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All-Wireless Industrial Control Technology for New Industrialization

White Paper



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1. Background of New Industrialization

1.1 New Industrialization Development Goals

New industrialization refers to the process of transforming industrial economy towards high-quality development, characterized by informatization, digitalization, networking, and intelligence, against the backdrop of a new round of technological revolution and industrial transformation. The state attaches great importance to new industrialization, elevating it to a strategic level related to comprehensively promoting the construction of a strong country. The 20th National Congress of the Communist Party of China explicitly focused on the real economy, promoting the high-end, intelligent, and green development of manufacturing, and striving to achieve new industrialization by 2035. The 2024 Government Work Report further emphasized leading industrial innovation through scientific and technological innovation and accelerating the construction of a modern industrial system.

New industrialization is digital-intelligent industrialization. Through technological innovation, it constructs a "technology-economy" paradigm change driven by new quality productive forces. Massive disruptive innovations in the digital field have spawned new industries and business formats, created new production factors, expanded factor types, improved factor quality, improved factor combinations, optimized production processes, and improved enterprise operations, having a profound impact on enterprises, markets, and the national economy:

First, for enterprise production, output growth with given factors can be achieved. Based on 5G, IoT and other technologies, factor types can be expanded (e.g., data becomes a new factor). Based on efficient computing, artificial intelligence and other technologies, factor quality can be improved (e.g., reducing manual operation errors, improving data quality). Based on wireless communication technology evolution, virtualized industrial control and other technologies, combination methods can be improved (e.g., increased production flexibility and automation), forming output growth [1].

Second, for market supply and demand, it can improve the conversion level from factor input to product output. At present, China's consumer demand shows a significant trend of scale expansion and structural diversification, further deriving flexible, agile, and personalized requirements for industrial production and manufacturing [2]. Based on the fusion and innovation of new sensing, communication, computing, intelligence, and

control technologies, it will improve the speed and quality of the supply side's response to the market side, while inversely optimizing the enterprise production process to achieve efficient supply-demand docking.

Third, for the national economy, it can support the construction of a modern industrial system and achieve high-quality development. By building a full-factor digital foundation through technological innovation, it supports the transformation of factor production to meet demand structure changes, improves the flexibility of industrial resource allocation, and optimizes the industrial structure [3].

New industrialization will build a new driving force for the industrial revolution based on technological innovation, support the digital transformation and development of industrial enterprises by constructing new quality productive forces, improve the resilience of industrial and supply chains, and move towards a new development stage of digitalization, networking, and intelligence.

1.2 New Industrialization Development Path

The development of new industrialization relies on new quality productive forces. New quality productive forces take the substantial improvement of total factor productivity as the core symbol. Therefore, its development places higher requirements on digitalization, automation, and intelligence. New industrialization takes the substantial improvement of total factor productivity as the core symbol, relying on the development of digitalization, automation, and intelligence, aiming to comprehensively improve production efficiency, optimize resource allocation, enhance enterprise competitiveness, and promote industry to develop in a more efficient, more flexible, and more intelligent direction. The development trend in the industrial field is reflected in full-factor digitalization, full-process automation, and full-business intelligence, with specific characteristics as follows:

First, "full-factor digitalization" is the foundation of new industrialization. It places higher requirements on sensing and connection technologies that can connect various production factors at low cost and high efficiency, needing to achieve the digitalization of personnel, assets, materials, production and transportation tools, finished products and other factors, transforming physical assets into data assets, further supporting enterprise automated and intelligent production operations [4].

Second, "full-process automation" is the carrier of new industrialization. Facing a new production model centered on "users," the core is to achieve truly unmanned, automated, and humanized production based on digital-physical integration. Therefore, it places higher requirements on wireless communication and industrial control technologies that can guarantee production reliability and meet manufacturing flexibility [5].

Third, "full-business intelligence" is the core of new industrialization. With the explosive development of AI technology led by generative artificial intelligence large models, it will have a profound impact on the industrial development model. Artificial intelligence and data factors have become typical representatives of new quality productive forces [6]. Facing the massive data generated by fragmented and differentiated industrial businesses, it places higher requirements on lightweight industrial large models, embodied intelligence, advanced computing and other technologies. Humanoid robots that support complex businesses have also become an important area of technology application.

Facing the industrial business development trend of "full-factor digitalization, full-process automation, and full-business intelligence," new sensing, communication, computing, control, and intelligence technologies need to evolve synchronously, expanding from single-point scenarios to all-scenario applications, extending from production line level to park level. Based on new sensing technology to achieve "sensible and connectable" full production factors, based on data collected by new sensing technology, through extreme wireless communication assurance technology to achieve all-weather, high-reliable data transmission capabilities, further supporting "manageable and controllable" full-process business, serving enterprise "intelligent" production operations. Through "ubiquitous factor sensing, wireless industrial networks, open industrial control, and intelligent production processes," we can achieve the integration of information collection, data transmission, cognitive decision-making, and feedback execution, accelerating industrial production and manufacturing towards high-end, intelligent, and green development.

First, through advanced sensing, achieve ubiquitous factor sensing. Facing the industrial digitalization demand for sensible and connectable full production factors and manageable and controllable full processes, the industry calls for the emergence of new IoT technologies, new products, new businesses, and new ecosystems to create low-cost and high-reliable production factor sensing capabilities. In addition, wireless signal

sensing technology can be used for real-time sensing of factory assets, equipment, and energy consumption, empowering industrial mobile robots to build basic capabilities for ubiquitous sensing.

Second, through extreme communication, achieve wireless industrial networks. Modern factories have further improved requirements for flexibility, security, and reliability. For field-level access important connections, communication technologies with characteristics such as nearby sensing, flexible access, comprehensive performance improvement, and coverage expansion are urgently needed to help flexible production and empower core production links.

