoperation require much more precision and a much higher throughput.

According to [Oul2020] a holographic teleportation of a person requires 4.32 Tbps of throughput and latency below sub ms for a raw holograph without compression at 30 fps. While for e-health few requirements are not that complicated and can be achieved with our approach like a drone requires an accuracy of 0.1-0.3 m (horizontal & vertical) and to maintain tracking for secure and reliable sample collection with an update rate of at least 1 second. [6G2021]

Figure 4: Feasibility

In Figure 5 the inner hexagon describes the more feasible usage scenarios from our approach, while the outer circle describes the usage that would be a little less feasible from our approach. All our approaches aim towards providing a sustainable solution, allowing the data throughput and massive communication to increase in a sustainable manner.

4 Use Cases

With 6G we are approaching very high data rates and throughput. This gives us an opportunity to have use cases like never before and to improve the existing use cases as now we can have our hands-on accurate sensing and positioning with computations being done in the cloud along with an intelligent scalable network.

The main idea is to connect both the physical and digital worlds seamlessly provide an immersive experience to the user and have solutions that would sustainably benefit the overall industry by providing them with enough insights for the generated data.

The use cases are endless, whether it be virtual gaming or having a UAV acting as a base station in case of an emergency or being used for rescue operations. Now, tele-operations are very much feasible by making accurate use of positioning and sensors. With the upcoming network changes, we will be able to monitor and provide solutions in real-time which would heavily reduce the cost of maintenance and would also avoid hazardous situations.

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

Digital Twin is how our world looks in the digital way taking in the scenarios from the real world. It replicates all the relevant characteristics, properties and dynamics an object goes through in its whole life cycle [6G2023]. It uses sensors to capture real-time data from a real-world equivalent and then processes it mathematically taking into consideration the physics of the object under investigation. It can provide real-time input which can help in reducing the consequences that could be caused if the object was not monitored regularly [Thr2024].

One Example could be the use of DT in localisation. With the world moving towards Automated Driving and Flying Taxis, it is important to get real-time data of all the dynamic and moving objects and humans around the dense environment to have a safe journey. We can consider the accurate traffic data from our maps which replicates the real-world traffic and provides us with input, where there is a seamless interaction between both worlds, and we can make an accurate timely decision. Another example could be a farmer having a digital twin model of the farmland, the model can get real-time readings of all the necessary parameters. By this, any inconsistency can be known which would help prevent the crop from damaging.

Figure 5: DT of an urban scene with Real-time data

Source: ChatGPT

Now, imagine incorporating Machine Learning with these Digital Twins. With enough data, ML can help to simulate all the possible scenarios that could happen in the near future. This will not only help to mitigate the crisis that could occur in the future but also enable us to think of more sustainable solutions and can work as a perfect prototype between the human, machine and environment interaction. [Liu2024]

However, the core dependency of this interaction lies in reliable wireless sensing and accurate localization in a dense environment along with real-time delivery of the processed data from all the embedded sensors, and thinking of the overall network as a sensor with intelligence from ML which extends our information beyond immediate surroundings. [Nok2024]

4.2 Multiway Virtual Meeting with Holographic Projection

Work from Home and Virtual Meetings are no longer a term of the future, now we have adapted to this new working environment. However, one thing that is lacking in this is the emotional and physical presence of the person in a meeting room. Recently we have been creating our 3D avatars on social platforms and interacting with each other through these avatars. These 3D avatars give us a sense of the physical presence of the person we are interacting with. The same is being incorporated with Holographic Projections in a virtual meeting by holographically projecting real people and not just their avatars.

The concept lies in capturing the 3D visual and audio information through multiple sensors, transmitting them and reconstructing them on the other side as a hologram. These meetings can also enable a much more realistic presence with the help of haptic sensors. But to enable this requires improved QoS in the network and complex edge computing with minimal latency as it requires encoding and rendering of the 3D data in real-time. If we are able to define proper protocols for this technology in 6G, we could soon be placing an immersive holographic call from our mobile phone dialler instead of a normal IP audio call. [Gao2023]

For the current technology, an AR device is equipped with SLAM (simultaneous localization and mapping) which uses the front cameras of the device and maps the surroundings which helps the device to localize itself and anchor content from a fixed location in the environment. This helps to see the hologram from different angles giving a total immersive experience [Esa2022].

4.3 Virtual and Augmented Reality

The key difference between Virtual (VR) and Augmented Reality (AR) is that we completely immerse ourselves in the virtual world in VR. At the same time, AR adds virtual elements to the real world taking in input as the surroundings.

With 5G, AR has greatly improved in the fields such as gaming and education. One example could be Pokemon Go, which uses AR to show us virtual elements around our surroundings and ways to interact with them. It uses accurate tracking and localization to show us Pokemons at different locations. A VR can be used in a museum to learn the stories visually in a virtual world.

The main issue for AR and VR is the latency between the user input and the system response and the high-resolution streaming requirement while handling a lot of data. While in 6G, seeing AI as a service, data rates shooting high and more precise localization can help give us a more personalized experience and seamlessly experience both the virtual and real world anytime.

4.4 Teleportation and Remote Surgery

Teleoperation simply put is operating a patient remotely. This application can help doctors see through the tissues with high-end cameras and perform operations with the help of robotic arms with greater precision than by doing it with the hand. Remote Surgery can help doctors operate the patients from a different location avoiding the travel a patient has to make during illness. This has an advantage in rural and hilly areas where the connectivity is great but there is a lack of high-end medical facilities. This also helps the patients to choose their doctors without being location-bound. A simple figure showing Teleoperation can be shown as in Figure 7:

