8. Future Prospects and Research Materials on 5G Mobile Communication System

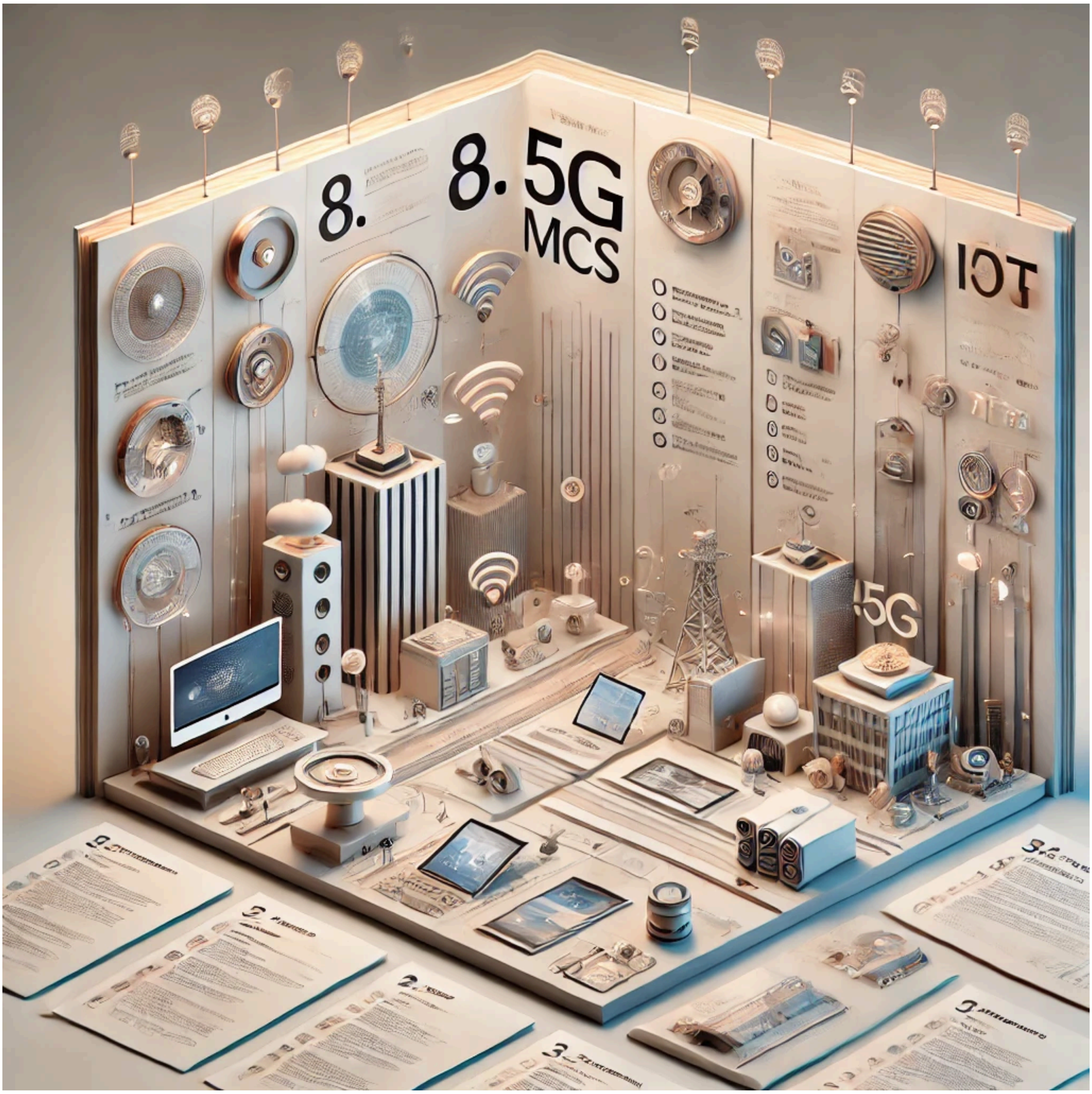


Table of Contents

Chapter 1: Introduction

1.1 Development and Limitations of 5G

1.1.1 Technological Evolution of 5G

Overview

5G MCS, as the fifth generation of mobile communication technology, represents a significant advancement compared to its predecessors. This evolution was driven by changes in technical requirements and the need to support emerging use cases.

1.1.1.1 Drivers of Evolution

Diversification of Use Cases

- eMBB (enhanced Mobile Broadband)
- mMTC (massive Machine Type Communications)
- URLLC (Ultra-Reliable Low-Latency Communications)

Social Demands

- Implementation of smart cities
- Growing demand for autonomous vehicles and C-V2X (Cellular Vehicle-to-Everything)
- Proliferation of IoT devices

Technical Requirements

- High throughput (up to 20 Gbps)
- Low latency (under 1 ms)
- Massive connectivity (up to 1 million devices per square kilometer)

1.1.1.2 Evolution of Technological Foundations

RAT Enhancements

- Adoption of OFDMA (Orthogonal Frequency Division Multiple Access)
- Utilization of millimeter wave spectrum
- Implementation of Massive MIMO (Multiple Input Multiple Output)

Network Architecture

- Cloud-native 5GC (5G Core)
- Introduction of Network Slicing
- Integration of Edge Computing

Protocol Evolution

- New Radio (NR) standard
- Dual Connectivity (simultaneous use of LTE and 5G)
- Flexible frame structure

1.1.1.3 Key Innovation Points in 5G

Dynamic Spectrum Sharing (DSS)

- Dynamic sharing of spectrum between LTE and 5G

AI/ML Integration

- Network optimization and traffic prediction

Security Enhancements

- IMSI encryption
- User plane encryption

Energy Efficiency

- Design optimization for low-power devices

1.1.1.4 Developer Insights

Impact on UE Development

- High integration and power-efficient design of 5G modems
- Optimization of 5G protocol stacks on RTOS