Third, through virtual control, achieve open industrial control. Through virtualization, it is expected to achieve soft-hard decoupling and ICT/OT integration, solving the drawbacks of traditional PLC architecture such as closed architecture, tight soft-hard coupling, and difficult interconnection, providing abstract operating environments for real-time industrial control computing tasks, thereby achieving white-boxing, virtualization, and servicization of industrial control, playing an important role in building open, intelligent, connected, and collaborative new industrial control systems.

Fourth, through ubiquitous intelligence, achieve intelligent production business. Lightweight transformation of edge-side large models reduces dependence on imported high-end computing chips, enabling them to run at industrial sites, avoiding privacy leakage caused by sensitive information transmission, while reducing operating costs and inference energy consumption. Deploying edge-side large models to empower data management, assist industrial design, and anomaly detection helps the intelligent development of all industrial businesses.

2. New Industrialization Capability Building

2.1 Challenges Facing Existing Technologies

New industrialization takes the substantial improvement of total factor productivity as the core, relying on the development of digitalization, automation, and intelligence to improve resource allocation efficiency and decision-making scientificity, improve production efficiency and product quality, and improve operational efficiency and service levels. Consolidating the technical foundation of sensing, communication, control, and intelligence helps achieve full-factor digitalization, full-process automation, and full-business intelligence, promoting industry to develop in a more efficient, more flexible, and more intelligent direction [7]. Although current technologies have made progress in promoting informatization and intelligence, they still face the following specific challenges:

First, facing ubiquitous factor sensing, existing sensing technologies have challenges in low power consumption, maintenance-free, and all-weather operation. Under the current background of new industrialization, industrial production sites have placed high-quality sensing requirements on low power consumption, maintenance-free, and all-weather unattended operation. Existing sensing technologies have limitations such as power supply constraints, need for human attendance, and regular maintenance. Wireless sensing technology has solved power supply constraints and need for human attendance to a certain extent, but still has problems such as multipath interference, insufficient accuracy, and incomplete sensing factors.

Second, facing wireless industrial communication, existing wireless communication technologies have challenges in high reliability and determinism. In terms of 5G networks, the development of 5G industry applications is restricted by ultra-low latency high reliability, time synchronization, network slicing and other aspects. 5G needs ultra-large bandwidth and deterministic transmission to meet the communication needs of industrial production core links and guarantee real-time processing of production data all day. In terms of short-distance communication, facing industrial high-rate, large-transmission, high-quality connection scenarios, Wi-Fi/Bluetooth and other technologies are difficult to meet the strict requirements of industrial production sites for latency, reliability, and anti-interference. Industrial-specific short-distance communication

technologies can meet basic communication needs in industrial scenarios, but still need continued optimization in high reliability and high performance.

Third, facing open industrial control, existing industrial control technologies have challenges in flexibility, compatibility, and scalability. Some industrial scenarios have needs for massive data circulation and open interconnection. However, traditional industrial control technologies have inherent closedness and specificity, making it difficult to integrate with new-generation information technologies such as artificial intelligence and big data, which to some extent slows down the development of new industrial control systems. DCS and PLC hardware and software are bundled, leading to a lack of compatibility and interoperability between products from different manufacturers. This technical barrier also limits the open development of industrial control technology.

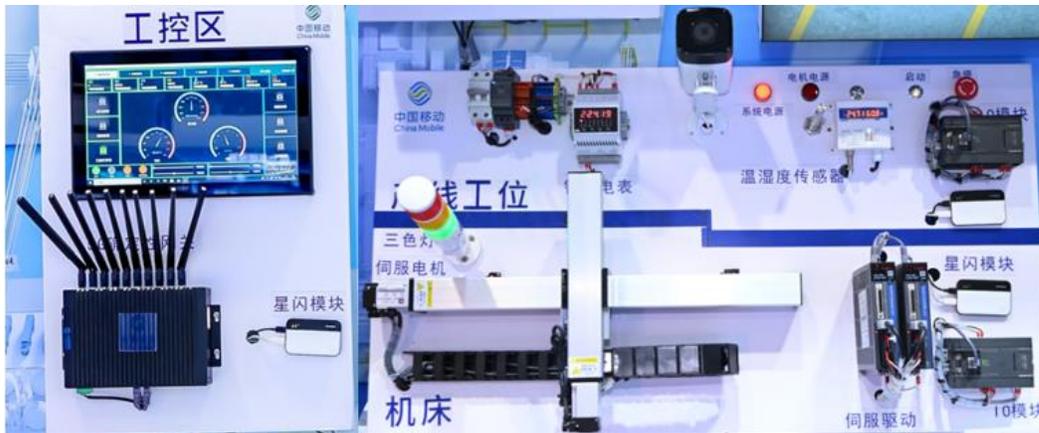
Fourth, facing intelligent production processes, existing AI technologies have challenges in generalization, accuracy, and low-cost scalability. AI applications in industry mainly focus on single scenarios, with the limitation of "one scenario, one training, one model," only serving single-point scenarios and not yet forming large-scale applications. For example, existing industrial models are mainly applied to single scenarios such as quality inspection and predictive maintenance. In addition, because industrial businesses have extremely high requirements for reliability, they have strict requirements for visual acquisition equipment, lighting, etc., and different scenarios have poor reproducibility. Compared with marketing text, image libraries, and videos generated using large models, errors in industrial large model predictions or decisions may cause production accidents or significant economic losses. Therefore, industrial-grade large models have higher requirements for accuracy. At the same time, the computing cost of training large models in the early stage is very high. Especially when parameters are higher and models are larger, although generalization ability is enhanced, the corresponding costs also increase significantly.

