

Review

Reconceptualizing Industrial Measurement and Control Networks

Kun Geng^{1,2}, Yueyan Qi⁴, Yingzi Zhang^{1,2}, Qiang Li^{1,2}, Gaigai Liu^{1,2}, Fei Li³, Kangwei Chu^{1,2}, Yingping Hong^{1,2}, Huixin Zhang^{1,2}, Yanjun Zhang^{1,2}, Haifeng Hu⁴, Lisheng Liu⁴, Jianyun Ren⁴, Wenyi Liu^{1,2*}

¹ School of Instrument and Electronics, North University of China, Taiyuan, Shanxi, China

² State Key Laboratory of Extreme Environment Optoelectronic Dynamic Measurement Technology and Instrument, North University of China, Taiyuan, Shanxi, China

³ College of Computer Science and Technology, North University of China, Taiyuan, Shanxi, China

⁴ Shanxi Zhongbei Measurement and Control Technology Co., Ltd., Taiyuan, Shanxi, China

* Corresponding author email: liuwenyi@nuc.edu.cn

Abstract: Driven by the growing needs of high-end equipment manufacturing, complex system verification, and distributed testing, industrial networks are moving beyond device connection and data communication to support deterministic control, real-time data exchange, and coordinated testing. Although deterministic communication technologies have improved time-critical transmission, local synchronization, and priority control, existing industrial control networks still face limits in wide-area distributed testing, multi-source synchronous acquisition, transient event capture, flexible scheduling, and dynamic adaptation. To address these challenges, the evolution of industrial networks is reviewed, and the fundamental differences between test-and-measurement tasks and logic-control tasks are compared in terms of service features, trigger modes, time references, and system boundaries. On this basis, a conceptual framework for industrial measurement and control networks (IMCN) is proposed. The framework defines ten core capabilities: synchronous execution, synchronous acquisition, precise time capture, strict priority assurance, sensor network support, deeply embedded built-in testing, adaptive multi-source timing, dynamic topology reconstruction, network-shared storage, and a native networked instrumentation bus architecture. It also highlights the connotations in four aspects: inheritance, testability, traceability, and autonomy. The applicability and practical value of the proposed conceptual framework are further illustrated through the case of SharkNet in aerospace and other high-end measurement and control systems, while its potential significance for self-organizing, reconstructible, and brain-inspired physical network architectures is also discussed.

Keywords: industrial measurement and control networks(IMCN); distributed testing; industrial control systems; system integration; SharkNet



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1 Introduction

With the continuously rising demand for high-end equipment manufacturing and large-scale complex system testing, industrial networks^[1] are no longer merely

communication channels for device interconnection. Instead, they have become essential infrastructure in modern industrial systems, supporting deterministic control, real-time data exchange, and collaborative execution of complex tasks.

This transformation is closely related to the evolution of industrial systems themselves. From the closed interconnections of early automated production lines to contemporary system forms such as digital twins and cyber-physical systems (CPS)^[2], industrial networks have evolved in two major directions. On the one hand, the range of interconnected objects and supported services has continuously expanded. On the other hand, network services have shifted from best-effort data transmission toward predictable, schedulable, and verifiable deterministic guarantees. However, as aerospace systems, large-scale scientific facilities, and high-end equipment development demand wider-area coverage, higher precision, and stronger dynamic adaptability, conventional industrial networks have gradually exposed inherent architectural limitations in complex measurement-and-control scenarios.

From the perspective of technological evolution,

changes in the form of industrial networks are highly correlated with the staged transformation of industrial production modes, showing a gradual extension from underlying signal connection to system-level collaboration. As shown in Fig. 1, the development of industrial networks can generally be summarized into three stages: "signal-level connection," "digital interconnection," and "deterministic bearer with intelligent integration." The technical characteristics of these stages respectively responded to the dominant requirements of industrial systems at the time in terms of control stability, device interconnection, and task coordination. Early industrial electrified control mainly relied on analog signal transmission, with the 4-20 mA standard point-to-point hardwired system being a typical example. This stage was closer to an engineering combination of signal links and had not yet formed an industrial network with system-level organizational capability.

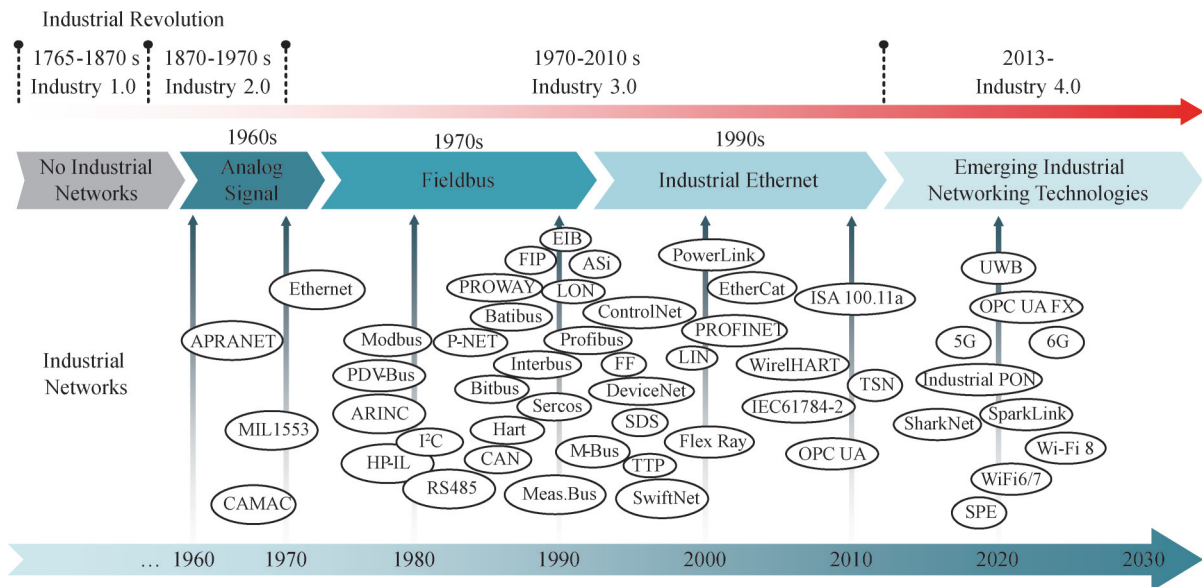


Fig.1 Development of industrial networks

Entering the 1970 s, the Third Industrial Revolution drove production systems toward digitalization and automation. Industrial communication gradually shifted from analog signals to digital data transmission, and the demand for inter-device connectivity increased substantially. Industrial networks thus entered a development stage characterized by "digital interconnection and closed-loop control." In the evolution of industrial communication networks, fieldbus technologies^[3] gradually became an important path for device-level interconnection. Fieldbus systems represented by CAN^[4], Profibus^[5], and Foundation Fieldbus^[6] enabled data exchange among controllers, sensors, and actuators through dedicated protocol stacks, thereby improving the level of digital connectivity in industrial systems to a certain extent. However, such technologies usually depended on relatively closed protocol systems and specialized communication

mechanisms. Constrained by bandwidth, compatibility, and ecosystem openness, their capabilities for system expansion and cross-domain collaboration remained limited, giving rise to typical "automation islands." Meanwhile, some technical routes relied excessively on backward compatibility with existing systems, which also restricted continuous innovation at the network architecture level to some degree^[7,8]. Subsequently, the rise of Industrial Ethernet technologies, such as PROFINET^[9] and EtherNet/IP^[10], broke down the barriers between IT and OT, enabled vertical integration between the enterprise layer and the control layer, and laid a solid foundation for the advancement of Industry 4.0^[11-14]. Nevertheless, the core capability of these technologies still centered on connectivity assurance, while their support for strict real-time performance and transmission determinism remained insufficient.

To meet the latency and jitter requirements imposed

by closed-loop control in highly dynamic systems, the inherently non-deterministic transmission mechanism of standard Ethernet had to be specifically enhanced. Representative solutions such as TTEthernet (TTE)^[15] and EtherCAT^[16] constrain the transmission timing, forwarding path, and resource occupation of periodic control data through mechanisms such as time-slot scheduling^[17], traffic shaping^[18], and high-precision clock synchronization^[19]. In engineering applications, such networks have already been able to constrain jitter to the microsecond level, providing a relatively stable transmission environment for real-time tasks operating within millisecond-level control cycles^[20-22]. It should be noted, however, that the network architecture at this stage still largely follows a separated and parallel arrangement of the control domain and the information domain. Cross-domain data circulation is constrained by the system architecture, making it difficult to support complex applications in which measurement, control, and decision-making are continuously coupled.

Since the beginning of the twenty-first century, the Fourth Industrial Revolution has further promoted the transition of industrial systems from traditional automated production toward intelligence, networking, and collaboration. Correspondingly, the requirements imposed on industrial networks are no longer limited to local closed-loop control. Instead, they have gradually extended to diverse scenarios such as cross-regional collaborative manufacturing, cloud-edge integration, multi-source sensing fusion, and remote operation and maintenance, showing comprehensive characteristics that emphasize ubiquitous connectivity, deterministic bearer capability, and intelligent collaboration^[23]. Against this background, next-generation technologies such as time-sensitive networking (TSN)^[24], industrial 5G^[25], OPC UA^[26], industrial optical networks^[27], and satellite networks^[28] are accelerating their convergence. These technologies are progressively weakening the boundary between industrial control networks and information networks, and are advancing toward unified bearer and multi-service collaboration, thereby providing an important technical foundation for the intelligent upgrading of industrial systems.

However, in high-end testing and measurement tasks, the design focus of existing industrial networks still remains mainly on "logic control" scenarios. Tasks such as aerospace ground testing, large-scale structural health monitoring, and wide-area distributed weapon system testing require more than the reliable delivery of control commands. They also require full-domain nodes to achieve action alignment under a nanosecond-level time reference, and to synchronously capture and return transient events and high-frequency measurement data^[29-31]. Such strongly coupled measurement-and-control requirements reveal the capability boundaries of conventional network architectures designed primarily for periodic control.

In terms of performance, four prominent gaps can be identified. First, time synchronization accuracy in existing control networks typically remains at the microsecond level, whereas high credibility testing and measurement scenarios often require the establishment of a nanosecond-level time reference. There is therefore a clear order-of-magnitude gap between the two^[32,33]. Second, measurement and control systems typically contain both low-speed, large-scale sensor nodes and high-bandwidth, burst-type measurement nodes. Traditional scheduling mechanisms struggle to effectively coordinate resource competition between short-frame control flows and long-frame data flows within a unified network architecture. As a result, critical control services may experience queuing delays or even transmission blocking^[34], and the granularity of tolerable time jitter has consequently shifted from the millisecond level to the nanosecond level. Third, mainstream deterministic networks mostly rely on static configuration. In large-scale test environments, their flexibility and scalability remain insufficient when facing topology changes and dynamic node access^[35]. Fourth, the adaptation of edge-side capabilities is inadequate. Many low-power measurement and control nodes are constrained by their own computing and storage resources, making it difficult for them to bear the synchronization and scheduling overhead introduced by complex protocol stacks. Consequently, high-performance networking capabilities cannot be effectively extended to the system edge, which restricts the improvement of full-domain measurement and control capability.

The above analysis indicates that current industrial networks still lack an integrated paradigm capable of establishing unified constraints across communication, control, and precision measurement. In recent years, research on integrated measurement and control networks has begun to unfold around unified time references^[36], industrial CPS architectures^[37], and system-level collaborative control^[38]. In this context, the "industrial measurement and control network" has gradually become an important direction for supporting high-end test systems and overcoming the bottlenecks of measurement-control integration. Conceptual clarification and architectural reconstruction of this category are not intended to simply rename existing networks. Rather, the key lies in identifying the differences between testing and measurement tasks and traditional logic control tasks in terms of traffic characteristics, triggering mechanisms, and time synchronization requirements, and on this basis constructing a unified network capability system adaptable to multiple scenarios.

From the perspective of engineering implementation, explorations represented by the next-generation measurement and control network SharkNet attempt to embed a high-precision time reference, deterministic transmission, and distributed measurement capability simultaneously into the underlying

mechanisms. For scenarios such as aerospace testing and precision measurement, the value of this approach lies in providing a common spatiotemporal reference for both measurement data and drive control, rather than simply increasing the communication rate. The development of industrial measurement and control networks is therefore not a linear extension of industrial communication technologies, but rather reflects a transformation in the organizational mode of "communication + control + testing."

2 Evolution and Bottlenecks of Networked Measurement and Control Technologies

2.1 Evolution of Networked Measurement and Control Capabilities

For a relatively long period, networked measurement and control technologies in the industrial sector^[39,40] evolved along two largely independent trajectories: "control" and "measurement." The persistence of this separated pattern was mainly rooted in the substantial differences between the fundamental requirements of the two types of systems. Control systems place greater emphasis on real-time performance, determinism, and tight synchronization, aiming to maintain closed-loop stability with relatively low communication overhead. By contrast, testing and measurement systems attach more importance to high bandwidth, precise synchronization, and trustworthy sampling. They require wide-area nodes to align their sampling operations on a nanosecond-scale time basis and to return large volumes of waveform data in full. Among them, control systems are typically represented by fieldbus and Industrial Ethernet, with the core mission of ensuring the real-time performance and reliability of closed-loop control. Testing and measurement systems, on the other hand, are represented primarily by LXI^[41], which focuses on highly reliable waveform acquisition and precision synchronization.

With the advent of Industry 4.0, the demand for integrated measurement and control has grown rapidly, and a single technology stack is no longer sufficient to support collaborative tasks in complex scenarios. Although emerging networking technologies represented by TSN can enhance deterministic service bearing through mechanisms such as gate control lists, time-slot allocation, frame preemption, and preemption recovery, thereby promoting the converged evolution of industrial testing networks and industrial control networks to some extent, these mechanisms generally rely, at the engineering implementation level, on a unified and high-precision time reference across the entire network. Once inter-node clock synchronization experiences drift or offset, scheduling and timing control may suffer from

systematic misalignment. In mild cases, gating windows and traffic-shaping policies may deviate from their intended behavior, leading to significant degradation in end-to-end latency and jitter. In severe cases, critical periodic frames may miss their transmission or reception windows, causing queue congestion, packet loss, or even timing disorder in the control loop, thereby affecting normal system operation.

