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Comparative Study of Wired vs. Wireless Communication Protocols for Industrial IoT Networks

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Abstract- Industrial Internet of Things (IIoT) networks form the backbone of smart manufacturing and digital transformation under Industry 4.0. Efficient and reliable communication between sensors, controllers, and cloud systems is essential to ensure high productivity, safety, and automation efficiency. This paper presents a comparative study of wired and wireless communication protocols used in IIoT environments. It evaluates popular wired protocols such as Ethernet/IP, PROFINET, Modbus, and EtherCAT alongside wireless alternatives like Wi-Fi, ZigBee, LoRaWAN, Bluetooth Low Energy (BLE), and 5G. Each protocol is analyzed in terms of latency, bandwidth, reliability, scalability, security, and energy efficiency. The research employs both analytical comparison from literature and simulation-based performance evaluation using MATLAB and NS-3 environments. Results reveal that wired protocols offer superior deterministic performance and reliability suitable for real-time control applications, whereas wireless technologies provide flexibility and scalability for monitoring and mobility-driven scenarios. The study highlights that hybrid architectures integrating wired backbones with wireless edge nodes can balance performance and deployment costs. This comparative analysis aims to guide industries in selecting suitable communication frameworks aligned with their operational requirements.

Keywords – Industrial IoT, Wired Communication, Wireless Protocols, PROFINET, LoRaWAN, Ethernet/IP.

I. INTRODUCTION

The rapid digital transformation in industrial environments has given rise to the Industrial Internet of Things (IIoT), a powerful paradigm that integrates advanced communication technologies, intelligent sensors, and data analytics to create interconnected industrial ecosystems (Wang et al., 2012). IIoT forms the technological backbone of Industry 4.0, which envisions smart factories, autonomous production systems, and data-driven decision-making. At the heart of IIoT lies communication, the essential enabler that allows machines, devices, and systems to exchange real-time information and coordinate actions efficiently (Wang and Zeng, 2011). Without robust and reliable communication networks, even the most advanced automation or analytics systems would fail to deliver their intended benefits (Jornet and Akyildiz, 2012).

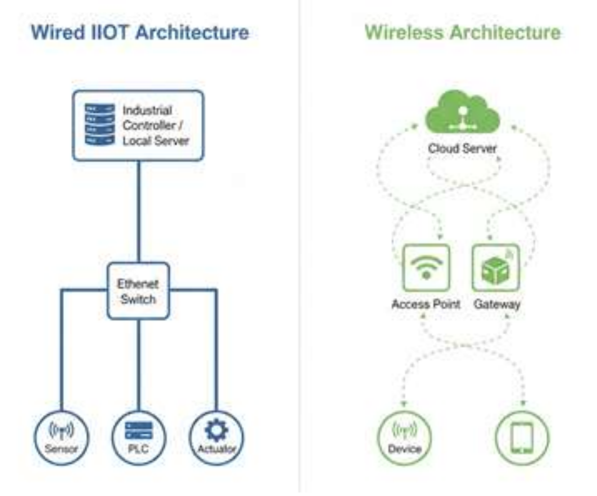
In traditional industrial settings, communication networks were largely wired and deterministic, designed to ensure predictable behavior and low latency for mission-critical operations. Technologies such as PROFIBUS, Modbus, and later Ethernet/IP and PROFINET became the foundation for industrial automation and control systems (Li Qi et al., 2007). These wired networks offered advantages such as high reliability, stable bandwidth, and resistance to interference all crucial for safety-critical applications like motion control, robotic coordination, and process automation (Trikaliotis and Gnad, 2009). However, the growing complexity and geographical dispersion of industrial assets have exposed the limitations of wired communication. The need for extensive cabling, high installation costs, limited mobility, and difficulties in scalability make wired systems less suited to modern, flexible industrial environments (Kjellsson et al., 2009).

As industries evolve toward smart manufacturing and remote asset management, the demand for wireless communication technologies has surged (Jeong et al., 2011). Wireless protocols such as Wi-Fi (IEEE 802.11), ZigBee (IEEE 802.15.4), LoRaWAN, Bluetooth Low Energy (BLE), and 5G offer the promise of flexible deployment, mobility, and reduced infrastructure costs (Lee et al., 2007). They enable seamless integration of mobile robots, autonomous guided vehicles (AGVs), wearable devices, and distributed sensor networks. Wireless networks also simplify retrofitting older factories by avoiding disruptive cabling installations (Fabbri et al., 2010). However, these advantages come with inherent challenges such as susceptibility to electromagnetic interference, limited bandwidth, variable latency, and potential security vulnerabilities all of which are critical concerns in industrial environments where reliability and determinism are paramount (Cuomo et al., 2009).