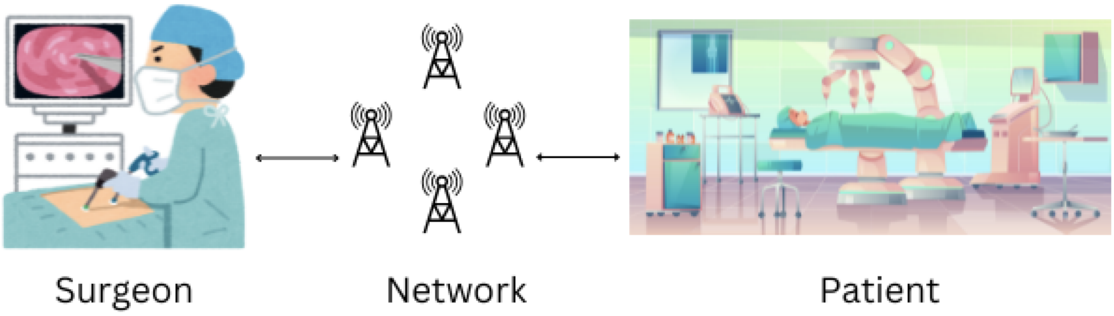

Figure 6: Remote Surgery through Wireless Network

This application uses a lot of haptic sensors which helps the surgeon analyse the texture of the tissues. These sensors have different latency tolerances, and the arms should also account for precise localization to perform the surgery at a precise body tissue. Thus, it all comes down to having a network with very low latency that can process complex calculations and provide an effective back to the surgeon. The surgeon then moves its console and lets the robotic arm do the rest considering it is tracking down the tissues precisely and working on the planned position. The feasibility to some extent depends upon the distance from the remote doctor as it can be directly proportional to latency. [Doh2024]

5 Reference Architecture

5.1 Standardization: 3GPP & O-RAN ALLIANCE

5.1.1 Introduction

The evolution of cellular networks is driving increasing complexity in next-generation wireless systems, which are now built on diverse technologies and operate across multiple frequency bands [Gio2020]. These advancements include massive Multiple Input, Multiple Output (MIMO) systems, millimeter wave and sub-terahertz communication, network-based sensing, network slicing, and digital signal processing powered by Machine Learning (ML) [She2017]. As a result, network operators face rising capital and operational expenses as they strive to keep their infrastructures current and aligned with advancing technologies and evolving customer demands. Effectively managing and optimizing these sophisticated networks calls for solutions that enhance the flexibility and openness of the Radio Access Network (RAN) [Bon2021].

Most RAN systems are built as standalone units that incorporate every protocol stack layer. Provided by a small number of vendors, these systems are often viewed by operators as “black boxes.” This black-box approach imposes several constraints on network operators, including limited reconfigurability, restricting the ability to fine-tune RAN operations for diverse deployment scenarios and varied traffic profiles, limited coordination between network nodes, preventing the joint optimization and control of RAN components, and vendor lock-in, which restricts operators to specific vendors, limiting their flexibility to integrate RAN components from different sources [Bon2021].

In response to these challenges, the past decade has seen significant research and standardization efforts focused on promoting Open RAN as a transformative approach for future RAN architectures. Open RAN frameworks leverage disaggregated, virtualized, and software-based components that communicate through open, standardized interfaces, enabling interoperability among equipment from multiple vendors. Founded in 2018, the O-RAN Alliance is an industry consortium that implements these principles within the 3GPP LTE and NR RAN standards. Specifically, the O-RAN Alliance supports and expands on the 3GPP NR 7.2 split for base station architecture, enabling a modular, interoperable approach to RAN design [RAI2017].

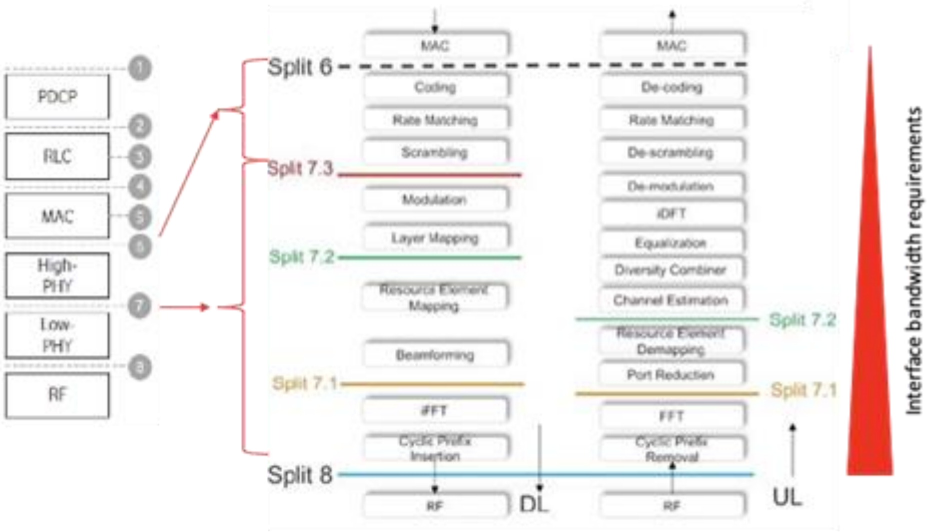

Figure 8: Split types

5.1.2 Key Architectural Principles

The Open RAN framework is grounded in years of research on creating open and programmable network architectures. These guiding principles have been instrumental in transforming wired networks through software-defined networking (SDN) over the past 15 years and are now being adapted to wireless networks [McK2008]. Building on this foundation, the research literature and O-RAN specifications highlight four core principles that define Open RAN: disaggregation, intelligent data-driven control through RAN Intelligent Controllers (RICs), virtualization, and open interfaces.

5.1.2.1 Disaggregation

Disaggregation in Open RAN refers to dividing the base station into several functional components, building on the functional disaggregation model introduced by 3GPP for Next Generation Node Bases (gNBs) in 5G networks. In this design, the gNB is split into a Central Unit (CU), a Distributed Unit (DU), and a Radio Unit (RU) [ArD2022]. The CU is then further segmented into two logical parts: one dedicated to the Control Plane (CP) and the other to the User Plane (UP). This hierarchical arrangement enables the Radio Access Network (RAN) functions to be spread across different locations and hardware platforms within the network, improving flexibility and scalability [Pol2023]. The O-RAN Alliance has explored the RU/DU split options suggested by 3GPP, paying particular attention to the physical layer partitioning between the RU and DU to enhance performance and simplicity. In this setup:

- **Radio Unit (RU)**: This unit is responsible for time-domain processing tasks, such as precoding, Fast Fourier Transform (FFT), cyclic prefix operations, and Radio Frequency (RF) functions. Designed to be cost-effective and easy to deploy, the RU supports basic signal processing functions that require minimal computational power [Pol2023].
- **Distributed Unit (DU)**: This unit performs more complex functions, handling the physical layer, Medium Access Control (MAC), and Radio Link Control (RLC) layers.

Tasks such as scrambling, modulation, and resource block mapping are managed here, requiring close synchronization. The DU also generates Transport Blocks (TBs) in the MAC layer based on data received from the RLC layer, facilitating seamless data flow between network components [PLD2018].