It can therefore be seen that existing TSN mechanisms still have significant limitations in simultaneously supporting "action-level temporal consistency" and "high credibility cross-node data coordination." The key bottleneck lies mainly in their deep dependence on high-precision global time synchronization^[42]. Starting from the evolutionary process of networked measurement and control technologies, this section analyzes the architectural difficulties encountered by existing technologies when integrating highly deterministic transmission with trustworthy measurement. On this basis, it further introduces the core capabilities that next-generation industrial measurement and control networks should possess.

2.1.1 The Era of Dedicated Fieldbus: Formation and Limitations of Digital Islands

(1) From Analog to Digital

In the early stages of the Industrial Revolution, industrial networks in the modern sense had not yet emerged. Measurement and control activities in factories mainly relied on mechanical mechanisms, pneumatic transmission, or manual operation. Mature electronic communication methods were not yet available, and point-to-point hardwiring was widely used on industrial sites for signal transmission.

Among these approaches, the most representative was the 4-20 mA analog signal standard, which was mainly used for long-distance signal transmission between sensors/transmitters and controllers^[43]. This standard marked the initial transition of industrial measurement and control from a purely mechanical mode to an electronic one. Although early point-to-point analog signal transmission featured a clear structure, reliable operation, and controllable implementation cost, and was able to meet the basic requirements for transmitting process variables, its limitations were also evident. First, it required extensive wiring and incurred high maintenance costs in later stages. Second, its information-carrying capacity was severely limited^[44]; a single cable usually corresponded to only one process variable, making it difficult to transmit device diagnostic information and configuration parameters together with the measurement signal. Third, analog signals were susceptible to noise. As the number of devices increased, both wiring complexity and system operating efficiency became constrained.

At this stage, measurement and control technologies

were still in the initial phase of networked development. Measurement and control mainly relied on dedicated physical cables to establish point-to-point mappings, while different loops were isolated from one another and operated independently. Because analog signals were inherently single-purpose and closed, the system could not yet develop capabilities for networked collaboration or resource sharing, nor could it support large-scale measurement and control tasks in complex industrial scenarios.

(2) The Fieldbus Competition

With the development of electronic computing and digital communication technologies, industrial control systems began to evolve from analog and isolated forms toward digital and networked architectures. The direct driving force behind this transition was that the traditional point-to-point analog signal transmission mode suffered from extensive wiring requirements, complicated maintenance procedures, and limited transmission accuracy. To reduce engineering deployment costs and improve system reliability and data transmission quality, countries successively developed fieldbus technologies in the 1980s and 1990s, connecting field devices and controllers to multi-point digital serial buses as a replacement for conventional one-to-one hardwiring.

Representative early fieldbus technologies included Modbus^[45], PROFIBUS, the CAN bus, and Foundation Fieldbus. These buses generally adopted serial physical layers and enabled data transmission through multi-point communication and digital encoding, allowing bidirectional communication between field devices and PLC/DCS systems. Compared with analog signal links, fieldbus technologies initially exhibited the basic characteristics of device interconnection, information sharing, and networked measurement and control.

Compared with traditional analog hardwired systems, fieldbus technologies significantly reduced cable consumption and wiring workload through bus sharing and centralized wiring. In typical industrial applications, installation costs could be reduced by 20%-40%^[46]. At the same time, digital communication greatly improved data transmission accuracy and anti-interference capability, making it possible to obtain device diagnostic information, configure parameters remotely, and monitor equipment status online. Industrial control therefore began to acquire basic capabilities for networked coordination.

In the early stage of engineering application, fieldbus technologies did not form a unified international specification capable of covering major vendors and application scenarios. Driven by considerations such as product ecosystems, market share, and proprietary control, different automation vendors successively introduced their own protocols, leading to the long-standing so-called "fieldbus wars." Germany incorporated PROFIBUS into its DIN national standard, while the ISA

organization in the United States promoted a unified specification through SP50, both of which indicate that standard competition and industrial interests were highly intertwined at this stage. The direct consequence was the parallel operation of multiple incompatible standards. Devices from different vendors within the same factory could not be naturally interconnected, and system interoperability became a prominent issue^[47].

It was not until 1999, when the International Electrotechnical Commission (IEC) released the IEC 61158 fieldbus standard^[48], that this dispute was formally addressed. Since fieldbus protocols from different countries and vendors remained incompatible, eight different protocols were ultimately incorporated into the standard in parallel. This "resolved" the dispute at the standardization level, but did not truly solve the interoperability problem in engineering applications. Fieldbus systems continued to operate in closed modes, each forming its own independent technical ecosystem. The negative impact of the "fieldbus wars" was not limited to interoperability difficulties in practical engineering. More importantly, it fundamentally separated the integration path of "measurement" and "control" at the architectural level, which was reflected in three aspects.

First, semantic barriers limited the deep integration of measurement and control data. Fragmented protocol systems turned devices from different vendors into heterogeneous and closed functional units, in which control data and measurement data were often locked within their respective protocol stacks. Cross-system measurement and control coordination usually required gateways for protocol conversion. This process was costly and inefficient, and it could also cause the loss of measurement metadata valuable for analysis^[49]. As a result, networks in practical applications often transmitted only simple process variables and could hardly support complex measurement-control fusion algorithms.

Second, physical-layer differences reinforced the pattern of "control first, measurement second." Early fieldbus technologies were mainly designed to ensure control reliability and real-time performance under limited bandwidth. For example, CAN could meet basic logic-control requirements, but its 1 Mbit/s bandwidth limit and 8-byte short-frame structure^[50,51] constrained the integration of high-frequency measurement data, such as vibration and acoustic signals, at the physical layer. This low-bandwidth, short-frame design made it difficult to incorporate precision measurement tasks into industrial networks, which therefore continued to rely on GPIB buses or dedicated acquisition cards.

Third, the absence of a unified time base limited synchronization capability. In fragmented fieldbus systems, different protocols defined, transmitted, and calibrated time in different ways, and there was no high-precision clock reference for all nodes. Devices located on different bus segments therefore could not usually

achieve nanosecond-level action alignment. They could only maintain basic synchronization through millisecond-level polling or low-speed coordination mechanisms. This

capability was clearly insufficient for system-wide synchronization required by distributed measurement and control.

Table 1 Performance Metrics of Typical Fieldbus

Fieldbus	Maximum bandwidth(Mbit/s)	Latency(ms)	Jitter(ms)	Synchronization accuracy
Modbus RTU	0.1152	10-100	<1	Not supported
PROFIBUS	12	1-50	<5	Not supported
DeviceNet	0.5	2-20	<1	Not supported
Foundation Fieldbus	0.03125	100-500	<10	±5 ms
ControlNet	5	2-10	<0.5	±10 μs

The typical indicators in Table 1 show that fieldbus technologies were already capable of digital transmission with a certain degree of anti-interference capability at the physical layer. Their latency was mostly at the millisecond level, and the jitter of some buses could reach the sub-millisecond level, which was generally sufficient to meet the real-time and deterministic requirements of closed-loop control loops. However, in terms of bandwidth and synchronization capability, even PROFIBUS, which offered relatively better performance, was still unable to support the real-time throughput of large volumes of high-frequency measurement data. Moreover, most fieldbus technologies did not regard time synchronization as a core design indicator from the outset. Therefore, fieldbus technologies were closer to low-speed data communication methods. Lacking a unified spatiotemporal reference and waveform alignment capability, they could not yet be regarded as testing networks in the true sense.

Overall, the fieldbus era completed the critical transition of industrial measurement and control from analog to digital forms and solved the basic control problem of "connectivity" on industrial sites. However, its fragmented technical ecosystem and physical-layer design optimized for low-speed control determined that it was essentially a "dedicated logic control network." This inherent architectural deficiency meant that "high credibility measurement" was excluded from the core architecture of industrial networks for a long period, preventing genuine measurement-control integration and foreshadowing the subsequent reconstruction of network architectures in the Industrial Ethernet era.

2.1.2 Industrial Ethernet Revolution

In the late 1990s, the concept of networked control systems (NCS) was proposed in academia^[52]. Its basic meaning is to incorporate sensors, controllers, and actuators into a closed-loop feedback chain through a network, thereby enabling control systems to operate across nodes. As a result, the network was no longer merely an external auxiliary communication tool for control systems, but became an inseparable component of the control loop itself. Control tasks expanded from local

scenarios to cross-node collaboration, which further increased the requirements placed on network communication capability in industrial environments.

During this period, industrial communication entered the era of Industrial Ethernet. Its development was driven by two major practical demands. First, the rapid development of Ethernet and Internet technologies in the IT field encouraged the OT field to integrate mature IT standards, so as to reduce equipment costs and reuse established product ecosystems. Second, scenarios such as complex distributed control and high-speed motion control imposed higher requirements on network bandwidth and latency performance, which traditional fieldbus technologies could no longer satisfy. The core logic of Industrial Ethernet evolution was to preserve compatibility with the physical layer of the IEEE 802.3 Ethernet standard while introducing technical enhancements to provide strict real-time determinism, thereby achieving the dual objectives of "general compatibility" and "real-time reliability."

Standard Ethernet has advantages such as high transmission rate, strong universality, and a mature industrial ecosystem. However, the CSMA/CD mechanism adopted by early Ethernet by default introduced considerable communication delay jitter and weak transmission determinism, making it difficult to directly satisfy the strict real-time control requirements of industrial sites. Therefore, how to compensate for the lack of determinism while retaining the openness and high-speed advantages of Ethernet became a key issue that had to be addressed in the evolution of Industrial Ethernet technologies.

To overcome these limitations, industry introduced various deterministic assurance mechanisms on top of Ethernet, forming seven representative Industrial Ethernet solutions^[53], including Modbus/TCP, PROFINET, EtherNet/IP, POWERLINK, EtherCAT, SERCOS-III, and CC-Link IE. Their core indicators are shown in Table 2. Through long-term technical competition and application promotion, PROFINET, EtherNet/IP, and EtherCAT gradually became the major standards in the Industrial Ethernet market by virtue of their respective technical routes and ecosystem advantages, jointly driving

industrial networks toward higher speed and higher-precision control. The three technologies are representative

in terms of mechanism design and application scenarios, while also exhibiting distinct characteristics.

Table 2 Performance of Mainstream Industrial Ethernet

Solutions	Modbus/TCP	PROFINET IRT	EtherNet/IP	POWERLINK	EtherCAT	SERCOS-III	CC-Link IE
Topology	Star, tree	Star, line, tree, ring	Star, tree, ring	Star, line, tree	Star, line, tree, ring	Line, ring	Star, line, ring
Nodes per segment	IP addressing	64	IP addressing	240	65,535	511	121
Min cycle	10-20 ms	250 μ s	5-10 ms	1-2 ms	12.5 μ s	31.25 μ s	1 ms
Jitter	Not available	<1 μ s	1-10 ms	<1 μ s	<1 μ s	<1 μ s	Not available
Synchronization accuracy	Not supported	\pm 1 μ s	< \pm 10 μ s	\pm 1 μ s	\pm 100 ns	\pm 1 μ s	< \pm 10 μ s
Recovery	1-4 s	200-500 ms	3 ms	50 ms	15 μ s	25 μ s	50-100 ms

(1) EtherNet/IP

EtherNet/IP is managed by ODVA. Its core design principle is to retain the standard Ethernet physical layer and data link layer without modifying the underlying hardware logic. Adaptation to industrial scenarios is realized at the application layer through the Common Industrial Protocol (CIP)^[54].

Early EtherNet/IP mainly relied on high-bandwidth switches and quality of service (QoS) mechanisms to provide soft real-time control capability, which was insufficient for hard real-time motion control. To address this limitation, ODVA introduced CIP Sync based on the IEEE 1588 Precision Time Protocol (PTP)^[55]. By synchronizing clocks across the network, CIP Sync enables devices to execute actions according to precise timestamps. It therefore supports coordinated control across nodes without major modification of the underlying hardware, while maintaining strong flexibility and scalability.

(2) PROFINET

PROFINET is managed by PI. Its core design concept is to divide different communication channels on the same network cable, thereby balancing openness and real-time performance. It supports three differentiated data-transmission modes for different levels of real-time requirements^[56].

PROFINET NRT (Non-Real Time) uses the standard TCP/IP protocol stack and is mainly used for non-real-time data transmission, such as device parameter configuration and fault diagnosis. Its real-time response is about 100 ms, making it suitable for general industrial control scenarios with low real-time requirements.

PROFINET RT (Real-Time) improves I/O data-transmission efficiency by bypassing the TCP/IP stack and encapsulating data directly at the Ethernet data link layer with a specific EtherType. This software-level real-time optimization can achieve cycle times of 1-10 ms. It is suitable for most discrete-manufacturing I/O control tasks at the PLC level and does not require dedicated hardware. Standard network interface cards can support

it, giving it a favorable cost-performance ratio.

PROFINET IRT (Isochronous Real-Time) is designed for absolute real-time performance. It isolates the deterministic data-transmission channel from ordinary Ethernet traffic and improves transmission determinism through hardware-level optimization. Its core mechanism is time slicing, which divides the transmission cycle into a "red phase" for deterministic data and a "green phase" for open data transmission. Dedicated ASIC chips are required. This mode can achieve sub-millisecond cycle times and microsecond-level jitter control, satisfying the real-time and synchronization requirements of most motion-control applications.

However, PROFINET also has clear limitations. Each slave address must be configured manually, and the addition of new slaves may affect the address allocation of the entire network, increasing address-management complexity. Under sudden load surges, such as intensive ARP requests, network stability may decline significantly, indicating limited interference resistance.

(3) EtherCAT

EtherCAT is a high-speed real-time Ethernet technology. Its positioning is similar to that of PROFINET IRT, as both rely on hardware mechanisms to guarantee real-time performance. Unlike conventional store-and-forward switching, EtherCAT uses an on-the-fly transmission mechanism, in which a data frame can be read or written as it passes through a node without waiting for a complete store-and-forward process. This mechanism reduces switching delay and improves communication efficiency.

EtherCAT can support servo cycles at the 100 μ s level. Related studies^[57] show that compared with EtherNet/IP and PROFINET, EtherCAT performs best in several measured indicators, including bus cycle time and average transmission delay. In addition, EtherCAT uses a dedicated distributed clock mechanism. During on-the-fly transmission, it collects timestamps and performs hardware-level clock-offset compensation, enabling trajectory synchronization errors of no more than 200 ns

in 100-axis servo systems. This effectively eliminates the adverse effects of latency jitter on control algorithms and makes EtherCAT suitable for high-precision motion control.

