6. 5G Mobile Communication System Use Case Specific Documentation

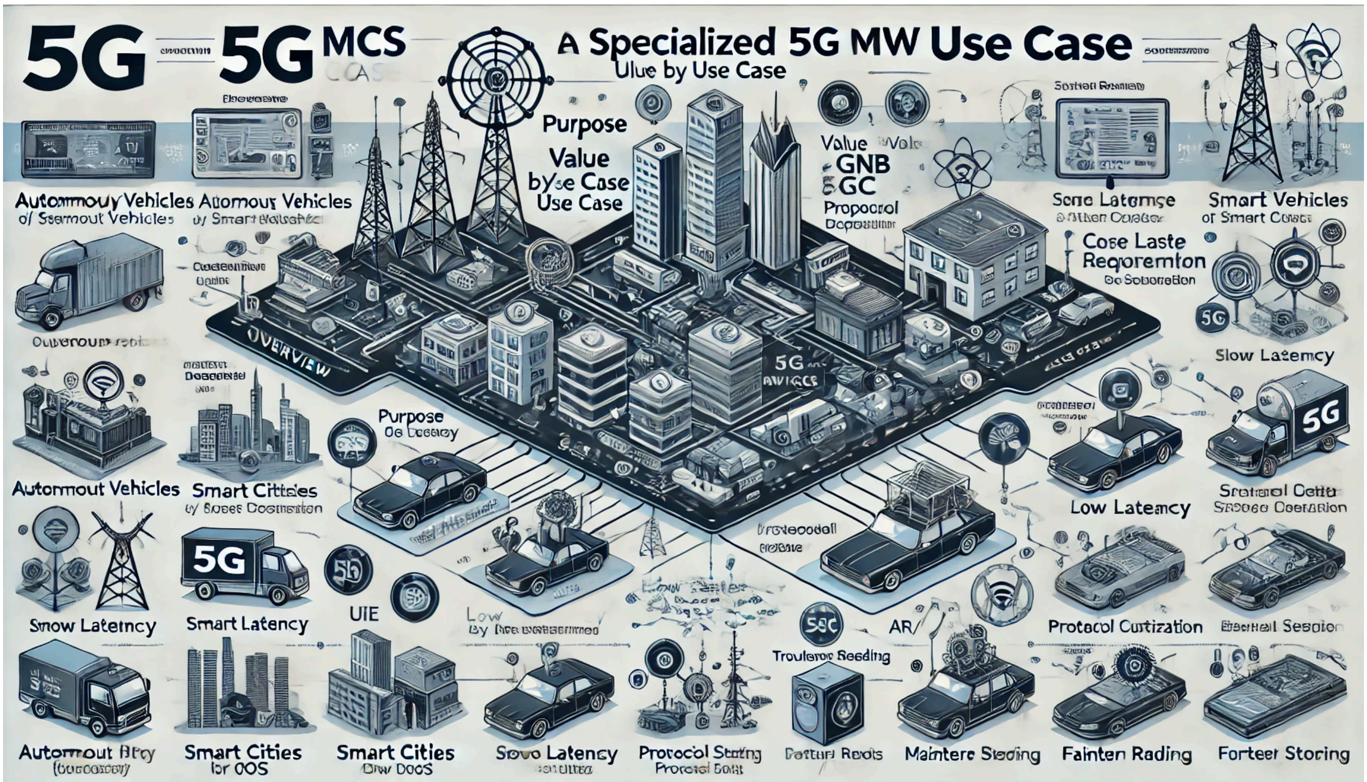


Table of contents

1. Overview

1.1 Purpose of This Document

The purpose of this document is to provide developers with the necessary design guidelines, implementation methods, testing strategies, and maintenance techniques required to build modern, high-performance, and feature-rich 5G network systems. In particular, it focuses on the following elements:

1. Use Case-Oriented Design

- Clarification of network requirements tailored to specific use cases such as autonomous vehicles, smart cities, and AR/VR
- Design methodologies for protocol stacks and network configurations based on those requirements

2. Practical Development Support

- Examples of specific modules and methods for customizing protocol stacks that are helpful during development
- Efficient utilization of edge computing and QoS configurations

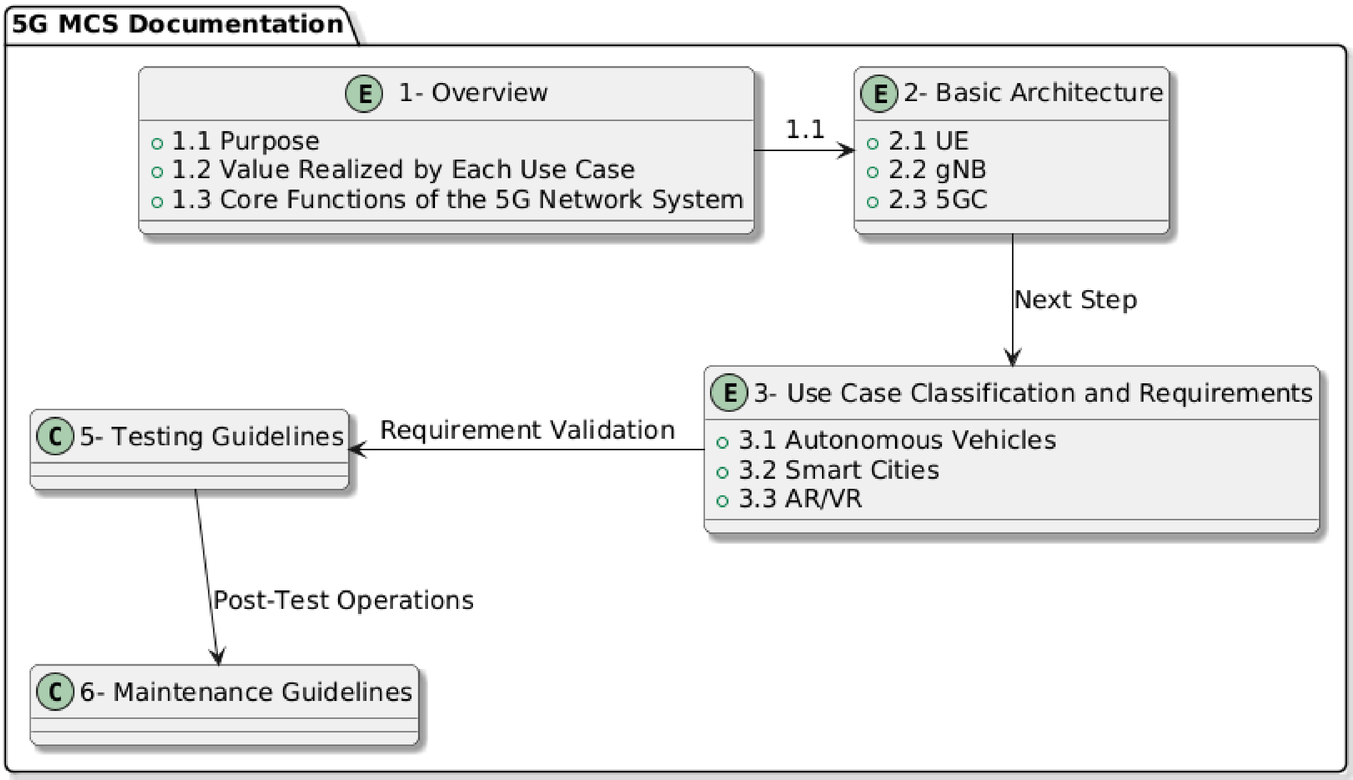
3. Guidelines for Testing and Verification

