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Low-latency communication protocols for industrial IoT

Mamatha Kotagi [1,*], Raghunath [1] and Kavitha N Mudnal [2]

[1] *Department of Electronics and Communication Engineering, Government Polytechnic, Kalaburagi, Karnataka, India.*
[2] *Department of Electronics and Communication Engineering, Government Polytechnic, Raichur, Karnataka, India.*

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Abstract

The Industrial Internet of Things (IIoT) requires robust, efficient, and low-latency communication protocols to enable seamless real-time data transmission, ensuring reliability, scalability, and interoperability across industrial environments. This paper provides a comprehensive exploration of various low-latency communication protocols, including Time-Sensitive Networking (TSN), MQTT-SN, OPC UA over TSN, and 5G Ultra-Reliable Low-Latency Communications (URLLC). Each protocol is analyzed in terms of its architecture, performance characteristics, and suitability for industrial applications such as smart manufacturing, predictive maintenance, and industrial automation. Furthermore, this study examines the advantages and limitations of each protocol, addressing key factors such as latency, jitter, bandwidth efficiency, security, and integration challenges. Comparative analyses using figures, tables, and bar charts illustrate the performance of these protocols in different IIoT scenarios. The paper also highlights emerging trends in IIoT communication, including the convergence of edge computing, artificial intelligence, and software-defined networking to further enhance real-time decision-making. Finally, potential research directions and future advancements in IIoT communication protocols are discussed, providing insights into the evolving landscape of industrial networking.

Keywords: Industrial IoT (IIoT); Low-Latency Communication; Time-Sensitive Networking (TSN); MQTT-SN; OPC UA over TSN; 5G URLLC

1. Introduction

The Industrial Internet of Things (IIoT) has revolutionized manufacturing and industrial processes by integrating advanced sensor networks, data analytics, and cloud computing to enhance efficiency, reliability, and automation. IIoT enables seamless connectivity between machines, devices, and control systems, allowing industries to optimize operations, reduce downtime, and improve decision-making through real-time data insights. As industries transition towards smart factories and Industry 4.0, the demand for efficient and low-latency communication protocols has become increasingly critical to support real-time monitoring, predictive maintenance, and autonomous industrial operations.

Low-latency communication plays a vital role in ensuring the success of IIoT applications, particularly in industrial automation, robotics, and control systems. In applications such as robotic assembly lines, autonomous guided vehicles (AGVs), and industrial motion control, even minor delays in data transmission can lead to significant inefficiencies, operational failures, or safety hazards. Therefore, IIoT networks require robust communication protocols that offer minimal delay, high reliability, and deterministic performance to meet the stringent requirements of industrial environments.

* Corresponding author: Mamatha Kotagi

Several communication protocols have been developed to address the low-latency needs of IIoT. Time-Sensitive Networking (TSN) extends traditional Ethernet with deterministic capabilities, ensuring precise timing and synchronized communication across industrial networks. Similarly, MQTT-SN (Message Queuing Telemetry Transport for Sensor Networks) optimizes lightweight messaging for low-power IIoT devices while maintaining low-latency transmission. Another significant protocol, OPC UA over TSN, enhances industrial interoperability and real-time data exchange by combining the flexibility of OPC Unified Architecture (OPC UA) with the deterministic capabilities of TSN. Additionally, 5G Ultra-Reliable Low-Latency Communications (URLLC) introduces high-speed wireless connectivity with minimal latency, enabling IIoT applications in dynamic and remote environments.

Each of these protocols has specific advantages, trade-offs, and implementation challenges, depending on the industrial use case. TSN is highly effective in wired industrial networks that require precise synchronization, while MQTT-SN is particularly suitable for low-power wireless sensor networks. OPC UA over TSN enhances cross-platform compatibility while ensuring deterministic performance, making it ideal for complex industrial automation systems. Meanwhile, 5G URLLC expands IIoT connectivity by providing low-latency, high-reliability wireless communication, facilitating mobile robotics, remote control systems, and large-scale industrial deployments.