In summary, after the transition to Industrial Ethernet, industrial communication capabilities improved by orders of magnitude compared with the fieldbus era. Network bandwidth increased from the kbps level to the Mbps level and beyond, while control cycles and synchronization accuracy gradually moved from the millisecond range to the microsecond range. In addition to improved real-time performance, capabilities such as hundred-nanosecond-level precision synchronization and tens-of-microseconds-level fault recovery began to be introduced into engineering systems. This provided more reliable networking conditions for complex closed-loop control scenarios, such as high-speed packaging and multi-robot collaboration.

However, these performance improvements mainly occurred within individual protocol stacks and represented vertical capability enhancement. They did not fundamentally solve the cross-domain fragmentation inherited from the fieldbus era. The divided protocol ecosystem continued to create high interoperability barriers. Semantic inconsistencies remained among devices using different standards, while measurement data and control commands were confined within local high-performance control loops^[58]. Global sharing, unified scheduling, and cross-system collaboration were therefore difficult to achieve. This paradox of "physical connectivity but logical isolation" seriously constrained global measurement and control coordination across vendors and system layers, hindered system-wide data fusion in industrial systems, and failed to meet the core requirements of large-scale distributed measurement and control. It thus became a major bottleneck in the evolution from Industrial Ethernet toward integrated measurement and control.

2.1.3 Time Synchronization and Deterministic Networking

The construction of an industrial measurement and control networking architecture is not a simple stacking of individual network capabilities. Its core lies in the integrated design of high-precision time synchronization, time-sensitive transmission, and end-to-end deterministic services within a unified architecture, so that the time base, transmission rules, and service guarantees can form a coordinated engineering closed loop. High-precision time synchronization provides a unified spatiotemporal reference for the whole system and is the foundation for distributed measurement and control coordination as well as multi-source data fusion. Time-sensitive networking builds deterministic transmission behavior within local networks through fine-grained scheduling and timing control, ensuring the real-time delivery of critical services. On this basis, deterministic networking extends deterministic service capabilities across links, networks,

and domains, ultimately forming an end-to-end verifiable and guaranteed deterministic communication system that provides core support for integrated measurement and control.

(1) High-Precision Time Synchronization

Stable operation of deterministic networks first requires network-wide time consistency. In distributed measurement and control systems, time synchronization is used not only to eliminate clock offsets and frequency drift among nodes, but also to support cross-node cooperative control, causal consistency of events, and time alignment of multi-source measurement data. As industrial measurement and control accuracy continues to improve, traditional Network Time Protocol (NTP)^[59], which relies mainly on software timestamps, can no longer meet high-precision synchronization requirements. Hardware-assisted time synchronization has therefore become the mainstream approach^[60]. Different solutions are suitable for different accuracy levels and application scenarios.

IEEE 1588 PTP^[61] is the mainstream synchronization standard in current industrial control networks. By recording packet transmission and reception times directly at the physical layer (PHY), PTP effectively eliminates the uncertain delay introduced by the operating-system protocol stack and can achieve sub-microsecond synchronization accuracy. Mainstream Industrial Ethernet protocols, including PROFINET IRT and EtherNet/IP CIP Sync, commonly adopt this standard as the basis for time synchronization, supporting the coordination requirements of medium- and high-precision control scenarios.

White Rabbit^[62] was developed for the extreme sub-nanosecond synchronization requirements of large scientific facilities, such as particle accelerators. It innovatively combines the frequency-transfer capability of synchronous Ethernet (SyncE) with the phase-calibration advantage of PTP, achieving sub-nanosecond synchronization accuracy. It represents one of the highest levels of current networked synchronization technology and provides an important technical reference for high credibility distributed measurement, such as wide-area temporal reconstruction, filling a gap in synchronization technology for advanced scientific experiments.

IEEE 802.1AS, also known as generalized PTP (gPTP)^[63], is a core component of the TSN protocol family. It simplifies and strengthens conventional PTP for demanding industrial and automotive scenarios. By removing the uncertain convergence process of the Best Master Clock Algorithm (BMCA) and improving the robustness and real-time performance of synchronization, gPTP provides a stable and reliable global time service for various TSN scheduling mechanisms, thereby supporting deterministic transmission.

(2) Time-Sensitive Networking

Time-Sensitive Networking (TSN) is widely regarded as a key direction for next-generation industrial

networks^[64-66] because it converts the unified time scale provided by high-precision synchronization into executable scheduling and forwarding rules at the data link layer. In other words, TSN is not a single protocol, but a set of standardized protocols developed by the IEEE

802.1 working group to address time synchronization, traffic scheduling, and reliable transmission^[67]. Its role is to reduce the uncertainty caused by medium contention in traditional Ethernet. The evolution of related standards is shown in Fig.2.

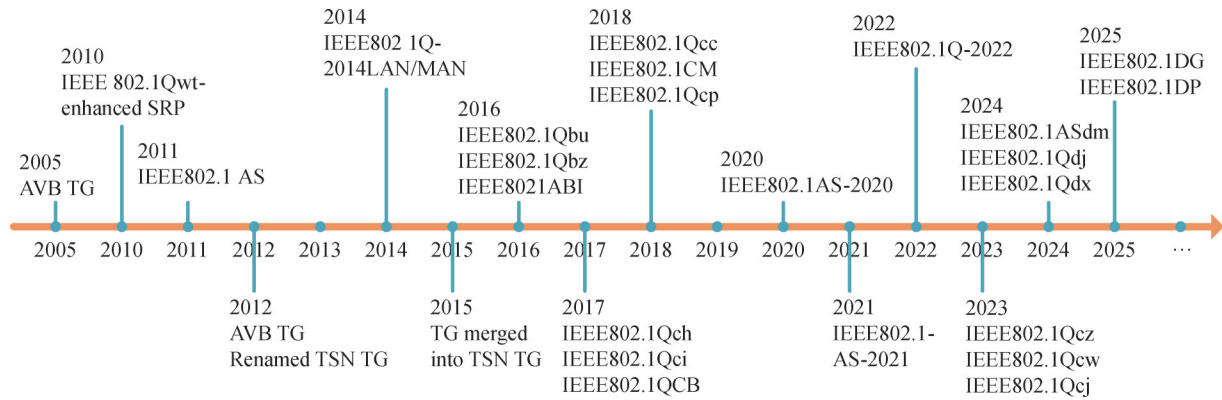


Fig.2 Release timeline of TSN-related standards.

To achieve deterministic transmission, TSN introduces industrial enhancements to Ethernet under the IEEE 802 framework, including time-aware scheduling, traffic shaping, frame preemption and recovery, and frame reservation. Through the combined operation of these mechanisms, Industrial Ethernet can provide sub-millisecond jitter control and highly reliable transmission services over a unified underlying infrastructure. It can further support hard real-time communication with microsecond- or even nanosecond-level clock synchronization, ultra-low latency, and low packet loss^[68]. As a result, measurement and control services gain a technical basis for coordinated transport over the same network.

(3) Diversified Deterministic Network

As the industrial Internet expands from local factory interconnection to cross-factory and cross-regional collaboration, industrial measurement and control services have become more heterogeneous and geographically distributed. A TSN framework designed mainly for local control scenarios can no longer fully cover complex application requirements. As shown in Table 3, typical industrial measurement and control services differ significantly in bandwidth, end-to-end latency, jitter constraints, and time-synchronization accuracy. They include periodic motion-control and process-control services with strict jitter requirements, non-periodic and high-throughput machine-vision measurement services, and wide-area remote operation, maintenance, and inspection services. This heterogeneity requires industrial networks to provide predictable latency bounds, controllable jitter, and verifiable time consistency over larger scopes, so that different types of measurement and control services can be carried in parallel.

At present, deterministic networking technologies are developing along diversified technical routes.

Different technologies are complementary in terms of applicable network layers, coverage scope, and implementation mechanisms. Together with TSN, they form a comprehensive technical system for deterministic services, covering typical network forms such as wired and wireless networks, as well as local-area and wide-area networks. These technologies can be summarized into the following four representative directions^[70].

First, local deterministic mechanisms. With TSN as the core, mechanisms such as time synchronization, time-slot allocation, and traffic shaping are used within Layer 2 networks to provide microsecond-level deterministic transmission assurance. This direction is suitable for high-precision control and measurement coordination scenarios within local-area environments.

Second, physical-layer bearer enhancement. FlexE^[71] introduces time-division-multiplexing-based slicing capability at the physical layer, establishing dedicated bearer channels with resource isolation for deterministic services. This effectively reduces the impact of link congestion and service competition on latency performance, thereby improving transmission stability.

Third, cross-domain predictable forwarding. DetNet^[72] extends the ideas of resource reservation and fine-grained scheduling to Layer 3 IP/MPLS networks, enabling predictable forwarding across domains and providing end-to-end deterministic assurance for wide-area cross-domain measurement and control services.

Fourth, wireless deterministic access. 5GDN^[73] and DetWiFi^[74] are oriented toward mobile and wireless measurement and control scenarios. They optimize the latency and jitter performance of wireless transmission, provide deterministic access capability, and meet the requirements of low-latency and high-reliability measurement and control services in wireless environments, thereby filling the gap in deterministic transmission for wireless scenarios.

Table 3 Representative Network Requirements of Industrial Services *

Type	Bandwidth (Mbps)	Latency (ms)	Jitter (μ s)	Synchronization accuracy	Description
Motion / process control	>0.05	<1(Cycle less than 10 ms); <0.1(Cycle less than 1 ms)	<1	$\pm 10 \mu$ s; $\pm 1 \mu$ s (Cycle less than 3125 ms)	Periodic signal, isochronous synchronization
Monitoring and measurement	>10	<60	--**	--	Periodic signal, non-isochronous synchronization
AGV control	>10	<10	<10	--	Periodic signal, strong determinism
Machine vision	>1000	<20	--	--	Aperiodic signal
Audio stream	>100	<50	--	--	Aperiodic signal
Digital twin	>100	<100	--	--	Aperiodic signal
Predictive maintenance	>10	<1	--	--	Aperiodic signal
Remote ultrasonic testing	>10	<10	--	--	Aperiodic signal
Urban rail transit	>1000	<20	<50	30 ns	Mixed signals
Power grid control	>10	<10	--	--	Aperiodic signal
Slow-varying sensors, such as temperature, humidity, and slowly varying pressure	0.001-0.1	10-500	--	--	Periodic signal
Fast-varying sensors, such as vibration, acceleration, and shock	0.1-5	5-20	<100	100 μ s	Periodic signal

* The table is partly adapted from [69], with additional entries compiled from other cited sources.

** -- = no explicit quantitative requirement specified in the cited source.

The development of the above-mentioned technologies is progressively driving the evolution of industrial networks toward those with trusted testing capabilities. The key features of this evolution are reflected in capability enhancements in the following three aspects.

First, nanosecond-level time-base consistency. The network should be able to provide verifiable high-precision time synchronization across nodes and domains, offering a unified temporal reference for measurement data alignment and cross-node action coordination. This is the core prerequisite for measurement-control integration.

Second, microsecond-level deterministic transmission and scheduling. With mechanisms such as TSN as the core, the network should provide bounded latency, low jitter, and predictable queuing behavior for critical measurement and control service flows, ensuring the stable transmission of closed-loop control data and real-time measurement data.

Third, full-domain deterministic bearer and cross-domain coordination. The network should be able to extend the coverage of deterministic services across heterogeneous network environments, including wired/wireless and local-area/wide-area networks. It should realize deterministic assurance and collaborative control across network segments and regions, and support the

parallel bearing of heterogeneous measurement and control services.

Only with the above three core capabilities can industrial networks provide stable support for large-scale, highly dynamic distributed measurement and control tasks in complex scenarios involving parallel transmission of heterogeneous services. Such capabilities enable the deep integration of determinism and synchronization, and promote the transition of industrial measurement and control from "separate-network operation" toward "integrated collaboration."

2.1.4 Networked Instrumentation Buses

While industrial control networks have strengthened deterministic transmission along the path of fieldbus, Industrial Ethernet, and TSN, the test and measurement (T&M) field has also evolved from centralized chassis-based systems toward distributed network synchronization. The core problem driving this transition is how to overcome physical-space limitations and enable high credibility waveform acquisition, signal analysis, and synchronous sampling over wide areas.

The development history of instrument buses is shown in Fig. 3. Early automated test systems relied heavily on physical backplanes to maintain synchronization performance. From GPIB (IEEE 488)^[75-77], which established the standard for programmable

instrumentation, to the "VME backplane" of VXI, and then to PXI/PXIe modular instruments based on PCI/PCIe architectures^[78], instrument buses have continuously evolved along the main trajectory of "moving testing technology into the computer chassis." Their bandwidth increased from 1 MB/s to 24 GB/s, and their synchronization accuracy improved from the millisecond level to the picosecond level, with the physical backplane remaining the core support for each performance leap. However, this computer-centered

centralized test architecture soon exposed limitations in physical space. Measurement modules usually had to be installed within the same chassis, forming a local synchronization domain with high performance but severely limited scalability. For scenarios such as aerospace static tests and large particle accelerators, where multi-point collaborative testing must be conducted across several kilometers, this architecture could hardly meet the requirements of wide-area distributed measurement.

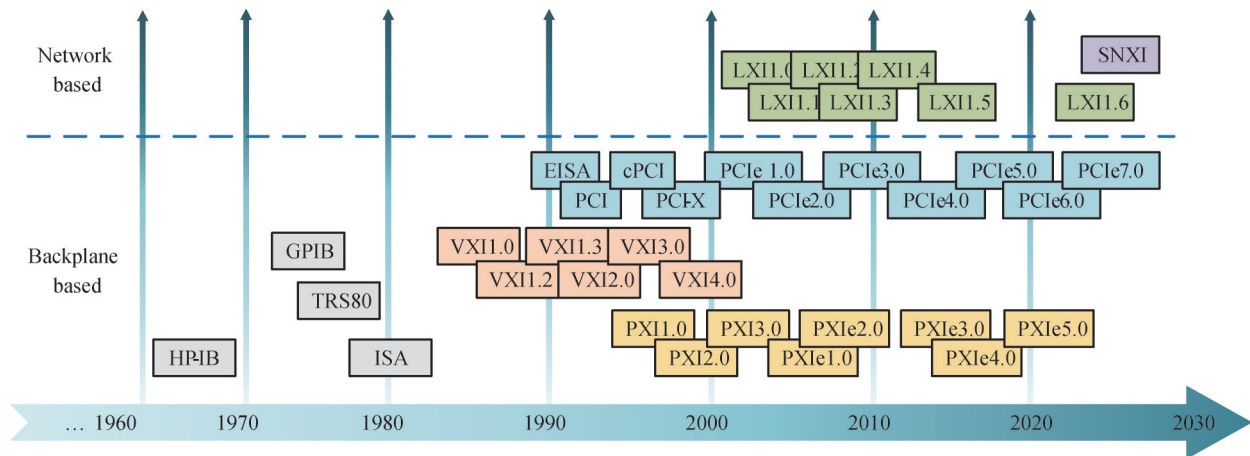


Fig.3 Evolution of instrumentation buses.

