

# ***5G/6G Enabled Embedded Applications for Ultra Reliable Low Latency***

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## ***Abstract***

*The evolution of wireless communication from 4G to 5G and now towards 6G is not only improving data rates but also drastically reducing latency and increasing reliability. These features are very important for embedded systems which are deployed in real-time critical applications such as autonomous vehicles, remote surgery, smart grids, industrial automation and unmanned aerial systems. Ultra Reliable Low Latency Communication (URLLC) is one of the key service categories defined in 5G and is expected to be more enhanced in 6G networks. This paper reviews how 5G and future 6G networks support embedded applications requiring ultra reliable and very low latency communication. The paper discusses architecture, enabling technologies, protocols, edge computing integration, and major application domains. Limitations, design challenges and future research directions are also presented. Tables and figures are included for better understanding of system interaction between embedded devices and 5G/6G infrastructure.*

## ***Keywords***

*5G, 6G, URLLC, Embedded Systems, Edge Computing, Real-Time Systems, IoT, Autonomous Systems, Industrial Automation*

## **1. INTRODUCTION**

Embedded systems are small computing units designed to perform dedicated functions inside larger systems. Traditionally, these systems were isolated or connected through wired

communication. With the rise of Internet of Things (IoT), embedded devices started relying on wireless networks for real time data exchange.

However, many embedded applications like robotic control, medical devices, and vehicle control systems cannot tolerate delays more than few milliseconds. Packet loss or jitter may lead to serious failure. This requirement leads to the need of Ultra Reliable Low Latency Communication (URLLC).

5G introduced URLLC as a service class, targeting latency less than 1 ms and reliability up to 99.999%. Future 6G networks are expected to reduce latency even below 0.1 ms with intelligence integrated in network. This makes wireless links suitable for critical embedded applications which were earlier possible only through wired networks.

## 2. URLLC REQUIREMENTS IN EMBEDDED APPLICATIONS

Ultra Reliable Low Latency Communication (URLLC) is specially designed to meet the strict timing and reliability demands of embedded systems working in real-time environments.

Unlike normal IoT or mobile data services, embedded control systems interact with physical processes where even a small delay, jitter, or packet loss can lead to unsafe conditions or system failure. Hence, URLLC requirements are much more stringent and deterministic.

### 2.1 Latency Requirement (End-to-End Delay)

Latency refers to the total time taken for a data packet to travel from the embedded device (sensor/actuator) to the controller and back.

- Typical URLLC target in 5G:  $\leq 1$  ms
- Expected in 6G:  $\leq 0.1$  ms
- Includes: transmission delay + processing delay + queuing delay + propagation delay

#### **Why it matters:**

In applications like robotic arm motion control, vehicle braking system, or drone stabilization, control commands must reach actuators almost instantly. A delay of even 10–20 ms can cause instability or wrong actuation.

#### **Example:**

A robotic gripper adjusting pressure based on sensor feedback requires response within microseconds to avoid damaging the object.

## 2.2 Reliability Requirement (Packet Success Probability)

Reliability means the probability that a packet is delivered successfully within the required time.

- URLLC reliability target: **99.999% (five nines)** or higher
- Packet loss rate: less than  **$10^{-5}$**

### Why it matters:

In remote surgery or smart grid protection systems, losing a control packet may lead to life-threatening situations or equipment damage.

### Example:

If a fault signal from a power grid sensor is not delivered in time, breakers may not trip, causing cascading failures.

## 2.3 Jitter (Variation in Delay)

Jitter is the variation in packet delay over time.

- Required to be **extremely low and predictable**
- Deterministic communication is preferred over best-effort delivery

### Why It Matters:

Control algorithms in embedded systems assume constant sampling intervals. Variable delay disturbs control loops and may cause oscillations.

### Example:

Autonomous vehicles exchanging position data must receive updates at constant intervals for accurate trajectory planning.

## 2.4 Deterministic Communication

Embedded systems often operate using real-time operating systems (RTOS) where tasks are scheduled with precise timing. Communication also must follow deterministic behavior.

- Guaranteed time slots
- Reserved bandwidth using network slicing
- Time Sensitive Networking (TSN) integration with 5G

**Why it matters:**

Factories using wireless robotic arms need the same determinism that wired Ethernet previously provided.

**2.5 High Availability and Redundancy**

URLLC systems require the network to be always available with minimal downtime.

- Multi-connectivity (device connected to multiple base stations)
- Redundant paths for packet transmission
- Seamless handover

**Why it matters:**

In UAV control or vehicle communication, losing connection even for a second is unacceptable.

**2.6 Energy Efficiency for Embedded Nodes**

Many embedded devices are battery powered or energy constrained.