Despite their benefits, implementing low-latency communication protocols in IIoT presents several challenges. Network congestion, jitter, security vulnerabilities, and interoperability issues can hinder seamless communication and real-time decision-making. Industrial environments often consist of heterogeneous systems, requiring standardized and flexible protocols that can integrate with legacy infrastructures while supporting next-generation automation technologies. Additionally, scalability and energy efficiency remain key concerns, especially for battery-powered IIoT devices and large-scale deployments[1].

To address these challenges, industries are increasingly adopting hybrid communication architectures that combine multiple protocols to optimize performance based on specific application requirements. The integration of edge computing and artificial intelligence (AI) further enhances IIoT communication by processing data closer to the source, reducing latency, and enabling intelligent decision-making. Future advancements in software-defined networking (SDN), network slicing, and machine learning-based network optimization are expected to further improve the reliability and efficiency of IIoT communication protocols.

This paper aims to provide a comprehensive analysis of key low-latency communication protocols, exploring their architectural features, performance characteristics, and industrial applications. Through comparative evaluations using figures, tables, and bar charts, the study highlights the strengths and limitations of each protocol and their suitability for different IIoT scenarios. The paper also discusses emerging trends, technological innovations, and future research directions that could shape the next generation of industrial communication networks.

By examining the role of low-latency communication in IIoT, this research contributes to a deeper understanding of how advanced networking technologies can drive industrial digital transformation. The findings of this study are expected to provide valuable insights for engineers, researchers, and industry professionals seeking to optimize IIoT network performance, enhance automation efficiency, and achieve greater reliability in industrial operations[2].

2. Related works

The Industrial Internet of Things (IIoT) has witnessed significant advancements in low-latency communication protocols, with various studies exploring their effectiveness in real-time industrial applications. Researchers have analyzed the performance, scalability, and reliability of communication technologies such as Time-Sensitive Networking (TSN), MQTT-SN, OPC UA over TSN, and 5G Ultra-Reliable Low-Latency Communication (URLLC) in diverse industrial settings. This section reviews key related works and presents a comparative analysis of different protocols in a tabular format.

Time-Sensitive Networking (TSN): Several studies have highlighted the role of TSN in providing deterministic Ethernet-based communication for industrial automation. Research by Zhang et al. (2022) examined TSN's ability to reduce jitter and latency in real-time control systems, showing its superiority over traditional Ethernet. However, TSN's reliance on wired infrastructure limits its flexibility in dynamic industrial environments.

MQTT-SN (Message Queuing Telemetry Transport for Sensor Networks): MQTT-SN has been explored for low-power IIoT applications due to its lightweight nature and efficient messaging capabilities. A study by Lee et al. (2021) demonstrated MQTT-SN's effectiveness in reducing network overhead and improving energy efficiency for wireless sensor networks (WSNs). However, the study also pointed out potential challenges in handling large-scale deployments with strict latency requirements.

OPC UA over TSN: The combination of OPC UA and TSN has been studied extensively for industrial automation and interoperability. Research by Müller et al. (2023) evaluated its impact on industrial control systems, highlighting how it enhances data exchange reliability while maintaining deterministic communication. Despite its advantages, integrating OPC UA over TSN with legacy systems remains a challenge.

5G URLLC (Ultra-Reliable Low-Latency Communication): Several studies have explored 5G's potential for IIoT applications. A study by Patel et al. (2022) demonstrated that 5G URLLC significantly reduces end-to-end latency and improves mobility support, making it suitable for mobile robotics and remote industrial control. However, concerns regarding deployment costs and network coverage still need to be addressed[3].

The table below provides a comparative overview of these low-latency communication protocols based on key parameters:

Table 1 Comparative overview of low-latency communication protocols

Protocol	**Latency**	**Reliability**	**Scalability**	**Energy Efficiency**	**Infrastructure**	**Best Use Cases**
TSN	Low (<1ms)	High	Moderate	Moderate	Wired (Ethernet)	Real-time control, industrial automation
MQTT-SN	Moderate	Moderate	High	High	Wireless	Low-power sensor networks, remote monitoring
OPC UA over TSN	Low (<2ms)	High	Moderate	Moderate	Wired (Ethernet)	Interoperable industrial automation
5G URLLC	Very Low (<1ms)	Very High	High	Low to Moderate	Wireless (5G)	Mobile robotics, remote industrial control

This comparison highlights the strengths and trade-offs of each protocol in terms of latency, reliability, scalability, and energy efficiency. TSN and OPC UA over TSN excel in deterministic wired networks, while MQTT-SN is well-suited for energy-efficient wireless applications. Meanwhile, 5G URLLC provides unparalleled low-latency and mobility benefits but comes with higher deployment costs.