2.2 Deep Integration of "Sensing, Communication, Control, and Intelligence"

To address the above challenges and provide first-class wireless industrial control services to industrial enterprises, China Mobile has broken through existing technical bottlenecks. At the 2023 China Mobile Global Partner Conference, together with industry partners such as Inspur, Teldra, Huawei, Instrumentation Research Institute, Shenyang Institute of Automation, and International Spark Alliance, it released the industry's first

all-wireless deterministic industrial control system based on 5G + new short-distance technology, providing a brand new technical solution for 5G smart factories to solve flexible production problems. This system pioneered the integration of new short-distance connection, deterministic transmission, and virtualization control capabilities through 5G deterministic gateways, achieving all-wireless, full-process, independent and controllable high-reliability industrial control applications. In the wireless access layer, based on 5G + SparkLink short-distance fusion communication technology, it achieved wireless southbound and northbound directions, simplifying on-site deployment difficulty. In the link backhaul layer, through 5G Time Aware Network (TAN) technology, it achieved intrinsic dual-transmission selection and latency control, guaranteeing ultra-high-quality communication transmission. In the system application layer, based on virtualized industrial control technology, it built a new industrial control architecture with soft-hard decoupling and flexible orchestration. Tests showed that it could reduce industrial control system costs by 50%, reduce packet loss rate by 40%, and achieve one-way transmission latency below 100 microseconds, effectively promoting the deep integration of 5G private networks into core production links.

On this basis, China Mobile will continue to conduct extensive cooperation and deep coordination with all parties, deeply cultivate the all-wireless industrial control field, and jointly promote the construction of a new information service system with "connection + computing + capability" that is fully independent and controllable. With core equipment such as edge gateways and intelligent mobile robots as fusion carriers, it will explore the fusion of advanced sensing, extreme communication, real-time control, and ubiquitous intelligence multi-dimensional capabilities to meet the differentiated needs of various applications such as remote engineering equipment control, intelligent production line control, production data collection, and collaborative robotic arms emerging under the background of new industrialization, empower new quality productive forces, support new industrialization development, and accelerate industrial transformation and upgrading.



Overall, industrial control systems continue to evolve from "north-south wireless," "communication-control integration" to "sensing-communication-intelligence-control fusion." Based on application requirements and technical solution evolution, wireless industrial control can be divided into three stages: north-south wireless industrial control 1.0, communication-control integrated industrial control 2.0, and sensing-communication-intelligence-control fusion industrial control 3.0, ultimately building service capabilities with sensing-communication fusion, control-intelligence fusion, and integrated sensing-decision-execution, supporting independent production line layout and robot integration, and building new industrial control with intrinsic intelligent sensing.

New Sensing: Will achieve sensing capabilities with low power consumption, low cost, and multi-capability fusion. By fusing passive sensing, environmental energy harvesting and other technologies, equipped with advanced sensor devices, further reducing data sensing power consumption, and improving sensing precision and accuracy. At the same time, it will continue to explore fusion sensing capabilities and new sensing methods, enhance communication capabilities through sensing capabilities, based on integrated waveform design of sensing signals and communication signals, combined with intelligent algorithms to achieve environmental status analysis and user behavior analysis of sensing data, achieve AI-empowered sensing-communication integration and multi-source heterogeneous sensing capability fusion, and obtain more accurate, more reliable, and more comprehensive sensing results.

New Communication: Will achieve communication capabilities with stable and reliable transmission and efficient intelligent networking. By adopting new short-distance communication, deterministic networks, and other technologies represented by new industrial wireless, it is expected to meet the high reliability requirements of IoT

interaction in complex environments and harsh scenarios, providing more stable, reliable, and efficient communication capabilities. At the same time, based on device adaptive capability for device intelligent networking, fully utilizing the optimization and integration of resources and services, achieving interconnection of more devices, simultaneously supporting fusion of multiple heterogeneous networks, fully leveraging the advantages of different networks, forming a unified, seamlessly connected network system, providing plug-and-play, heterogeneous fusion, flexible deployment intelligent networking capabilities.

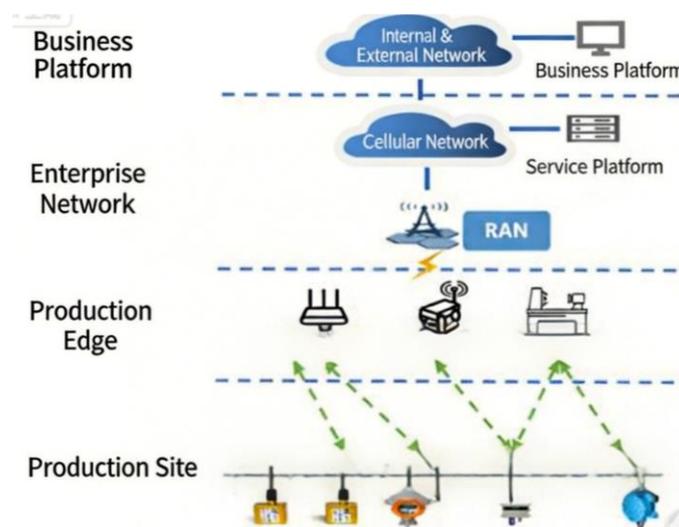
New Control: Will achieve new industrial control capabilities with soft-hard decoupling and flexible orchestration. Through control system soft-hard separation, based on general hardware replacing dedicated equipment, building a basic system foundation with high-real-time OT, high-computing IT, and high-deterministic CT application parallelism, creating new infrastructure for open automation. Based on virtualized PLC edge-end collaborative scheduling, achieving optimized allocation and on-demand deployment of software and hardware resources, building a unified orchestration operation system for virtualized PLCs in edge-end-cloud, providing users with real-time diversified interactive services.

New Intelligence: Will build intelligent capabilities with multi-model collaboration and lightweight deployment. By building industrial large models for diverse scenarios and complex tasks, and industrial small models for single scenarios and simple tasks, combined with collaborative application of large models and small models, providing new information services such as industrial understanding computing, code generation, and digital twins, strengthening the fusion innovation of computing intelligence, sensing intelligence, cognitive intelligence, and motion intelligence, creating embodied intelligent agents, comprehensively empowering all links of industry, and achieving improvement in industrial intelligence levels.