- Short packet transmission
- Grant-free uplink reduces signaling overhead
- Efficient sleep and wake cycles

**Why it matters:**

Sensors deployed in remote industrial plants or smart agriculture must operate for years without battery replacement.

**2.7 Small Packet Handling**

Embedded systems usually send small control packets instead of large data streams.

- URLLC is optimized for **short packet transmission**
- Reduced protocol overhead
- Faster processing

**Example:**

A temperature sensor sending 8 bytes of data every millisecond.

**Table 1: Embedded applications demand:**

Requirement	Typical Value	Application Example
Latency	< 1 ms	Robotic arm control
Reliability	99.999%	Remote surgery
Jitter	Very low	Autonomous vehicles
Deterministic behavior	Required	Industrial automation
Energy efficiency	High	Battery IoT nodes

These parameters are difficult to achieve in legacy wireless networks but are primary goals of 5G/6G.

### 3. 5G ARCHITECTURE SUPPORTING EMBEDDED SYSTEMS

5G network architecture is fundamentally different from previous generations because it is designed not only for high data rates but also for **ultra-reliable, deterministic, and low latency communication**. These characteristics make 5G highly suitable for embedded systems that require real-time control, fast feedback, and dependable wireless links.

The key architectural features of 5G that directly benefit embedded communication are explained below.

#### 3.1 Network Slicing

Network slicing allows multiple **virtual networks** to run on the same physical 5G infrastructure. Each slice is configured with its own Quality of Service (QoS), bandwidth, latency, and reliability parameters.

##### How it works

- The physical network is divided logically using Software Defined Networking (SDN) and Network Function Virtualization (NFV).
- Each slice is optimized for a particular service type such as eMBB, mMTC, or URLLC.
- Embedded URLLC devices are assigned to a dedicated slice where traffic is isolated from normal mobile users.

### **Benefits for Embedded Systems**

- Guaranteed bandwidth and latency
- Isolation from congestion caused by consumer traffic
- Deterministic communication behavior
- Custom security policies per slice

#### **Example:**

In a smart factory, robotic arms, AGVs, and sensors operate on a URLLC slice, while employee smartphones operate on a different slice. This prevents interference and ensures stable control signals.

### **3.2 Edge Computing (Multi-access Edge Computing – MEC)**

In traditional networks, data from embedded devices travels to a distant cloud server for processing, which adds delay. 5G introduces MEC where computation and storage are placed **very close to the radio access network**.

#### **How it works**

- Edge servers are deployed at or near the 5G base station (gNB).
- Sensor data from embedded nodes is processed locally.
- Only necessary information is forwarded to central cloud.

#### **Benefits for Embedded Systems**

- Significant reduction in round-trip delay
- Faster decision making for control loops
- Reduced backhaul traffic
- Local AI inference for predictive control

#### **Example:**

A vision sensor on a production line sends images to the edge server where AI detects defects instantly and sends stop command to actuator within 1 ms.

### **3.3 Massive MIMO and Beamforming**

5G uses a large number of antennas at the base station (Massive MIMO) and directs signals in specific directions using beamforming.

#### **How it works**

- Multiple antennas transmit the same signal with phase adjustments.

- Focused beams are directed towards embedded devices.
- Improves signal strength and reduces interference.

#### **Benefits for Embedded Systems**

- Higher link reliability
- Lower packet loss probability
- Better coverage in industrial environments with metal obstructions
- Stable connectivity for moving devices (robots, drones, vehicles)

#### **Example:**

An autonomous guided vehicle (AGV) moving inside a warehouse maintains a strong link with the base station because the beam follows its movement.

### **3.4 Flexible Numerology and Short TTI**

5G introduces flexible numerology, meaning different subcarrier spacing and symbol durations can be used. This allows shorter Transmission Time Intervals (TTI).

#### **How it works**

- Subcarrier spacing options: 15, 30, 60, 120 kHz
- Larger spacing → shorter symbol time → faster transmission
- Mini-slots allow transmission without waiting for full slot

#### **Benefits for Embedded Systems**

- Reduced air interface delay
- Faster scheduling of urgent packets
- Suitable for small and frequent control messages
- Supports real-time responsiveness

#### **Example:**

A sensor sends emergency fault data using mini-slot transmission without waiting for regular time slot, reducing delay drastically.

## **4. 6G VISION FOR EMBEDDED APPLICATIONS (ELABORATED)**

While 5G has introduced URLLC and edge computing for real-time embedded communication, 6G is envisioned to go much beyond by embedding **intelligence, sensing, extreme spectrum usage, and near-instant communication** directly into the network

fabric. For embedded systems that interact with physical processes in real time, 6G will act not only as a communication medium but also as a **distributed intelligent control layer**.