- **Central Unit (CU)**: This unit handles the higher layers of the 3GPP protocol stack, such as Radio Resource Control (RRC), which manages connection setup and mobility, Service Data Adaptation Protocol (SDAP) for Quality of Service (QoS), and Packet Data Convergence Protocol (PDCP) for critical functions like encryption and data reordering. By managing these advanced processes, the CU ensures efficient, secure data transmission and resource management across the network [Pol2023].

This disaggregated architecture enables network operators to deploy RAN components flexibly, integrating hardware and software from various vendors. This, in turn, increases interoperability and allows for more tailored network configurations.

5.1.2.2 RAN Intelligent Controllers and Closed-Loop Control

The second key innovation in O-RAN is the introduction of RAN Intelligent Controllers (RICs), which add programmable elements capable of executing optimization routines and managing closed-loop control to orchestrate the RAN. The O-RAN architecture includes two logical controllers designed with an abstract, centralized view of the network, supported by data pipelines that stream and aggregate hundreds of Key Performance Measurements (KPMs) on network status (e.g., user numbers, load, throughput, resource utilization) as well as additional context information from external sources. These RICs process extensive data inputs and apply AI and ML algorithms to generate and implement control policies for the RAN. This data-driven, closed-loop approach automatically optimizes various network functions, including network and RAN slicing, load balancing, handovers, and scheduling policies [Bon2021].

5.1.2.3 Virtualization

A third foundational principle of the O-RAN architecture is virtualization, which introduces advanced components for managing and optimizing network infrastructure across a continuum from edge systems to cloud-based platforms. All elements of the O-RAN framework are deployable within a hybrid cloud computing environment known as O-Cloud. O-Cloud is an integrated pool of computing resources and virtualization infrastructure across one or multiple physical data centers. This platform encompasses physical nodes, software elements, and management and orchestration functionalities, enabling efficient virtualization within the O-RAN architecture. O-Cloud provides decoupling of hardware and software components, standardized hardware capabilities for the O-RAN infrastructure, multi-tenant hardware sharing, and automated deployment and instantiation of RAN functionalities [OW12021].

The O-RAN Alliance Working Group 6 is further developing hardware acceleration abstractions, termed Acceleration Abstraction Layers (AALs), which establish standardized APIs between specialized hardware processors and O-RAN software, including tasks like channel coding/decoding and Forward Error Correction (FEC). These initiatives are mirrored in commercial, hardware-accelerated virtualized RAN implementations that support 3GPP New Radio (NR) use cases on commercial hardware. Virtualizing RAN components and compute elements within O-RAN reduces power consumption and enables dynamic scaling of compute resources to meet user demand, aligning power usage with actual network function requirements [Per2022].

5.1.2.4 Open Interfaces

Finally, the O-RAN Alliance has developed technical specifications to establish open interfaces connecting components within the O-RAN architecture. These open interfaces, defined by O-RAN specifications and 3GPP intra-RAN standards, enable flexible integration across radio resource management and virtual and physical network functions [Bon2020]. Without such open interfaces, these functions would remain closed and constrained by proprietary solutions. Standardizing these interfaces is a critical step toward reducing vendor lock-in within the RAN ecosystem, promoting market competition, and accelerating the cycles for updates and upgrades. This open approach also simplifies the design and deployment of new software components across the RAN ecosystem, enabling interoperability between DUs and RUs from different vendors [Pol2023].

5.1.3 The O-RAN Interfaces

The O-RAN architecture utilizes a suite of open interfaces specified by the O-RAN Alliance to enable communication and control across network elements through near-real-time and non-real-time RAN Intelligent Controllers (RICs). These interfaces support essential functions, such as telemetry reporting and closed-loop control, by defining structured message exchanges between endpoints, creating a cohesive network ecosystem that complies with industry standards like those of 3GPP and the O-RAN Alliance.

The E2 interface: Links the near-real-time RIC to various RAN nodes, including DUs and CUs. The E2 Application Protocol (E2AP) and specialized Service Models (SMs) allow xApps running on the near-real-time RIC to access data streams, adjust configurations, and enforce control policies in near real-time. This interface enables telemetry reporting and control operations across the RAN, facilitating responsive network management [OW32021].

The O1 interface: Manages the lifecycle and performance of O-RAN elements, including DUs and CUs. It supports reporting of Key Performance Indicators (KPIs) and allows real-time data streaming to enable enhanced network management. Using standardized protocols such as REST/HTTPS and NETCONF, the O1 interface monitors and controls RAN nodes, aiding in resource allocation, fault management, and overall operational efficiency [OW12020].

The A1 interface: Connects the non-real-time RIC with the near-real-time RIC, offering high-level policy guidance and management of machine learning (ML) models. This interface supports optimizations over longer timescales, such as load balancing and traffic forecasting, to improve network adaptability and efficiency. Through strategic oversight, the A1 interface aligns near-real-time operations with broader, long-term network objectives [OW22021].

The Fronthaul Interface: Supports the 7.2x functional split between DUs and Radio Units (RUs) and is essential for real-time signal processing and data transmission within the RAN. This interface manages physical layer tasks distributed between DUs and RUs, enabling efficient operation of advanced features like massive MIMO. The Fronthaul Interface is critical to meeting the O-RAN architecture's stringent latency and performance requirements by facilitating real-time data exchange and control [OW42021].