Future research should focus on integrating these protocols to create hybrid communication architectures that optimize performance for specific IIoT use cases. Additionally, advancements in AI-driven network management, edge computing, and 6G technology could further enhance the reliability and efficiency of IIoT communication networks.

3. Communication Protocols for Low-Latency IIoT

The Industrial Internet of Things (IIoT) requires communication protocols that provide low latency, high reliability, and scalability to support real-time applications such as industrial automation, predictive maintenance, and remote control systems. This section discusses four key communication protocols—Time-Sensitive Networking (TSN), MQTT-SN, OPC UA over TSN, and 5G Ultra-Reliable Low-Latency Communication (URLLC)—that enable efficient and deterministic data exchange in IIoT environments[4].

3.1. Time-Sensitive Networking (TSN)

Time-Sensitive Networking (TSN) is an extension of standard Ethernet that introduces deterministic communication capabilities for industrial networks. It is designed to provide predictable data transmission by ensuring low latency, reduced jitter, and high reliability, making it ideal for time-critical IIoT applications. TSN employs time synchronization and traffic scheduling mechanisms to guarantee the timely delivery of messages, even in congested network conditions.

3.1.1. Key Features:

- Time Synchronization: TSN ensures that all devices in an industrial network operate in a synchronized manner using the IEEE 802.1AS standard.

- Traffic Shaping: Implements mechanisms such as time-aware shaping (IEEE 802.1Qbv) to prioritize critical data packets.
- Fault Tolerance: Supports redundancy and seamless failover mechanisms for network reliability.

3.1.2. Use Cases

- Industrial automation and process control.
- High-precision motion control in manufacturing.
- Smart factories requiring synchronized communication between robotic systems.

3.1.3. Performance Metrics

- Achieves latencies below 1 millisecond in real-time control loops.
- Provides deterministic data delivery with minimal jitter.