The following key capabilities of 6G are expected to significantly enhance mission-critical embedded applications.

#### 4.1 AI-Driven Network Management

6G networks are expected to be **AI-native**, meaning artificial intelligence will be integrated into every layer of the network for self-optimization, fault prediction, traffic control, and resource allocation.

##### How it helps embedded systems

- Predictive allocation of bandwidth before congestion occurs
- Intelligent routing of control packets through the fastest path
- Automatic detection of link degradation and instant rerouting
- Learning traffic patterns of embedded devices for better scheduling

##### Example:

In an industrial plant, the network learns the periodic communication pattern of robotic arms and pre-allocates resources exactly when needed, avoiding delay and packet collision.

#### 4.2 Terahertz (THz) Communication

6G is expected to use Terahertz frequency bands (0.1–10 THz) which offer extremely high bandwidth and ultra-fast data transmission.

##### Advantages

- Data rates in Tbps range
- Extremely low transmission time
- Suitable for high-density embedded sensor networks
- High precision localization due to short wavelengths

##### Embedded relevance

Although THz has limited range, it is ideal for **indoor environments** like factories, hospitals, laboratories where many embedded devices operate in close proximity.

**Example:**

Hundreds of sensors and actuators in a smart factory communicate simultaneously without interference using THz links.

**4.3 Sub-Millisecond and Microsecond Latency**

6G aims to reduce end-to-end latency to **hundreds of microseconds** or even lower.

**How this is achieved**

- Advanced air interface design
- AI-based scheduling
- On-device and edge intelligence
- Integrated communication and computation

**Embedded impact**

This enables wireless links to behave almost like **direct electrical connections**, making them suitable for very tight control loops.

**Example:**

A drone swarm maintaining formation in air requires microsecond-level coordination between units.

**4.4 Integrated Sensing and Communication (ISAC)**

One revolutionary concept in 6G is combining sensing and communication in the same signal.

**What this means**

- Radio signals used for communication also detect position, motion, and environment
- No need for separate sensors like radar or lidar in some cases
- Real-time environmental awareness through the network

**Benefits to embedded systems**

- Reduced hardware complexity
- Accurate localization and tracking
- Better situational awareness for autonomous systems

**Example:**

An autonomous vehicle uses 6G signals not only to communicate but also to sense nearby obstacles and road conditions.

**4.5 Holographic and Tactile Communication**

6G is expected to support holographic communication and advanced tactile internet.

**Features**

- Real-time transmission of touch, motion, and 3D visuals
- Extremely high data rate with ultra-low latency
- Accurate replication of physical actions over network