- Suggestions for field-applicable test cases including performance testing, security testing, and end-to-end (E2E) testing

4. Maintenance and Optimization

- Methods for troubleshooting and maintenance planning aimed at improving operational efficiency and network reliability

The following diagram visually represents the structure of this document.



1.2 Value Realized by Each Use Case

1.2.1 Value in Autonomous Vehicles

- **Enabling Low-Latency Communication:**
  Enables vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, providing real-time control.
- **High Reliability:**
  Supports collision avoidance systems and emergency communications.
- **Optimized Bandwidth:**
  Enables efficient data delivery through dynamic resource allocation.

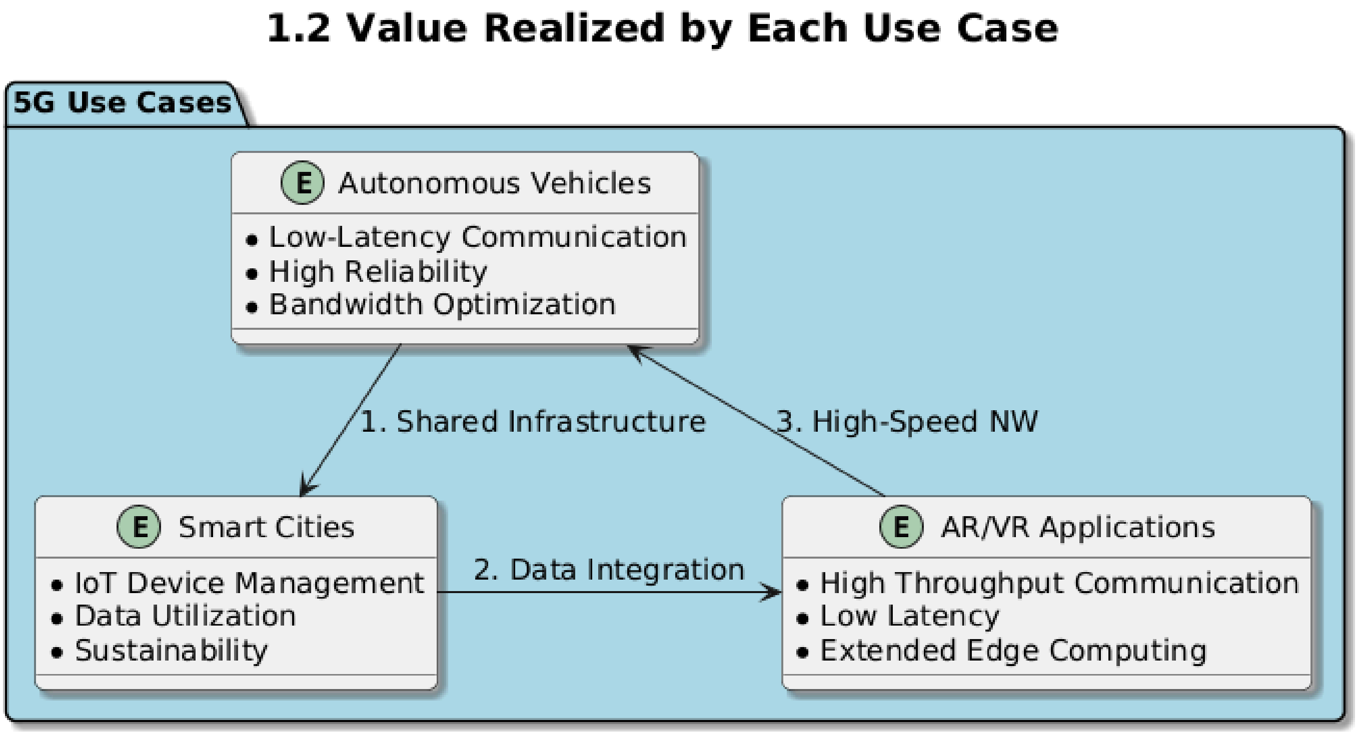
1.2.2 Value in Smart Cities

- **Efficient IoT Device Management:**
  Allows integration of large-scale IoT sensors, optimizing urban management.
- **Advanced Data Utilization:**
  Improves traffic flow and energy usage through real-time analysis using edge computing.
- **Contribution to Sustainability:**
  Adopts green network technologies to reduce environmental impact.

1.2.3 Value in AR/VR Applications

- **High Throughput Communication:**
  Enables ultra-high-definition streaming, enhancing immersion.
- **Importance of Low Latency:**
  Ensures responsive user interactions.
- **Extended Edge Computing:**
  Improves efficiency and responsiveness in content delivery.

Figure: Relationship Diagram of Value Realization Across Use Cases



1.2.4 Explanation of the Diagram

The diagram above illustrates the interrelationships between key 5G-enabled use cases: Autonomous Vehicles, Smart Cities, and AR/VR Applications. It visualizes how each use case builds upon 5G technology to enhance mutual value.

1. Autonomous Vehicles → Smart Cities: "Shared Infrastructure"

Overview:

The low-latency, high-reliability communication infrastructure and sensor data processing required by autonomous vehicles can be supported by leveraging the communication infrastructure of smart cities (e.g., roadside units, traffic control systems).

Example:

V2V and V2I communications for autonomous vehicles become more effective when integrated with IoT networks provided by smart cities. This enables real-time sharing of traffic signal data and road conditions.

2. Smart Cities → AR/VR Applications: "Data Integration"

Overview:

The vast data collected and managed by smart cities (e.g., environmental and traffic data) enables sophisticated AR/VR services.

Example:

Using smart city infrastructure data, applications like in-city AR navigation and immersive VR tourism experiences can be provided, creating new value through data sharing.