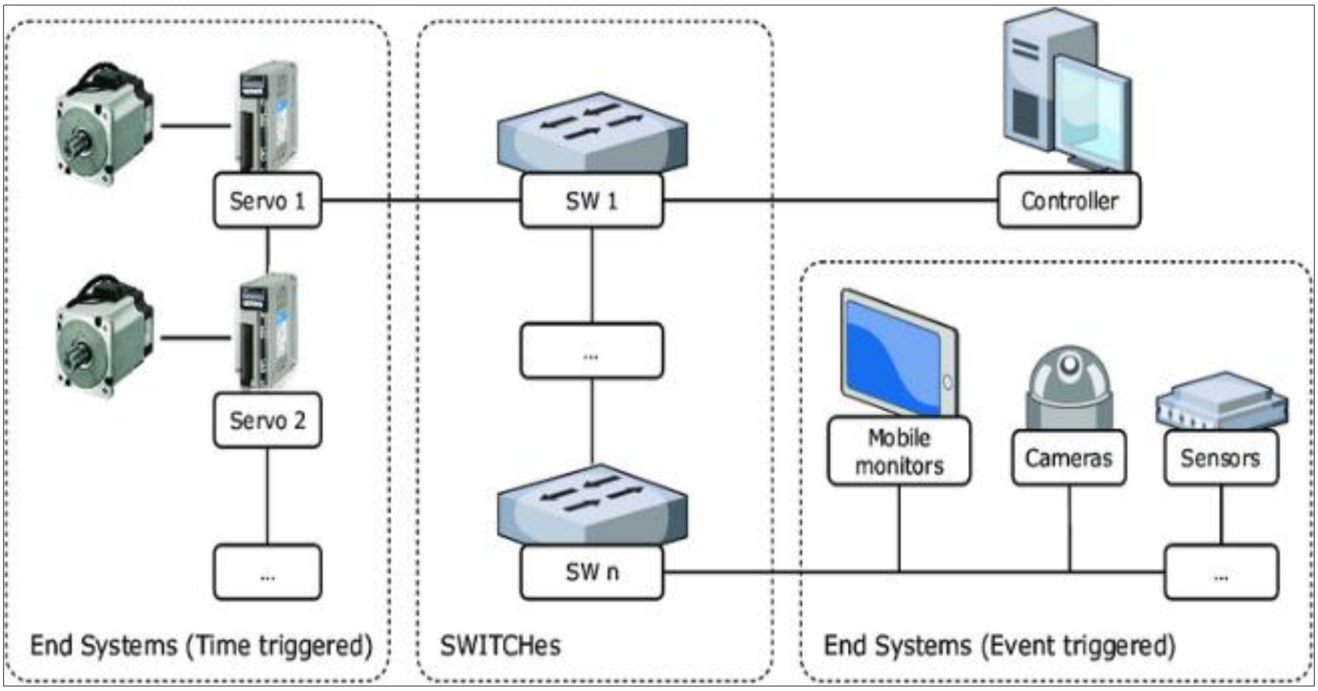

Figure 1 Architecture of TSN in an industrial network

3.2. MQTT-SN (Message Queuing Telemetry Transport for Sensor Networks)

MQTT-SN is a lightweight, optimized version of MQTT designed specifically for sensor networks and low-power IIoT devices. It reduces communication overhead, making it highly efficient for constrained environments such as wireless sensor networks (WSNs) and battery-operated IIoT nodes. MQTT-SN supports topic-based publish-subscribe communication, ensuring efficient data exchange with minimal latency.

3.2.1. Key Features

- Lightweight Protocol: Optimized for resource-constrained devices with low processing power and limited bandwidth.
- Optimized for Wireless Sensor Networks: Supports direct communication between sensors without requiring a continuous network connection.
- Efficient Message Handling: Uses short topic IDs to minimize payload size and improve transmission speed.

3.2.2. Use Cases

- Remote industrial monitoring and control.
- Factory automation systems where low-power devices must communicate efficiently.
- IoT gateways aggregating data from distributed sensor nodes.

3.2.3. Performance Comparison

- MQTT-SN reduces protocol overhead compared to traditional MQTT.
- Lower bandwidth consumption makes it suitable for large-scale IIoT deployments.

Table 2 Comparison of MQTT and MQTT-SN in IIoT applications

Feature	MQTT (Message Queuing Telemetry Transport)	MQTT-SN (MQTT for Sensor Networks)
Protocol Type	TCP/IP-based messaging protocol	UDP-based lightweight protocol
Overhead	Higher due to persistent TCP connections	Lower due to connectionless UDP
Optimized for	General-purpose IoT and IIoT applications	Low-power, constrained devices
Network Efficiency	Requires stable TCP connections	Reduces network load and power consumption
Message Format	Standard topic-based messaging	Short topic IDs for reduced payload size
QoS Support	QoS 0, 1, and 2	QoS 0, 1 (simplified for efficiency)
Transport Protocol	TCP (higher reliability, increased latency)	UDP (lower reliability, reduced latency)
Latency	Higher due to TCP overhead	Lower due to simplified UDP transactions
Use Cases	General IIoT, cloud connectivity, industrial automation	Wireless sensor networks, battery-powered IIoT nodes

3.3. OPC UA over TSN

OPC Unified Architecture (OPC UA) over TSN is a convergence of industrial communication and deterministic networking, providing a scalable and secure framework for IIoT applications. By leveraging TSN, OPC UA ensures real-time data exchange with sub-millisecond latencies, making it a preferred choice for high-performance industrial automation and control systems[5].

3.3.1. Key Features

- Secure Communication: Implements authentication, encryption, and access control to ensure data integrity.
- Scalable Architecture: Supports seamless integration of legacy and modern industrial devices.
- Deterministic Networking: Guarantees time-sensitive data transmission for real-time operations.

3.3.2. Use Cases

- Real-time process control in manufacturing.
- Smart grids and energy management systems.
- Robotics and industrial automation requiring deterministic data exchange.