To break through the constraints of physical chassis and realize wide-area synchronized testing, the LXI (LAN eXtensions for Instrumentation) Consortium was established in 2005 and released the LXI 1.0 specification. This specification aimed to combine the measurement accuracy of instruments with the openness of networks, introduce Ethernet technology into test automation, and integrate instrument performance, modular design flexibility, and the high-bandwidth characteristics of Ethernet^[79]. The significance of LXI lies in its change to the synchronization implementation mode: test systems no longer relied primarily on physical wiring to perform hardware triggering, but shifted toward soft synchronization based on a unified time base.

LXI 1.3, released in 2008, focused on the "unification of the spatiotemporal reference." By deeply integrating the IEEE 1588 PTP protocol^[80,81] with the LAN event triggering mechanism, and by performing hardware timestamping at the network interface layer, it eliminated the uncertainty of the protocol stack and achieved sub-microsecond network clock synchronization. As a result, oscilloscopes or signal sources distributed across different workshops and separated by several kilometers could be locked to the same "virtual system clock." This effectively overcame the non-determinism of standard Ethernet and established sub-microsecond synchronization and coordination capability for distributed instruments^[82]. LXI 1.4, released in 2011, further focused on "flexible architectural reconstruction and security compliance." By

decoupling the "core specification for interoperability" from "extended function packages," it weakened the Class A/B/C hierarchical framework in earlier standards and strengthened support for network security and API standardization. This promoted the evolution of test systems from simple hardware interconnection toward an industrial Internet architecture characterized by software definition, agile integration, and intrinsic security.

LXI brought instrument buses into the networked stage. It directly uses low-cost Ethernet cables, namely LAN, to transmit commands and data. Therefore, test nodes can be deployed in workshops, experimental stations, or test areas several kilometers apart. For large facilities and multi-site collaborative testing, this distributed connection mode provides more flexible system organization conditions than centralized chassis. To compensate for the insufficient determinism of Ethernet, high-end LXI devices introduced dedicated hardware trigger buses, enabling nanosecond-level trigger response through dedicated physical wiring in addition to network cables. This hybrid mode, in which "the network transmits data while hardwiring transmits triggers," became a typical transitional form of networked measurement and control^[83].

Although LXI successfully realized the networking of instruments, it has always existed as a "measurement-dedicated network" independent of industrial control systems such as PLC/DCS. Protocol stack isolation remains an important limitation in LXI applications. LXI devices usually communicate with the host computer

through protocols such as VXI-11 or HiSLIP, which are not control protocols that can be directly parsed by industrial controllers such as PLCs. Therefore, measurement data often cannot enter the closed-loop control process in real time, and application-layer and protocol-layer isolation still exists between testing and measurement networks and industrial control networks.

LXI provides sufficient synchronization but insufficient scheduling. It solves the problem of "all devices acting at the same moment," namely synchronization, but does not solve the problem of data "being delivered stably within a specified time," namely determinism. LXI data transmission mainly relies on TCP/IP and remains constrained by Ethernet queuing jitter under high-load conditions^[84,85]. Although measurement data can be assigned precise timestamps, the transmission delay of data packets in the network is still uncontrollable, making it unable to satisfy the stringent real-time feedback requirements of closed-loop control.

To address the series of inherent issues that LXI faces due to its use of Ethernet, North University of China has introduced SNXI (SharkNet eXtensions for Instrumentation), which offers a more radical solution. It completely abandons support for Ethernet and, instead, builds upon the SharkNet network, fully inheriting all the functions and performance specifications of SharkNet. Its innovation lies in leveraging SharkNet's extremely high synchronization performance to completely forgo the backplane traditionally relied upon by instrument buses, with all boards interconnected directly via SharkNet. Devices and boards distributed across wide spatial ranges can be automatically identified and associated with a test system without requiring user programming. These features indicate that SNXI is a native board-level networked instrument bus, providing a novel architecture for the distributed integration at the instrument layer.

2.1.5 Sensor Networks

Complex industrial measurement and control systems involve a large number of distributed sensor nodes, and how to integrate them efficiently via networking is a major challenge in the testing field. When traditional sensor networks are integrated, parameters such as distance, bandwidth, number of nodes, real-time performance, and cost are often subject to severe trade-offs. For example, increases in distance and node count make bandwidth improvement difficult. Although existing technologies have formed systems such as fieldbus, process instrumentation buses, avionics buses, and real-time Industrial Ethernet, different technical routes usually have only local advantages and struggle to simultaneously meet the comprehensive requirements of long distance, high bandwidth, large scale, tight synchronization, and high reliability.

Traditional serial differential buses, such as RS-422, RS-485, Modbus, and CAN/CANopen, have simple structures, low cost, and strong anti-interference

capability, and can be used for distributed sensor networking. However, their bandwidth of only a few Mbps and their node capacity of roughly 30 nodes are completely insufficient to support large-scale sensor integration. IO-Link and AS-Interface are mainly used to connect field devices such as sensors and actuators at the bottom layer of industrial automation systems with control systems, and they face the same problem.

Process instrumentation buses, including HART, Foundation Fieldbus H1, and PROFIBUS PA, serve slowly varying process instruments. They have low data rates, typically 31.25 kbit/s or lower, and focus on long-distance reliable control. However, they are not suitable for high-bandwidth, highly dynamic, multi-physical-quantity synchronous acquisition.

2.1.6 Summary

In summary, industrial networks have long developed along two relatively independent paths: the "control network" and the "measurement network," forming a typical dual architecture. This structural separation has led to contradictions in capability allocation. Measurement systems can provide high-precision, high-bandwidth, and tightly synchronized state acquisition, but they usually struggle to implement real-time closed-loop control over physical processes at the same level. Control networks, by contrast, can maintain stable hard real-time closed loops with relatively low communication overhead, but they have difficulty supporting the synchronous return and fusion processing of high credibility, multi-source heterogeneous measurement data.

Existing technologies are more oriented toward general industrial scenarios and mainly address device access, system interconnection, and efficiency improvement. However, for same-domain coordination between nanosecond-level trustworthy measurement and hard real-time control, a complete mechanism that integrates the time reference, scheduling rules, and engineering assurance is still lacking. Especially under distributed measurement and control conditions, wide-area heterogeneous links must not only maintain microsecond-level deterministic transmission, but also ensure the stable consistency of a nanosecond-level time base in software-defined and multi-domain collaborative environments. This remains a question that current systems have difficulty fully answering.

2.2 Bottleneck Analysis

For measurement and control tasks under extreme conditions, what existing industrial networks expose is not the insufficiency of a certain local indicator, but a generational mismatch between their underlying mechanisms and emerging measurement and control requirements. The root cause lies in the fact that existing industrial network systems rely deeply on the general-purpose TCP/IP protocol foundation. This protocol stack

was originally designed for large-scale networking scenarios such as the Internet and cloud computing, with an emphasis on universal connectivity and bandwidth throughput. It did not consider, at the level of underlying mechanisms, the special requirements of high-end equipment systems for highly real-time and highly deterministic interaction^[86].

Specifically, when existing network architectures are applied to high-end equipment, they face four core challenges: the protocol system design cannot meet the requirements of efficient real-time transmission; agile real-time access methods for devices and applications are lacking; network planning and application deployment are insufficiently flexible; and security protection is difficult to implement^[87]. This section systematically reveals the inherent limitations of traditional architectures in supporting next-generation measurement and control tasks from five dimensions: synchronization accuracy, traffic scheduling, architectural performance, protocol efficiency, and Built-In Test (BIT) mechanisms.

2.2.1 Mechanistic Absence of Synchronization Accuracy

Although existing control networks can already achieve sub-microsecond clock synchronization with the help of IEEE 1588, a deterministic gap still exists when high-precision "network time" is stably converted into reproducible "physical action timing." This problem is not caused by a defect in any single protocol. Rather, it stems mainly from differences in field-terminal capabilities and limitations in implementation mechanisms. The relevant constraints are concentrated in insufficient terminal-side synchronization capability and unstable conversion of physical event timing, which directly affect the closed-loop realization of high-precision collaborative measurement and control.

On the one hand, a large number of legacy devices in industrial sites are constrained by early hardware architectures and lack physical-layer support for precision synchronization mechanisms such as IEEE 1588. As a result, they cannot directly participate in high-precision time distribution and alignment. Although such devices can be functionally connected through gateways or protocol conversion, they are difficult to incorporate into a unified deterministic scheduling domain, creating time-isolated blind spots that are "accessible but not synchronizable." Consequently, they are unable to undertake high-precision collaborative tasks.

On the other hand, even for low-computing-power measurement and control terminals with digital capabilities, although they may support time synchronization at the protocol level, the internal path from time acquisition to action execution still contains multiple non-deterministic factors. These factors weaken and distort terminal-side timing semantics. This deficiency can be observed at three levels: terminal timing, resource contention, and link assumptions.

Without hardware timestamps, time marks are usually generated by driver or application-layer software. Between the occurrence of a physical event and the recording of its timestamp, the signal passes through bus transmission, interrupt response, and system scheduling inside the terminal node and operating system, which may introduce random jitter at the microsecond level or above^[88]. Under multitasking concurrency or high-load conditions, CPU resource contention, cache misses, and related factors may further delay time-processing procedures and weaken the temporal consistency of data. Even if synchronization has already been completed at the network layer, time drift may still occur inside the terminal^[89]. In addition, the link symmetry assumption on which IEEE 1588 relies is difficult to strictly satisfy in complex industrial networks. Multi-stage switching devices, heterogeneous PHY chips, and asymmetric physical paths may cause uplink and downlink delay differences to accumulate continuously, forming significant synchronization offsets and persistently eroding the high-precision time base established at the protocol layer^[90].

Therefore, even if the network layer already has high-precision time distribution capability, deficiencies in terminal-side implementation mechanisms may still degrade time consistency at the critical stage from "time" to "action." This is also an important reason why synchronization accuracy is difficult to guarantee in closed loop in current high-end distributed measurement and control systems.

2.2.2 Limitations of Complex Traffic Scheduling

In integrated measurement and control scenarios, network traffic is extremely heterogeneous and mainly consists of two types of service flows with very different characteristics. The first type is control flow, represented by isochronous synchronization and command data. Such packets are short, typically 30-100 B, fixed in length, and periodic, with stringent requirements for microsecond-level latency and jitter. The second type is measurement flow, represented by waveform sampling and audio/video monitoring. Such packets are long, up to 1500 B, highly bursty, variable in length, and extremely throughput-intensive. When these two types of service flows coexist in existing Ethernet architectures, they fall into a "latency-bandwidth" resource deadlock that is difficult to reconcile.

Even EtherCAT's "on-the-fly" transmission mechanism, which emphasizes extreme real-time performance, has shortcomings in large-scale and high-reliability measurement and control scenarios. Single-frame cut-through transmission can achieve latency at the hundred-microsecond level, but it sacrifices system autonomy and topology flexibility to some extent. Node order is strongly bound to physical connection relationships. After network expansion, both frame length and end-to-end latency increase, and a single point of

failure is more likely to affect downstream nodes.

Conversely, if the TSN Time-Aware Shaper (TAS, IEEE 802.1Qbv) mechanism is used for rigid isolation, control flows can be given priority through time-slot planning, but this also introduces a high idle cost of bandwidth resources. To accommodate long measurement frames entering control time slots, the system must reserve a large guard band. In high-load mixed-traffic scenarios, the bandwidth waste caused by guard bands accumulates continuously^[91], thereby weakening the network's ability to carry high-throughput measurement services.

The above mechanism-level contradiction makes it difficult for a single existing network to simultaneously meet the low-latency requirements of control services and the high-throughput demands of measurement services. In engineering practice, scenarios such as rocket ground tests and aircraft avionics systems often build separate control networks and measurement networks through physical isolation to reduce the risk of service interference. However, this approach also leads to system fragmentation, difficulty in data coordination, and complex later-stage maintenance. From this perspective, enabling the stable coexistence of high-bandwidth measurement flows and low-latency control flows over a unified infrastructure remains a key issue that next-generation industrial measurement and control networks must prioritize.

2.2.3 Architectural Performance Bottlenecks in Large-Scale Node Collaboration

When a measurement and control system expands to tens of thousands of interconnected points, the network interaction mode itself becomes a limiting factor. Under the traditional TCP/IP stack, the "message passing" mechanism must maintain handshakes, connection states, and protocol-processing procedures when nodes issue concurrent requests. As the number of nodes increases rapidly, these overheads are amplified accordingly, compressing the real-time response window and becoming an important bottleneck for the continued expansion of large-scale measurement and control systems.

Even EtherCAT's "on-the-fly" transmission technology, designed to pursue extreme real-time performance, has significant shortcomings in large-scale and high-reliability scenarios. Although its "single-frame cut-through" mechanism achieves microsecond-level latency, it essentially sacrifices system robustness and flexibility. Its "chain dependency" feature makes a single point of failure likely to propagate across the entire network, while the physical topology is fixed into a linear daisy chain, making it difficult to adapt to complex wiring requirements. At the same time, bandwidth and node count are strongly coupled, and the reconstruction process is complex. As a result, this technology faces nearly insurmountable engineering barriers in test

scenarios involving tens of thousands of nodes or frequent changes.

2.2.4 Protocol Overhead in High-Frequency Interaction Scenarios

In measurement and control networks where mixed traffic coexists, the cliff-like decline in the "payload ratio" forms a protocol barrier that is difficult to overcome. Byte-level short control frames generated by large numbers of sensors consume substantial bandwidth and energy due to the large headers of standard Ethernet packets^[92], which runs counter to the principles of low-power and high-efficiency transmission.