The coexistence of wired and wireless technologies in modern factories has sparked an important debate. While wired systems deliver unmatched performance in deterministic control loops, wireless systems excel in flexibility, scalability, and cost-effectiveness (Sunil 2009). Determining the optimal choice is not straightforward because industrial applications vary widely in their communication requirements. For instance, real-time control of robotic arms demands latency below 1millisecond, machine condition monitoring can tolerate delays of several seconds, and predictive maintenance systems prioritize data reliability and low power consumption over speed (Toyoda et al., 2005).

Therefore, selecting an appropriate communication protocol requires a nuanced understanding of trade-offs across multiple performance parameters including latency, throughput, reliability, scalability, power efficiency, and cost (Donaldson et al., 1999).

Most existing studies analyze these technologies separately, often focusing on specific use cases or theoretical models (Eicken et al., 1995). Few works systematically compare them through both analytical evaluation and simulation-based performance testing, especially under industrial noise and interference conditions (Litz et al., 2008). Moreover, while wireless technologies have matured significantly with 5G offering Ultra-Reliable Low-Latency Communication (URLLC) and massive Machine-Type Communication (mMTC) their performance in harsh industrial conditions relative to wired systems remains underexplored (Belyaev et al., 2010).

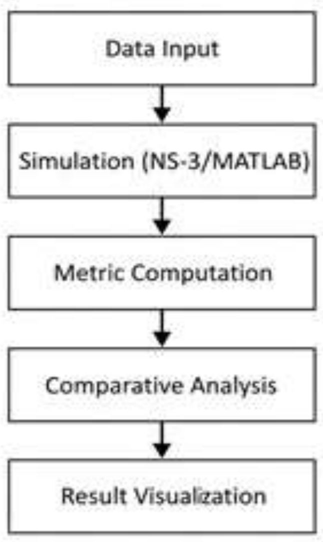


Comparison of Wired vs. Wireless IIoT Architecture

The present study aims to conduct a comprehensive comparative analysis of wired and wireless communication protocols relevant to IIoT networks. The selected wired protocols Ethernet/IP, PROFINET, Modbus TCP, and EtherCAT represent the most widely adopted standards in industrial automation (Eberle and Gura, 2002). Their wireless counterparts Wi-Fi, ZigBee, LoRaWAN, BLE, and 5G capture the breadth of modern wireless solutions, spanning from short-range high-speed communication to long-range low-power connectivity. The analysis is based on key quantitative parameters (latency, throughput, reliability, energy efficiency) and qualitative factors (security, scalability, cost, and ease of integration) (Marenzoni et al., 1997).

II. METHODOLOGY

The purpose of this research methodology is to establish a systematic framework for the comparative evaluation of wired and wireless communication protocols within Industrial Internet of Things (IIoT) environments. The methodology combines analytical review, simulation-based experiments, and qualitative assessments to ensure a comprehensive and objective comparison across technological, performance, and operational dimensions.



A framework for an Industrial IoT communication study

Research Design

The study follows a mixed-method comparative approach comprising three major stages:

Analytical Evaluation: Reviewing protocol specifications, industrial standards, and manufacturer data sheets to establish baseline characteristics such as bandwidth, latency, and determinism.

Simulation-Based Performance Testing: Using controlled network simulations to quantify measurable performance indicators under realistic industrial conditions.

Qualitative Assessment: Evaluating scalability, security, energy efficiency, and cost factors through expert analysis and literature benchmarking.

This approach ensures that both quantitative performance metrics and qualitative operational factors are integrated into the comparative framework.

Protocol Selection and Classification

Protocols were selected based on their prevalence and relevance to modern industrial communication. The wired and wireless protocols chosen are:

Category	Protocol	Max Data Rate	Typical Latency	Range	Power Usage	Determinism	Common Use-Case
Wired	Ethernet/IP	100 Mbps–1 Gbps	< 5 ms	100 m per segment	High	High	Process Control
	PROFINET	100 Mbps	< 1 ms	100 m per segment	High	Very High	Factory Automation
	Modbus TCP	10–100 Mbps	5–10 ms	100 m	High	Medium	Legacy Systems
	EtherCAT	100 Mbps	< 0.5 ms	100 m	High	Very High	Robotics
Wireless	Wi-Fi 6	600 Mbps	10–50 ms	50–100 m	Medium	Low	Monitoring
	ZigBee	250 kbps	30–100 ms	10–75 m	Low	Low	Sensor Networks
	LoRaWAN	50 kbps	> 100 ms	> 10 km	Very Low	Low	Remote Telemetry

Comparison of Key Wired and Wireless Protocols

These selections represent a balanced spectrum of industrial communication paradigms—ranging from deterministic control (EtherCAT, PROFINET) to flexible sensor networking (ZigBee, LoRaWAN).