3.3.3. Performance Analysis

- Achieves sub-millisecond latency, ensuring high-speed communication between industrial systems.
- Reduces network congestion and optimizes bandwidth usage compared to traditional OPC UA implementations.

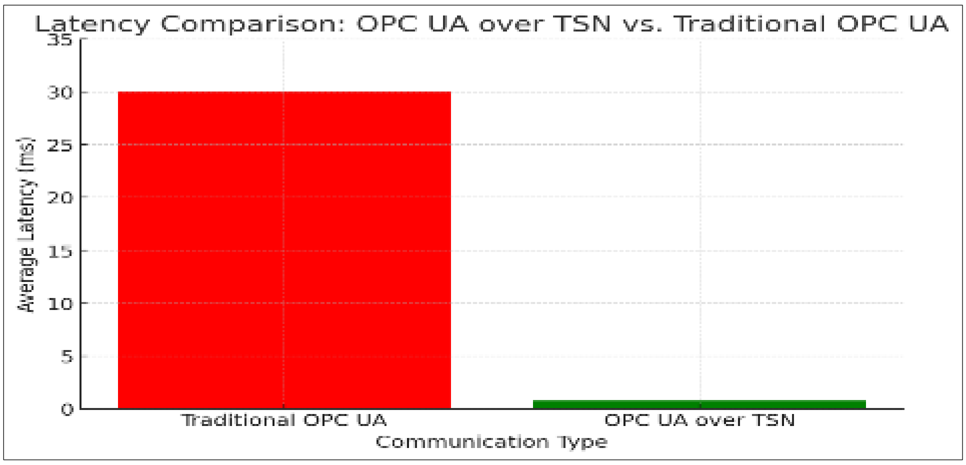

Figure 2 Latency comparison of OPC UA over TSN vs. traditional OPC UA)

3.4. 5G URLLC (Ultra-Reliable Low-Latency Communication)

5G URLLC is a next-generation wireless communication technology that provides ultra-low latency and high reliability for mission-critical IIoT applications. By leveraging network slicing, advanced error correction, and adaptive modulation techniques, 5G URLLC ensures robust and real-time connectivity for dynamic industrial environments.

3.4.1. Key Features

- Ultra-Low Latency: Provides latencies as low as 1 millisecond, enabling real-time data transmission.
- High Reliability: Ensures reliability levels exceeding 99.999%, making it ideal for safety-critical applications.
- Network Slicing: Allocates dedicated network resources for industrial applications, ensuring predictable performance.

3.4.2. Use Cases

- Autonomous vehicles and industrial robotics requiring instant decision-making.
- Remote industrial automation and teleoperation.
- Smart factories deploying wireless machine-to-machine (M2M) communication.

3.4.3. Performance Metrics

- End-to-end latencies below 5 milliseconds, even in highly dynamic environments.
- High mobility support, ensuring seamless connectivity for moving industrial equipment.