3. AR/VR Applications → Autonomous Vehicles: "High-Speed NW"

Overview:

The high-throughput, low-latency communication environment required by AR/VR applications contributes to the real-time control and in-vehicle entertainment systems of autonomous vehicles.

Example:

New-generation services such as augmented reality driving guides or immersive VR experiences for passengers become possible through AR technologies integrated into autonomous vehicle interfaces.

1.2.5 Intent of the Diagram

This diagram emphasizes how 5G networks enable mutual complementarity across use cases, generating synergies such as:

- **Shared Infrastructure:**
  Infrastructure and data from one use case are utilized by others.
- **Data Integration:**
  Data exchange between different use cases creates new value.
- **Technological Versatility:**
  Core 5G features (low latency, high reliability, high throughput) benefit multiple use cases in common.

In this way, it demonstrates how 5G technology forms the foundation for generating new societal value.

1.3 Core Functions of the 5G Network System

5G MCS incorporates advanced technologies and design principles to meet the demands of next-generation communication. This section describes the core system functions. It focuses on the key components—UE, gNB, and 5GC—and explains their roles and capabilities in detail.

Core Functions

UE (User Equipment)

UI:
The primary interface enabling users to access the network. Integration with applications and services is crucial.

Data Communication Management:
Efficient management of data transmission and reception. Ensures communication quality and secures necessary bandwidth.

Energy Efficiency:
Implements algorithms that minimize power consumption during communication to extend battery life.

gNB (Next-Generation Node B)

Radio Interface Management:
Manages wireless communication between UE and the network. Optimizes signal processing and ensures efficient use of radio spectrum.

Traffic Control:
Dynamically adjusts traffic prioritization to maintain network stability under increased load.

QoS (Quality of Service) Management:
Allocates resources appropriately to meet the requirements of each session, such as low latency and high throughput.

5GC (5G Core)

Session Management:
Establishes user communication sessions and optimizes network resource usage. Supports dynamic session control.

Network Slicing:
Creates virtual networks tailored for different use cases (e.g., autonomous driving, IoT), ensuring service quality.

Edge Computing Support:
Executes data processing at the edge to minimize latency and enable real-time communication.

Supplementary Functions

Security

Data Encryption: Protects communication data from UE to 5GC.

Authentication: Ensures the trustworthiness of users and devices through robust authentication procedures.

Operations Management

Performance Monitoring: Monitors the performance of the entire network and optimizes operations.

Fault Detection and Recovery: Enables rapid recovery and root cause analysis in the event of system failures.

System Flow Overview

Communication between UE and gNB

UE establishes a connection with the gNB through signal processing and transmits communication data.

The gNB dynamically allocates resources to maintain communication quality.

Session Management between UE and 5GC

Connection requests sent from the UE are processed by the 5GC, where sessions are established.

Data Exchange between gNB and 5GC

The gNB forwards control-plane (C-Plane) data to the 5GC, which then applies the appropriate network slice.

Security and Operations Management

While ensuring security, the 5GC uses operations management functions to monitor the overall network status.

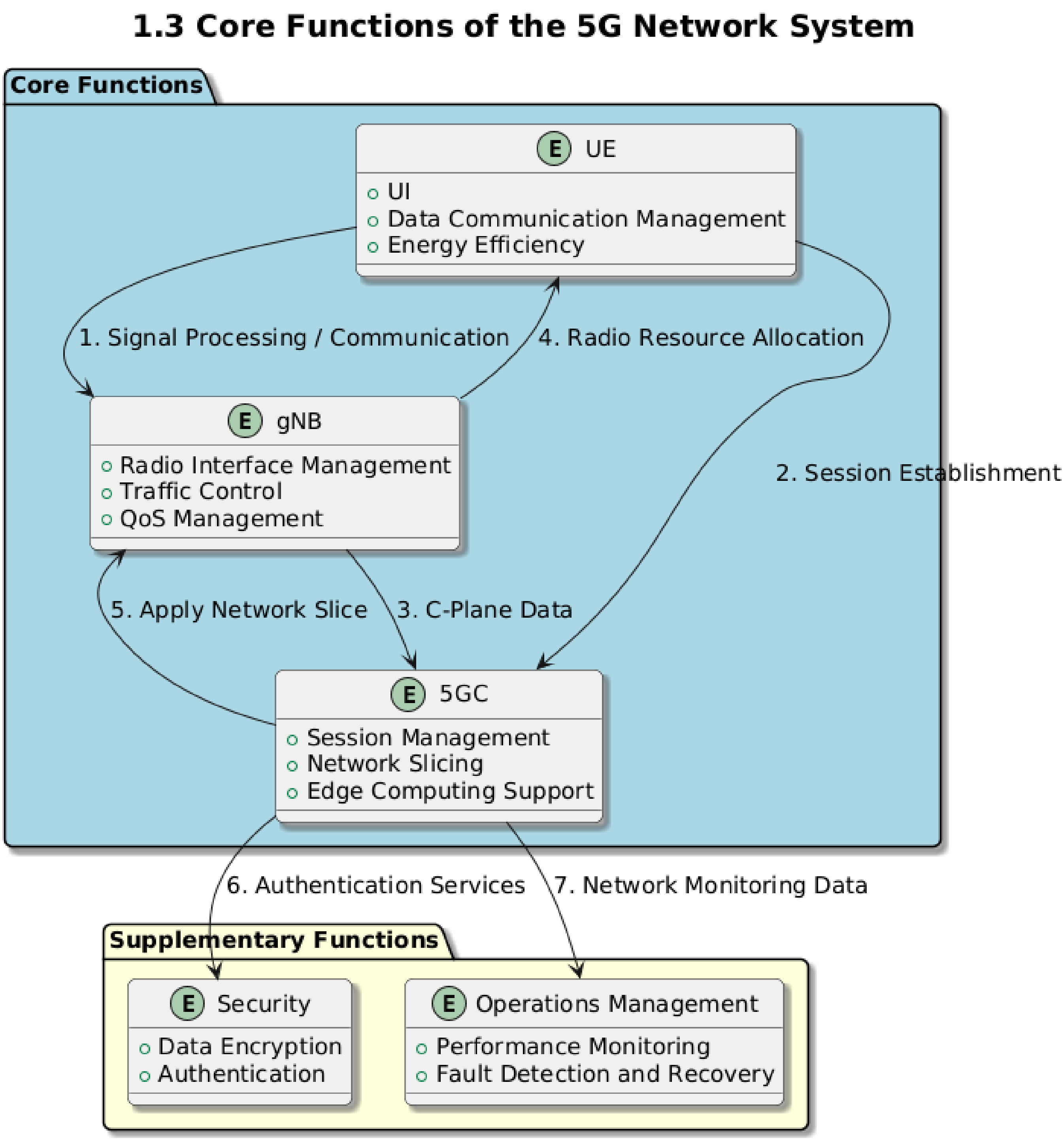


Diagram Explanation

The diagram above illustrates the functions and their interactions.
Each entity (UE, gNB, 5GC, and supplementary functions) is organized according to its role.
The arrows indicate the flow of each process, with annotations describing the communication sequence.
Through the diagram and explanation, the core functions of the 5G MCS can be clearly understood.
This diagram highlights the functional relationships among UE, gNB, and 5GC while also incorporating supplementary functions like security and operations management.