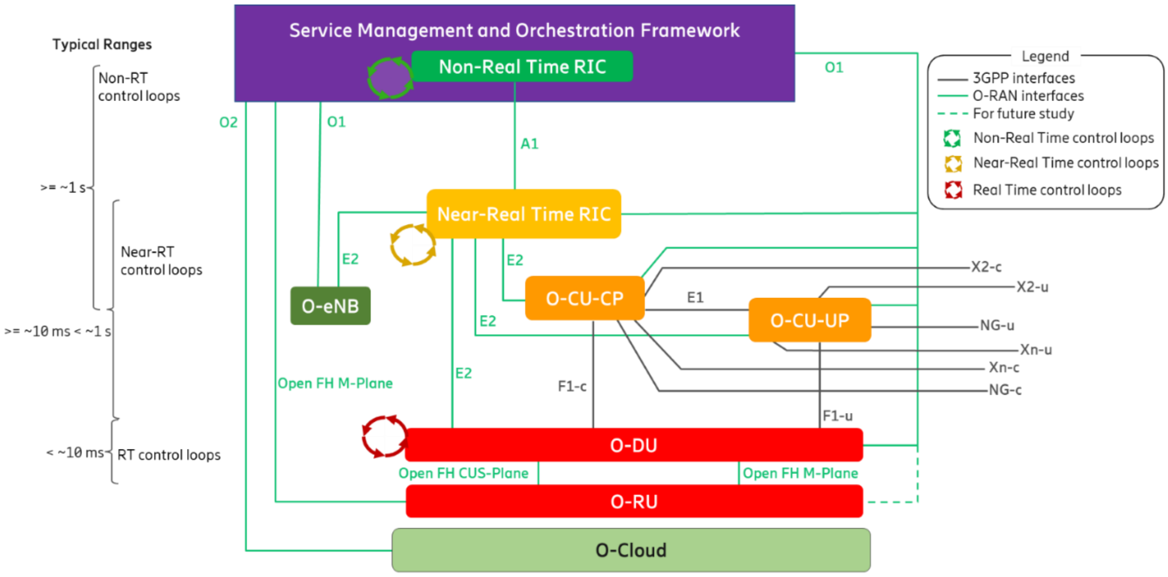

Figure 9: ORAN architecture defined by ORAN Alliance

5.1.4 O-RAN Development and Standardization

The O-RAN Alliance is a collaborative consortium of operators, vendors, research institutions, and industry partners dedicated to transforming the RAN ecosystem into an intelligent, open, virtualized, and interoperable architecture. The Alliance's initiatives span three primary areas [OWP2018].

Specification: This effort extends traditional RAN standards from standard development organizations (SDOs) such as 3GPP, ETSI, and ITU to incorporate principles of openness and intelligence into the RAN.

Software Development: The Alliance actively develops and contributes open-source software for O-RAN components, supporting a more accessible and collaborative software ecosystem.

Testing and Integration: The Alliance provides guidance for testing and integrating O-RAN-compliant solutions, assisting members in validating and refining their O-RAN implementations.

Note that the O-RAN Alliance is currently not an SDO. Thus, any standard-related activity will require liaisons with SDOs like 3GPP or ETSI [Pol2024].

The Alliance's specification tasks are managed by ten Working Groups (WGs), each addressing specific components of the O-RAN architecture. Complementing the WGs, the Alliance has established Focus Groups (FGs) to concentrate on particular areas of strategic interest. Oversight is provided by a Technical Steering Committee (TSC), supported by four sub-committees, which focus on defining a minimum viable framework for a fully compliant O-RAN network, establishing procedural guidelines for Alliance operations, fostering industry engagement, and promoting research to advance future RAN technologies, including 6G. Additionally, the O-RAN Alliance collaborates with external organizations to contribute to the

Open RAN ecosystem, reinforcing its vision of an interoperable, innovation-driven network environment [Pol2023].

5.2 L1 Acceleration: In-Line vs. Look-Aside

As previously mentioned, the widespread adoption of open RAN encounters a major obstacle in achieving optimal end-to-end network performance while addressing the considerable RAN processing requirements of 5G and future advancements. The 5G RAN, characterized by its broad channel bandwidths, stringent low-latency necessities, sophisticated channel coding methods, and intricate MIMO antenna arrays, imposes a substantially greater computing load on the network than earlier generations. Depending exclusively on general-purpose processors for 5G RAN may result in unmanageable power usage and cost implications, which may impede large-scale deployment. Hardware acceleration is essential as it allows delegating heavy computational RAN tasks to specialized hardware, thereby supporting the rapid, low-latency processing demanded by 5G networks [Aza2024].

In L1 (PHY layer) processing, hardware acceleration is often the only practical solution since computational needs often surpass the efficient capabilities of general-purpose CPUs. A hardware accelerator transfers resource-intensive PHY layer signal processing tasks away from the CPU using completely programmable devices like GPUs or custom-built fixed-function accelerators. The decision between different types of accelerators and their level of programmability hinges on the specific RAN task and the extent of acceleration needed [Fer2021], [AAL2023].

Typically, hardware acceleration for 5G RAN employs look-aside and in-line modes. In look-aside mode, the CPU delegates particular data processing assignments to the hardware accelerator and waits for the outcomes before continuing its operations. This approach, often used for functions like forward error correction (FEC), has drawbacks due to the repeated data transfers between the CPU and the accelerator, which can rapidly utilize double data rate (DDR) bandwidth. This back-and-forth data movement can lead to notable bottlenecks in complex 5G scenarios requiring multiple look-aside accelerations [Sha2020].

With the advent of massive MIMO antenna arrays and the necessity to process data across newer, wider 5G frequency bands with shorter transmission time intervals (TTIs), the requirements for L1 processing have surged dramatically. In-line acceleration has emerged as a more effective strategy to tackle this, wherein the entire L1 processing workflow is transferred to the hardware accelerator. By directing output data straight from the accelerator to the next phase, in-line acceleration circumvents the CPU, eliminating the data transfer bottleneck and preserving DDR bandwidth. This efficient data handling is vital for attaining the low-latency, high-throughput processing that 5G requires.

As the architecture of 5G RAN transitions into a more open, multi-vendor environment, there is a growing demand for various acceleration solutions to be compatible across different applications. The O-RAN Alliance's Accelerator Abstraction Layer (AAL) framework addresses this issue by abstracting the details of each hardware accelerator from network applications. This method promotes interoperability while providing implementation flexibility. The framework aids in integrating diverse accelerators and acceleration modes from various vendors, paving the way for a more adaptable and scalable RAN architecture.

5.3 Distributed vs Centralized

5.3.1 Distributed RAN

Distributed RAN is a network architecture in which Baseband Units are placed near their corresponding RUs at the network edge. This architecture resembles today´s traditional network deployments, where baseband elements and radio units are placed at the radio site. Unlike centralized architectures, distributed systems eliminate the need to pool BBUs in a central location, reducing dependency on high-capacity fronthaul links [Akh2024]. Each BBU is dedicated to serving its associated site, enabling localized processing and decision-making.

Distributed RAN offers several key advantages. First, it minimizes latency because BBUs are co-located with RUs, avoiding delays introduced by signal transmission over the fronthaul. This feature makes distributed systems particularly well-suited for real-time applications and latency-sensitive services. Another strength of this architecture is its resilience. A failure in a BBU only affects its specific site, ensuring that other parts of the network remain operational. This contrasts with centralized systems, where a failure in the pooled BBUs could disrupt multiple sites [Akh2024], [PPC2024].

