

Journal Scientific and Applied Research, Vol. 30, 2026
International Journal

ISSN 1314-6289 (Print)
ISSN 2815-4622 (Online)

Original Contribution

INVESTIGATION OF DETERMINISTIC NETWORK ARCHITECTURES FOR CRITICAL INDUSTRIAL APPLICATIONS

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Abstract: *Modern industrial automation systems increasingly rely on network communication for the exchange of time-critical information between sensors, controllers, actuators, robots, and supervisory systems. In conventional Ethernet networks, communication delays, packet loss, congestion, and variable latency can make it difficult to guarantee predictable system behavior. These limitations become particularly important in critical industrial applications, where communication failures or excessive delays may affect production processes, equipment safety, and system availability. Deterministic network architectures address these challenges by providing predictable communication latency, low jitter, accurate time synchronization, traffic prioritization, and mechanisms for redundancy and fault tolerance. Technologies such as Time-Sensitive Networking, EtherCAT, PROFINET, and OPC UA have become important components of modern industrial communication architectures. This report investigates the main principles of deterministic networking and examines the characteristics of several technologies used in industrial environments. Particular attention is given to latency, synchronization, reliability, scalability, and security. The analysis demonstrates that deterministic networking provides an important foundation for the integration of real-time control, industrial automation, and emerging Industrial Internet of Things applications.*

Key words: *Deterministic networking, Industrial Ethernet, Time-Sensitive Networking, TSN, EtherCAT, PROFINET, OPC UA, real-time communication, Industrial automation, Low latency, Jitter, Synchronization, Fault tolerance.*

1. Introduction

Industrial automation systems have traditionally used dedicated fieldbus technologies to provide reliable and predictable communication between controllers and field devices. However, the increasing complexity of modern factories has created a need for more flexible and scalable communication infrastructures. Industrial robots, programmable logic controllers (PLCs), sensors, actuators, machine-vision systems, and supervisory applications increasingly need to exchange information over common Ethernet-based networks. Standard Ethernet provides high bandwidth and interoperability, but it was not originally designed to guarantee

deterministic communication. Network congestion, queuing mechanisms, retransmissions, and competing traffic can introduce variable delays. For applications such as motion control, robotic coordination, electrical protection, and safety-critical automation, this variability can be unacceptable. Deterministic networking aims to make network behavior predictable. Instead of considering only the average communication delay, deterministic architectures attempt to establish defined limits for latency, jitter, synchronization accuracy, and packet delivery. The IEEE 802.1 Time-Sensitive Networking standards represent one of the major developments in this area, extending Ethernet with mechanisms for time synchronization, traffic scheduling, and reliability [1], [2]. The objective of this report is to investigate the architecture and characteristics of deterministic industrial networks and to examine how different technologies address the requirements of critical industrial applications. Figure 1 shows the comparison between conventional and deterministic industrial communication.

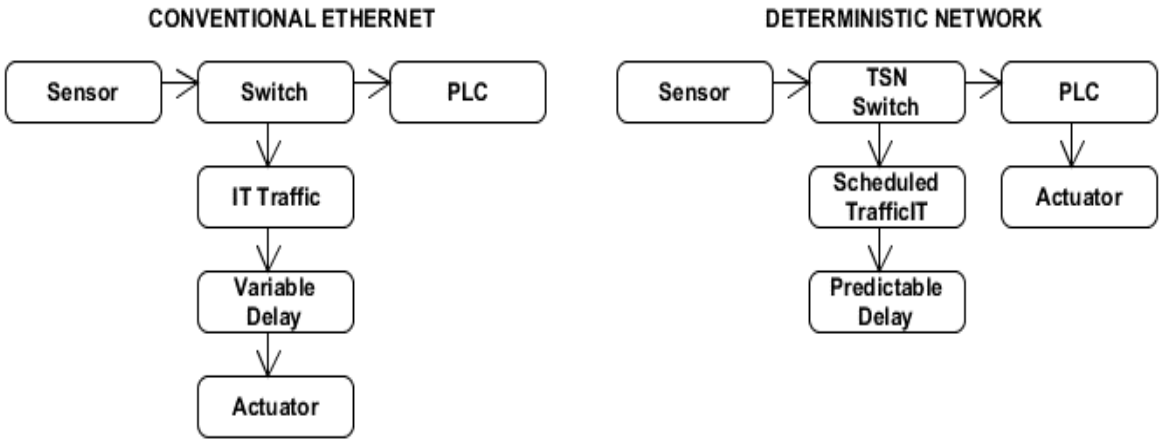


Fig. 1. Comparison between conventional and deterministic industrial communication