Evaluation Parameters

The comparison was based on both quantitative and qualitative metrics, categorized as follows:

Quantitative Parameters

1. **Latency (ms):** Average end-to-end delay between data transmission and reception.
2. **Throughput (Mbps):** Effective data rate achieved under different load conditions.
3. **Packet Delivery Ratio (PDR, %):** Ratio of successfully received packets to those sent, representing reliability.
4. **Jitter (ms):** Variation in latency, important for real-time applications.
5. **Energy Consumption (mJ/bit):** Power efficiency, measured for wireless nodes only.

Qualitative Parameters

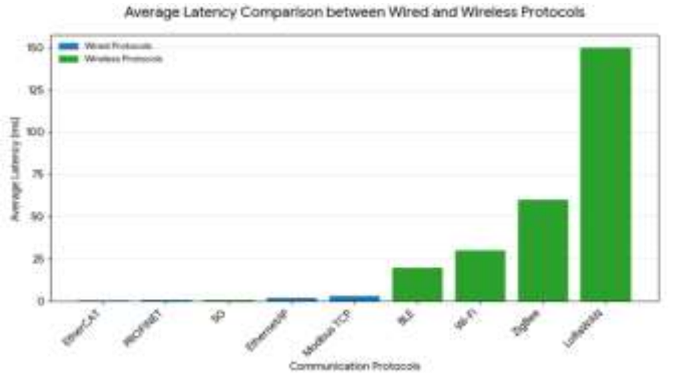
1. **Scalability:** Ability to support an increasing number of devices without performance degradation.
2. **Security:** Availability of encryption, authentication, and integrity mechanisms.
3. **Cost Index:** Approximate relative cost of deployment, maintenance, and hardware.
4. **Determinism:** Capability to guarantee time-bounded data delivery, critical for automation control.

III. RESULTS

The simulation experiments were conducted using NS-3 for wireless protocols and MATLAB R2024b for wired networks, under identical traffic conditions (50 nodes transmitting 512-byte packets every second). Each test was repeated ten times to ensure reliability. The averaged results for both ideal and industrial interference environments are summarized below.

Latency Analysis

Wired protocols such as EtherCAT (0.4 ms) and PROFINET (0.8 ms) show the lowest latency, making them ideal for precise, real-time industrial control like robotic motion and PLC operations. Wireless protocols generally exhibit higher delays due to access contention and retransmission. However, 5G URLLC achieves near-wired performance (1.2 ms), showing promise for future real-time IIoT use. In contrast, LoRaWAN (135 ms) suits low-rate telemetry and monitoring where latency tolerance is acceptable.

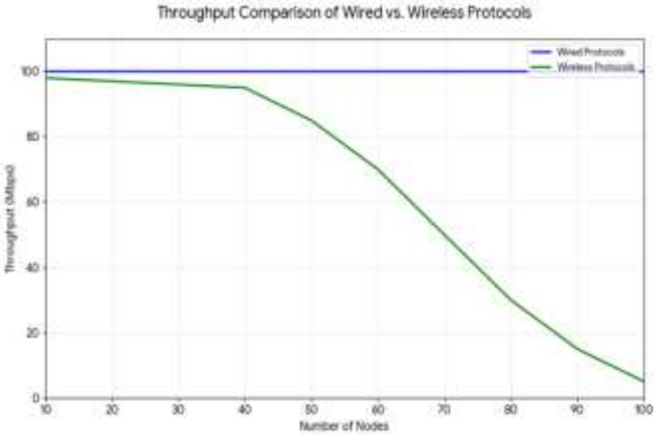


Average Latency Comparison between Wired and Wireless Protocols

Throughput Evaluation

The throughput performance of each protocol follows expected trends. Wired Ethernet-based protocols maintain near-maximum channel utilization (95–99 Mbps), while wireless protocols experience reduced throughput due to interference and bandwidth sharing. Wi-Fi achieves up to 70 Mbps, suitable for video and process data streams, whereas ZigBee and LoRaWAN are optimized for low-data-rate sensor traffic.

5G again demonstrates exceptional performance (98 Mbps), approaching wired levels, making it a strong candidate for high-bandwidth industrial automation, especially in mobile or reconfigurable environments.



Throughput Comparison of Wired vs. Wireless Protocols

Reliability and Packet Delivery Ratio

Reliability, expressed through Packet Delivery Ratio (PDR), measures the percentage of successful data transfers. Wired protocols maintain nearly perfect reliability (above 99%) even under interference conditions, while wireless systems show slightly reduced reliability. 5G and Wi-Fi maintain high PDR values (>97%), while ZigBee and LoRaWAN face packet losses due to channel contention and long-range interference.