2. Basic Structure

2.1 Overview of UE, gNB, and 5GC

The 5G MCS mainly consists of the following three core components. Their roles and functions are described in detail below.

1. UE

Overview:
The UE is the device directly operated by the user and communicates with the 5G network. This includes smartphones, IoT devices, AR/VR devices, and more.
Main Functions:

- Application Access: Enables access to network services through various applications.
- Wireless Signal Transmission/Reception: Establishes communication with the gNB and transmits/receives data.

2. gNB

Overview:
The gNB is the 5G base station and plays a crucial role in connecting the UE to the 5GC. It manages radio resources, controls traffic, and supports real-time data transfer.
Main Functions:

- Radio Resource Management:
  Allocates resources to UEs and applies QoS (Quality of Service).
- Data Transfer Control:
  Optimizes user data communication and ensures stable connectivity.

3. 5GC

Overview:
The 5GC is the central part of the network, responsible for overall control and management. It handles session management, mobility control, and supports network slicing.
Main Functions:

- Session Management:
  Establishes and maintains sessions for data communication.
- Network Slice Control:
  Enables separation and optimization of the network for specific use cases.
- Mobility Management:
  Maintains and optimizes connectivity as the UE moves.

2.1.2 Roles of Supporting Components

Auxiliary functions supporting the 5G MCS are also crucial.

Security Functions
Ensure secure communication through authentication and encryption.
Main Functions:

- Authentication:
  Verifies that the UE is a legitimate user.
- Encryption:
  Protects communication data.

2.1.3 QoS Management

Maintains service quality and supports individual use cases through network slicing.
Main Functions:

- Service Quality Assurance:
  Ensures appropriate bandwidth and delay control.
- Network Slice Application:
  Provides optimized network conditions for each use case.

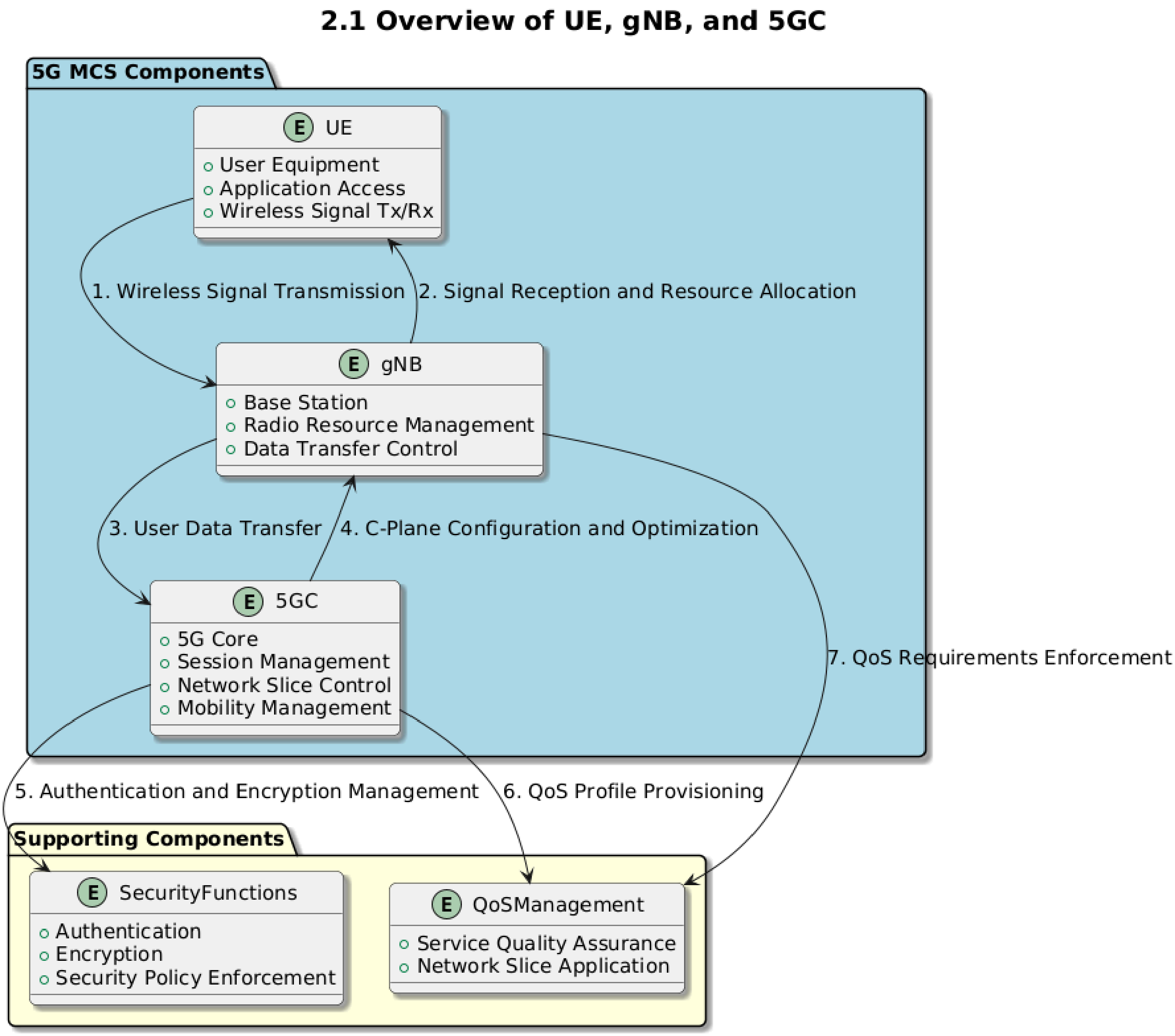
2.1.4 System Flow Description

- UE → gNB:
  The user device sends wireless signals to the gNB.
- gNB → UE:
  The gNB processes received signals and allocates resources.
- gNB → 5GC:
  The gNB transfers user data to the 5GC.
- 5GC → gNB:
  The 5GC performs control plane configuration and optimization and sends instructions to the gNB.
- 5GC → Security Functions / QoS Management:
  The 5GC applies security and QoS profiles to ensure communication quality and safety.