2. Related work

Recent research has investigated deterministic networking from several perspectives, including Time-Sensitive Networking (TSN), Industrial Ethernet, traffic scheduling, networked control, and Industry 4.0. Zhang et al. [1] present a comprehensive review of TSN for industrial automation, focusing on deterministic communication, synchronization, scheduling, and reliability. Jiang et al. [2] experimentally investigate TSN traffic scheduling and demonstrate the importance of practical network configuration. Lo Bello et al. [3] study the schedulability of TSN networks with scheduled traffic and frame preemption, focusing on the ability to satisfy timing requirements. Real-time Industrial Ethernet has also been extensively studied. Vitturi et al. [4] analyze Ethernet technologies for motion-control applications, while Wang et al. [5] evaluate the performance of Industrial Ethernet protocols in networked control systems. Ferrari et al. [6] specifically examine the performance characteristics of PROFINET networks. The transmission of different traffic types in industrial networks has been addressed by Song et al. [7], who investigate routing and scheduling algorithms for heterogeneous industrial data streams. Nasrallah et al. [8] provide a broader analysis of ultra-low-latency networking and discuss TSN and DetNet technologies. The development of industrial communication toward Industry 4.0 has been discussed by Wollschlaeger et al. [9], with emphasis on the integration of automation networks and IoT technologies. Pfrommer et al. [10] investigate OPC UA PubSub over TSN, demonstrating the potential of combining standardized industrial communication with deterministic networking. Specht and Samii [11] study urgency-aware packet scheduling for time-sensitive software-defined networks. Overall, the reviewed studies show that deterministic industrial networking

depends on predictable latency, low jitter, synchronization, efficient scheduling, and reliable communication. These research results provide the basis for investigating deterministic network architectures and their application in critical industrial systems.

3. Problem description and results

A deterministic network is a communication system in which important characteristics of data transmission can be predicted within defined limits. The primary objective is not necessarily to minimize every delay, but to ensure that the delay remains within an acceptable and known range. One of the most important parameters is latency. Latency represents the time required for a data packet to travel from the sender to the receiver. In industrial control systems, a predictable maximum latency can be more important than a low average latency. Another important parameter is jitter, which describes the variation in packet transmission or reception time. High jitter can negatively affect control loops because a controller may receive measurements at irregular intervals. Figure 2 shows the fundamental characteristics of deterministic networking.