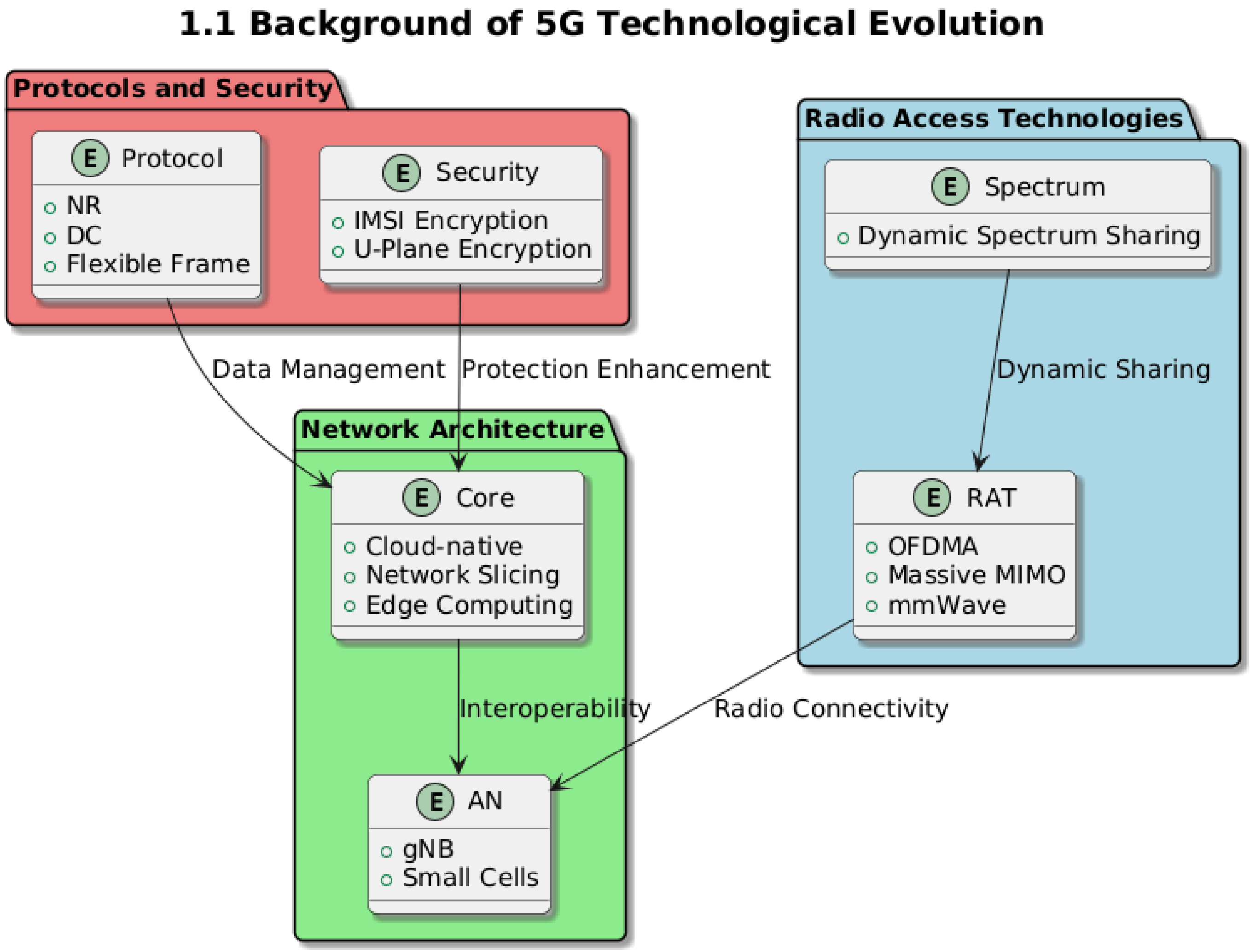
Impact on gNB Development

- Design of high-density antenna arrays
- Utilization of high-performance SoCs

Impact on 5GC Development

- Microservice-based Network Functions (NFs)
- Highly scalable container-based architecture

Diagram



Conclusion

Section 1.1 "Technological Evolution of 5G" provides a comprehensive explanation of the core innovations driving 5G and serves as foundational knowledge for engineers preparing for next-generation development. The diagram aids in structural understanding of the interconnected technologies.

1.1.2 Current Status and Challenges of 5G MCS

1.1.2.1 Current Status of 5G MCS

Large-Scale Commercial Deployment

The global adoption of 5G is progressing, with mobile operators particularly driving the transition from NSA (Non-Standalone) to SA (Standalone) architecture.
Usage is expanding in metropolitan and industrial areas, though deployment in rural and remote regions still lags behind.

Key Architectures

- gNB:
  Implementation of high-throughput transmission, Massive MIMO, and beamforming
- 5GC:
  Support for Network Slicing and Edge Computing
- UE:
  Performance improvements through advanced chipsets and protocol stack integration

Outcomes of Technological Evolution

- eMBB (enhanced Mobile Broadband):
  Supports high-quality video streaming and XR services
- URLLC (Ultra-Reliable Low-Latency Communications):
  In testing for specific industrial use cases such as factory automation
- mMTC (massive Machine Type Communications):
  Increasing IoT device support capabilities

1.1.2.2 Challenges

Coverage and Density

Due to the propagation characteristics of mmWave bands, indoor and rural coverage remains inadequate.
Interference issues persist in high-density urban environments.

Energy Efficiency

While enabling high-speed, high-capacity communication, energy consumption of base stations has significantly increased.
There is a growing need for green network technologies.