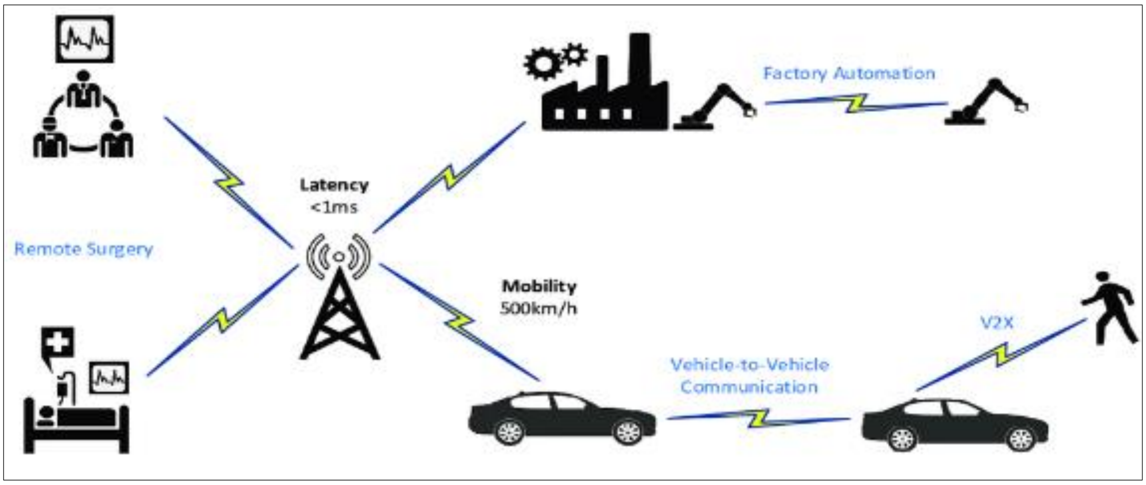

Figure 3 5G URLLC deployment in smart factories

Low-latency communication is critical for the success of IIoT applications, ensuring seamless and reliable data transmission across industrial networks. TSN provides deterministic Ethernet-based communication for wired industrial environments, while MQTT-SN optimizes low-power wireless sensor networks. OPC UA over TSN enhances interoperability and real-time control, while 5G URLLC extends ultra-reliable, low-latency wireless connectivity for mobile and remote industrial applications.

As IIoT continues to evolve, integrating these communication protocols with emerging technologies such as edge computing, artificial intelligence, and software-defined networking will further enhance performance and scalability. Future research should focus on hybrid communication models that leverage the strengths of multiple protocols to meet diverse industrial requirements[6].

4. Comparative Analysis of Low-Latency Protocols

Table 3 Performance Comparison of Low-Latency IIoT Protocols

Feature	**TSN (Time-Sensitive Networking)**	**MQTT-SN (Message Queuing Telemetry Transport for Sensor Networks)**	**OPC UA over TSN**	**5G URLLC (Ultra-Reliable Low-Latency Communication)**
Latency	<1 ms	Low (depends on network conditions)	<1 ms	<1 ms (end-to-end)
Reliability	High (deterministic Ethernet)	Moderate (optimized for constrained devices)	High (secure and deterministic)	Very High (>99.999% reliability)
Scalability	High	High	Moderate	High
Transport Protocol	Ethernet	UDP	Ethernet over TSN	5G NR (New Radio)
Network Type	Wired (industrial Ethernet)	Wireless	Wired	Wireless
Use Cases	Industrial automation, robotics	Wireless sensor networks, factory monitoring	Smart grids, process automation	Autonomous vehicles, smart factories, remote healthcare
Overhead	Moderate	Low	High (security features)	Moderate
Security	Moderate	Low (lightweight protocol)	High (integrated security)	High (5G encryption and authentication)
Power Consumption	Moderate	Low	High (due to Ethernet)	High (depends on 5G deployment)

4.1.1. Analysis Summary

- TSN is best for wired industrial automation, ensuring deterministic and real-time communication.
- MQTT-SN is lightweight, making it ideal for wireless sensor networks but with lower reliability compared to others.
- OPC UA over TSN provides secure and deterministic industrial communication but with higher overhead.
- 5G URLLC is highly reliable and low-latency, best suited for mission-critical IIoT applications like autonomous vehicles and remote control systems.

5. Challenges and Future Directions in Low-Latency IIoT Communication

The adoption of low-latency communication protocols in Industrial IoT (IIoT) has revolutionized industrial automation, real-time monitoring, and predictive maintenance. However, several challenges must be addressed to ensure seamless implementation, scalability, security, and future advancements.

5.1. Scalability Issues: Integrating Multiple Low-Latency Protocols

- As IIoT networks grow, integrating multiple low-latency communication protocols such as TSN, MQTT-SN, OPC UA over TSN, and 5G URLLC becomes increasingly complex.
- Managing large-scale industrial networks with mixed communication standards requires efficient data routing, synchronization, and congestion management.
- Expanding IIoT networks while maintaining low latency demands optimized resource allocation and edge computing solutions.
- Future advancements may involve dynamic protocol selection algorithms that adapt to varying industrial workloads.

5.2. Interoperability: Ensuring Seamless Communication between Heterogeneous Systems

- Industrial environments often consist of diverse devices, controllers, and communication standards that must work together seamlessly.
- Lack of unified standards among different protocols can lead to compatibility issues when integrating legacy systems with modern IIoT solutions.
- OPC UA over TSN attempts to bridge interoperability gaps, but broader adoption is still in progress.
- The introduction of universal industrial gateways and protocol translation mechanisms can improve system integration and real-time communication.