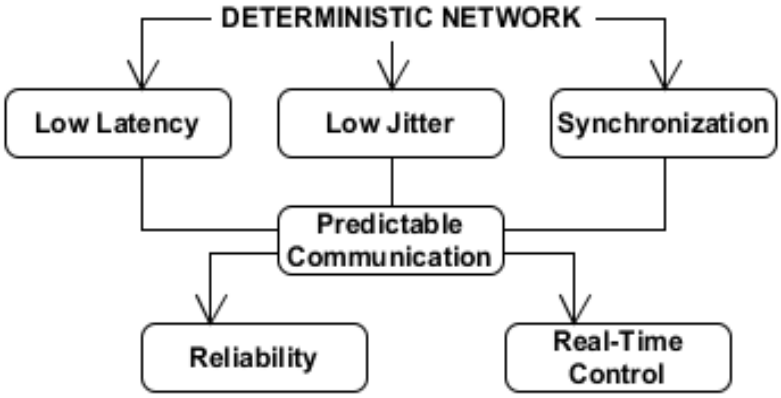


Fig. 2. Fundamental characteristics of deterministic networking

Time synchronization is also essential. Industrial devices often need to operate according to a common time reference. Accurate synchronization allows network nodes to execute scheduled communication and coordinated control operations. IEEE 802.1AS, for example, defines mechanisms for synchronization in TSN networks [2]. Deterministic networks can also employ traffic scheduling and prioritization. Critical control traffic can be assigned transmission opportunities or higher priority than less time-sensitive traffic. This prevents large amounts of background traffic from interfering with real-time communication. Finally, critical systems require reliability and redundancy. A deterministic network should not only provide predictable timing but also maintain communication in the presence of equipment or link failures. Standards such as IEEE 802.1CB introduce mechanisms for frame replication and elimination to improve network reliability [3].

Time-Sensitive Networking and Industrial Ethernet Technologies

Time-Sensitive Networking represents a collection of IEEE 802.1 standards developed to introduce deterministic communication capabilities into Ethernet networks. The main objective of TSN is to provide predictable transmission of time-critical data while maintaining compatibility with conventional Ethernet traffic. This characteristic makes TSN particularly relevant to modern industrial environments, where real-time control traffic must often coexist with monitoring, diagnostics, and information technology services on the same physical network. One of the fundamental characteristics of TSN is precise time synchronization

between network devices. IEEE 802.1AS defines mechanisms for establishing a common time reference across the network, allowing devices to coordinate their communication and operational activities. In addition to synchronization, TSN provides mechanisms for traffic scheduling and shaping. IEEE 802.1Qbv, for example, introduces the Time-Aware Shaper, which enables network switches to transmit specific classes of traffic during predefined time intervals. This approach makes it possible to reserve communication opportunities for critical industrial traffic and significantly reduce the influence of non-critical network traffic [1], [2]. Another important aspect of TSN is reliability. Industrial control systems may need to remain operational even when a communication link or network device fails. IEEE 802.1CB provides frame replication and elimination mechanisms that can be used to create redundant communication paths. When a frame is transmitted through multiple paths, the receiving system can eliminate duplicate frames and continue communication if one of the paths becomes unavailable [3]. These mechanisms make TSN suitable for applications where predictable communication and high availability are required. In addition to TSN, several Industrial Ethernet technologies have been developed specifically for automation applications. EtherCAT is designed for high-performance real-time communication and is widely used in motion control, robotics, and machine automation. Its communication architecture allows devices to process data while Ethernet frames pass through the network, which reduces processing overhead and contributes to efficient cyclic communication [4]. Fig 3 shows a deterministic Industrial Network Architecture. PROFINET is another widely used Industrial Ethernet technology. It provides different communication mechanisms for different application requirements, including highly deterministic communication for demanding automation and motion-control applications. PROFINET also allows industrial equipment to communicate with conventional Ethernet systems, making it suitable for environments in which automation and enterprise communication need to coexist [5]. OPC Unified Architecture has a somewhat different role. It is primarily designed to provide standardized and platform-independent communication and information modeling between industrial systems. OPC UA supports structured data models, interoperability, security, and communication between different levels of an industrial architecture [6]. The combination of OPC UA with TSN is particularly significant because it can provide both standardized industrial information exchange and deterministic network communication. This combination is an important element in the development of future Industry 4.0 architectures [7]. Table 1 shows a comparison of Industrial ethernet technologies.