Increasing Complexity of Network Management

As slicing and dynamic resource allocation become more advanced, the burden of operations and maintenance is rising.
Although automation via AI/ML is being introduced, standardization is still insufficient.

Security and Privacy

The massive connection of IoT devices has increased potential threats.
Achieving end-to-end Zero Trust security across the network remains a major challenge.

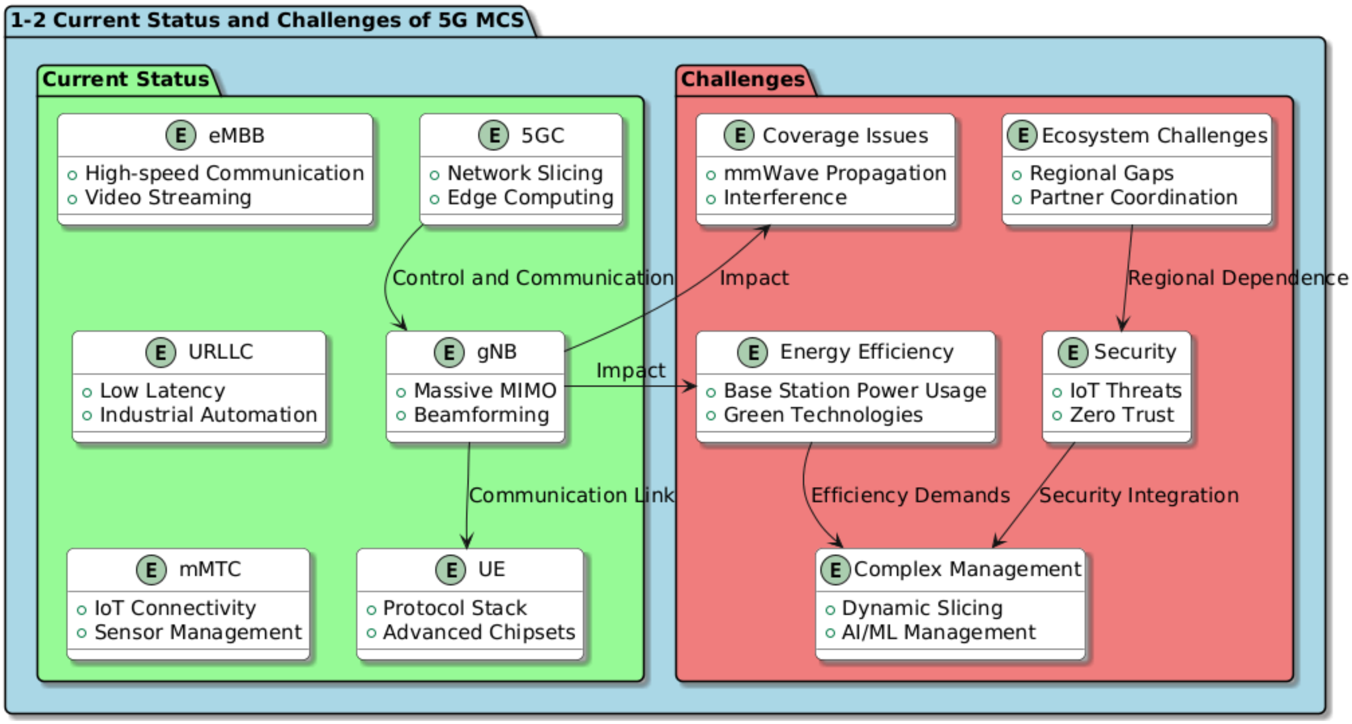
Ecosystem Diversity

Differences in the pace of standardization have led to deployment gaps between countries and regions.
Collaboration among partner companies also presents coordination challenges.

Diagram

The following diagram visualizes the current status and challenges of 5G MCS, grouping functions by category and showing their interrelationships with color distinctions.

1.2 Current Status and Challenges of 5G MCS



This diagram separates the current status and challenges, illustrating the relationships among key elements in each group.

1.1.3 Requirements for Next-Generation Technologies

This section outlines the expected directions for evolution in next-generation communication technologies, as well as the requirements necessary to address current issues in 5G MCS.

1.1.3.1 Support for Advanced Use Cases

Low Latency and High Reliability

Sub-millisecond latency and reliability exceeding 99.999% are required for ultra-precise robotic control and AR/VR applications.

Ultra-High-Speed Communication

Data rates up to 1 Tbps are expected through communication in the THz band.

Integration with Edge Computing

Strong collaboration between network and computing resources is necessary to perform dynamic data processing at the edge.

1.1.3.2 Intelligent Network Operations

Autonomous Network Optimization via AI

Dynamic network optimization and resource allocation based on traffic prediction using AI.

Real-Time Monitoring

Distributed AI systems must enable real-time detection of user experience quality and security threats.

Dynamic Slice Management

Greater flexibility is needed for network slicing, requiring architectures that support real-time resource scaling and reconfiguration.

1.1.3.3 Improved Environmental Adaptability

Power Saving and Energy Efficiency

Technologies that reduce the power consumption of network equipment (e.g., sleep modes, automatic load balancing).

Reconfigurable Intelligent Surfaces (RIS)

Technologies that dynamically adjust the radio environment to improve network flexibility.

Optimization of Dense Topologies

Network topologies that can support extremely high device densities, especially in urban and indoor environments.

1.1.3.4 Enhanced Security and Privacy

Quantum Cryptography Technologies

Introduction of encryption schemes resistant to quantum computing threats.