3. All-Wireless Industrial Control System and Technology Architecture

3.1 All-Wireless Industrial Control System Architecture

Facing the challenges of existing technologies in new industrialization, and comprehensively considering the needs for full-factor, full-process, and full-business management, there is an urgent need to provide systematic capabilities that are sensible, connectable, manageable, controllable, and intelligent for people, machines, and objects [8]. The all-wireless industrial control system will build multi-dimensional basic core functional modules by integrating characteristics such as sensing, communication, control, and intelligence, providing capabilities such as new sensing, new communication, new control, and new intelligence, supporting the differentiated needs of various applications, and achieving all-scenario deep empowerment for new industrialization [9].



The all-wireless industrial control system is mainly deployed within the factory network. The southbound direction provides multi-dimensional systematic data such as personnel, machines, materials, methods, and environment provided by on-site production factors, providing capabilities such as wireless connection for on-site production factors. The northbound direction opens capabilities such as data access to business platforms, aggregates data generated by devices and business processes to business platforms for joint analysis and rapid decision-making, achieving the construction of an end-to-end closed-loop system from information collection, information transmission, information calculation, to information application.

The all-wireless industrial control system uses industrial gateways, intelligent mobile robots, etc. as carriers to achieve the fusion of sensing, communication, control, intelligence, and other capabilities. Taking the deployment of industrial sensors, industrial controllers, actuators, and other terminal nodes on-site as an example, different terminal nodes can achieve multi-dimensional, refined sensing of underlying data and information through southbound wireless transmission or east-west device collaboration, and complete seamless transmission and reliable transmission between various factors and various systems at production line edge network elements, enabling heterogeneous systems to "understand" and interoperate at the data level. Then the collected and preprocessed information is transmitted in real-time to the service platform through the enterprise network, achieving efficient resource scheduling and informatized management through functions such as intelligent resource allocation and intelligent decision-making, reducing costs and resource waste. Based on the data access capability provided by the all-wireless industrial control system, highly automated data scheduling and highly adaptable business platform deployment can be achieved, improving open iteration speed. Finally, achieving resource factor transformation centered on data, connection method reconstruction driven by networking, control form transformation oriented towards flattening, and business model innovation guided by intelligence, creating new capabilities of ubiquitous sensing, efficient transmission, flexible control, and intelligent processing.

3.2 All-Wireless Industrial Control Technology Architecture

Based on the network architecture of the all-wireless industrial control system, and comprehensively considering business data processing levels, the technical architecture of the all-wireless industrial control system can be divided into hardware layer, capability layer, and service layer. The main functions of each layer are as follows:

(1) The hardware layer mainly provides the basic hardware and environment required for the operation, communication, and storage of the all-wireless industrial control system. It can include hardware such as intelligent sensing, 5G/new short-distance communication modules, MPUs, MCUs, deterministic transmission modules, and antennas [10]. The hardware layer can achieve hardware device 打通 with on-site production factors and protocol and runtime environment adaptation, providing basic hardware devices and environment supporting capabilities such as sensing, communication, control, and intelligence for the capability layer.

(2) The capability layer mainly provides the basic capabilities of the all-wireless industrial control system. Under the premise of complying with the logical constraints of each protocol layer, it reconstructs functional entities into flexibly combinable functional modules such as sensing, communication, control, and intelligence. Each module can be combined on demand and flexibly deployed to provide basic core capabilities such as new communication, new control, new intelligence, and new sensing, achieving multi-level, multi-technology, and multi-dimensional capability fusion.

(3) The service layer mainly provides the basic services of the all-wireless industrial control system. For the differentiated needs of different businesses, it provides multi-dimensional and multi-capability orchestration scheduling services such as network-business collaboration, QoS orchestration scheduling, and information models, building a business intelligent processing form with automatic business deployment and on-demand resource allocation, and opening capabilities to business platforms to form a closed-loop system deeply integrated with the industry.

4. Key Technologies of All-Wireless Industrial Control

4.1 New Sensing

Sensing technology is an important bridge connecting the physical world and digital space, providing the data foundation for building accurate digital mapping of physical objects [11]. With the in-depth promotion of industrial digitalization, the demand for sensing moving objects, assets, and energy consumption in factories continues to grow. As a major manufacturing country, China produces a huge number of goods every year, reaching the tens of trillions. Through the sensing of massive production factors, a large amount of high-value data will be generated, providing key factor support for building new quality productive forces and promoting industrial upgrading. Therefore, new sensing capabilities for massive production factors are an important development direction of the Industrial Internet of Things.

In the Industrial Internet of Things, sensing is key to ensuring that the system can accurately and real-time obtain and process various industrial environment information. Main sensing needs include positioning, energy consumption sensing, environmental sensing, asset management, and production process monitoring.

- 1) Positioning: Achieving real-time location tracking of industrial equipment, vehicles, personnel, etc., with different positioning accuracy requirements for different application scenarios. For example, indoor positioning may need to reach centimeter-level accuracy.
- 2) Energy consumption sensing: Using sensors to real-time monitor the energy consumption of industrial equipment and production lines, evaluating equipment energy efficiency levels through energy consumption data analysis, providing data support for energy saving and consumption reduction.
- 3) Environmental sensing: The system can quickly respond to environmental changes and real-time update environmental information such as temperature and humidity, ensuring that the industrial environment is in suitable production conditions.
- 4) Asset management: Achieving unique identification and tracking management of assets through technologies such as RFID and QR codes.
- 5) Production process monitoring: Monitoring the entire production process through visual image analysis to ensure coordination of various links and improve production efficiency.

To meet diverse sensing needs, all-wireless industrial control node devices integrate technologies such as passive sensors, AI + indoor integrated sensing and communication, and high-integration visual sensing, achieving low-cost sensing through

their own wireless communication capabilities, and can also provide integrated capabilities of power supply, communication, and sensing for the massive sensors on the southbound direction, thereby achieving maintenance-free massive sensors.

4.1.1 Passive Wireless Sensing

Most traditional sensing terminals use battery power supply, requiring regular replacement or charging. This not only increases maintenance costs but may also affect system stability and reliability. Especially in industrial production of certain special industries, due to harsh environments and other factors, maintaining sensing terminals is even more difficult. Therefore, maintenance-free sensing terminals have become an inevitable trend in industry development. Industrial passive sensors, as devices that do not rely on external power supplies, integrate composite micro-energy management technology to achieve continuous energy supply for sensors without batteries.