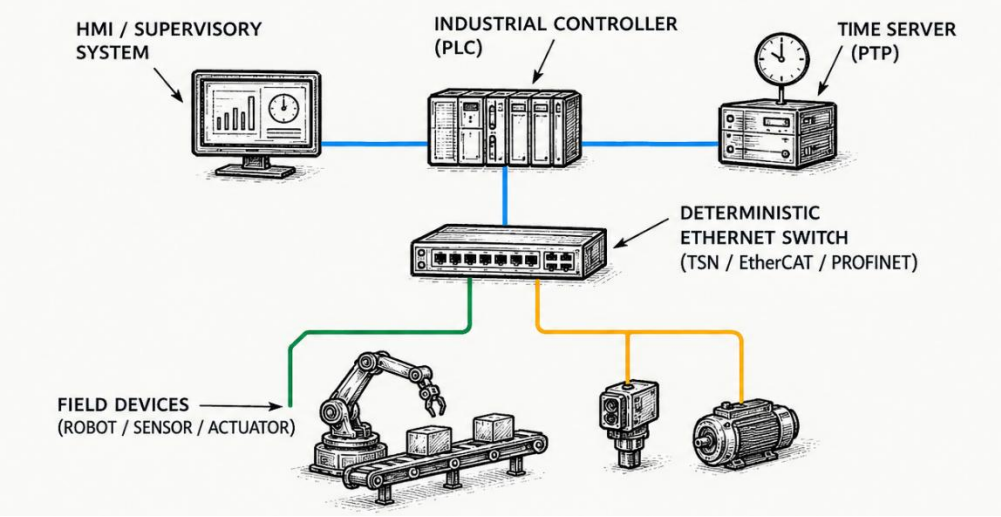


Fig. 3. Deterministic Industrial Network Architecture

Table 1. Comparison of Industrial Ethernet Technologies

Technology	Cycle Time	Synchronization	Typical Application
TSN	$< 1\ ms$	$\pm 1\ \mu s$	Industrial automation
EtherCAT	$< 100\ \mu s$	$< 1\ \mu s$	Motion control
PROFINET IRT	$250\ \mu s - 1\ ms$	$< 1\ \mu s$	Robotics
OPC UA over TSN	$< 1\ ms$	$\pm 1\ \mu s$	IIoT / Industry 4.0

Applications in Critical Industrial Systems

Deterministic networks are particularly important in industrial environments where communication timing directly influences physical processes. One major application is robotic and motion control. Industrial robots and coordinated motion systems require controllers and drives to exchange data at predictable intervals. Excessive latency or jitter can result in synchronization errors and degraded control performance. Another application is automated production lines. A production line may contain hundreds of sensors and actuators operating according to a common sequence. Deterministic communication can ensure that control commands and sensor measurements are delivered within defined time constraints. Deterministic networking is also relevant to electrical power and energy systems. Protection and control applications can require communication with strict timing requirements. A predictable communication infrastructure can help coordinate distributed monitoring and control functions. A further area is process automation, where controllers continuously receive measurements from sensors and generate commands for actuators. Predictable communication delays can improve the stability and reliability of closed-loop control systems. Finally, deterministic networks support the development of Industrial Internet of Things architectures. Modern factories increasingly combine real-time operational technology with information technology, cloud services, analytics, and artificial intelligence. Deterministic Ethernet allows critical traffic to coexist with less time-sensitive traffic on a converged network [9]. Figure 4 shows the applications of deterministic networks in critical industrial systems.

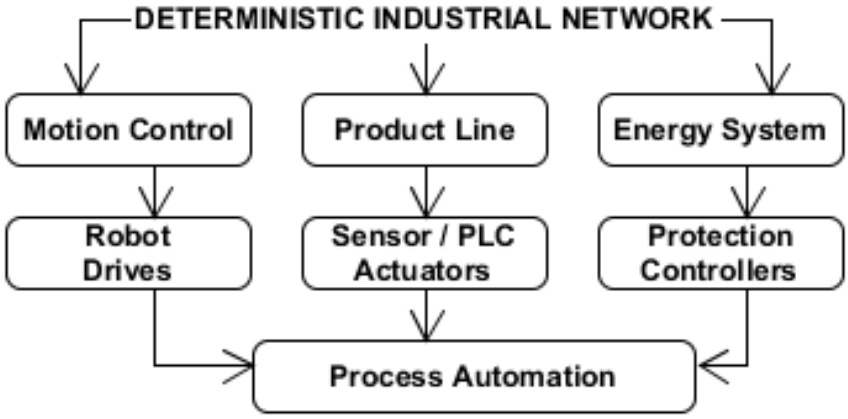


Fig. 4. Applications of deterministic networks in critical industrial systems

Performance Reliability and Security Considerations

The performance of a deterministic industrial network depends on several interconnected factors, including communication latency, jitter, synchronization accuracy, reliability, and the ability of the network to handle different classes of traffic. In conventional