Moreover, Distributed RAN proves advantageous in sparsely populated or rural areas where deploying high-speed fronthaul infrastructure is impractical. Each site's autonomy allows these regions to maintain functionality without depending on broader network coordination. Finally, distributed systems can be more cost-effective in areas lacking fronthaul infrastructure, bypassing the need for significant centralized equipment and connections.

However, Distributed RAN also comes with notable challenges. One drawback is the potential for inefficient resource utilization. Since each BBU operates independently, resources allocated to one site cannot be shared with others, leading to possible underutilization in some areas and overloading in others.

Additionally, maintenance demands are higher in distributed systems, as each BBU requires individual monitoring, maintenance, and upgrades. This increases operational complexity compared to centralized architectures, where such functions are pooled.

Scalability can also be challenging for Distributed RAN, particularly when integrating technologies like SDN or NFV, which benefit from centralized processing. Lastly, spectrum efficiency may be reduced in distributed setups. Without centralized coordination, the system has limited capability to manage spectrum usage across sites, which can lead to less optimal utilization of available frequencies [PPC2024].

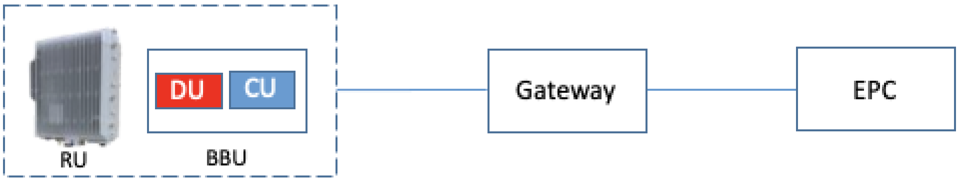

Figure 10: Distributed RAN

5.3.2 Centralized RAN

Centralized RAN is an architecture based on aggregating the Baseband Units (BBUs) in BBU pools and leaving the Radio Units close to the base station due to the time sensitive nature of its functions [Akh2024]. It is the previous stage of Cloud-RAN, where the BBUs are deployed in COTS hardware. Sometimes both terms are often used interchangeably, despite Cloud-RAN being centralized, but not the other way around.

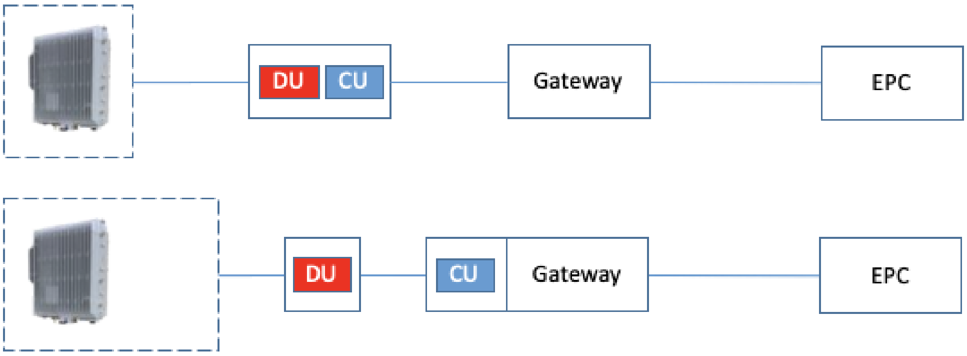

Figure 71: Centralized RAN architecture (up) and Disaggregated Open RAN architecture (down)

Figure 11 shows two architectures. The first one corresponds to Centralized RAN, where the non-key functions of the Radio Unit have been moved to a separate Base Band Unit (BBU), which is composed by the Distributed Unit (DU) and the Centralized Unit (CU). The second architecture depicted in figure 10, corresponds to the evolution of Centralized RAN, Open RAN. In Open RAN the CUs have been separated from the DU. This separation allows for a common CU between several DUs. Having a common CU enables the automation of the higher layers of the 3GPP protocol stack, e.g., RRC or SDAP for QoS. This is done through xApps, which can be deployed in the RICs.

Centralized RAN has many benefits due to it enabling the possibility of operating different BBUs in a coordinated manner. As a result, a more efficient operation is achieved, which increases spectrum and energy efficiency, and reduces operating costs [Cent2024].

Moreover, Centralized RAN allows for network capacity improvements that come from the hand of fully scalable BBU pooling, which allows for easier and cheaper scalability. This is due to the site deployments being lighter because of the displacement of the BBU to the centralized BBU pool. This also eases the maintenance and upgrades, as well as enhances the security due to the reduced number of exposed BBU that could be attacked.

Finally, Centralized RAN allows for the incorporation of SDN and NFV technologies to transition into Cloud-RAN. Which further enhances the benefits provided by Centralized RAN and is the previous step from Open RAN.

The main challenge that stands against the adoption of a centralized architecture for the RAN is the high load it puts on the fronthaul due to the movement of the BBUs closer to the core network. Moreover, the design of the fronthaul must consider the latency [Cent2024], which is crucial for some functions like Massive-MIMO. This increases substantially the complexity of the fronthaul design. The latency requirements and expensive fronthaul suggest that Centralized RAN is a more adequate architecture for dense urban scenarios, while it would not be as efficient in disperse environments.

Moreover, there must be coherence between the architectures used by different ISPs in shared sites. Because of this, the architectural upgrade of a shared site from distributed to centralized must get the approval of all the ISPs operating it. This can cause delays in the adoption of a centralized architecture paradigm.

Finally, the centralized architecture is less resilient than the distributed one. This is due to one failure in the centralized BBU affecting multiple sites, unlike in the case of Distributed RAN, where one BBU failure affects only one site [Cent2024].

5.4 Cloudification

The cloudification of the RAN refers to the displacement of network elements traditionally deployed in the radio tower to the cloud. This is done through the separation of the software and hardware of the RAN. By making the software independent of the hardware it is possible to run key RAN functions in COTS hardware, which need not be in the same location as the hardware [Clo2024], [Nok2024].

Due to many functions of the RAN being related to the Physical layer, it is not possible to move all the RAN to the cloud. Those functions are not virtualized and are kept in the Radio Unit (RU), the only element of the RAN that is still physically located at the Base Station.