The occupation of edge-side computing resources by the network protocol stack is a constraint that is easily overlooked in high-frequency control scenarios. In high-frequency control loops below 500 μ s, the CPU must not only execute control algorithms, but also undertake communication-processing tasks such as packet encapsulation, decapsulation, context switching, protocol verification, and data copying. Existing estimates show that when the control cycle is compressed to within 500 μ s, two socket/pipe-level message round trips alone can consume 6%-12% of the raw time budget. After other protocol-processing tasks are added, communication-related overhead may exceed 20%^[93]. For conventional embedded microcontrollers (MCUs), such overhead squeezes the computing resources available for core control algorithms and further amplifies real-time risks as the control cycle continues to shorten.

2.2.5 Absence of Network BIT Mechanisms

Existing industrial network architectures lack full-link deep observability mechanisms matched to high-precision measurement and control tasks. They have not established a "microscopic" sensing system. Most monitoring methods remain at the macroscopic level, such as link connectivity and port traffic statistics, and cannot penetrate into the physical layer and data link layer to capture microscopic dynamic characteristics.

Because embedded high-precision Built-In Test capability is lacking, the system cannot sample and quantify, in real time, nanosecond-level clock synchronization jitter, transient degradation of signal integrity, or burst electromagnetic noise^[94-96]. As a result, the network remains in a long-term state of "gray operation": the link appears to be "normally connected," but hidden degradation has already occurred in the underlying transmission quality, such as fluctuations in bit error rate and accumulated phase offsets. This creates a large blind spot in health assessment.

Under this operating mode, fault diagnosis degenerates into delayed experience-based troubleshooting. Operation and maintenance personnel cannot obtain accurate data at the instant a fault occurs, and can only rely on empirical inference or trial and error. This makes it difficult to locate the root causes of

occasional "soft faults" and also prevents industrial systems from evolving intelligently from "post-fault repair" toward "predictive maintenance."

2.2.6 Insufficient Dynamic Adaptability

The concept of "flexible manufacturing" in Industry 4.0 and the requirement for "dynamic task reconstruction" in test-oriented measurement and control both demand highly elastic networks. However, existing deterministic network architectures generally adopt a paradigm of "static resource locking" and "offline global planning" in exchange for transmission determinism. This design, which sacrifices flexibility, leads to a temporal mismatch between architectural rigidity and the dynamics of the physical environment in scenarios such as wide-area transient topology changes and multi-source clock switching.

(1) Lack of topology adaptability

Existing TSN/DetNet schemes mostly rely on a centralized network controller (CNC) to maintain a global network view. In local-area scenarios where the topology is relatively fixed and link states are stable, this mode is operationally feasible. However, in wide-area measurement and control environments, factors such as link-delay differences, synchronization-error fluctuations, dynamic node access, and uncontrollable intermediate nodes become more prominent. A centralized controller has difficulty reflecting global state changes in a timely manner, while static configuration and centralized reconstruction mechanisms are prone to delayed responses. In traditional SDN architectures, this recovery process may take seconds^[97], far from meeting the update requirements of optical links, which range from tens of microseconds down to hundreds of nanoseconds. Moreover, a single CNC becomes a performance bottleneck as the network scale expands.

In addition, existing network architectures have limited adaptability to changes in control domains and network forms^[98]. During joint testing of complex large-scale systems, testing activities are often not completed in one step, but repeatedly switch among standalone subsystem verification, local combined testing, and full-system integration testing. Correspondingly, the network should be able to split into several independent subnets or converge again into a unified measurement and control domain as task boundaries change. Current centralized or strongly pre-built architectures usually bind the control plane to a predefined topology. Configuration adjustments depend on manual intervention, making it difficult to complete rapid reconstruction in synchrony with changes in the organization of testing tasks.

(2) Limitations of scheduling mechanisms

In multi-hop, multi-flow concurrent networks^[99], the computation of TSN gate control lists (GCLs) is essentially an NP-hard joint routing and scheduling (JRS) problem. In highly dynamic measurement and control scenarios, sensor nodes are frequently added or removed

as testing progresses. Even slight traffic changes require the CNC to recompute the global scheduling table. The temporal mismatch between "static optimal solving" and "dynamic real-time change" causes control-plane optimization to lag behind service changes^[100].

The frame preemption mechanism proposed in IEEE 802.1Qbu/802.3br can indeed alleviate the blocking caused by long frames occupying links under bursty traffic conditions, but its effectiveness is jointly constrained by the link environment and device capabilities. First, this mechanism requires support across the entire link. As long as any intermediate device lacks the corresponding capability, services may fall back into long-frame queuing and blocking. Second, preemption mainly occurs at the MAC Merge Sublayer. It cannot directly cut the bitstream being transmitted at the physical layer, and it also introduces additional overhead such as CRC and SFD, typically counted as approximately 4 bytes per subframe. Third, in high-load mixed-flow scenarios, low-priority long frames may yield for long periods and trigger PFC backpressure. If the subframe FCS check fails, retransmission of the original frame may be required, further affecting effective throughput.

2.2.7 Difficulty of Dynamic Switching Among Timing Sources

The stability and survivability of the timing system are also insufficient. Traditional networks usually rely on a single GPS or BeiDou timing source, with the master control node providing reference timestamps for network data. Other functional nodes in the network can only operate under the network time architecture and have difficulty directly referencing a standard timing source. At the same time, after dynamic network decomposition, each subnet lacks a new timing source. This causes the subnet to lose the standard time reference and fall into an independent "time domain," resulting in invalid tests.

3 Core Capability Characteristics and Connotations of IMCN

3.1 Ten Core Capabilities of IMCN

In response to the development trends of high-end equipment R&D, major engineering verification, and full-lifecycle testing of complex systems, the service objects of networks have expanded from single periodic closed-loop control to high credibility spatiotemporal measurement and coordinated actuation systems across domains, scales, and carriers. The industrial measurement and control network is not a simple replacement for existing industrial networking technologies. Rather, on the basis of inheriting their real-time performance, transmission determinism, and basic time synchronization capabilities, it aims to achieve a comprehensive leap in capability dimensions for high credibility measurement and control tasks. In other words, it has evolved from a

traditional data transmission carrier channel into a unified spatiotemporal reference platform and a trusted data acquisition and transmission foundation for distributed measurement and control systems, filling the capability gaps of traditional network architectures in high-precision full-domain synchronization, end-to-end behavioral predictability, and system-level observability.

Around the above objectives, the IMCN needs to

establish a hierarchical and systematic capability framework. As shown in Fig. 4, this framework should be based on high real-time performance and deterministic transmission, and can be summarized into ten key technical characteristics according to the depth of support provided for measurement and control services. These characteristics can be divided into essential foundational capabilities and extended enhancement capabilities.

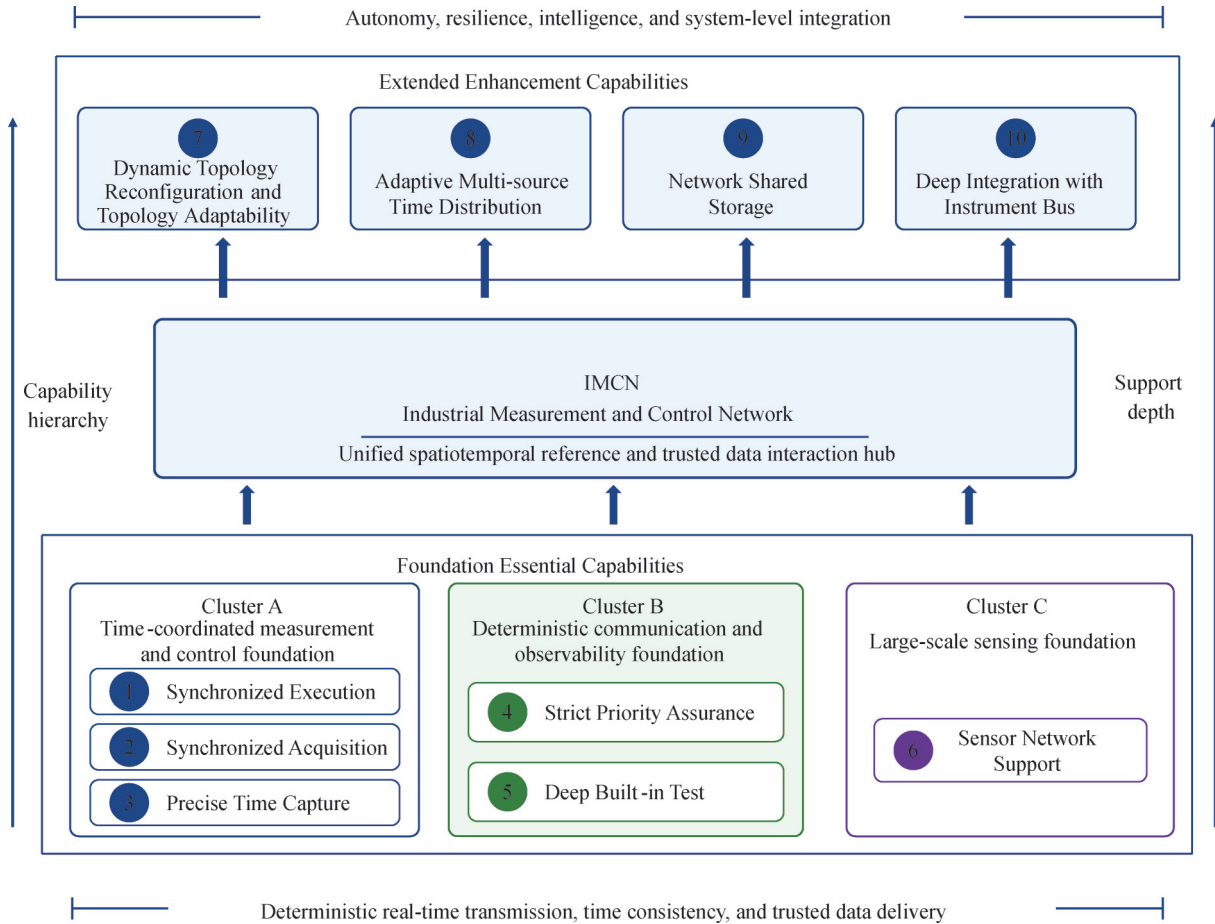


Fig.4 Key technical characteristics and hierarchical capability framework of the IMCN

(1) Essential foundational capabilities

Essential foundational capabilities constitute the core basis and operational prerequisite of the IMCN. Their primary objective is to guarantee temporal consistency, behavioral determinism, and data trustworthiness throughout the full process of sensing, control, and verification from the underlying network mechanisms, thereby providing fundamental support for precise collaborative operation among distributed nodes and for system verifiability.

The IMCN should first possess high-precision time and consistency coordination mechanisms, including synchronous execution, synchronous data acquisition, and precise time capture. Only by improving network-wide time synchronization accuracy from the microsecond level to the nanosecond level can distributed nodes perform action triggering, data sampling, and event recording under the same time reference. This is also the

basic condition for subsequent high credibility measurement and control analysis.

Second, the network needs to provide strong real-time service priority assurance and intrinsic testability and diagnosability. Hardware-level scheduling mechanisms and frame-level preemption technologies should be used to ensure deterministic transmission for critical control and synchronization services under various network-load conditions. Through online monitoring and deep diagnosis of data paths, synchronization links, and core functional units, the network can realize full-link state awareness, precise fault localization, and traceability of the operating process. This provides quantifiable credibility and health assessment for measurement and control data, supporting long-term stable operation in scenarios with high reliability and high safety requirements.

In addition, for high-density distributed sensing

tasks, the industrial measurement and control network also needs to support large-scale sensor deployment. Traditional bus-type or time-division multiplexing architectures have inherent trade-offs among transmission distance, number of nodes, bandwidth utilization, communication efficiency, and signal integrity. When the number of nodes, network branches, and sampling frequency all increase simultaneously, the risks of system performance degradation and local instability also rise. Therefore, support for large-scale sensor networks is not merely a matter of access quantity; it also involves the coordinated design of scheduling mechanisms, link quality, and overall stability.

(2) Extended enhancement capabilities

Extended enhancement capabilities provide advanced support for enabling the IMCN to adapt to complex dynamic operating conditions and to improve intelligence and operational resilience. For application environments involving multi-source heterogeneity, dynamic disturbances, and high reliability requirements, the network should further possess extended capabilities such as adaptive multi-source timing, autonomous dynamic topology reconstruction, networked shared storage, and native instrument-bus integration. These capabilities enable autonomous clock source selection, rapid topology self-healing, and secure and reliable data retention in decentralized and highly dynamic scenarios, thereby supporting decentralized and intelligent distributed measurement and control application modes.

Based on the above hierarchical capability classification, this section systematically describes the technical characteristics, implementation mechanisms, and engineering application value of the ten core capabilities.

3.1.1 Synchronous Execution

Synchronous execution is the core foundation for the IMCN to realize strongly real-time control. Its essence is to transform the execution mode of control logic from one driven by packet reception behavior into one driven by unified network-time sequencing. In traditional networks, the execution time of control commands is jointly affected by switch forwarding jitter, operating-system interrupt response, and software scheduling delay, and the coordination deviation among multiple nodes can reach the microsecond level.

The IMCN should therefore integrate a time-driven engine into the underlying hardware. Control commands are distributed and preset together with behavior identifiers and trigger-time identifiers. On the basis of network-wide clock synchronization, network interfaces and edge nodes do not need to rely on the performance of host processors. Instead, they can directly output drive signals and control commands to execution units at preset absolute physical times. This mechanism decouples control planning from field execution. The master control device only needs to push commands to the network edge

before a specified deadline, after which execution components distributed at different physical locations can perform coordinated actions with nanosecond-level accuracy. This effectively suppresses the accumulation of transmission uncertainty and ensures precise synchronization for high-speed dynamic control tasks such as attitude regulation and coordinated actuation.

3.1.2 Synchronous Acquisition

Synchronous acquisition is an important capability for the IMCN to support high-precision distributed measurement. Taking wide-area distributed testing tasks such as aircraft static tests and modal analysis as examples, multi-channel measurement data must be placed within comparable time coordinates. If phase deviations exist among the sampling clocks of different channels, even very small deviations may be amplified during physical-field reconstruction, thereby affecting the accuracy and validity of measurement results.