Ethernet networks, the exact transmission time of a packet may vary depending on network congestion and the amount of competing traffic. For industrial control applications, however, predictable behavior is often more important than simply achieving a low average communication delay. Latency represents the time required for information to travel between two network nodes. In a critical industrial application, it is important not only to know the average latency but also to establish an upper bound for the maximum expected delay. If a control message arrives significantly later than expected, the controller or actuator may not be able to perform its operation at the required moment. Deterministic networking mechanisms therefore attempt to control the transmission process and establish predictable communication windows. Jitter is closely related to latency and represents the variation in transmission delay over time. Even when the average latency is relatively low, significant variations can negatively affect industrial control loops. For example, if measurements from a sensor arrive at irregular intervals, the controller may receive outdated information or perform calculations based on inconsistent sampling periods. Table 2 shows key performance parameters of deterministic networks.

Table 2. Key Performance Parameters of Deterministic Networks

Parameter	Typical Value	Main Effect
Latency	$< 1\,ms$	Fast response
Jitter	$< 10\,\mu s$	Stable timing
Time synchronization	$< 1\,\mu s$	Coordinated operation
Packet loss	$< 10^{-6}$	High reliability
Availability	$> 99.99\%$	Continuous operation

Deterministic scheduling and accurate time synchronization can reduce such variations and improve the stability of distributed control systems. Time synchronization is particularly important when multiple industrial devices must coordinate their operations. A common time reference allows controllers, switches, sensors, and actuators to operate according to a shared schedule. IEEE 802.1AS provides mechanisms for synchronization in TSN networks and is therefore an important component of deterministic Ethernet architectures [8]. Accurate synchronization also enables scheduled communication, where specific types of traffic are transmitted at predetermined moments. Reliability is another major consideration in critical industrial networks. A communication failure can interrupt production or, in certain applications, create safety risks. For this reason, deterministic architectures may use redundant communication paths and mechanisms for detecting and recovering from failures. IEEE 802.1CB, for example, allows frames to be replicated and transmitted through multiple paths. The receiving device can eliminate duplicate frames while retaining a valid copy if one of the network paths fails [3]. Although redundancy increases reliability, it also introduces additional network traffic and configuration requirements. Security must also be considered when designing deterministic industrial networks. The convergence of operational technology and information technology means that industrial networks are increasingly connected to enterprise systems, remote monitoring platforms, cloud services, and external applications. This connectivity can increase the potential attack surface of industrial infrastructure. Security mechanisms such as authentication, authorization, network segmentation, encryption, secure device configuration, and continuous monitoring are therefore important components of a modern industrial network architecture. At the same time, security mechanisms must be implemented carefully because additional processing and communication overhead can potentially influence deterministic behavior. Industrial network designers therefore need to consider security and real-time requirements together rather than treating them as completely

independent problems. A successful architecture must provide an appropriate balance between predictable communication, system availability, and protection against unauthorized access or malicious activity. [11]

Quantitative Performance Analysis

The performance of a deterministic industrial network can be evaluated using measurable parameters such as transmission time, latency, and jitter. These parameters are directly related to the network's ability to provide predictable communication for time-critical industrial applications. The transmission time of an Ethernet frame can be calculated as:

$$T_{trans} = \frac{L}{R} \quad \textbf{(1)}$$

where L is the frame size in bits and R is the data rate. For a 1000-byte frame, the transmitted payload corresponds to 8000 bits. At a network speed of 100 Mbps, the transmission time is therefore:

$$T_{trans} = \frac{8000}{100 \times 10^6} = 80\mu s \quad \textbf{(2)}$$

When the same 1000-byte frame is transmitted over a 1 Gbps connection, the transmission time becomes:

$$T_{trans} = \frac{8000}{1 \times 10^9} = 8\mu s \quad \textbf{(3)}$$

This example demonstrates that increasing the physical data rate can significantly reduce the time required to place a frame on the transmission medium. However, the data rate alone does not guarantee deterministic communication. The overall communication delay may also include propagation delay, switching and processing time, queuing delay, and delays introduced by traffic scheduling and network congestion. Jitter describes the variation in communication latency between successive transmissions. Consider five representative latency measurements of 95, 102, 98, 105, and 100 μs. The average latency is:

$$\bar{T} = \frac{95+102+98+105+100}{5} = 100\mu s \quad \textbf{(4)}$$

A simple peak-to-peak measure of jitter can be calculated as the difference between the maximum and minimum measured latency:

$$J = T_{max} - T_{min} = 105 - 95 = 10\mu s \quad \textbf{(5)}$$

The example illustrates that both latency and jitter are important when evaluating industrial communication performance. A network can exhibit a relatively low average latency while still producing considerable variations in packet arrival time. Deterministic network architectures therefore employ mechanisms such as traffic scheduling, time synchronization, prioritization, and traffic shaping to constrain communication delays and their variation. For illustrative comparison, consider a conventional Ethernet network with a maximum latency of 150 μs and jitter of 50 μs, and a deterministic network with a maximum latency of 90 μs and jitter of 10 μs. Under these assumed values, the reduction in maximum latency is:

$$R_L = \frac{150-90}{150} \times 100 = 40\% \quad \textbf{(6)}$$

Similarly, the reduction in jitter is:

$$R_j = \frac{50-10}{50} \times 100 = 80\% \quad \textbf{(7)}$$

These calculations illustrate the potential impact of deterministic communication mechanisms on latency and latency variation. In critical industrial applications such as motion control, robotics, and distributed control systems, limiting communication delay and its variation can help ensure that control information is exchanged within predictable timing constraints. The numerical comparison above is illustrative; actual performance depends on the network technology, topology, traffic load, configuration, and specific deterministic mechanisms employed.

Challenges and Future Development

Despite the advantages of deterministic networking, several challenges remain. The first challenge is system complexity. Deterministic networks require careful configuration of traffic classes, schedules, synchronization, and network resources. Incorrect configuration can reduce or eliminate the expected deterministic behavior. The second challenge is interoperability. Industrial environments frequently contain equipment from different manufacturers and generations. Standards such as TSN and OPC UA aim to improve interoperability, but practical integration can still require vendor-specific engineering. Another challenge is the integration of IT and OT networks. Industrial organizations increasingly require production systems to exchange data with enterprise applications, analytics platforms, and cloud infrastructure. These different traffic types have different requirements, making traffic management an important architectural problem. Future industrial networks are expected to increasingly combine deterministic Ethernet, wireless communication, edge computing, and distributed intelligence. Wireless deterministic communication is particularly challenging because radio propagation, interference, and changing environmental conditions can introduce additional uncertainty. The continued development of TSN, OPC UA, industrial 5G, and edge computing is likely to contribute to increasingly flexible industrial architectures. The long-term objective is to provide a common infrastructure capable of supporting both conventional information traffic and highly time-sensitive control applications. [10] Table 3 shows the main challenges in deterministic industrial networks. Figure 5 illustrates the data from Table 3.

Table 3. Main Challenges in Deterministic Industrial Networks

Challenge	Relative importance (%)
Network configuration complexity	25
Interoperability	20
Cybersecurity	20
Scalability	15
Integration with IT/OT	12
Wireless integration	8
Total	**100**

The results presented in Table 3 and the corresponding graph illustrate the relative importance of the main challenges associated with deterministic industrial networks. Network configuration complexity has the highest relative importance, with 25%, indicating that the implementation and management of deterministic communication mechanisms can significantly increase network complexity. Interoperability and cybersecurity follow with 20% each, highlighting the need for compatibility between different industrial technologies and adequate protection against cyber threats. Scalability represents 15%, reflecting the challenge of expanding deterministic networks while maintaining predictable performance. IT/OT integration accounts for 12%, while wireless integration has the lowest value of 8%.

Overall, the results indicate that technical complexity, interoperability, and cybersecurity represent major areas that should be considered when developing future deterministic industrial network architectures.