End-to-End (E2E) Security

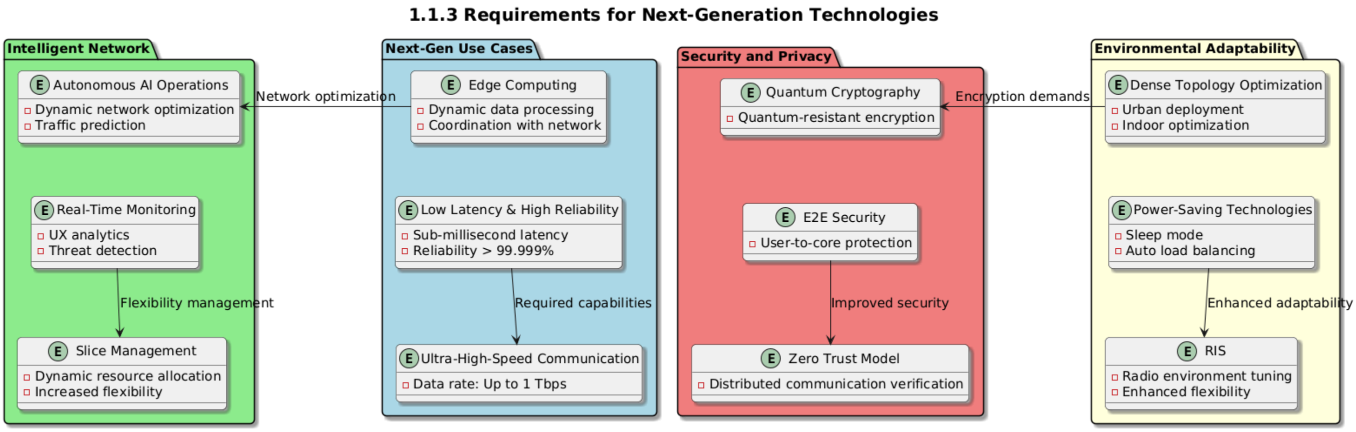
Protocol designs that ensure security from the user to the core network.

Zero Trust Model

Construction of communication frameworks based on distributed architecture in which every transmission is verified.

Diagram: Structured View of Requirements for Next-Generation Technologies

The following diagram visualizes the various dimensions of next-generation technology requirements, providing developers with a clear understanding of areas needing attention.



This visualization captures the multifaceted requirements for next-generation technologies and helps developers clearly identify areas for focused innovation.

1.2. Overview of 5G Advanced and 6G

1.2.1 Evolution Highlights of 5G Advanced

5G Advanced (from Release 18 onward) represents an evolutionary step in expanding the capabilities of 5G MCS, focusing on addressing next-generation communication demands as outlined below.

1.2.1.1 Key Technological Advancements

1. Evolution of Radio Access

- **Expanded Frequency Bands**
  Utilization of higher-frequency bands such as millimeter-wave (mmWave) and sub-THz enables ultra-wideband communication.
- **Spectrum Sharing Technologies**
  Enhances coexistence with other wireless services.
- **MU-MIMO Enhancements**
  Improves throughput in high-density areas and refines interference control.
- **AI/ML-Based Radio Control**
  Enables real-time traffic prediction and dynamic resource allocation.

2. Network Efficiency Improvements

- **Improved Energy Efficiency**
  Reduces power consumption of UEs and gNBs through techniques like sleep modes and Dual Active Protocol Stack (DAPS).
- **Enhanced Uplink (UL)**
  Increases uplink bandwidth to support video streaming and cloud gaming.
- **Integration with Edge Computing**
  Enables low-latency processing at edge nodes for applications such as V2X and industrial use cases.

3. Enhancement of Ultra-Reliable Low Latency Communication (uRLLC)

- **Ultra-Low Latency Control**
  Introduces new MAC scheduling techniques targeting sub-millisecond latency.
- **Improved Reliability**
  Prevents communication outages via multi-link connectivity and redundant paths.

1.2.1.2 Expansion of Application Domains

1. Emerging Use Cases

- **Metaverse Communication**
  Meets the demands of high-bandwidth, low-latency communication required for AR/VR and haptic interaction.
- **Smart Infrastructure**
  Extends to smart cities, drone communication, and industrial automation.

2. Evolution of IoT and mMTC (Massive Machine-Type Communication)

- **Low-Power Communication**
  Enables battery-efficient operation for long-life IoT devices.
- **Optimized Massive Connectivity**
  Manages large-scale connections without relying on cell density.