To meet this requirement, the IMCN needs to rely on a high-precision global clock to uniformly control the sampling rhythm of front-end sensors and analog-to-digital converters. Through network hardware, periodic or one-time synchronous trigger signals are broadcast to designated nodes, enabling all nodes to complete analog sampling-and-hold and conversion initiation at the same nanosecond-level instant. In this way, the measurement mode shifts from "independent acquisition followed by software alignment" to "source-side synchronization and natural alignment." This can reduce uncertain phase noise caused by synchronization differences among devices and provide a reliable data-comparison basis for capturing transient processes such as explosive shock-wave propagation.

3.1.3 Precise Time Capture

For events with extremely short durations and complex coupling relationships, such as pyrotechnic ignition and structural fracture, relying solely on post-event communication-packet timestamps is often insufficient to eliminate deviations introduced by link transmission and processing procedures. Therefore, the IMCN needs to move time-latching capability forward to the physical layer. When a dedicated capture interface senses an external trigger signal, such as the arrival of a rising edge, the node should immediately lock the current globally unified high-precision timestamp and provide it for subsequent reading, comparison, and timing reconstruction. In this way, discrete events recorded by distributed nodes can be reconstructed in chronological order with nanosecond-level resolution, providing a more accurate temporal basis for fault tracing, action verification, and timing-logic analysis of complex systems.

3.1.4 Strict Priority Assurance

In measurement and control systems, time-sensitive

control commands coexist with large volumes of test waveform data and ordinary monitoring traffic. Without an effective arbitration mechanism, high-volume test data can easily block critical control channels. Therefore, the IMCN must provide strict priority assurance.

In terms of traffic assurance, the IMCN should allow priority mapping of different services according to task criticality, with the switching protocol executing strict priority scheduling based on hardware queues. Compared with merely increasing link bandwidth, it is more important to reduce the blocking of high-priority short packets by long frames through data-frame design and forwarding mechanisms, so that different services participate in arbitration using finer-grained data units. In this way, even when measurement services continuously occupy link bandwidth, critical control data can still be inserted and forwarded in time, maintaining real-time and low-jitter requirements.

Through the above mechanisms, the network can carry high-bandwidth measurement flows and highly real-time control flows in parallel under a single architecture, without interrupt-style suspension or physically isolated channels. This avoids structural blocking of critical control services by large-frame transmission and fundamentally guarantees deterministic communication performance in mixed-service scenarios.

3.1.5 Deep Built-in Test

The IMCN should also provide intrinsic full-link observability and diagnosability, enabling online monitoring of key indicators such as link latency, delay jitter, node health status, and time synchronization accuracy. After self-test mechanisms are embedded into the network operation process, the network is no longer a traditional "black-box pipe," but becomes a component of the measurement and control system that can sense itself, diagnose itself, and provide self-verifying information.

Only with self-test and self-verification capabilities can the network reliably support high-reliability measurement and control tasks. When packet loss, abnormalities, or timing offsets occur, the Built-In Test mechanism can reconstruct the transmission process of data across nodes and links, accurately locating the fault position and stage. Communication anomalies are thereby transformed from "unknown results" into "traceable processes."

Using the real-time operational data generated by built-in testing, the system can dynamically verify the timestamps of sensor data and evaluate data credibility. This helps maintain the consistency and verifiability of multi-source measurement data during time alignment and fusion processing, avoids confusion, and provides fundamental support for high-precision measurement and control tasks and highly reliable system operation.

3.1.6 Sensor Network Support

Sensor networks are a typical application form of the

IMCN, involving distributed access and coordinated acquisition by a large number of sensor nodes. In current engineering practice, sensor networks mostly adopt bus-type topologies and time-division multiplexing mechanisms. These are feasible when the node scale is small, but as the number of nodes and network branches increases, problems such as limited bandwidth, low communication efficiency, intensified node competition, and degraded signal integrity emerge. These problems restrict the access scale and performance of sensors, forcing the use of low-bandwidth and low-rate sensors.

Some measurement and control systems attempt to improve efficiency through ring-network "on-the-fly capture" mechanisms. In such systems, the master station periodically sends long frames, while each slave station does not need to receive and forward the complete frame. Instead, it directly reads or writes designated bytes at the hardware layer when the frame passes through the switching chip, and the frame eventually returns to the master station to form a closed loop. Such mechanisms usually have advantages such as single-frame polling, pipeline processing, bufferless forwarding, high bandwidth utilization, and deterministic latency. However, their constraints in engineering applications are also evident. First, node hardware requirements are high and usually depend on dedicated slave chips. Second, the complexity of network maintenance and management has a direct impact on reliability. Third, as the network scale expands, frame length and end-to-end latency increase linearly. Fourth, an abnormality in a single node or link may affect the entire network, increasing the difficulty of fault localization and isolation.

Therefore, the IMCN should natively support efficient sensor-network construction at the architectural level, minimizing dependence on additional circuits and non-standard protocols. It should unify high bandwidth utilization, deterministic latency, and good scalability, treating large-scale sensor access as an intrinsic capability. This would break through the limitations of traditional sensor networks in scale, performance, and evolutionary capacity, and support the long-term deployment and continuous expansion of sensor networks in complex systems.

3.1.7 Dynamic Topology Reconstruction and Network Topology Adaptability

Aerospace and many other complex measurement and control scenarios, as well as mobile measurement and control scenarios, involve large topology differences, fluctuating task loads, frequent node addition and removal, random link failures, and local damage. These complex conditions place extremely high requirements on the topology adaptability of the IMCN. The ideal objective is to achieve highly dynamic self-adaptive reconstruction under arbitrary topologies. In terms of topology organization, the IMCN is better suited to a decentralized structure rather than a master-slave

topology that fully depends on fixed hierarchies. After joining the network, nodes should be able to automatically discover adjacency relationships and form a reconstructible dynamic structure through mesh redundant links. When required by tasks, the network can be split into relatively independent measurement and control subdomains, or recombined into an integrated domain. Based on underlying hardware logic, after a link failure or topology change occurs, the network can complete route reconstruction, backup path activation, and data-path recovery on the microsecond time scale. In this way, topology adjustment no longer depends entirely on manual maintenance, but becomes part of the autonomous operation of the network. The engineering objective is not simply to pursue switching speed, but to reduce the duration of uncertainty and loss of control introduced by user management under complex boundary conditions. It also aims to ensure the verifiable continuity of deterministic latency, critical service flows, and the unified time reference during reconstruction, while providing stable link conditions for engineering verification and reproducible experiments.

3.1.8 Adaptive Multi-source Network Timing

Merely achieving internal time consistency within the network cannot meet the consensus requirement for "standard time" in major engineering verification. The IMCN needs to go beyond internal synchronization and possess the ability to automatically distribute international standard time, namely UTC, across the entire network, thereby constructing a highly robust timing-assurance system.

Adaptive multi-source network timing requires the network to support multiple external standard timing interfaces, such as B-code and BeiDou/GPS pulse-per-second signals. Through a built-in multi-source redundancy management mechanism, the network should effectively manage multiple timing sources and complete seamless switching without manual intervention. Even under extreme conditions such as network partitioning, boundary expansion, or local failure, the system should be able to automatically switch or take over timing sources and maintain temporal continuity. This capability integrates timing, synchronization, and timestamp writing into a unified infrastructure, reducing the burden on users in complex timing management and ensuring controllable time-base drift and traceable absolute time in long-duration, large-span test tasks.

3.1.9 Network Shared Storage

To address the pain points of bandwidth congestion caused by highly concurrent data distribution and data loss caused by node failure in measurement and control systems, the IMCN introduces a decentralized "general network register" (GNR) mechanism. This mechanism does not replace the persistent storage of large volumes of waveform data by NAS or local SSDs. Instead, it uses

hardware registers embedded in switching nodes and end systems to construct a fine-grained, highly reliable "network switching buffer," mainly realizing three functions.

(1) Traffic balancing and bandwidth optimization. In traditional point-to-point communication, when a source node distributes data to multiple destination nodes, it must send data repeatedly, which easily occupies bus resources and increases network load. GNR addresses this problem through a hardware-based "publish/subscribe" mode. With only a small number of "write" operations, the source node can store data in specific registers on the network side, forming multiple distributed "subscribed sources." Subscribing nodes then directly read data from nearby registers. This mechanism decouples data production from data consumption, reducing backbone-link pressure and source-node load, while enabling more automatic traffic-balancing scheduling.

(2) Passive data disaster recovery and stateless retention. In extreme test scenarios, when an edge sensor node fails, the data it has recently generated but has not yet distributed is lost simultaneously under traditional architectures. In the GNR architecture, however, data has already been written into network-side shared registers in real time. Even if the terminal fails, the final state data can still be retained, providing "black box" support for accident analysis and fault tracing, and improving the survivability of measurement and control tasks in uncontrolled environments.

(3) Metadata-based intelligent management. Drawing on the design idea of the smart transducer electronic data sheet in the IEEE 1451 standard, GNR can carry node metadata, such as logical address mapping, sampling strategy, and physical attributes. A newly connected node can complete configuration synchronization by reading specific register areas, without complex upper-layer software handshakes. Network management is thereby simplified into low-level register read and write operations, enabling self-description and dynamic management of large-scale measurement and control resources with extremely low overhead.

3.1.10 Deep Integration with Instrument Buses

As described above, in traditional measurement and control systems, the role of the network is device-level data transmission and time synchronization. Since the lowest-level carriers that actually generate data and perform actions in a measurement and control system are modules, this architecture cannot eliminate measurement and control errors introduced between devices and modules. Instead, it introduces extremely high hardware costs and highly complex management protocols. The ideal objective of the IMCN is to break the rigid constraints of traditional test platforms such as PXI and LXI, including physical chassis backplane slots, bus length, and power-supply capability. By replacing traditional physical backplanes with network switches

and interconnecting all test boards/modules through the network with high-precision time synchronization, the IMCN constructs a globally reachable "logical foundation," making the network an infinitely extendable virtual backplane.

Under this architecture, acquisition, excitation, and measurement and control modules distributed over several kilometers can realize logical "backplane interconnection" through a single network cable. The operating experience is consistent with that of modules installed in the same physical chassis backplane, enabling deep coupling between the physical form of the measurement and control system and the large-scale test object. Its core advantages are reflected in two aspects.

(1) Native module-level networking and access across the entire network. The network gives the system the ability to "access every node across the entire network." Users can directly read, write, and configure registers of any distributed module through the network, without protocol conversion or gateway relay. This idea of a native networked instrument bus, such as SNXI, allows isolated oscilloscopes, signal sources, or DAQ boards to be combined in a plug-and-play manner into a logically unified measurement-device array.

(2) Fault-oriented self-healing and reconstruction. By combining deep built-in testing with highly dynamic topology self-adaptive reconstruction mechanisms, the

system can sense link-quality degradation or node failures in real time and autonomously trigger path reconstruction, switching to redundant backup links when necessary. This idea of "network as instrument" not only changes the scale and synchronization-accuracy constraints of traditional test systems, but also pushes self-healing capability down to the network hardware layer, providing stronger assurance for continuous observation in dynamic environments. As a result, the measurement and control network is no longer merely a data channel, but becomes the infrastructure for reliable closed-loop operation of testing tasks.

3.2 Four System-Level Connotations of IMCN

After the conceptual reconstruction of the IMCN, it has evolved from a general-purpose communication infrastructure in the traditional sense into a core carrier that defines the overall capability boundary of measurement and control systems. Its functional positioning is no longer limited to the passive transmission and bearing of data and information flows. Instead, it actively participates in the closed loop of measurement, control, and operation and maintenance. Based on this understanding, this paper summarizes the core connotations of the IMCN into four aspects: Inheritance, testability, traceability, and autonomy, as shown in Fig. 5.

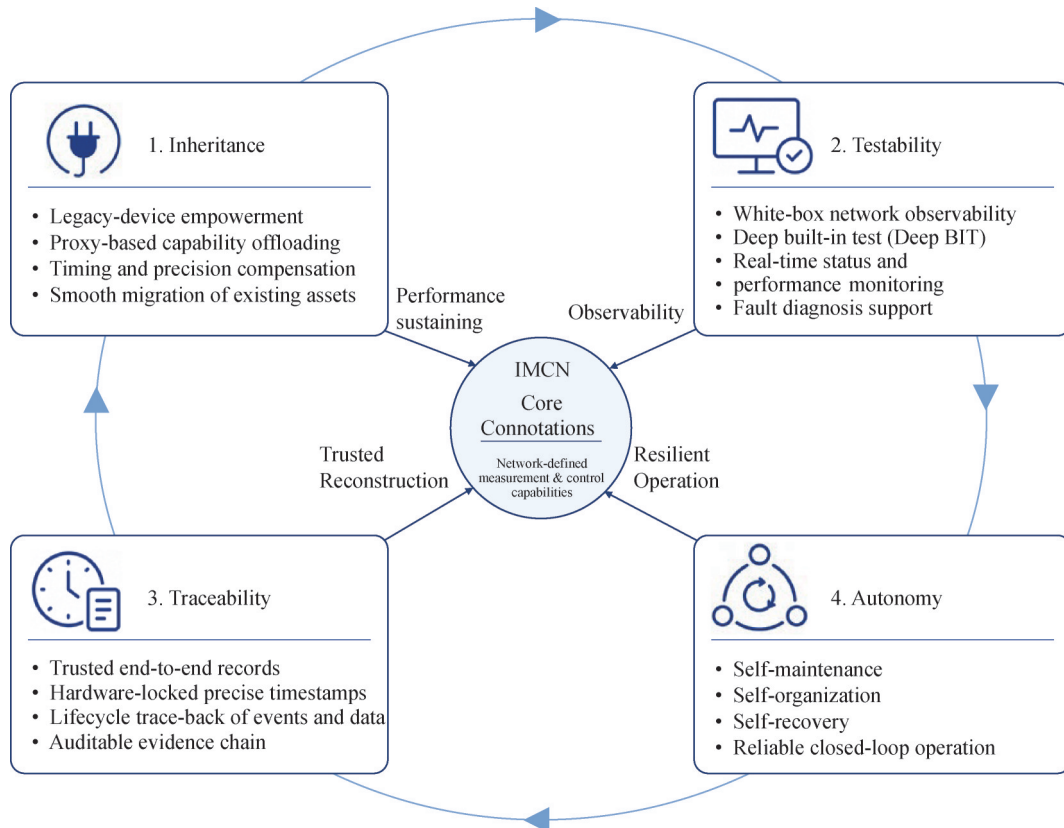


Fig. 5 Core connotations of the IMCN

Inheritance addresses smooth access between network interfaces and terminal devices, along with

capability continuity. Testability strengthens the observability of network states and Built-In Test

capabilities. Traceability ensures trusted tracking of data, events, and timestamps during measurement and control processes. Autonomy supports network self-maintenance, self-organization, and self-recovery. Together, these four aspects indicate that the IMCN has shifted from a purely communication-bearing network to a core support mechanism for measurement and control systems, with capabilities for performance preservation, state awareness, trusted reconstruction, and resilient operation. At the architectural level, it supports the future performance leap of measurement and control systems.