5.4.1 Enablers

The key technologies that have enabled the cloudification of the RAN are Network Function Virtualization (NFV), Software Defined Networks (SDN) and Edge Computing [SDx2024].

NFV and SDN are the core enablers of cloudified networks. NFV consists of replacing dedicated hardware with virtual machines running on COTS hardware [NFV2024]. SDN builds on top of NFV and separates the network control plane from the data plane [SDN2024], which allows for high flexibility, efficient operations and deployment, as well as significant cost reductions. Despite the RAN being limited by the impossibility of virtualizing the functions related to the PHY layer, there are many benefits to be obtained from virtualization.

Edge computing is needed for the virtualization of network functions that, despite being possible to virtualize, still have strict latency requirements, e.g., Radio Resource Management. It is also required for time sensitive applications, e.g., self-driving cars.

5.4.2 Benefits

The main benefits brought by the cloudification of the RAN are given by its flexibility in both deployment and operation, given by its SDN nature. The fact that most RAN functions can be deployed in the form of virtual machines in COTS hardware reduces the time to market, as well as the scalability costs [Clo2024],[Nok2024]. Moreover, the possibility of dynamically controlling the allocation of resources has not only increased efficiency, but also enabled new functionalities, like network slicing.

Finally, the cloudification of the RAN has paved the way for the opening of the interfaces proposed by Open RAN, which brings its own list of benefits.

5.4.3 Challenges

Cloudifying the RAN does not come without a set of technological challenges, the main ones revolve around making disaggregated elements work together seamlessly, high computing and latency requirements, as well as higher throughput requirements in the fronthaul due to the movement of the Baseband Units to the cloud [Top2024].

5.5 Automation

The cloudification of the RAN means that it is now possible to remotely control its infrastructure and resources. This creates new automation possibilities impossible in previous RAN architectures. Moreover, with the rise of AI as an automation tool, a powerful combination emerges. This extends the benefits brought by cloudification and brings us one step closer to level 5 Self-Organizing Networks [Man2024].

The concept of RAN Automation is aimed towards achieving fully autonomous networks. These networks should be able to, without human intervention, configure, i.e. automate the deployment of new network nodes; optimize, i.e. adjust parameters such as power levels, handovers, and load balancing; and heal, i.e. identify and resolve network issues like coverage holes or equipment failures. This is what is defined a Self-Organizing Networks (SON) [Man2024].

5.5.1 Enablers

RAN automation comes from the combination of C-RAN architecture with AI automation. The cloudification of the RAN allows for high flexibility in the use of resources, e.g., network slicing, which can be optimized through AI. Furthermore, AI can use all the network monitoring data coming from C-RAN to optimize the operation of the network and increase efficiency, such is the case of Intelligent Agents, which are the first step of bringing AI into RAN operation [Hua2024], [Int2024].

To implement RAN automation, a full AI-oriented data pipeline needs to be built. To do this, real data from the network needs to be collected and passed to the AI models implemented in the RICs of O-RAN. This needs to be done in an iterative manner that allows for real-time control of the network, as well as for continuous improvements. As a result, orchestration tools and edge computing are very valuable tools for the implementation of AI automation.

5.5.2 Areas of Application and Benefits

Many areas can benefit from the automation capabilities of AI, with the main ones being network configuration, network optimization and self-healing [Man2024]. Network configuration and optimization allow for a more efficient use of resources, while self-healing decreases the probability of outage through automated fault resolution and intelligent responses to system failures.

As a result, the more efficient use of resources provided by network automation brings key benefits like reduced operation costs, reduced manual labor requirements, better performance, less time to market, and superior performance [Man2024], [RAN2024]. These translate into features like dynamic spectrum sharing, automatic load balancing and predictive maintenance.

The future appears bright for AI Automation. The advances in AI, which are expected to bring more capable and sophisticated models, combined with edge computing, which allows for low latency high performance computing, will pave the way for fully autonomous (level 5) SON in 6G.

6 Reference Scenarios

6.1 Macro: Dense-Urban

MiFuture project is designed to develop umMIMO and related technologies, addressing the critical needs of beyond 5G systems. These include achieving even higher throughput, energy efficiency, positioning accuracy, and manageable complexity. Macro scenarios, in this context, represent high-level, large-scale use cases or operational environments that define the overarching requirements, challenges, and opportunities for future communication systems. They serve as a guiding framework to address the performance demands expected in 6G, such as ultra-high data rates reaching up to 1 Tbps, ultra-low latency of approximately 0.1 milliseconds, and the ability to support massive connectivity. These capabilities aim to enable groundbreaking applications, including immersive extended reality experiences, advanced smart city infrastructures, and seamless space-air-ground integrated networks [Viz2024].

To achieve these ambitious goals, the project emphasizes innovations in three core areas: spectrum utilization, artificial intelligence (AI) integration, and network design. Advancements in spectrum usage will unlock higher frequency bands and more efficient allocation methods, enabling the bandwidth necessary for 6G applications. AI integration will play a pivotal role in optimizing network operations, enhancing system adaptability, and supporting real-time decision-making. Similarly, next-generation network designs will address scalability and complexity challenges while ensuring sustainability and resilience. Together, these breakthroughs aim to transform future communication systems, unlocking new possibilities for industries and society. Key Macro scenarios envisioned for these novel technologies are:

- **High density areas**: umMIMO can be highly effective to manage large quantities of user devices simultaneously in crowded and high-density zones like stadiums, urban centers, or large events. The spectral efficiency and low complexity/scalable resource allocation of umMIMO can give increased data throughput and beamforming optimization can improved connectivity to all the user devices, while also aiming to obtain ubiquitous connectivity [Ngo2024]. Additionally, ISAC will allow the network to gather and analyze information from the environment to enable features such as creating detailed maps, recognizing gestures and activities, detecting and tracking objects or individuals, enhancing security through surveillance, and assisting with navigation. Figure 12 sumarizes the technologies that can enable this scenario.

Figure 12: High density areas scenario

- **Connected vehicles**: The integration of umMIMO and ISAC technologies can significantly enhance vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, where continuous interaction between vehicles and roadside units is essential. These advancements enable critical safety applications, such as collision avoidance and the detection of pedestrians, cyclists, or obstacles that are not connected to the network. With extremely low latency (as low as 0.1 ms), massive connectivity, and ultrahigh throughput to handle large volumes of data, these systems can provide the reliability needed for complete automation in intelligent transportation systems [Liu2019]. As seen in Figure 13, these technologies are critical to develop advanced transportation systems.