2.1.5 Significance of This Structure

- Flexibility:
  Enables flexible network configuration through network slicing and QoS management.
- Scalability:
  The inclusion of supporting components allows adaptation to a wide range of use cases.
- Efficiency:
  Achieves high-speed and low-latency communication through edge processing and resource management.
  This architecture provides a highly reliable communication foundation for diverse 5G network use cases.

2.1.6 Diagram


2.1 Overview of UE, gNB, and 5GC
5G MCS Components
UE
User Equipment
Application Access
Wireless Signal Tx/Rx
1. Wireless Signal Transmission
2. Signal Reception and Resource Allocation
gNB
Base Station
Radio Resource Management
Data Transfer Control
3. User Data Transfer
4. C-Plane Configuration and Optimization
5GC
5G Core
Session Management
Network Slice Control
Mobility Management
7. QoS Requirements Enforcement
5. Authentication and Encryption Management
6. QoS Profile Provisioning
Supporting Components
SecurityFunctions
Authentication
Encryption
Security Policy Enforcement
QoSManagement
Service Quality Assurance
Network Slice Application

2.2 Structure of the Protocol Stack

The 5G network adopts a multi-layered protocol stack structure combining various layers from the UE to the gNB and the 5GC to achieve high-speed and low-latency communication. This structure clearly separates the roles of each layer, enhances flexibility and efficiency, and meets the unique requirements of 5G.

Overview of Protocol Layers (Basic Structure)

Application Layer

Role: Handles data requests from user applications.
Key Protocols:

- HTTP/2: Next-generation protocol enabling high-speed data transfer.
- QUIC: UDP-based transport protocol designed for low-latency communication.

Transport Layer

Role: Manages data transmission by session and ensures reliable delivery.
Key Protocols:

- UDP: Supports lightweight and fast data delivery.
- TCP: Guarantees reliable data transmission.

Network Layer

Role: Manages data routing and forwarding.
Key Protocols:

- IP: Fundamental protocol for data transmission between networks.
- GTP-U: Tunnels user plane data.

Data Link Layer

Role: Frames data and converts it into a transmittable format for the physical layer.
Key Protocols:

- RLC: Supports reliable data transmission.
- MAC: Manages efficient usage of radio resources.

Physical Layer

Role: Performs actual wireless communication by converting data into signals.
Key Technologies:

- OFDM (Orthogonal Frequency Division Multiplexing): Modulation scheme for high-speed transmission.
- MIMO (Multiple Input Multiple Output): Enhances performance using multiple antennas.

Uu Interface (Between UE and gNB) Protocol Layers

NAS Layer

- 5GMM: Manages mobility, authentication, and session management.
- 5GSM: Handles session establishment, maintenance, and release.

AS Layer

- RRC: Allocates and manages radio resources.
- SDAP: Manages QoS flows and maps them to the data link layer.

- PDCP: Performs encryption and compression of data.
- RLC: Implements retransmission control for reliable delivery.
- MAC: Schedules data transmission.
- PHY: Handles sending and receiving of radio signals.

Classification of Protocol Layers over the Uu Interface

Protocol	Layer	Role
5GMM	Network Layer	Provides mobility, authentication, and session management.
5GSM	Network Layer	Handles session lifecycle.
RRC	Network Layer	Manages radio resources and connection control.
PDCP	Data Link Layer	Provides encryption, compression, and alignment.
RLC	Data Link Layer	Implements retransmission control for reliable delivery.
MAC	Data Link Layer	Manages radio resource scheduling and channel access.
PHY	Physical Layer	Transmits data as radio signals and demodulates received signals.

Protocol Layers between gNB and 5GC (NG Interface) and within 5GC

NG Interface (Between gNB and 5GC)

- **Control Plane**
  - NGAP: For control signal exchange.
  - SCTP: Provides reliable control plane communication.
  - IP: For routing in the network layer.
  - L2 (Ethernet): For data link communication.
- **User Plane**
  - GTP-U: Tunnels user data.
  - UDP: Lightweight transport layer protocol.
  - IP: For network layer routing.
  - L2 (Ethernet): Data link layer.

Within 5GC (Service-Based Architecture)

- HTTP/2: Communication between NFs (Network Functions).
- REST API: Enables service-based interaction.
- TCP/UDP: Transport layer protocols.