1.2.1.3 Security and Privacy

1. New Cryptographic Technologies

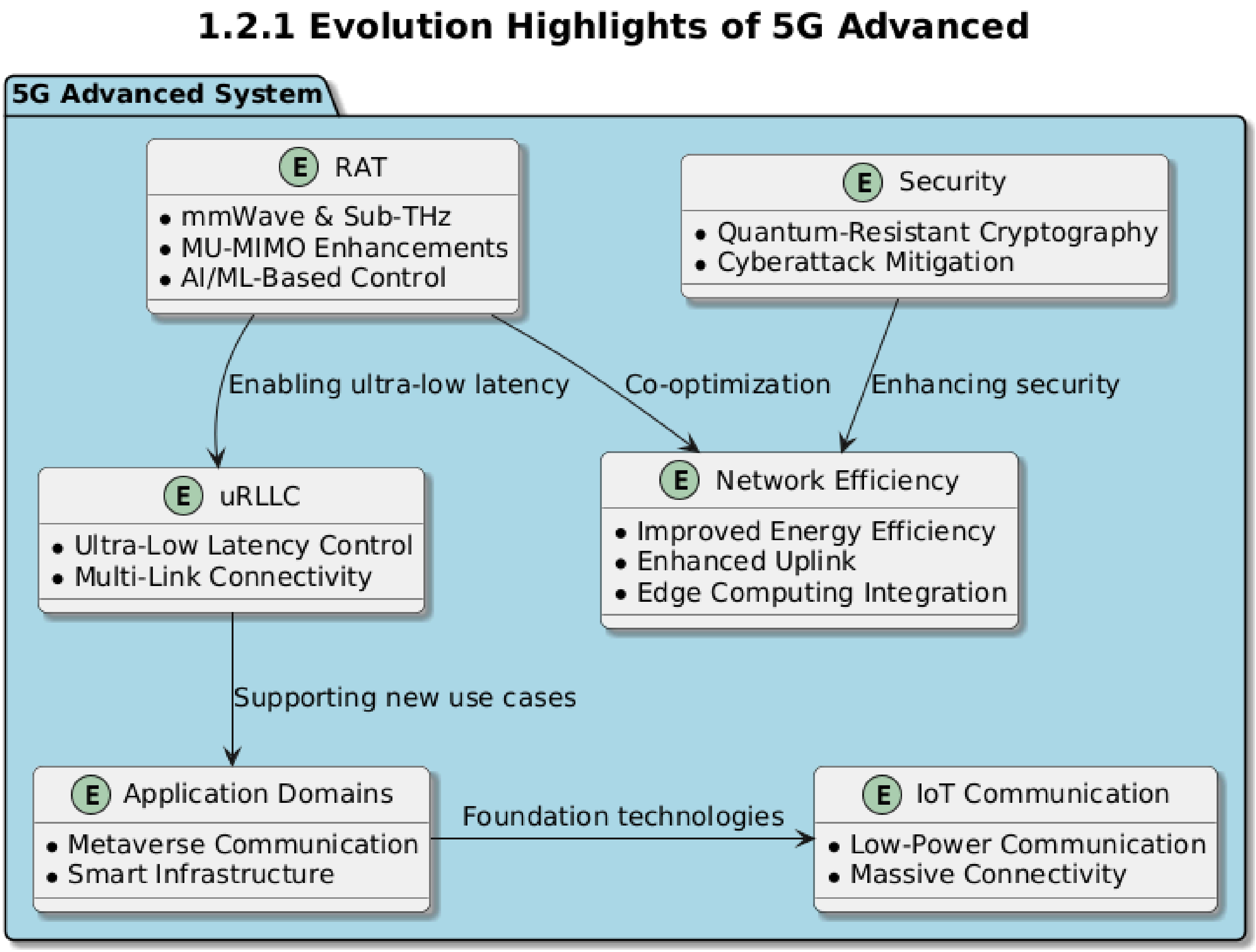
- Implements quantum-resistant cryptography.
- Ensures data protection during network segmentation.

2. Cyberattack Mitigation

- Employs AI for real-time detection and defense against cyber threats.

1.2.1.4 Diagram: Overview of Technological Evolution

The following diagram visually summarizes the evolution highlights of 5G Advanced.



This section provides a comprehensive overview of the technological evolution within 5G Advanced, focusing on both innovation and practical applications. The advancements presented here indicate continuous progress in the communications industry and underscore the broader social impact of 5G evolution.

1.2.2 Initial Outlook and Vision of 6G

Overview

6G is the next-generation mobile network that extends beyond the advancements of 5G, addressing emerging use cases, technical requirements, and societal challenges. The early outlook emphasizes the following three axes:

- **Expansion of Ubiquitous Connectivity**
  Integration of terrestrial, satellite, drone, maritime, and space communications into a comprehensive global network.
- **Ultra-Low Power and Sustainable Technologies**
  Drastically improved energy efficiency to achieve carbon neutrality.
- **Human-Centric Communications**
  Interfaces more closely aligned with human experiences, such as wearable devices, digital twins, and ultra-high-definition metaverse environments.

Technical Components

- **Utilization of New Frequency Bands**
  - Terahertz (THz) Communications: Use of frequencies above 300 GHz is under consideration to achieve ultra-high throughputs in the Tbps range.
  - Integration of Optical Communication: Development of hybrid networks combining wireless and optical transmission.
- **Integration of AI/ML**
  Full AI-driven control of the network to optimize traffic prediction, resource allocation, and fault response in real time.
- **New Architecture from Edge to Core**
  - Decentralized Networks: Edge devices will play a critical role in data processing.
  - Highly Flexible Network Slicing.
- **Quantum Communication and Security**
  - Quantum Key Distribution (QKD)-based encryption technologies.
  - Next-generation Zero Trust security models.

Use Cases

- **Advanced Metaverse and Augmented Reality (AR)**
  Realization of a “Tactile Internet” where physical and digital spaces are seamlessly integrated.
- **Autonomous Transportation and Robotics**
  Integration of ultra-precise autonomous control with low-latency communication.
- **Next-Generation Healthcare**
  Remote diagnosis, real-time patient monitoring, and personalized medical services.