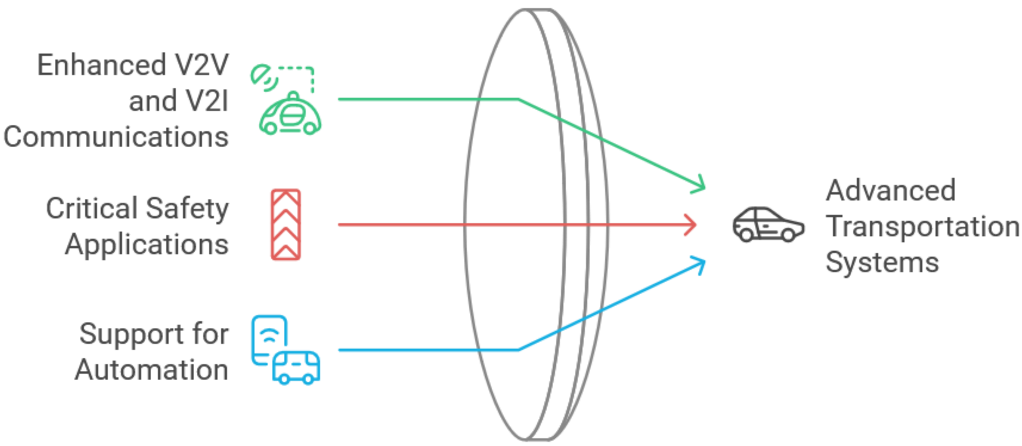

Figure 13: Connected vehicles scenario

- **Aerial user applications**: MiFuture project also involves research on mm-Wave positioning, which can be applied specially for precise positioning and environmental sensing in aerial contexts, like unmanned aerial vehicles (see Figure 14). Multi-antenna systems with umMIMO in mmWaves frequencies enable precise directional beamforming, which is essential for aerial applications where drones must distinguish between multiple objects or paths. Beamforming and adaptive umMIMO antennas help focus energy on desired directions, enabling drones to detect small or distant obstacles while maintaining stable connectivity and positioning in dynamic environments. This could be useful for tasks like inspecting power lines, bridges, or buildings, where drones must maintain a safe distance while performing the inspection. Additionally, mmWaves allows sub-centimetre (high resolution) accuracy in object detection and positioning [Liu2019].

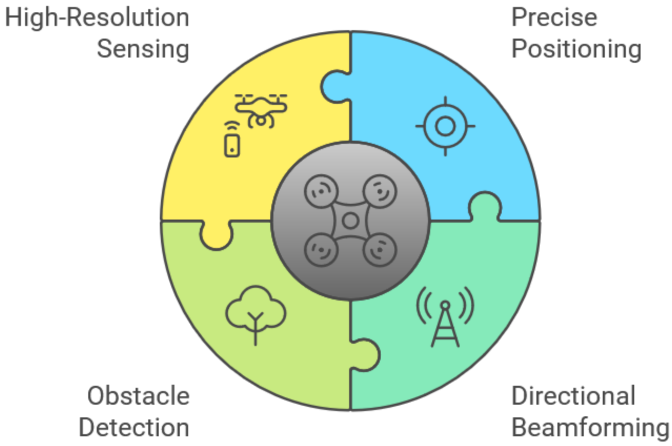

Figure 14: Aerial user applications

6.2 Small Cells

Small cells are low-powered cellular radio access nodes that provide coverage for smaller areas compared to traditional macro cells. Traditional macro-cell networks are designed to provide coverage over wide geographic areas. However, these networks face challenges in accommodating the rapidly growing demand for high data rates and seamless connectivity, especially in densely populated urban environments. As an alternative approach, dense deployment of small cells has emerged, offering significantly increased spectral and energy efficiencies and improved network capacity by reducing the distance between the Base Station (BS) and the end-user. Small cells include various types, such as microcells, picocells, and femtocells, each varying in range and power to suit specific deployment needs [An2017]. These small cells can be strategically deployed in different scenarios to optimize network performance as shown in Figure 15, and can be classified as follows:

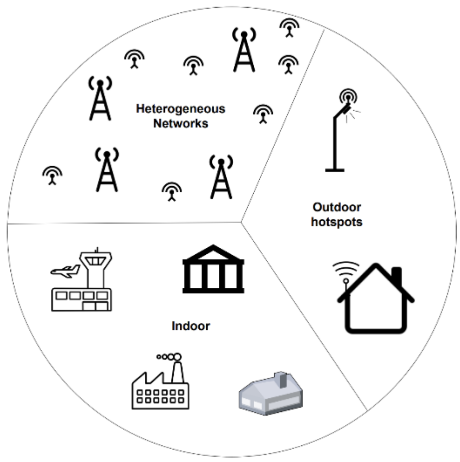

Figure 15: Small cell deployment methods

- **Heterogeneous networks (HetNets)**: HetNets enable various types of small cells to operate alongside macro-cells. The use of low-power small cells enhances network capacity and fills coverage gaps, providing extended connectivity in previously underserved areas. Additionally, the over-lap of small cells with macro cells facilitates more efficient frequency reuse, optimizing overall spectral efficiency [Agi2016].
- **Indoor Areas**: Small cells can be strategically deployed in high-traffic areas, such as airports, shopping malls and stadiums, where large numbers of users gather, to enhance Quality of Service (QoS) [Alt2019].
- **Outdoor Hotspots**: In such scenarios, small cells are typically installed on structures like streetlight poles or building exteriors, allowing the network to achieve significant capacity enhancements in densely populated areas [Anp2015].