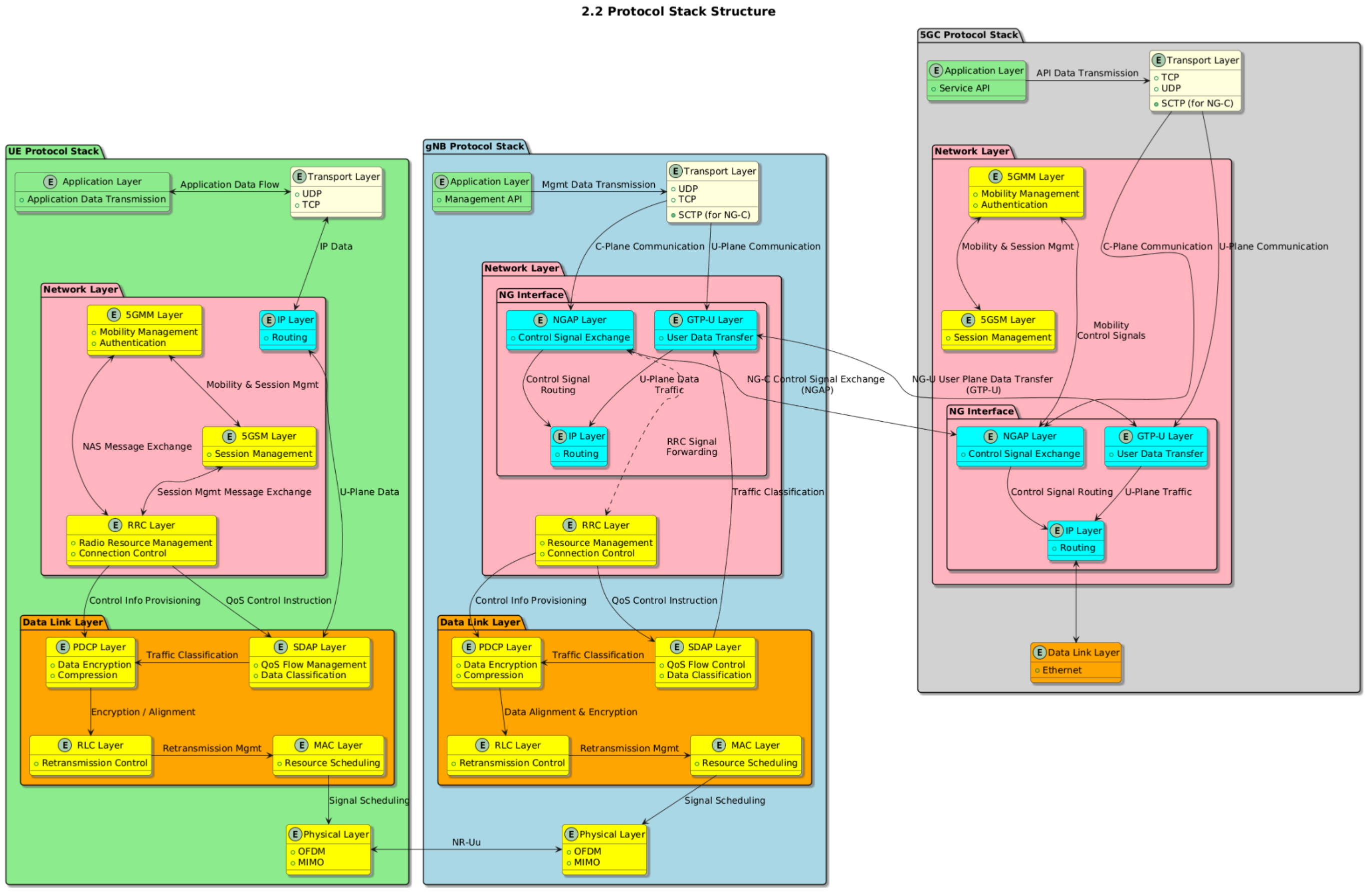
Protocol Stack Operational Flow

1. The application layer generates a data transmission request.
2. The transport layer encapsulates it into a packet.
3. The network layer adds routing information.
4. The data link layer frames the data and converts it to a transmittable signal.

5. The physical layer sends it as a radio signal; the reverse is performed during reception.

Through this structure, the 5G protocol stack achieves high-speed, low-latency communication with flexibility. Understanding the functions and relationships among the layers in the UE, gNB, and 5GC enables optimal network design and tuning.

Diagram of Protocol Stack



2.3 Network Flow Diagram

This diagram visualizes the flows involved in registration and authentication, session establishment, data communication, and auxiliary services within a 5G network. The key steps are described in detail below.

1. Registration and Authentication Flow

1. Registration Request:
The UE sends a Registration Request to the gNB to initiate network connection.

2. Forwarding Registration Request:
The gNB forwards the request to the 5GC.

3. Authentication Challenge:
The 5GC (specifically, the AMF) sends an Authentication Challenge to the UE, including authentication parameters (RAND, AUTN).

4. Authentication Response:
The UE generates encryption keys (CK, IK, K_AMF) using the received information and returns the response (RES*) to the 5GC.

5. Security Mode Command Indication:
The 5GC sends instructions for security configuration to the gNB to establish secure communication with the UE.

6. Security Mode Command:
The gNB sends a Security Mode Command to the UE, enabling encryption and integrity protection.

7. Security Mode Complete:
The UE notifies that security setup is complete.

8. Security Setup Complete Notification:
The gNB reports completion of the setup to the 5GC.

9. Registration Accept / 10. Registration Complete:
The 5GC sends a Registration Accept message to the UE, granting access to the network, and the UE replies with a Registration Complete message.

2. Session Establishment Flow

11. PDU Session Establishment Request:
The UE sends a session establishment request to the gNB to initiate data communication.

12. Forwarding the PDU Session Request:
The gNB forwards the request to the 5GC.

13. Session Setup Indication:
The 5GC (SMF) sends session setup instructions to the gNB.

14. Session Setup Complete Notification:
The gNB notifies the UE that the session has been successfully established.

3. Data Communication Flow

15. Data Transmission:
The UE sends encrypted data to the gNB.

16. Data Flow Control:
The gNB manages the data flow and forwards it to the 5GC.

17. QoS Application Indication:
The 5GC sends QoS application instructions for data transmission to the gNB.

18. Data Delivery:
The gNB delivers data to the UE.

4. Auxiliary Service Flow

Authentication Info Verification:
The 5GC sends authentication info to the authentication server (AUSF) for verification.

Authentication Success Response:
The authentication server returns a success response to the 5GC.

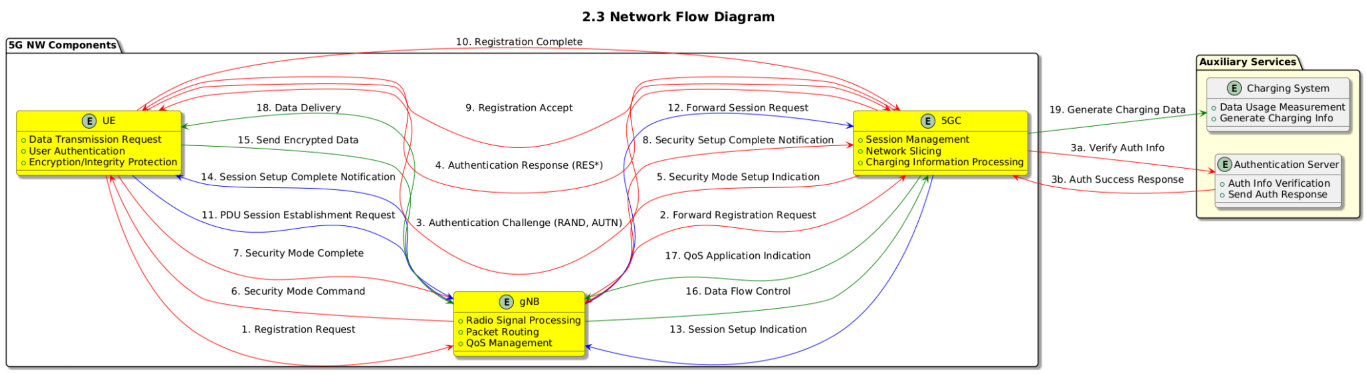
Charging Data Generation:
The 5GC sends usage information to the charging system to generate billing data.