Composite micro-energy management technology is a technology that collects and utilizes tiny energy from the surrounding environment, mainly used to power small electronic devices and sensor networks, solving the problem of IoT terminal dependence on DC power supply, achieving "zero carbon" terminal energy use, and greatly expanding sensing application scenarios. Composite micro-energy management technology mainly includes antenna design, RF-DC conversion, composite micro-energy management, etc., achieving 390mV ultra-low voltage cold start, energy conversion efficiency above 10% at -26dBm received power conditions, and stably outputting 2.2V voltage, significantly improving energy harvesting efficiency.

Based on composite micro-energy management technology, facing national new industrialization strategic development needs such as semiconductor processing, carbon footprint tracking, aerospace, and urban lifeline governance, China Mobile has innovatively developed "diversified" passive sensing sensor products for complex scenarios, including high-temperature resistant passive wireless wafer temperature sensors, energy consumption sensing passive smart sensors, and environmental monitoring passive wireless sensors.

High-temperature resistant passive wireless wafer temperature sensors: Facing the sensing needs of miniature sensors in wafer manufacturing temperature control systems, for the first time in China, developed a sensing intelligent microsystem integrating MTC thin-film temperature sensors and high-temperature resistant RFID chips, effectively

meeting high-precision measurement needs at 300°C high temperature, performance reaching the level of international mainstream products, breaking foreign technology monopoly, and achieving domestic substitution.

Energy consumption sensing passive smart sensors: Innovatively developed a passive energy consumption sensing microsystem for full collection of electrical parameters such as voltage, current, power factor, and temperature, with advantages such as non-intrusive installation, battery-free maintenance-free, small safety hazards, and high collection accuracy, capable of serving many industrial scenarios such as energy-carbon analysis, energy efficiency management, electricity safety, and equipment maintenance.

Environmental monitoring passive wireless sensors: Facing multi-dimensional environmental monitoring needs, integrating temperature, humidity, vibration MEMS sensors to achieve "cutting off the braids" of sensor power lines and communication lines, facilitating large-scale deployment. They have been successfully implemented at the Space Center Ground Mirror Station of the Chinese Academy of Sciences and Beijing Urban Lifeline, solving bottleneck problems in the national aerospace engineering field, improving industrial intelligence levels, and laying a solid foundation for national scientific and technological progress and industrial upgrading in the industrial field.

Diversified passive sensing sensors based on composite micro-energy management technology have achieved passive full-factor sensing capabilities for all-wireless industrial control networks, with broad application prospects.

4.1.2 Industry-Integrated Sensing and Communication

Industrial scenarios have strong needs for environmental monitoring, personnel positioning, and energy consumption management. With the maturation of flexible production motion control, more and more scenarios also require decimeter-level positioning accuracy. Currently, wired sensing technology has high deployment and maintenance costs and is difficult to scale.

Industry indoor integrated sensing technology uses wireless signals to capture complex propagation paths of signals during transmission through phenomena such as reflection, diffraction, and scattering in passive IoT. These multipath superposition signals are processed for physical modeling and AI generalization by extracting Channel State Information (CSI) and detecting Doppler frequency shift after passing through the

receiver, thereby achieving precise perception of the environment and objects. This technology captures the amplitude, phase, and waveform changes of reflected signals, precisely calculates the spectral characteristics of wireless signals, and constructs a CSI perception model oriented towards industrial scenarios. In addition, combining advanced machine learning, large models, and neural network technologies, the system can effectively classify, cluster, and identify collected feature information, achieving non-contact real-time monitoring and intelligent recognition, greatly improving the efficiency and safety of automated production, intelligent warehousing management, enterprise informatization management, and industrial robot operation, helping factories reduce costs and increase efficiency.

In wireless communication, CSI describes the channel properties of the communication link, that is, the state of the signal during transmission. Solving CSI usually uses reference signals, especially pilot signals or sounding reference signals. These reference signals are known and are sent by the sender in a specific manner so that the receiver can use them to estimate channel characteristics. The general process of solving CSI is: sending reference signals, receiving reference signals, channel estimation, solving CSI. Once CSI is obtained, the receiver can use it for subsequent signal processing such as multi-user scheduling, resource allocation, and precoding to improve communication system performance.

The amplitude and phase of CSI are affected by multiple factors, including the position of the sender and receiver, the presence of surrounding objects, and human displacement and movement. Changes in these factors will cause corresponding changes in CSI, thereby providing us with a unique sensing means. Based on this characteristic, CSI has shown great application potential in event detection, behavior recognition, and parameter estimation. For example, in smart home systems, we can detect family members entering and leaving or recognize their daily activities by analyzing CSI changes. In wireless monitoring systems, CSI can also be used to estimate the position and motion state of target objects.

CSI-based AI + indoor integrated sensing technology has high application value in industrial applications: 1) No additional equipment needed: Using wireless signals such as Wi-Fi, 5G, and RFID to achieve sensing, without deploying additional sensors or equipment in the environment, greatly reducing deployment costs and maintenance work.

2) Unobtrusive sensing: Because it does not rely on additional hardware equipment, sensors do not need to be deployed on users or devices, making it "unobtrusive" sensing for users. 3) Flexibility and scalability: Indoor integrated sensing technology can be easily extended to new areas or scenarios, as long as these areas are covered by wireless signals.

With the rapid development of technology, in addition to the AI + indoor integrated sensing mentioned above, new short-distance technology has also become a key technology in industrial integrated sensing. New short-distance access technology perceives the environment through specially designed waveform sequences, not only defining new evaluation indicators but also expanding the scope of channel measurement information acquisition. Using ultra-wideband signals or through bidirectional composite virtual channel frequency-hopping virtual large-bandwidth signals, precise position information measurement can be performed between transceivers. This frequency-hopping measurement method can achieve decimeter-level ranging accuracy, providing powerful technical support for precise position sensing in industrial applications.