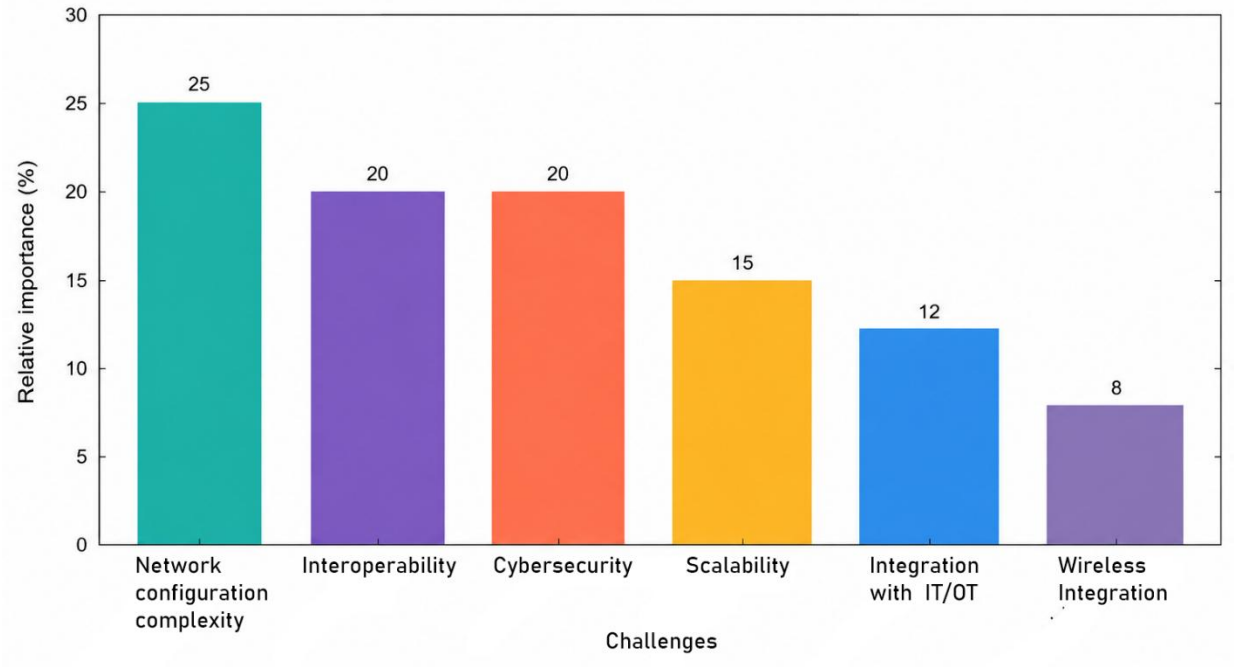


Fig. 5. Relative importance of challenges

5. Conclusion

Deterministic networking is an important technological foundation for modern critical industrial applications. Traditional Ethernet provides excellent flexibility and scalability, but its original communication model does not inherently guarantee predictable latency and jitter. Deterministic architectures address this limitation through mechanisms such as precise time synchronization, traffic scheduling, prioritization, shaping, and redundancy. Technologies including TSN, EtherCAT, PROFINET, and OPC UA address different aspects of industrial communication. TSN extends standardized Ethernet with mechanisms for deterministic transmission, while EtherCAT and PROFINET provide specialized solutions for industrial automation and real-time control. OPC UA contributes interoperability, standardized information modeling, and secure communication between industrial systems. The future of industrial networking is increasingly based on converged infrastructures in which real-time control, monitoring, diagnostics, and higher-level information services operate on coordinated network architectures. Deterministic networking can therefore play a central role in the development of reliable, scalable, and interconnected industrial systems.

Acknowledgment

I would like to express my appreciation to the researchers and scientific community whose published studies contributed to the development of this work. I would also like to acknowledge the valuable research conducted in the fields of deterministic networking, Time-Sensitive Networking, Industrial Ethernet, and industrial automation, which provided the theoretical foundation for this study. I am grateful for the opportunity to contribute to this field and to further develop my understanding of deterministic communication technologies and their role in critical industrial applications.

This publication will be funded by the fund “Support for Publishing Publications in Journals with Impact Factor (IF) and Impact Rank (SJR)” of Konstantin Preslavsky University of Shumen, Republic of Bulgaria.

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