Diagram Highlights

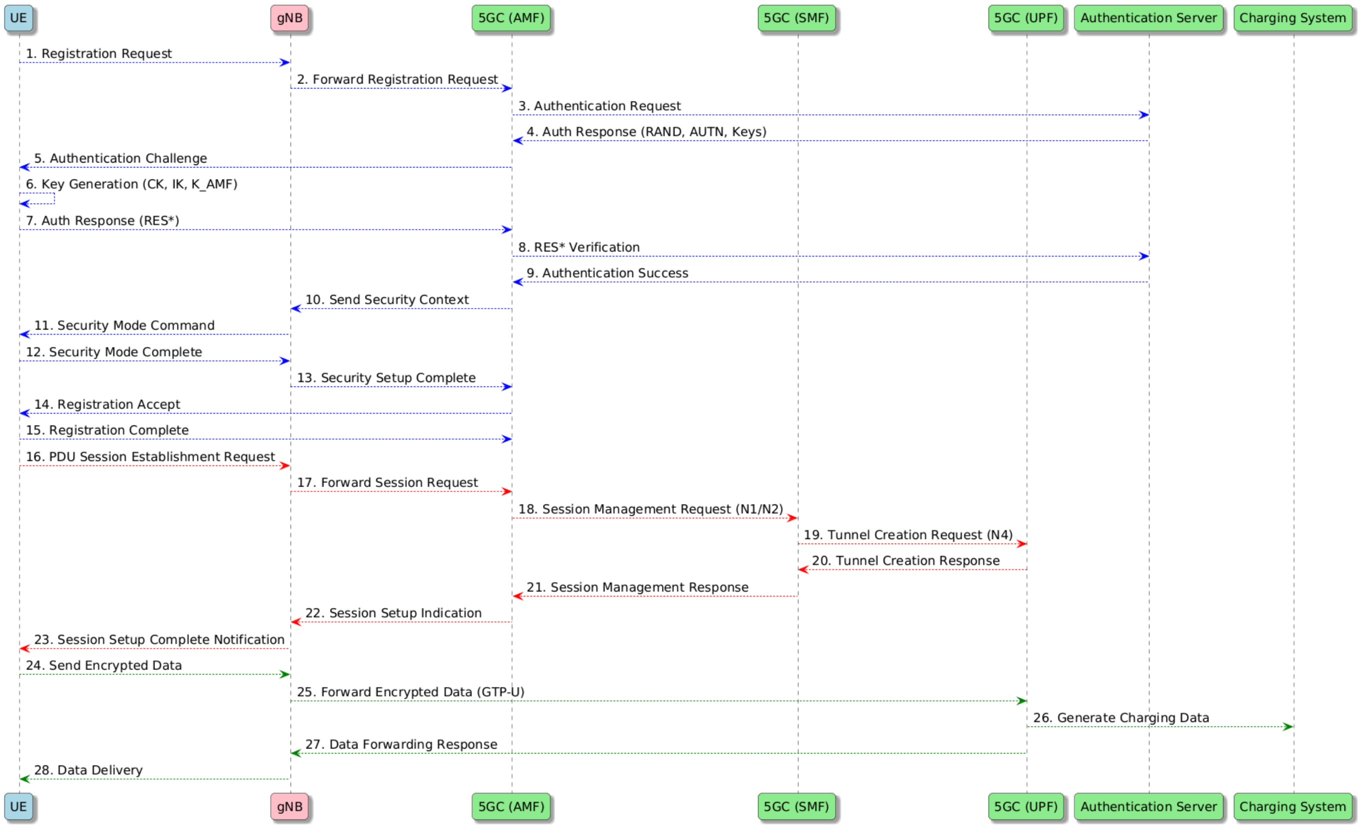
Roles of each component (UE, gNB, 5GC) are clearly defined.

- Main flows such as registration, session setup, and data communication are color-coded in red, blue, and green respectively.
- Auxiliary services (authentication server and charging system) are shown operating in the network backend.

This flow diagram comprehensively illustrates basic 5G network processes and the interactions between services.



2.3 Network Flow Sequence Diagram



3. Use Case Classification and Requirements

3.1 Autonomous Vehicles

3.1.1 Importance of Low Latency

Overview

Low latency is a particularly critical feature in the 5G network use case of autonomous vehicles (AVs). In environments where real-time communication is required for vehicle control, collision avoidance, and coordination, network latency directly affects safety and operational efficiency. This section provides a detailed technical explanation of the importance of low latency.

Necessity of Low Latency in Use Cases

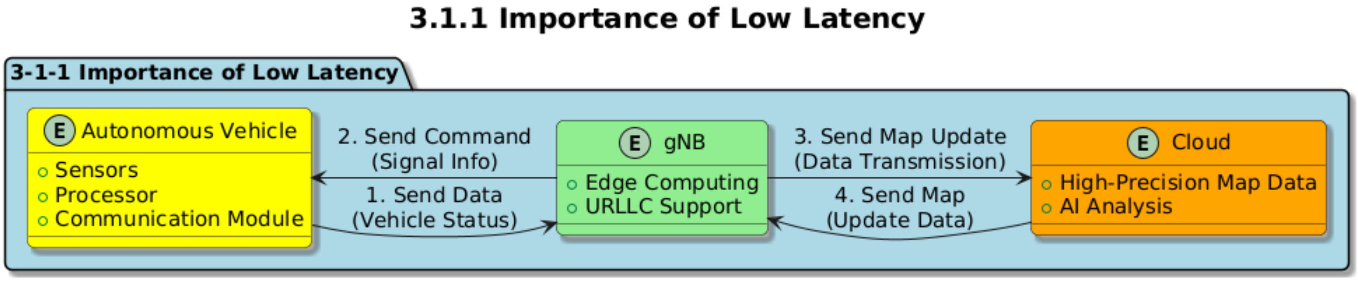
1. **Vehicle-to-Vehicle Communication (V2V)**
   Low latency is required for the following scenarios:
   - Collision Avoidance: Immediate response to braking signals from other vehicles within milliseconds.
   - Platooning: When vehicles travel in a convoy on highways, low-latency communication enables real-time sharing of speed and position information.
2. **Vehicle-to-Infrastructure Communication (V2I)**
   - Real-Time Coordination with Traffic Signals: Instantly notify vehicles of signal changes to optimize control.
   - Notification of Road Conditions: Immediate reception of obstacle or traffic accident information.
3. **Cloud Integration**
   - High-Precision Map Updates: Instantly retrieve map data from cloud servers.
   - Sharing of AI Analysis Results: Send sensor data to the cloud for analysis and reflect results in real-time driving behavior.

Technical Challenges

To achieve low latency, the following technical challenges must be addressed:

- **Network Architecture**
  - Use of edge computing to process data near the gNB.
  - Adoption of mesh-type networks to shorten communication paths.
- **Protocol Optimization**
  - Optimization of RLC and PDCP layers.
  - Use of URLLC (Ultra-Reliable Low Latency Communication).
- **Hardware Acceleration**
  - Adoption of high-performance modems and processors.
  - Reducing latency in DRAM and SRAM.

Architecture for Low Latency



Conclusion

Low latency is essential for ensuring the safety and efficiency of autonomous vehicles. When designing and implementing 5G networks, it is crucial to minimize latency by leveraging technologies such as edge computing and URLLC.