In the future, China Mobile will also work with the industry to further expand the new fusion model of cellular network "base network" and new short-distance wireless "overlay network" with passive sensing and high-precision positioning capabilities. Facing the connection needs of innovative applications in industrial sites, exploring integrated sensing and communication all-wireless connection capabilities to achieve one-network multi-functional network coverage.

4.1.3 High-Integration Vision

Industrial high-integration vision technology obtains high-precision visual data through cameras and computer vision to monitor industrial production processes, which can significantly improve industrial automation and intelligence levels. It can be deeply integrated with robots to ensure they maintain high precision and high stability in complex industrial environments. Simultaneous Localization and Mapping (SLAM) algorithms are currently the mainstream technology for high-integration vision.

SLAM algorithms achieve precise positioning and environment mapping for robots in unknown environments through sensor integration and data fusion. First, sensors such as laser scanners, cameras, radar, and Inertial Measurement Units (IMUs) work collaboratively to provide data on distance measurements, visual information, object

positions and velocities, and robot motion states. These data are precisely synchronized and fused to form comprehensive environmental perception. SLAM algorithms extract feature information such as edges, corners, and textures from sensor data and determine the correspondence of the same feature points in data collected at different time points through data association. Through Extended Kalman Filters (EKF), Unscented Kalman Filters (UKF), or particle filters, uncertainty and noise are processed, providing the best state estimation for robots. Loop closure detection is used to correct accumulated positioning errors, improving map construction quality.

Industrial high-integration vision technology has wide applications in industrial scenarios. In robotic arm grasping, by monitoring the angle and distance between objects and robotic hands, precise control of the grasping direction of non-metallic objects is achieved, improving the accuracy and efficiency of robot grasping. In quality inspection, it can real-time detect product quality on production lines, identifying and classifying defects. In equipment monitoring, it can timely discover and prevent equipment failures, reducing downtime and maintenance costs. In automated operations, vision systems are used to guide and control robot operations, improving the accuracy and efficiency of tasks such as welding. In logistics management, vision systems are used to identify and track goods, achieving automatic sorting and inventory management.

In the future, industrial high-integration vision technology will develop in the direction of more efficient visual perception and more intelligent visual processing. On one hand, cameras, processing chips, and sensors will be further integrated. The widespread application of new visual perception technologies such as polarized structured light technology will further improve robot visual perception capabilities. On the other hand, combined with artificial intelligence and machine learning technologies, vision systems will have stronger self-learning and adaptive capabilities, capable of handling more complex tasks such as AR/VR, face recognition, and eye tracking, adapting to more complex and dynamic industrial environments.

4.2 New Communication

4.2.1 5G Deterministic Technology

Determinism is proposed relative to the "best effort" transmission of the Internet, providing a wireless network with deterministic bandwidth, deterministic latency, and bounded jitter, better meeting the diverse needs of industrial customers. 5G deterministic networks aim to provide higher quality cellular network services for industrial customers, helping 5G empower core production links.

Deterministic transmission in traditional industrial networks is implemented by industrial Ethernet technologies such as PROFINET and EtherCat. To achieve system interconnection, standards have proposed protocol designs for unified link layer technologies. TSN, DetNet, and TSC are projects or technical names of deterministic technologies under different standards organizations, complementing each other in various complex scenarios.

In addition to the main deterministic technologies mentioned above, building a complete 5G deterministic network also requires integrating other communication technologies, such as uRLLC, 5G LAN, slicing, QoS guarantee technologies, as well as TAN, Flex-E, MPLS TE, SRv6 and other technologies. These technologies need to achieve fusion collaboration and ultimately form end-to-end overall service capabilities.

(1) Multi-Transmission Selection Technology

5G networks can be considered as a local area network of the entire Internet, forwarding data with the Internet. Terminals and external networks send and receive data in the form of data packets. To ensure that data packets are not lost during the communication process of 5G networks, multi-transmission selection technology is usually used for sending and receiving data. The implementation interfaces of the 3GPP multi-path redundancy transmission scheme mainly include air interface multi-path redundancy transmission between UE and 5G-AN (① UE↔5G-AN), multi-path redundancy transmission between 5G-AN and UPF (including ②5G-AN↔UPF and ③UPF↔UPF), multi-path redundancy transmission between UE and UPF (④UE↔UPF), and multi-path redundancy transmission between UE and DN (⑤UE↔DN).

The dual-transmission selection scheme is based on the collaboration of the core network side and the terminal side, utilizing the FRER protocol to achieve data packet

redundancy transmission through dual links. Terminal devices replicate data packets at the dual-transmission selection module/device. The same data packets can be transmitted through independent PDU redundancy sessions established in the 5G network or independent tunnels established between UE and DN, achieving dual-transmission selection.

(2) High-Precision Time Synchronization Technology

High-precision time synchronization is key to ensuring consistency of industrial control task scheduling, and is also a prerequisite for achieving 5G network determinism. Functions such as precise gate control and traffic shaping are based on high-precision clock synchronization.

The 5G system internal clock comes from Beidou/GPS satellites and other sources. After base stations obtain nanosecond-level timing, they provide timing to UEs through SIB9 information and provide timing to UPFs through PTP transmission networks, achieving sub-microsecond-level high-precision time synchronization within the 5G system. To support the timing of industrial applications by the 5G system internal clock, 5G terminals can provide southbound timing to industrial networks through supporting multiple timing protocols, meeting diverse mode requirements for time synchronization in industrial networks.

China Mobile's 5G deterministic gateway adopts the industry's mainstream high-precision time synchronization algorithm PTP, improves data frame timestamp generation precision through hardware upgrades, updates the local clock after receiving clock information in SIB9, and simultaneously provides southbound timing to field equipment through B code or IEEE 1588V2, achieving whole-network high-precision clock synchronization error less than 1 μ s.