3.2.1 Inheritance

The IMCN is no longer limited to "interconnection and interoperability" at the physical level. Instead, it means that all terminal nodes in a measurement and control network, regardless of their computing capability, protocol generation, or degree of digitalization, can equally benefit from the nanosecond-level time synchronization, deterministic latency assurance, and full-link testability provided by the network itself.

In existing industrial sites, a large number of dumb devices and resource-constrained edge nodes still remain in long-term use. These devices usually provide only analog outputs or simple serial communication capabilities. They cannot run complex TSN/IP protocol stacks, nor can they bear the computational overhead required for high-precision clock synchronization. In response, traditional industrial networks mostly adopt a passive adaptation approach, in which gateways are used to complete protocol format conversion. Although this method solves the problem of making devices "connectable," it cannot eliminate measurement inaccuracies and synchronization instability caused by gateway processing delays and software scheduling.

Therefore, the IMCN can upgrade the meaning of Inheritance from "compatibility" to "active empowerment" by introducing a companion-agent mechanism. This mechanism assigns an intelligent agent module to each existing legacy device. On the one hand, the agent module directly takes over interaction with the local physical interface of the legacy device. On the other hand, it joins the measurement and control network as a fully functional logical node. Its core value is reflected in two aspects.

First, it realizes "capability offloading" of the protocol stack and computing resources. The agent module processes complex network protocols, traffic shaping, and priority arbitration on behalf of dumb devices, allowing low-computing-power nodes that cannot run complex protocols to be integrated into the deterministic network system.

Second, it provides "capability compensation" in timing and accuracy. The network no longer depends on the internal clock of the legacy device. Instead, the agent module uses the high-precision synchronization clock intrinsic to the network to directly issue hardware-level

synchronous drive pulses or sampling trigger sequences to the legacy device. At the instant when data is generated, the agent module immediately encapsulates a high-precision timestamp and attaches quality labels.

Based on this network-side enhancement mechanism, legacy devices can be mapped into intelligent nodes with standardized digital-twin interfaces. A sensor that originally had only a single acquisition function can obtain nanosecond-level synchronous triggering and a network-wide consistent time reference without replacing its body hardware. This demonstrates that the value of Inheritance is not merely to "continue using old devices," but to enable the performance ceiling of existing assets to increase as network capabilities evolve, thereby extending both their service life and functional capability.

From an industrial perspective, this means that IMCN deployment does not need to proceed through costly "demolition and reconstruction." Instead, it follows the principle of "transforming existing assets into incremental capabilities," using intelligent agents to support a smooth transition from analog and discrete architectures to digital and networked systems. Ultimately, this approach promotes the systematic evolution of measurement and control systems from device-dominated architectures to network-dominated architectures.

3.2.2 Testability

The testability of the IMCN emphasizes the network system's inward-facing sensing capability for its own state. That is, it should be able to monitor and verify its own functional logic, performance indicators, real-time behavior, determinism, and security and trustworthiness in real time and across multiple dimensions. Unlike traditional IT networks, which mainly focus on coarse-grained monitoring of link connectivity, the testability of measurement and control networks requires a "network as instrument" perspective. The network itself should be incorporated into a measurable, diagnosable, and verifiable white-box system.

To support this capability, the network needs to integrate a hardware-level deep Built-In Test (Deep BIT) mechanism. This mechanism does not obtain state information through active self-tests with high resource consumption. Instead, it uses the accompanying behaviors in the node data-exchange process to write operating features, such as port health, packet transmission and reception counts, congestion marks, and interaction timing, into hardware registers in real time. These intrinsic state snapshots can provide objective low-level diagnostic evidence for the system, enabling operation and maintenance personnel or automatic test systems (ATSS) to read the status of all network nodes and determine whether data loss originates from terminal transmission failure, link transmission abnormality, or network congestion. This not only greatly reduces the

difficulty of troubleshooting large-scale distributed systems, but also lays a data foundation for building intelligent measurement and control systems with self-diagnosis capability.

3.2.3 Traceability

The traceability of the IMCN mainly refers to the network's ability to provide trusted confirmation and full-process backtracking throughout the entire lifecycle of data transmission. Relying on intrinsic operating records of nodes, such as port transmission and reception statistics and interaction timing logs, the system can locate and assign responsibility for abnormal transmission behaviors such as packet loss and delay. This refines the granularity of fault diagnosis from system-level judgment to link-level and node-level analysis. In high credibility measurement and control scenarios, the focus of traceability also lies in establishing strict spatiotemporal consistency constraints, so as to provide verifiable physical evidence for the temporal relationship among event occurrence, data generation, and action execution.

From the perspective of traceability requirements, the network can also embed a unified time reference into service flows as tamper-resistant metadata. Relying on a physical-layer hardware latching mechanism, the system can generate a high-precision absolute time mark at the instant when external transient events occur, such as pyrotechnic triggering, structural failure, or contact action. This mark is not a software-estimated value calculated afterward by the operating system or protocol stack, but a physically trusted record directly formed by the underlying hardware. It can provide a basis for subsequent error correction, fault tracing, and timing reconstruction of multi-source data. When data is transmitted and fused across multiple nodes, media, and paths, the unified time anchor can help the system overcome spatial distribution constraints and accurately restore the logical timing relationships among multi-source measurement and control information. This mechanism not only provides a unified reference for error correction of test data, but also builds a verifiable and auditable digital evidence chain for fault tracing, responsibility determination, and full-lifecycle review of critical industrial processes.

3.2.4 Autonomy

As the number of nodes, spatial coverage, and real-time response requirements of the IMCN continue to increase, the risks of traditional centralized control architectures are further amplified. Systems that rely on centralized controllers or a single master-control computer are easily constrained by scheduling delays in high-frequency collaborative control. Once the central node or a key control link fails, the impact may also propagate through the system. Therefore, network autonomy should not be understood merely as "less

configuration" or "automatic access." Rather, it should be defined as a combination of self-maintenance, self-organization, and self-recovery capabilities oriented toward closed-loop measurement and control tasks, supporting the system's ability to automatically maintain reliable operation under complex working conditions.

(1) Self-maintenance

Self-maintenance means that network resources can be dynamically orchestrated as scale and tasks change. When new nodes join, network boundaries expand, or testing tasks are reorganized, nodes should negotiate logical addresses, communication time slots, and service mapping relationships according to global policies, enabling an access process without item-by-item manual configuration. In terms of time synchronization, the network's built-in clock management mechanism needs to continuously evaluate the quality of multiple clock sources and complete clock-tree construction, master-clock selection, and switching. In terms of transmission paths, it should also plan deterministic routes based on link health and load conditions, so that critical service flows are transmitted as much as possible along stable and reliable paths.

(2) Self-organization

Self-organization reflects the network's breakthrough beyond the constraints of centralized architectures, forming a centerless self-organizing network based on a peer-to-peer structure. Traditional industrial networks usually adopt master-slave structures, and physical connections must strictly follow a preset hierarchical topology. Once the central node fails or the hierarchical structure is damaged, the operation of the entire network may be severely affected or even paralyzed.

An important feature of IMCN self-organization is to weaken the rigid dependence on central nodes, allowing all nodes to remain relatively peer-level and functionally complete at the logical level. Through neighbor discovery and link negotiation protocols, nodes can identify physical connection relationships on site and automatically form hybrid topologies such as ring, star, or mesh structures according to the physical topology. This mechanism can also support the integration of multiple media, including wired, wireless, and optical communication, allowing network deployment to better adapt to the physical form of the object under test, rather than requiring the field environment to conform to a preset cabling scheme.

(3) Self-recovery

Self-recovery emphasizes the rapid response of the network under abnormal or extreme working conditions. Fault discovery should not mainly depend on periodic polling by upper-layer software, but should be realized by underlying hardware logic that senses link disconnection, node failure, or quality degradation in real time. Once a path is determined to be unavailable, the system should immediately initiate protection switching, migrate the

relevant service flows to backup links, and keep this process as transparent as possible to upper-layer measurement and control applications. The value of this capability lies in the fact that even when local physical damage or topology disturbance occurs, critical control links and the unified time reference can still maintain continuity and stability.

The above analysis of characteristics and connotations shows that the industrial measurement and control network is not a simple extension of existing industrial networks or instrument buses, but a convergent leap based on the two technical routes of control-oriented networks and measurement-oriented networks.

Fig. 6 illustrates the capability evolution and integration process of industrial networks. Control-oriented networks mainly develop along the path of "bandwidth improvement—latency, jitter, and synchronization optimization—time-sensitive scheduling and traffic regulation," focusing on real-time control and deterministic communication. Measurement-oriented

networks have gradually evolved from backplane-based instrument buses represented by GPIB, VXI, and PXI/PXIe to networked instrument buses represented by LXI, focusing on high-bandwidth acquisition, unified time references, and wide-area synchronization. On the basis of these two types of network capabilities, the industrial measurement and control network further integrates measurement and control service capabilities such as synchronous execution, synchronous acquisition, network time distribution, precise time capture, and shared storage. As a result, the network cannot only transmit data, but also directly support collaborative measurement, real-time control, and distributed instrument organization in complex measurement and control systems. Therefore, it breaks through the separate limitations of traditional control networks, which emphasize real-time control, and traditional measurement networks, which emphasize data acquisition, and significantly expands the application scope of industrial networks in complex measurement and control scenarios such as aerospace.

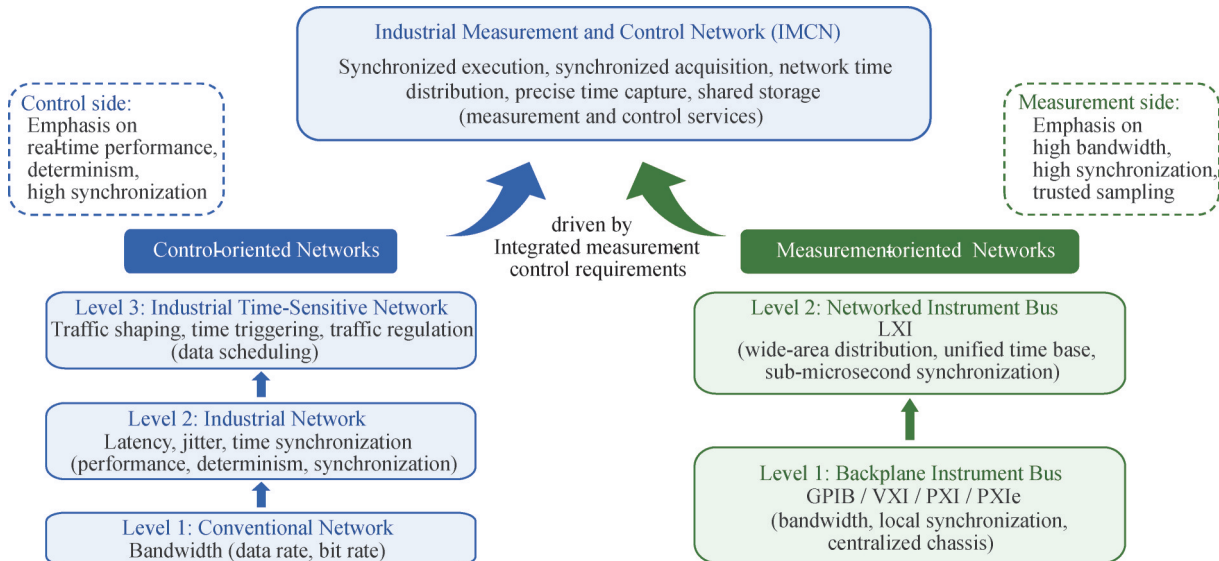


Fig.6 Capability evolution and integration of industrial networks

4 Case study

As a typical engineering carrier of the IMCN concept, SharkNet is not merely a theoretical networking vision. Instead, through integrated software-hardware design, it implements the aforementioned core capabilities and basic connotations as a deployable physical system. Developed by the Instrument Science and Technology team of North University of China, SharkNet is the first network that attempts to integrate the above characteristics and transform the "industrial measurement and control network" from a concept into a physical entity. It has already been extensively applied in multiple testing scenarios in the aerospace field, and its functional indicators have undergone rigorous testing by the authoritative China CEPREI Laboratory, fully

verifying its characteristics and advantages. This section introduces how SharkNet realizes underlying mechanism innovation from multiple technical dimensions, including topology evolution, synchronization capability, timing capability, transmission scheduling, enhanced distributed interaction, and instrument bus integration.

4.1 Decentralized Self-organizing Networking and Dynamic Topology Reconstruction

The objective of SharkNet is to provide a networked solution that can adapt to various systems ranging from simple to complex. High adaptability to different forms of physical topology is one of its most important characteristics. In scenarios such as large rocket launches and space station docking, network decomposition and fusion, dynamic node addition and removal, and possible

link failures may occur. SharkNet adopts a centerless, highly dynamic topology reconstruction mode, verifying the "strong adaptability" and "high survivability and self-recovery" capabilities of a measurement and control network.

Arbitrary-topology self-adaptation: SharkNet has strong physical-layer adaptability. It supports arbitrary topologies, including star, ring, mesh, and hybrid structures, and can automatically discover topology changes through hardware-based link-state sensing and drive network reconstruction accordingly. This capability enables test systems to adapt to complex cabling requirements ranging from inside aircraft to wide-area test sites.

Microsecond-level fault self-healing: In a mesh topology, the system is designed to identify all links for redundant transmission backup. When a link fault is detected, optimal path switching can be completed automatically at the hardware level without user

intervention. Measurements show that, under fault conditions, the communication recovery time for a hundred-node scale network is $\leq 30 \mu\text{s}$, demonstrating the high reliability of the measurement and control network in maintaining continuity of critical services under extreme environments.

4.2 Nanosecond-level Synchronous Driving and Synchronous Acquisition

The core foundation of SharkNet's enhanced testing capability lies in establishing a unified and traceable "absolute network time" across the entire network, whose comparative advantages in topology, reconstruction, synchronization accuracy, latency, and data rate are summarized in Table 4. In typical hard real-time synchronous control scenarios such as rocket component separation and pyrotechnic ignition, the system imposes stringent requirements on synchronization accuracy.