3.1.2 Integration with On-Demand Networks

Overview

Autonomous vehicles require real-time, highly adaptive network coordination to improve safety and efficiency. 5G networks support ultra-low latency and high reliability through tight integration with on-demand network slices and edge computing resources. This section explains the need for on-demand networking in AVs, its components, communication flow, and design considerations.

Need for On-Demand Networks

AVs require on-demand networking in the following scenarios:

- **Accident Avoidance:**
  In emergencies, ensure low-latency communication for prompt V2V and V2I interaction.
- **Traffic Congestion Mitigation:**
  Dynamically allocate communication resources to distribute route information to nearby vehicles efficiently.
- **Support for Diverse QoS:**
  Build slices tailored to use cases such as video streaming and high-precision map sharing.

Key Components

- **5GC:**
  Handles network slice management, PCF, and UPF.
- **gNB:**
  Enables wireless connectivity and local processing (edge computing).
- **Vehicle On-Board Unit (OBU):**
  Manages communication on the vehicle side.
- **MEC Node:**
  Minimizes latency and provides local services.

Communication Flow

- **Resource Request from Vehicle:**
  The vehicle requests dynamic slice resources.
- **Slice Assignment by gNB:**

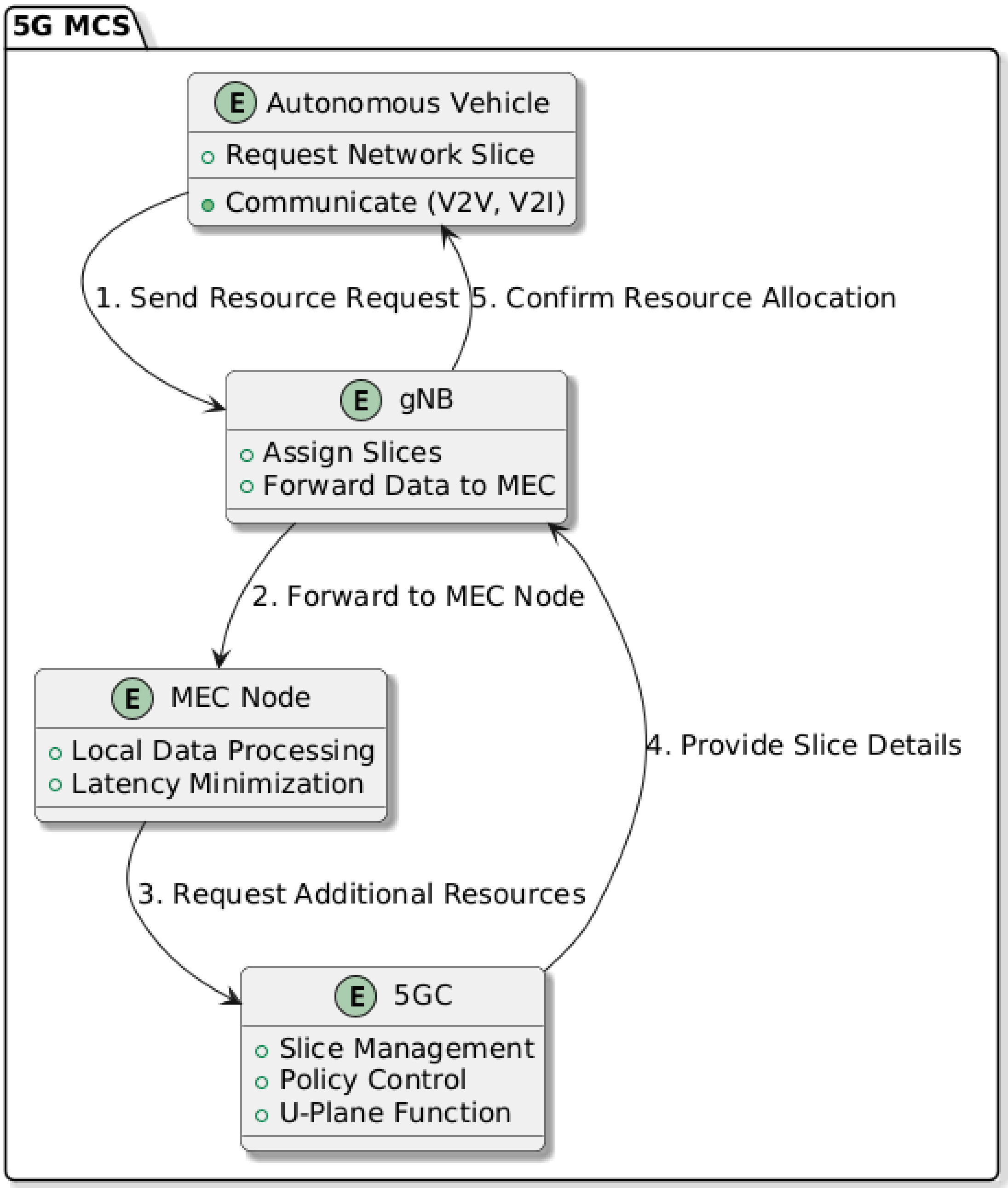
Assigns optimal slices based on the vehicle's situation.

- **Local Processing at MEC:**
  Processes required data at the edge.
- **Resource Control by 5GC:**
  Core Network manages resource allocation.

Design Considerations

- **Flexible Slice Design:**
  Dynamically create slices based on vehicle density and traffic volume.
- **Edge-Core Coordination:**
  Balance local processing at the edge and resource management in the core.
- **Security Enhancements:**
  Protect the communication path from vehicle to core network.

3.1.2 Integration with On-Demand Networks



3.1.3 QoS Design Guidelines

Overview of Design Guidelines

Communication in autonomous vehicles requires high reliability and low latency. Therefore, QoS design should be based on the following points:

- **URLLC (Ultra-Reliable Low Latency Communication)**
  - High reliability (packet loss rate: <10^-5)
  - Ultra-low latency (round-trip <1ms)
- **Network Slicing**
  - Provide dedicated bandwidth and QoS policies for AVs.
  - Meet multiple QoS requirements simultaneously (low latency and high throughput).

- **Edge Computing**
  - Process data at the edge to minimize delay.
  - Ensure instant response in V2X communications.
- **Priority Control**
  - Set packet priority based on importance.
  - Ensure emergency control signals take precedence over other traffic.

System Flow Explanation

As shown in the diagram, data sent from the autonomous vehicle reaches the edge server through the 5G network for real-time processing. The results are returned to the control unit, enabling immediate reaction.

Future Expansion Points

- Enhanced Security: End-to-end encryption across the network.
- High Throughput Communication: Combine URLLC with eMBB for hybrid communication.

3.1.3 QoS Design Guidelines - For Autonomous Vehicles