(3) Ultra-Low Latency and Bounded Jitter

Latency and jitter are core communication needs for industrial core production control. Process industry businesses have their own production rhythms, with extremely strict requirements for communication latency and jitter of commands. If the number of command packets exceeding arrival time limits or if the interval between adjacent command packets arriving is too large exceeds the threshold, it will directly cause business downtime, resulting in extremely serious losses.

To improve the ultra-low latency and bounded jitter performance of 5G networks, China Mobile performs technical enhancement and performance optimization for terminals, wireless, transmission, and core network sides. On the terminal side, timestamps are added to incoming network data frames, and precise scheduling of data egress times at edge nodes is implemented to achieve high-precision jitter control. On the wireless side, innovative mechanisms such as pre-scheduling, Mini-Slot, and DS frame structures reduce waiting latency and data transmission latency, and technologies such as network-business collaboration guarantee bounded jitter ranges and precise and efficient use of air interface resources. The transmission network reduces device forwarding latency through MTN hard channel isolation. The core network can reduce user plane processing latency through means such as hardware acceleration, scheduling strategy optimization, and TSN precise gate control. Through end-to-end capability enhancement, millisecond-level extreme latency guarantee and microsecond-level jitter control for 5G end-to-end networks can be achieved.

4.2.2 Heterogeneous Network Integration Technology

Heterogeneous network integration is used for collaborative networking of various short-distance wireless and 5G cellular networks in the Industrial Internet of Things, leveraging the advantages of different networks to form a unified, seamlessly connected network system, driving cellular networks to penetrate into more harsh industrial core production links. As a new connection element of cellular networks, it should have three typical characteristics:

- 1) Plug-and-Play: Field network terminals based on device adaptive capability access various short-distance wireless networks, automatically completing network settings and starting normal work without manual configuration, which can significantly reduce network equipment deployment and network maintenance workload, with advantages such as simple deployment, flexible access, and controllable costs.
- 2) Performance Improvement: Further improving intrinsic deterministic capabilities to better support deterministic service requirements such as low latency, high reliability, and high security, driving more application scenarios. Additionally, comprehensively considering multi-dimensional indicators such as access rate, latency, reliability, energy efficiency, and traffic density to promote full-scenario coverage.

3) Flexible Deployment: Fully utilizing the optimization and integration of resources and services to achieve interconnection of more devices, simultaneously supporting fusion of multiple heterogeneous networks, meeting integrated deployment and customized fusion air interface transmission requirements with heterogeneous networks such as cellular networks, achieving all-wireless network coverage with collaboration between wide-area and local-area, and between local-area and local-area.

Combining the above typical characteristic requirements, China Mobile will fully leverage its advantages in technological innovation and industrial ecosystem integration, continue extensive cooperation with all parties, and promote the continuous evolution of heterogeneous network integration technology facing networking needs for north-south edge-cloud collaboration and east-west edge-edge collaboration.

(1) Industrial Short-Distance Air Interface Technology

To meet latency-sensitive industrial control business needs, industrial short-distance air interface technology can use short frame structure design, introduce simplified protocol stacks and cross-layer transparent transmission mechanisms, enable semi-persistent scheduling based on business characteristics, promoting one-way user plane transmission latency to reach below 100 μ s. To achieve high-reliability transmission in complex electromagnetic environments, the physical layer can introduce higher-performance channel encoding and decoding technologies, optimized for random interference and burst interference, combined with physical layer fast feedback retransmission mechanisms and flexible interference detection avoidance mechanisms. Based on a standard unified air interface protocol framework, time division duplex based on field management nodes can also be introduced, achieving synchronization accuracy of less than 1 μ s under medium and low SNR through synchronization sequence and resource mapping optimization, effectively supporting field high-performance synchronization processing needs. On this basis, more efficient fragment aggregation, encapsulation parsing and retransmission flow control mechanisms are constructed at the protocol layer, as well as control plane mechanisms for quality management and networking strategy management oriented to industrial control businesses, helping field network unified access, lossless data transmission, and scheduling.

Facing industrial wireless needs, various companies or organizations are exploring new short-distance air interface technologies, achieving performance improvements in low

latency, high reliability, precise synchronization, and high concurrency, but industry maturity is generally low. In the future, industrial short-distance air interface can also be based on low-power orthogonal multiple access such as code division multiple access, combined with non-contention access mechanisms and more refined resource mapping and indication methods, achieving precise synchronization capabilities and optimized channel division schemes, achieving efficient support for multi-path concurrent services in low-latency high-reliability scenarios, significantly improving channel utilization rates under dense deployment of underlying equipment.

(2) Multi-Domain Collaborative Networking Technology

There are many network access methods in industrial field networks. Cellular networks and various wireless access methods in industry field networks integrate for networking to meet needs such as seamless connection of mobile device access and wireless remote control. Based on north-south multi-domain collaborative design, new short-distance wireless can use flexible 5G + short-distance wireless multi-links for redundant transmission of northbound business data, guaranteeing transmission reliability of all-wireless multi-hop networks. At the same time, new short-distance wireless with east-west direct communication characteristics can also perform fine-grained blind spot supplementation for insufficient 5G stability and weak coverage areas in workshop internal networks, driving new 5G applications to develop from warehousing and logistics links to industrial production core link applications.

China Mobile is promoting the innovative design of new short-distance technology and 5G network protocol fusion solutions, aiming to face 5G + short-distance heterogeneous integrated communication networks, combining characteristics such as access security, quality guarantee, and link state control of heterogeneous networks, and based on the types of network elements and different functions involved in fusion networking interaction, using new short-distance wireless to supplement and extend dynamic service capabilities of cellular networks, improving capabilities such as high reliability, precise synchronization, high concurrency, and anti-burst interference of the entire 5G system. In the future, China Mobile will also work with the industry to further promote key technologies such as field-level terminal mobility management and short-distance wireless collaborative sensing, building flexible networking and multi-domain collaborative fusion networks facing industrial scenarios, promoting the implementation

of all-wireless industrial control network technology solutions in mobile industrial robot collaborative control applications.