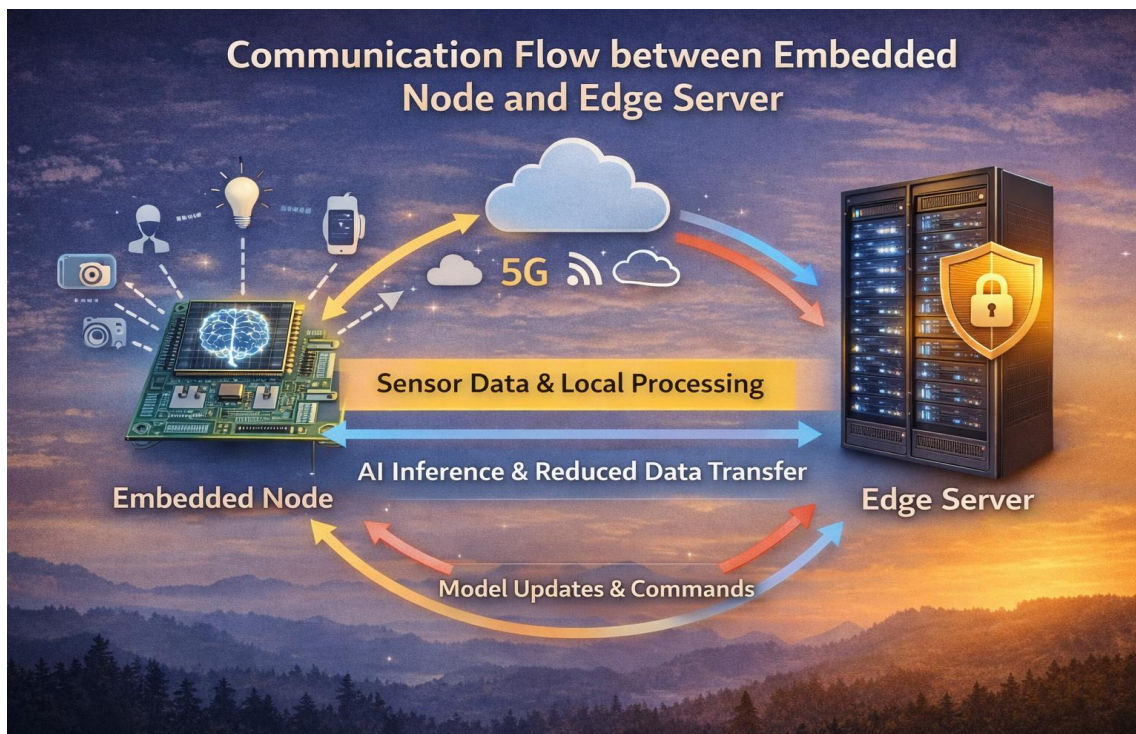
**Embedded application relevance**

- Remote robotic surgery with realistic touch feedback
- Teleoperation of heavy machinery
- Virtual presence in hazardous environments

**Example:**

A surgeon operates robotic instruments in a distant location while feeling the tissue feedback as if physically present.

**5. INTERACTION BETWEEN EMBEDDED DEVICES AND 5G/6G NETWORK**



*Figure 1: Communication flow between embedded node and edge server.*

## 6. APPLICATION AREAS

### 6.1 Autonomous Vehicles

Vehicles need real time information exchange with other vehicles and infrastructure. Delay more than few milliseconds can cause accidents.

### 6.2 Remote Surgery

Robotic surgical tools controlled over network need extremely reliable link with no packet loss.

### 6.3 Industrial Automation (Industry 4.0)

Wireless control of machines, AGVs, robotic arms inside factories.

### 6.4 Smart Grid Systems

Fault detection and protection in power systems.

### 6.5 UAV and Drone Control

Remote navigation and surveillance.

## 7. ROLE OF EDGE COMPUTING

Edge computing reduces distance between embedded device and processing unit.

Feature	Cloud Computing	Edge Computing
Latency	High	Very Low
Processing	Centralized	Distributed
Reliability	Moderate	High
Suitable for URLLC	No	Yes

## 8. PROTOCOL STACK OPTIMIZATION FOR EMBEDDED URLLC

Traditional TCP/IP is not suitable for real time. 5G introduces:

- Short packet transmission
- Grant free uplink access
- Hybrid ARQ
- Preemptive scheduling

These improve deterministic communication.

## 9. CHALLENGES IN IMPLEMENTATION

### 9.1 Hardware Constraints

Embedded devices have limited power and memory.

### 9.2 Network Congestion

Multiple devices may create traffic load.

### 9.3 Security Issues

Critical systems require strong encryption but encryption adds delay.

### 9.4 Synchronization

Precise time synchronization is needed.

## 10. COMPARISON OF 4G, 5G AND 6G FOR EMBEDDED USE

Feature	4G	5G	6G (Expected)
Latency	50 ms	1 ms	0.1 ms
Reliability	99%	99.999%	99.99999%
Data Rate	100 Mbps	10 Gbps	1 Tbps
Edge Support	No	Yes	Intelligent Edge

## 11. DESIGN CONSIDERATIONS FOR EMBEDDED ENGINEERS

- Use lightweight protocol stacks
- Implement hardware acceleration
- Adopt time sensitive networking
- Use local buffering and fail-safe modes
- Integrate AI at edge for prediction

## 12. FUTURE RESEARCH DIRECTIONS

- AI based traffic prediction
- Secure URLLC protocols
- Energy efficient 6G transceivers
- Digital twin of embedded systems

- Integration with satellite networks

### **13. CASE STUDY: SMART FACTORY ROBOT CONTROL**

In smart factory, robotic arm is controlled wirelessly through 5G URLLC slice. Edge server processes sensor feedback and sends control commands within 1 ms. This reduces wiring complexity and improves flexibility of layout.

### **14. LIMITATIONS**

Even with 5G, coverage issues, interference and cost of infrastructure are limitations. 6G may reduce these but research is ongoing.

### **15. DISCUSSION**

The shift from wired deterministic networks to wireless URLLC is a big change for embedded systems. Reliability which was once impossible over wireless is now becoming practical. This opens new design opportunities but also needs new thinking in system architecture.

### **16. CONCLUSION**

5G and upcoming 6G technologies are transforming embedded applications by providing ultra reliable and ultra low latency communication. Applications like autonomous driving, remote surgery, industrial robotics and smart grids are now possible with wireless links. Integration of edge computing, network slicing and AI will further enhance performance. However, design challenges related to security, power and synchronization still exist. Future research in 6G and intelligent networking will make embedded systems more powerful and flexible than ever before.

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