6.3 NTN

Non-Terrestrial Network (NTN) systems refer to communication networks that rely on spaceborne or airborne platforms to deliver connectivity, rather than traditional ground-based infrastructure. These systems are designed to provide network coverage to areas that are otherwise difficult or impossible to reach with terrestrial networks, such as remote regions, oceans, or underserved communities. By operating beyond the constraints of terrestrial infrastructure, NTN systems enable global communication and bridge connectivity gaps. NTN platforms are broadly categorized into two types: spaceborne and airborne. Spaceborne platforms include Geostationary Earth Orbit (GEO), Medium Earth Orbit (MEO), and Low Earth Orbit (LEO) satellites. The airborne category includes platforms such as Unmanned Aircraft Systems (UAS). The several potential use cases for NTN are shown in Figure 16 and listed below [Rin2020]:

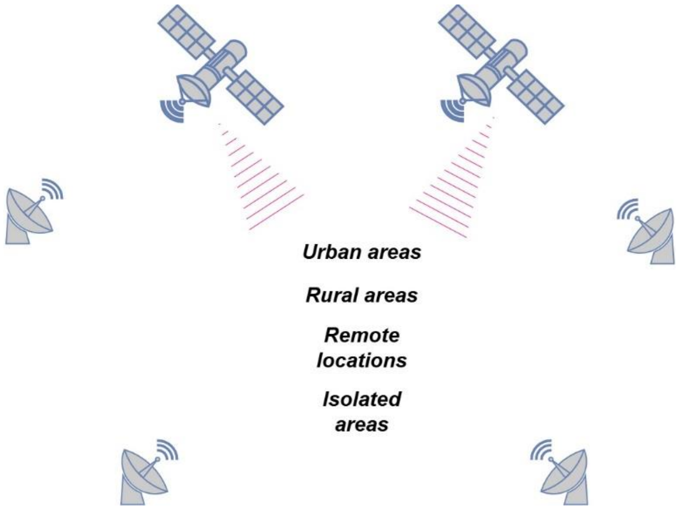

Figure 16: Non-terrestrial network use cases

- **Urban**: NTN systems can serve as a reliable alternative to fixed network backhaul in urban areas, providing enhanced connectivity where terrestrial infrastructure is limited. Additionally, they offer flexible backhaul solutions for mobile networks, supporting high data demands and improving coverage for automotive applications within dense urban environments.
- **Rural**: In rural areas, NTN systems provide a crucial connectivity alternative, offering consistent internet access to communities that lack reliable terrestrial networks. These networks also function as effective mobile network backhaul solutions, supporting expanded rural coverage and enabling essential communication for disaster relief operations.
- For **remote locations**, NTN enables highly distributed networks, offering isolated connectivity to regions without any terrestrial options. This is especially valuable for emergency response and safety communications, ensuring reliable contact in critical, hard-to-reach areas.
- **Isolated**: NTN plays a key role in providing broadband services for maritime environments, enabling high-speed internet for vessels far from terrestrial networks. Furthermore, NTN enhances maritime safety by delivering dependable communication for emergency situations on open waters.

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8 Acronyms

3GPP	3rd Generation Partnership Project
3GPP – TSG	3rd Generation Partnership Project - Technical Specification Group
5G NR	5th Generation New Radio
6G	6th Generation
ABF	Analog Beamforming
AI	Artificial Intelligence
AP	Access Point
API	Application Programming Interface
AR	Augmented Reality
BBU	Baseband Unit
BER	Bit Error Rate
CA	Carrier Aggregation
C-Cloud	Centralized Cloud
CDS	Cyclic Difference Set
CP-OFDM	Cyclic Prefix OFDM
CQI	Channel Quality Index
C-RAN	Centralized/Cloud Radio Access Network
CSI	Channel State Information
CSMA	Carrier-sense Multiple Access
CU	Centralized Unit
DBF	Digital Beamforming
DDoS	Distributed Denial-of-service Attack
DL	Deep learning

DoS	Disk Operating System
DSL	Digital Subscriber Line
DU	Distributed Unit
E2E	End-to-End
EC	European Commission
EE	Energy Efficiency
EH	Energy Harvester
eMBB	Enhanced Mobile Broadband
eNodeB or eNB	Evolved Node B
EPC	Evolved Packet Core
ESR	Early Stage Researcher
ETSI – ATTM	ETSI-(Access, Terminals, Transmission and Multiplexing)
ETSI – ITS	ETSI-(Intelligent Transport System)
ETSI	The European Telecommunications Standards Institute
EUTRAN	Evolved Terrestrial Radio Access Network
FG-ML5G	Focus Group on ML for Future Networks Including 5G
FPGA	Field Programmable Gate Arrays
GFDM	Generalized Frequency Division Multiplexing
HAD	Hybrid Analog-Digital
HDL	Hardware Description language
HetNets	Heterogeneous Networks
IBFDX	In-Band Full Duplex
ID	Information Decoder
IDPS	Intrusion Detection and Prevention System
IDS	Intrusion Detection System

IIoT	Industrial Internet of Things
IMT-Advanced	International Mobile Telecommunication Advanced
IOS	International organization of Standardization
IP	Intellectual property
JCAS	Joint Communications and Sensing
KF	Kalman Filter
KPI	Key Performance Indicator
LIS	Large intelligent surfaces
M2M	Machine to machine
MAC	Medium Access Control
MIMO	Multiple-input Multiple-output
NL	Nonlinear
PA	Power Amplifier
PHY	Physical layer
RA	Resource Allocation
rApp	RApplication (Non-RT RIC)
RF	Radio Frequency

RIC	Radio Intelligent Controler
RIS	Reconfigurable Intelligent surfaces
RRM	Radio Resource Management
RSU	Road Side Unit
RU	Radio Unit
RX	Receiver
SC	Small Cell
SCNs	Small Cell Networks
SDAP	Service Data Adaptation Protocol
SDO	Standards Developing Organizations
SDR	Software Defined Radio
SER	Symbol Error Rate
SIC	Successive Interference Cancellation
SIC	Success Interference Cancellation
SINR	Signal-to-interference-plus-noise Ratio
SISO	Single Input Single Output
SLS	System Level Simulator
SNR	Signal-to-noise ratio
SON	Self-Organizing Network
SOTA	State of the Art
SOTA	Self Organizing Tree Algorithm
SrsENB	Sounding Reference Signal EnodeB
SSIM	Structural Similarity Index Metric
sub cm	Sub-centimeter
SWIPT	Simultaneous Wireless Information and Power Transfer

OTFS	Orthogonal Time Frequency Space
TDMA	Time-division Multiple Access
TRL	Technology Readiness Level
TS	Technical Specification
THz	Terahertz
UAV	Unmanned Aerial Vehicle
UDN	Ultra-dense Network
UE	User Equipment
UHF/SHF	Ultra high frequency /Super High Frequency
UMiLoS	Urban Micro Line-of-Sight
URLLC	Ultra-reliable low latency communication
USRP	Universal Software Peripheral Radios
VLC	Visible Light Communication
VQM	Video Quality Measurement
VR	Virtual Reality
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network
xAPP	xApplication (Near-RT RIC)