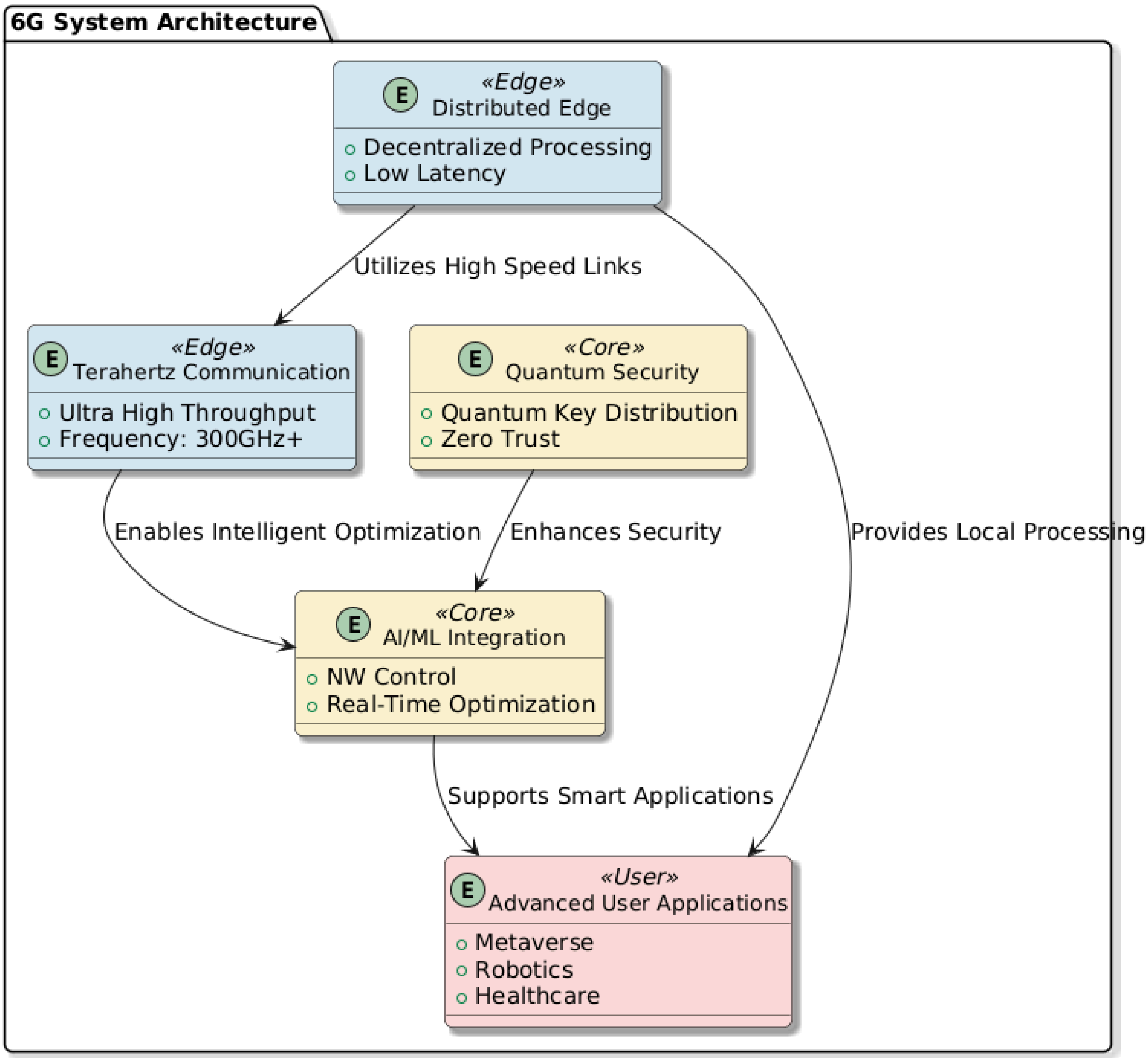
Initial Roadmap

- 2025–2030: Launch of fundamental research and standardization processes.
- Post-2030: Technology integration and trial deployments toward commercialization.

Diagram

The following diagram illustrates the key components of the initial 6G technology vision.

1.2.2 Initial Outlook and Vision of 6G



This content serves as a valuable introduction for researchers and developers to understand the early vision of 6G. The diagram visually maps the core technological elements and their interrelations.

Chapter 2: Next-Generation Use Cases

2.1 Extended Reality (XR) and the Metaverse

2.1.1 Technologies for Achieving High Throughput and Low Latency

Overview

High throughput and low latency are critical goals of 5G MCS that support next-generation use cases such as extended reality (XR) and industrial robotics. To achieve these goals, the following technologies are combined:

Technological Components for High Throughput

- **Wideband Access**
  Utilizes millimeter wave and Sub-THz bands to expand bandwidth.
- **Massive MIMO**
  Expands communication capacity through parallel transmission using a large number of antennas.
- **Network Slicing**
  Provides virtual networks optimized for each use case.

Technological Components for Low Latency

- **URLLC (Ultra-Reliable Low-Latency Communication)**
  Achieves millisecond-level latency by prioritizing control signal processing.
- **Edge Computing**
  Reduces latency by processing data near base stations or devices.
- **Time-Sensitive Networking (TSN)**
  Enables precise timing control of data flows.

Technical Details

- **Wideband Access**
  While 5G typically uses bandwidths of 100MHz to 400MHz, achieving high throughput requires even wider bandwidths. To this end, the following are being considered:
  - Sub-THz (100GHz–300GHz) Communication
    Enables expansion of bandwidth at ultra-high frequencies and supports multi-terabit-per-second transmission.
  - Improved Spectral Efficiency
    Adoption of advanced modulation schemes such as 256QAM and 1024QAM.