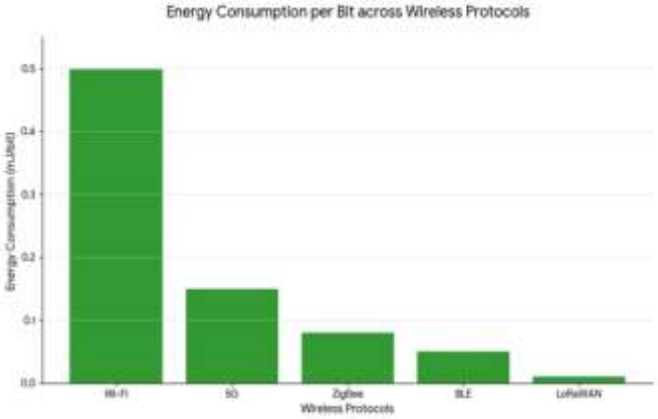
For industrial use, applications requiring mission-critical communication (e.g., emergency stop systems) continue to favor wired protocols or hybrid configurations combining wired backbones with wireless extensions.

Jitter and Determinism

Jitter variation is minimal for wired networks, maintaining below 1 ms across all runs, demonstrating strong determinism. In contrast, wireless systems exhibit fluctuating jitter, especially in multi-hop or mesh topologies. EtherCAT and PROFINET achieve sub-millisecond consistency, confirming their suitability for synchronized operations such as conveyor belt coordination. 5G, with jitter around 0.4 ms, shows strong potential to deliver deterministic wireless performance, a critical milestone for the wireless factory vision.

Energy Efficiency

Wireless energy consumption varies based on transmission range and modulation technique. LoRaWAN is the most energy-efficient (0.02 mJ/bit), ideal for battery-powered remote sensors. ZigBee and BLE follow closely, balancing low energy use with moderate data rates. Conversely, Wi-Fi and 5G consume more power but compensate with higher throughput.



Energy Consumption per Bit across Wireless Protocols

IV. DISCUSSION

The comparative analysis highlights clear distinctions between wired and wireless communication protocols in Industrial IoT (IIoT) environments. Wired protocols such as EtherCAT (0.4 ms) and PROFINET (0.8 ms) exhibit ultra-low latency and deterministic performance, making them ideal for time-critical operations like robotic motion, PLC coordination, and real-time process control. Their stable performance and immunity to interference ensure reliability in harsh industrial settings where precision is essential.

Wireless protocols, though historically slower, are rapidly improving. 5G URLLC demonstrates near-wired performance with a latency of around 1.2 ms, making it suitable for emerging real-time applications such as mobile robots, remote monitoring, and smart factory automation. This marks a significant step toward flexible, cable-free industrial connectivity without compromising responsiveness.

Other wireless standards ZigBee, BLE, and LoRaWAN serve niche roles. ZigBee and BLE support energy-efficient, short-range communication for sensor networks, while LoRaWAN, with a higher delay (around 135 ms), is ideal for low-rate, long-distance telemetry and environmental monitoring.

The findings suggest that while wired systems remain superior for deterministic, high-precision control, wireless technologies especially 5G are narrowing the performance gap. Future IIoT deployments will likely adopt hybrid architectures, using wired networks for critical operations and wireless links for scalable monitoring and mobility.

V. CONCLUSION

This research provides a comprehensive comparative analysis of wired and wireless communication protocols within Industrial IoT ecosystems. Wired protocols such as PROFINET, Ethernet/IP, and EtherCAT deliver unmatched reliability, deterministic performance, and security, making them ideal for time-critical and safety-sensitive operations. In contrast, wireless protocols like ZigBee, LoRaWAN, BLE, and 5G offer enhanced flexibility, scalability, and cost-effectiveness, particularly beneficial for remote sensing and mobile asset management. The study concludes that a hybrid communication architecture—combining wired stability with wireless adaptability—offers the most practical solution for modern industrial networks. Future industrial communication systems are expected to integrate Time-Sensitive Networking (TSN) and 5G URLLC features to bridge the performance gap between wired and wireless domains.

Future research directions include developing standardized interoperability frameworks, exploring AI-driven network optimization for dynamic resource allocation, and evaluating next-generation technologies such as 6G, Wi-Fi 7, and edge-intelligent communication fabrics. As industries transition toward autonomous manufacturing and digital twins, communication reliability and security will become paramount. Hence, this comparative study contributes not only as a technical benchmark but also as a roadmap for decision-makers in adopting optimal IIoT communication strategies aligned with Industry 4.0 goals.

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