5.3. Security Concerns: Protecting Low-Latency Industrial Networks from Cyber Threats

- Low-latency communication protocols often prioritize speed over security, making them vulnerable to cyber threats such as data breaches, DDoS attacks, and industrial espionage.
- TSN-based networks require enhanced encryption mechanisms to prevent unauthorized access.
- 5G URLLC networks introduce new security risks, including potential vulnerabilities in network slicing and edge computing architectures.
- Future security strategies may include AI-driven threat detection, blockchain-based authentication, and post-quantum cryptography for securing IIoT networks.

5.4. Future Trends in Low-Latency IIoT Communication

To address current challenges and enhance IIoT communication, several emerging technologies are being explored:

- AI-Driven Optimizations
  - Artificial Intelligence (AI) and Machine Learning (ML) will play a crucial role in network optimization, anomaly detection, and adaptive protocol selection to minimize latency.
  - AI-powered predictive maintenance will further improve system efficiency by proactively identifying faults before they impact operations.
- 6G-Based IIoT:
  - While 5G URLLC has significantly improved reliability and latency, 6G networks will introduce sub-microsecond latency, ultra-high data rates, and AI-native network management.
  - Terahertz (THz) communication and intelligent reflective surfaces (IRS) will enhance industrial wireless connectivity.
- Quantum Communication for Industrial Networks:
  - The integration of quantum key distribution (QKD) could enhance security in industrial networks by preventing eavesdropping.
  - Future IIoT networks might leverage quantum-enhanced computing to process real-time data with unprecedented speed and accuracy.

While low-latency IIoT communication protocols have significantly enhanced industrial automation and efficiency, addressing challenges related to scalability, interoperability, and security is crucial for their widespread adoption. Future advancements in AI, 6G, and quantum communication will further refine these protocols, paving the way for next-generation industrial networks with unmatched speed, reliability, and security.

6. Conclusion

Low-latency communication is a critical enabler of Industrial IoT (IIoT), ensuring real-time data exchange, minimal latency, and high reliability in industrial operations. The ability to transmit data with sub-millisecond delays is essential for applications such as robotic control, predictive maintenance, smart manufacturing, and autonomous industrial systems. As industries continue to embrace digital transformation, the role of low-latency protocols becomes even more significant in optimizing efficiency, reducing downtime, and improving overall system performance. This paper has explored four key low-latency communication protocols—Time-Sensitive Networking (TSN), MQTT-SN, OPC UA over TSN, and 5G URLLC—each designed to address specific challenges within IIoT environments.

- TSN, as a deterministic Ethernet-based solution, ensures precise time synchronization and jitter-free communication, making it ideal for real-time industrial automation and motion control.
- MQTT-SN, a lightweight messaging protocol, is particularly well-suited for wireless sensor networks that require low-power and low-overhead communication.
- OPC UA over TSN integrates secure, scalable, and deterministic data exchange with time-sensitive networking, improving real-time process automation and smart grid applications.
- 5G URLLC offers unparalleled ultra-reliable, low-latency wireless connectivity, enabling critical IIoT applications like autonomous vehicles, remote-controlled industrial machinery, and smart factory ecosystems.

The successful integration of these low-latency communication technologies will reshape industrial automation by enabling faster decision-making, seamless interoperability between heterogeneous systems, and improved fault tolerance in connected environments. However, challenges such as scalability, interoperability, and security vulnerabilities must be addressed to maximize the potential of these communication protocols. Looking ahead, the future of low-latency IIoT will be shaped by advancements in AI-driven network optimizations, 6G-based ultra-fast communication, and quantum-secured industrial networks. These innovations will further enhance speed, security, and intelligence in IIoT deployments, paving the way for a new era of hyper-connected smart industries. By continuously evolving and integrating emerging networking technologies, Industrial IoT will move towards fully autonomous, highly efficient, and resilient smart factories, revolutionizing the way industries operate in the fourth industrial revolution (Industry 4.0) and beyond.

Compliance with ethical standards

Disclosure of conflict of interest

Author have No conflict of interest.

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