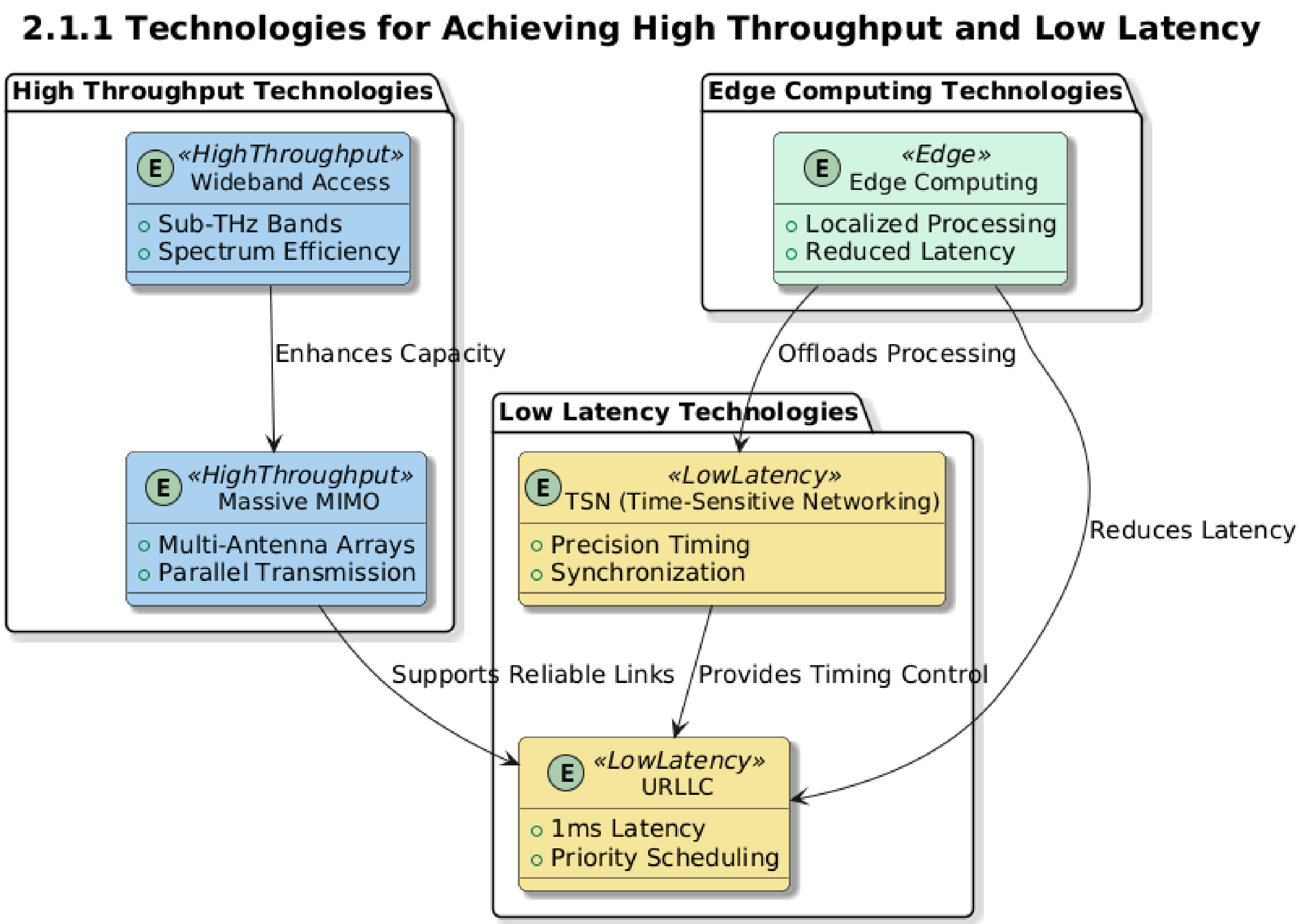
- **Implementation of URLLC**
  Industrial robots and remotely operated vehicles require latency under 1ms and high reliability. These needs are supported by the following technologies:
  - Optimization of Hybrid Automatic Repeat Request (HARQ)
  - Scheduling algorithms to minimize delay
- **Evolution of Edge Computing**
  Real-time processing is enabled by distributed computing resources at user devices and base stations. This results in a 10–20% reduction in communication latency.

Application to Use Cases

- **XR and the Metaverse**
  - Ultra-high throughput enables real-time delivery of 3D data.
  - Ultra-low latency provides a natural and immersive experience.
- **Industrial Automation**
  - Enhances synchronization accuracy in machine-to-machine (M2M) communication.
  - Enables real-time monitoring for rapid fault recovery.

Diagram

The following diagram illustrates the technological components that enable high throughput and low latency.



This content and diagram provide a clear explanation of the technological components required to achieve high throughput and low latency, serving as a practical reference for researchers and developers.

2.1.2 XR Devices and Network Requirements

Overview

Extended Reality (XR), which includes Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR), is a core technology for next-generation use cases and is regarded as a key application over 5G MCS. To ensure smooth operation of XR devices, the following network requirements must be met.

Characteristics of XR Devices

- **Ultra-High Definition Content Rendering**
  - Supports resolutions of 8K and above
  - Real-time synchronization of 360° stereoscopic video and 3D audio
- **Real-Time Interaction**
  - Ultra-low latency to support interaction between devices and users
  - Immediate reflection of motion and gaze tracking
- **Portability and Lightweight Design**
  - Standalone (fully wireless) or network-dependent devices

Network Requirements

- **High Throughput**
  - Requirement: Communication speeds of 1Gbps or higher are ideal
  - Use Case: Delivery of high-resolution streaming and cloud rendering
- **Ultra-Low Latency**
  - Requirement: End-to-end latency under 1ms
  - Use Case: Reduction of Motion-to-Photon (MTP) latency
- **Utilization of Edge Computing**
  - Requirement: Integration of cloud rendering and edge AI
  - Use Case: Lightweight devices and reduced power consumption
- **High Reliability and Stability**
  - Requirement: Maintain 99.999% connectivity
  - Use Case: Stable support for multi-user sessions
- **Flexible Network Slicing**
  - Requirement: Provision of dedicated XR slices
  - Use Case: Optimization of backend processing and end-user experience