Table 4 Comparison between SharkNet and international fieldbus technologies

Fieldbus	1553B	TSN	EtherCAT	TTE	FC	SpaceWire	AFDX	SharkNet
IP / Origin	United States	IEEE international standard	Beckhoff, Germany	TTTech	United States	European Space Agency	Airbus	China
Topology	Bus	Star, tree, ring, line, hybrid	Line, star, daisy chain, ring	Point-to-point, star, ring	Ring, star	Point-to-point, star	Star	Arbitrary topology
Hybrid Media	Not supported	Supported	Supported	Not supported	Not supported	Not supported	Not supported	Supported
Automatic reconstruction	Dual backup	Dynamic reconstruction	Ring redundancy	Dual reconstruction	Supported	None	Dual reconstruction	Fully autonomous
Nodes per segment	31	2^{48}	65,535	2^{48}	127/16 million	224	Hundreds	65,535
Synchronization Accuracy	$\pm 25 \mu\text{s}$	$\pm 1 \mu\text{s}$	$\pm 100 \text{ ns}$	$\pm 1 \mu\text{s}$	$\pm 50 \text{ ns}$	$\pm 5 \text{ ms}$	$\pm 100 \text{ ns}$	$\pm 8 \text{ ns}$
Latency	$20 \mu\text{s}$	$10 \mu\text{s}$	μs -level	μs -level	$2 \mu\text{s}$	$1 \mu\text{s}$	μs -level	$1 \mu\text{s}$
Data Rate	1 Mbps	1 Gbps	100 Mbps	1 Gbps	4.24 Gbps	400 Mbps	100 Mbps	1.6 Gbps

Non-blocking transmission mechanism for message packets: SharkNet's high-precision synchronization is built upon a special protocol design. Its protocol frame is designed as a variable-length combined structure based on fixed-length basic packets. All messages, status information, and data transmission are strictly aligned and processed based on a 10-byte basic packet. Message and status packets can consist of a single basic packet, whereas data packets are composed of multiple basic packets. This design effectively combines the simplicity of protocols such as Modbus with the high efficiency of Ethernet. The mode field in the basic packet is used to distinguish message packets, status packets, and data packets, enabling the receiver to identify different types of transmission units at a unified 10-byte boundary.

Based on this fixed-length alignment mechanism, the protocol allows message and status packets to be inserted into the data-packet sequence at base-packet boundaries without interrupting, waiting for, or reorganizing the original data transmission process, thereby enabling non-blocking transmission. This mechanism greatly reduces the delay uncertainty of automatic time synchronization based solely on internal message packets, laying a solid foundation for high-precision synchronization across the entire network.

Hardware-level high-precision clock synchronization: For different application scenarios, SharkNet basically supports optional NTP and PTP protocols. Between two synchronization events, it adopts a self-developed single-clock proportional compensation algorithm. In the PTP

algorithm, SharkNet uses hardware timestamping, enabling single-hop synchronization accuracy to reach approximately 0.5 clock cycles. For special ring topologies, SharkNet can additionally enable a cyclic iterative precision-tuning algorithm, achieving network-wide accuracy better than ± 100 ns in large-scale node-cascading mode.

Synchronous execution and synchronous acquisition: Based on the above synchronization performance, the SharkNet chip provides synchronous execution drive signals with an accuracy of up to ± 40 ns, which are used to synchronously drive actuator events in distributed architectures. It also integrates synchronous A/D conversion enabling, data acquisition, timestamping, packetization, and forwarding functions driven by this signal. This synchronous acquisition capability even allows sensor nodes to realize signal digitization and networking without control units such as MCUs or FPGAs, providing strong support for lightweight sensor design.

4.3 Multi-source Fusion Timing Technology

External timing and internal network timing: To meet the traceability requirements of avionics systems for true time references, SharkNet is designed with external timing interfaces and supports BeiDou/GPS pulse-per-second signals and IRIG-B code input.

Meanwhile, SharkNet integrates a network timing algorithm that can reconstruct true time and pulse-per-second signals at the interface chips of all network terminals based on standard timing-source input, with an accuracy of up to ± 40 ns.

Multi-source timing fusion and seamless switching: As a dynamic network architecture that supports automatic decomposition and fusion, SharkNet inherently integrates multi-source timing-source management. It can continuously monitor the activity status of timing sources. When network topology changes or the current timing source fails due to interference, the system can automatically activate and seamlessly switch to a backup timing source, ensuring that network terminals continue to operate under the standard reference time framework.

4.4 Frame Data Management and Transmission Scheduling

For the transmission of messages and data frames, SharkNet provides multiple mechanisms to optimize and guarantee efficiency and real-time performance.

Non-blocking transmission of message frames: As mentioned above, message frames are the minimum operating unit of SharkNet. They unconditionally have the highest priority and can be forwarded immediately upon arrival without being affected by data frames.

Whole-frame transmission and basic-packet transmission modes for data frames: Data frames are transmitted through pipes. SharkNet allows immediate forwarding in units of basic packets before a complete frame has been received, which can greatly reduce the

transmission delay of large data frames. SharkNet also allows the traditional approach, in which forwarding begins only after a complete frame has been received. This mode can reduce pipe occupation time and improve link transmission efficiency.

On-the-fly transmission: For ring topologies, SharkNet allows users to enable an "on-the-fly transmission" mode. In this mode, the "organizer" node sends out a data frame. As the frame is transmitted hop by hop, nodes in the ring network can load and unload data within the frame. **Time triggering and traffic policing:** SharkNet supports functions similar to those in TSN networks. In TT mode, message or data frames are forcibly constrained to be transmitted within specific time slots, while all other virtual links remain silent. Once a time-slot agreement is violated, the transmitted frame is forcibly terminated. In traffic-policing mode, if a specific terminal exceeds the agreed traffic volume within a timing cycle, subsequent traffic will be restricted.

Industrial testing scenarios differ from control scenarios in that they require more complex data transmission strategies. In control scenarios, complex scheduling modes are designed only to guarantee time determinism and reliability, and bandwidth loss can be tolerated. In testing scenarios, however, multiple scheduling methods may be enabled simultaneously to achieve different data transmission objectives for different nodes or links. This is also the fundamental reason why most existing networks have difficulty adapting to testing scenarios.

4.5 Distributed Memory Sharing and State Coordination

To solve the bottleneck of information interaction among high-traffic-density nodes and the problem of data preservation, SharkNet introduces network shared register (NSR) technology. It reserves eight groups of 64 16-bit registers for each node. These registers can be shared, read, and written by any terminal across the entire network, and protection can also be implemented by group. This mechanism fully realizes the functions described in Section 3.1.9 of this paper. Through a certain amount of data mirroring, terminals distributed in different physical spaces logically form a tightly coupled whole, reducing protocol-stack overhead and effectively supporting the collaborative execution of large-scale parallel acquisition tasks. This demonstrates the data preservation and interaction capability of the measurement and control network as a "trusted intermediary," providing an important means for optimizing traffic distribution in testing scenarios.

4.6 Native Networked Instrument Bus SNXI

Based on the SharkNet network, an extended architecture for instrumentation, namely SNXI (SharkNet eXtensions for Instrumentation), has been constructed. This architecture fully demonstrates the integration

between the industrial measurement and control network and the instrument bus described in Section 3.1.10, and its networking advantages are prominent for measurement and control systems. However, although the synchronization accuracy of SNXI, which is within ± 8 ns, is already close to that of backplane-based instrument buses, which is 1-5 ns, a gap still remains. The related

performance comparison is shown in Table 5. The greatest advantage of backplane -based instrument buses is high bandwidth. At present, relying on single-link connections, the bandwidth of any network still cannot match that of backplane-based buses. This is also a direction in which SNXI needs to achieve further breakthroughs in the future.

Table 5 Comparison between SNXI and international instrument buses

Instrument Bus	VXI	PXI	PXIe	LXI	SNXI
Transmission Width	8, 16, 32	32/64	Serial	Serial	Serial
Throughput	80 MB/s	132/264 MB/s	24 GB/s	10 Gbps	1.6 Gbps
Timing and Control Capability	8 TTL trigger lines and 2 ECL trigger lines	8 TTL trigger lines	TTL trigger lines	Bus, time and message triggering	Time and message triggering
Trigger Accuracy	8 ns	5 ns	1 ns	5 ns/m, 100 ns, ms-level	8 ns, 1 μ s
Communication Level	Device level	Device level	Device level	Device level	Board-card level
BIT Capability	Weak	Weak	Weak	Weak	Strong
Form Factor	Medium	Small to medium	Small to medium	Small to medium	Ultra-compact
Communication Mode	Master-slave	Master-slave	Master-slave	Multi-master	Masterless
Load Capacity	13 slots	7+1 slots	256	Thousands	65,535
Synchronization Technology	Asynchronous	Synchronous	Synchronous	Synchronous ,asynchronous	Asynchronous
Connection Method	Backplane	Backplane	Backplane	Backplane / optical fiber / twisted pair	Optical fiber / twisted pair
Architecture	Backplane bus	Backplane bus	Backplane bus	Backplane + network bus	Pure network bus

5 Summary and Outlook

Industrial measurement and control networks are undergoing a capability transition from "communication interconnection" to "deterministic control" and further to "high credibility measurement and control," driven by the evolving demands of high-end equipment manufacturing and large-scale complex system testing. Taking the conceptual and technological evolution of industrial networks as the main thread, this paper systematically clarifies the essential differences among industrial communication networks, industrial control networks, and industrial measurement and control networks in terms of objectives, capability boundaries, and performance indicators. It focuses on the fundamental differences between test-and-measurement services and logic-control services in traffic characteristics, triggering mechanisms, and synchronization requirements, and reveals the internal mechanism by which the mixed carriage of these two types of services may lead to deterministic degradation. On this basis, the paper argues that industrial measurement and control networks are not a simple enhancement of existing industrial control networks, but a systematic reconstruction required to

meet new demands for high determinism, strong synchronization, and high trustworthiness.

In response to these engineering requirements, this paper further summarizes the core capability framework of industrial measurement and control networks by organizing specific technical capabilities around the four system-level connotations of IMCN: Inheritance, Testability, Traceability, and Autonomy.

For Inheritance, sensor network support and native networked instrumentation architecture enable legacy devices and instruments to be integrated into a unified measurement-and-control infrastructure. For Testability, strict priority assurance and deeply embedded built-in testing enhance the observability and verifiability of network states and service quality. For Traceability, synchronous execution, synchronous acquisition, precise time capture, and network-wide shared storage provide consistent temporal references and reconstructible data records. For Autonomy, adaptive multi-source network timing, dynamic topology reconstruction, and network topology adaptability support self-maintenance, self-organization, and self-recovery under changing engineering conditions. These capabilities can serve as important criteria for determining whether a network can

function as a foundational measurement and control infrastructure.

From the perspective of future applications, industrial measurement and control networks may play a more fundamental supporting role in critical infrastructure, high-end manufacturing, aerospace measurement and control, and large-scale experimental systems. Their impact will not be limited to communication links themselves, but will further reshape the organization of test-and-measurement and control systems. It is even possible to envision their potentially transformative role in future intelligent systems.

AI technology is developing rapidly. However, existing AI systems, ranging from large language models to various neural networks, are essentially large-scale mathematical computations performed on silicon-based chips, classical von Neumann architectures, and TCP/IP-based digital networks. In essence, they remain digital and rely on the centralized accumulation of computing power. The human brain, however, does not operate in this way. It has no "central CPU" or "master station"; instead, intelligence emerges spontaneously from highly dynamic, decentralized connections among tens of billions of neurons in physical space.

Similar to SharkNet, the "industrial measurement and control network" constructed in this paper is a fully decentralized, highly dynamic, automatically reconstructible physical network with extremely high timing precision. In terms of its physical characteristics, it is highly analogous to a brain-like neural network. This provides an unprecedented possibility for future exploration of non-digital "physically emergent artificial intelligence."

First, at the physical level, it suggests a form of "decentralized emergence" and neuron-like autonomy. Traditional industrial networks, such as EtherCAT or TSN, require a master station to coordinate the overall system, resembling a rigid mechanical structure in which commands must be issued layer by layer. By contrast, SharkNet is masterless: each node can autonomously sense, elect, and reconstruct. This is highly similar to the behavior of neurons in the brain. A single neuron is not intelligent, but when a massive number of masterless nodes are interconnected through high-precision and low-latency physical pathways, the network itself can generate complex self-healing and cooperative behavior through self-organization. This collective self-organization of physical entities constitutes a key foundation for the emergence of brain-inspired intelligence.

Second, high-dynamic automatic reconstruction provides an analogy to neural plasticity. Human learning and environmental adaptation involve the continuous disconnection, reconnection, and formation of new neural pathways. At present, digital AI systems based on massive computing power are beginning to encounter limitations related to energy consumption, data

bottlenecks, and physical constraints. Academia and the broader scientific community have been searching for new directions, including embodied intelligence, brain-inspired computing, and physical morphological intelligence. If future research seeks to explore a form of "non-digital intelligence" that does not rely on large-scale digital matrix operations, but instead allows physical signals to emerge spontaneously through self-organization and self-reconstruction of network topology, SharkNet may serve as an ideal physical carrier.

Looking ahead, the reconstruction of the concept of "industrial measurement and control networks" can not only address the practical need for trustworthy data transmission in complex engineering systems, but also provide a unified network foundation for future applications in aerospace testing, high-end equipment manufacturing, critical infrastructure monitoring, and intelligent industrial systems.

Author Contribution:

Kun Geng: Formal analysis, Data interpretation, Writing-originaldraft, Software. Yueyan Qi, Haifeng Hu and Lisheng Liu: Methodology, Protocol design and optimization. Yingzi Zhang and Gaigai Liu: Comparative analysis of implementation principles, Supervision. Qiang Li and Kangwei Chu: Indicator testing and validation. Fei Li: Visualization. Yingping Hong and Huixin Zhang: Resources, Supervision. Yanjun Zhang: Application analysis. Jianyun Ren: Investigation of industrial status. Wenyi Liu: Conceptualization, Supervision, Writing - review & editing. All authors have read and agreed to the published version of the manuscript.

Data Availability:

The authors declare that the main data supporting the findings of this study are available within the paper.

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The authors declare no competing interests.

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