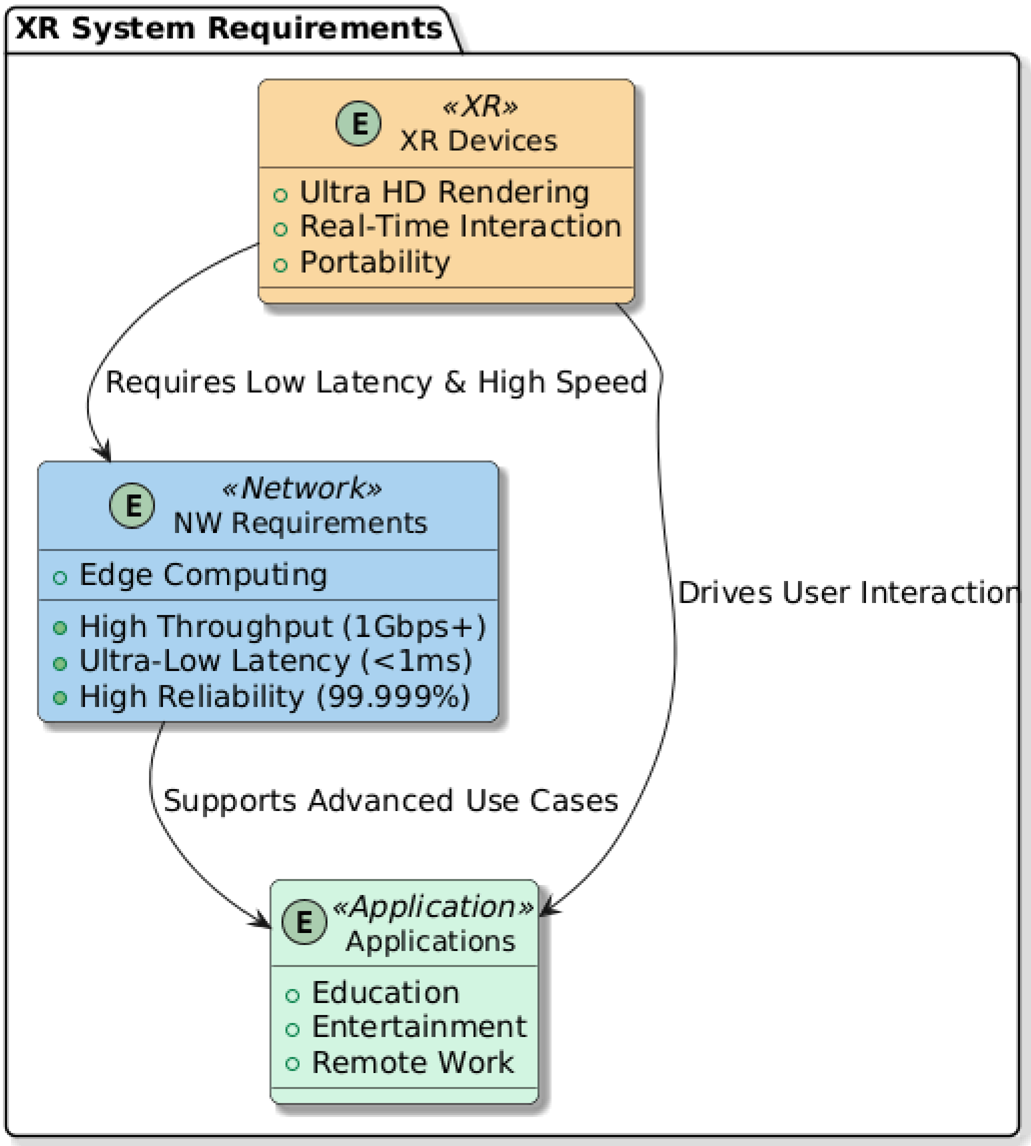
Use Cases and Application Scenarios

- Education and Training:
  Medical surgery simulations and industrial machinery training
- Entertainment:
  Real-time immersive games and live events
- Remote Work:
  Collaboration in metaverse environments

Diagram

The following diagram visualizes the relationship between XR devices and the supporting network requirements.

2.1.2 XR Devices and Network Requirements



2.1.3 Use Cases and Challenges

Overview

Use cases such as Extended Reality (XR) and the Metaverse are representative examples that utilize the high performance of 5G MCS. However, implementing these use cases in real-world commercial networks presents several challenges. The following describes specific use cases and elaborates on the technical and operational challenges.

Use Cases

- **Real-Time Remote Meetings (Virtual Office)**
  - **Example:**
    Companies hold meetings in the Metaverse where participants gather as avatars in a virtual space and share digital whiteboards and documents in real time.
  - **Requirements:**
    - Throughput: 1Gbps or more (for high-definition 3D content transmission)
    - Latency: Less than 10ms (to preserve a sense of real-time interaction)
- **Virtual Experiments in Education**
  - **Example:**
    Students in high schools or universities use XR headsets to perform chemistry experiments in virtual labs.
  - **Requirements:**
    - Throughput: 500Mbps or more
    - Latency: Less than 20ms (to enable smooth interaction without perceived delay)
- **Entertainment (XR Live Events)**
  - **Example:**
    Viewers around the world participate in the same XR live event and interact with artists in real time.
  - **Requirements:**
    - Throughput: 2Gbps or more (to support multi-user environments)
    - Latency: Less than 5ms (for ultra-low-latency bidirectional communication)

Challenges

- **Network Coverage and Backhaul**
  - **Current Situation:**
    While high throughput 5G is available in urban areas, it is often difficult to achieve sufficient communication speeds in rural or indoor environments.
  - **Solution:**
    Deploy small cells and enhance fiber optic backhaul.
- **Computing Power and Power Consumption of UE**
  - **Current Situation:**
    High-performance XR devices possess strong computing capabilities, but are limited by battery life constraints.

    - **Solution:**
      Leverage distributed computing (MEC) to reduce UE workload.
- **Scalability in Multi-User Environments**
    - **Current Situation:**
      When many XR users connect simultaneously, efficient management of network slices becomes essential.
    - **Solution:**
      Use AI/ML for dynamic network resource allocation.
- **Optimization of Quality of Experience (QoE)**
    - **Current Situation:**
      Increased latency significantly degrades user experience.
    - **Solution:**
      Further optimization of ultra-low latency communications (URLLC).

Diagram

The following diagram illustrates the key components related to XR and Metaverse use cases and their associated challenges.

2.1.3 Use Cases and Challenges