4.3 New Control

The ISA-95 automation architecture with PLC (Programmable Logic Controller) as the core solves the problem of integrating enterprise global operations and workshop production, meeting different control application needs for discrete manufacturing and process industries. With the cross-fusion of control science with computing, information, communication, and other disciplines, control theory has developed from classic feedback control and modern control to data-driven intelligent control, and control systems have evolved from single-point control and networked control to distributed control. Openness, intelligence, networking, and collaboration have become typical characteristics and development trends of new industrial control systems. Due to the closedness and specificity of traditional PLCs, they cannot cope with massive data circulation and open interconnection needs. New-generation information technologies such as artificial intelligence and big data are difficult to introduce to production sites, hindering the development of new industrial control systems.

Virtualization is a key enabling technology for building new industrial control systems. Virtualized industrial control technology aims to provide abstract operating environments for real-time industrial control computing tasks through virtualization, thereby achieving white-boxing, virtualization, and servicization of industrial control. It has three typical characteristics:

1) Soft-Hard Decoupling: Traditional PLCs use embedded hardware and real-time operating systems, with tight software-hardware coupling. With the surge of I/O devices at industrial production sites, traditional controllers with proprietary hardware face difficulties in computing power expansion and high costs. Only controllers based on general hardware can meet computing power needs.

2) Virtual Operation: Based on general hardware, deploying the PLC runtime environment in a virtual operating system (Guest OS), with PLC tasks independent of the host operating system and underlying hardware. At the same time, virtualization provides characteristics such as resource isolation and fault isolation, supporting new modes such as centralized deployment of industrial control and mixed deployment of industrial control and IT systems.

3) Ubiquitous Deployment: Virtualized industrial control is essentially PLC software services that can be orchestrated and deployed in edge-end-cloud systems, and can

also be dynamically scheduled during runtime, providing flexibility and scalability significantly different from traditional PLCs.

Virtualized industrial control technology achieves soft-hard decoupling and ICT/OT integration through virtualization, solving the drawbacks of traditional PLC architecture such as closed architecture, tight soft-hard coupling, and difficult interconnection, playing an important role in building open, intelligent, connected, and collaborative new industrial control systems.

4.3.1 PLC Industrial Control Software Technology

PLC industrial control software includes PLC development software and PLC runtime environment (PLC Runtime). PLC development software is deployed on developer upper computers, providing PLC application development environments and responsible for PLC programming language compilation and download. The PLC runtime environment is deployed in controllers, responsible for loading, executing, scheduling, and monitoring compiled PLC applications. The PLC runtime environment is the core component of PLC industrial control, achieving a certain degree of soft-hard decoupling and playing an important role in building new industrial control systems. PLC industrial control software currently consists of two categories: commercial software and open source software. In commercial software, CodeSys is relatively common. Domestic companies such as INOVANCE, Kyland, and Aotce are also developing autonomous industrial control software. Open source software still has a gap from actual production application, and maturity needs further improvement.

4.3.2 Real-time Container Technology

Real-time container technology builds container runtime environments on real-time operating systems to provide industrial control services. On one hand, PLC tasks run as operating system processes on operating systems according to industrial control cycles, and must ensure that PLC processes can receive external inputs and obtain CPU processing time in each industrial control cycle. To provide reliable PLC control services, the real-time nature of the operating system is a key factor. On the other hand, with continuous growth in chip computing power, container technology has permeated from the cloud side to the edge-end. As an operating system lightweight virtualization technology, containers have characteristics such as small overhead, fast startup, and easy scalability, suitable for use in resource-constrained environments. To meet industrial control needs, relevant container services need to be provided simultaneously

during container construction, including I/O peripheral access, network port mapping, container volume management, CPU core isolation, health status monitoring during container operation, etc.

Providing industrial control services based on real-time container technology can meet most medium and high-speed logic control performance requirements, and is convenient for integrating industrial control services with other ICT services, suitable for end-side industrial control equipment or edge-side industrial control centralized deployment scenarios. However, the performance of real-time containers mainly depends on the real-time nature of the operating system. Additionally, all containers share the operating system kernel, and there is still a certain gap from scenario requirements such as high-performance motion control and operating system fault isolation in terms of real-time nature and isolation.

4.3.3 Heterogeneous Operating System Hybrid Virtualization Technology

Heterogeneous operating system hybrid virtualization is a Type-1 type virtualization software technology (Hypervisor). It runs between hardware and virtual machines using hardware-provided virtualization capabilities. Unlike traditional homogeneous virtual machines, heterogeneous operating system hybrid virtualization supports General Purpose Operating System Virtual Machines (GPOS VM) and Real-Time Operating System Virtual Machines (RTOS VM).

The core of virtualization software is completing the virtualization of CPU, memory, interrupts, clocks, and I/O. When a virtual machine executes sensitive instructions, it causes the virtual machine to exit to the virtualization software, which executes the sensitive instructions, and re-enters the virtual machine after completion to continue executing virtual machine applications. When a hardware interrupt occurs, the interrupt is first handed to the virtualization software for processing, which injects the interrupt into a specific virtual machine. At the same time, the virtualization software is also responsible for I/O peripheral management. For high-speed I/O, direct access mode can be set to improve access efficiency. For certain I/O devices, RTOS VMs may lack drivers, which can be completed by GPOS VMs performing I/O access, and then injecting data into RTOS VMs through inter-VM data communication methods.

Heterogeneous operating system hybrid virtualization can achieve integrated ICT and OT business 承载, with advantages such as high efficiency, flexible use, and support for

operating system-level or even hardware-level fault isolation. Because it supports real-time operating systems, this architecture can meet motion control performance requirements and expand the application scope of virtualized industrial control. Currently, there is broad application space for heterogeneous operating system hybrid virtualization in scenarios such as ICT/OT fusion industrial control equipment and intelligent robots. Taking intelligent robots as an example, on one hand, robots need to run motion control algorithms on real-time operating systems, emphasizing control real-time nature. On the other hand, with the development of embodied intelligence, robots need high-computing general operating systems to complete sensing intelligence and cognitive intelligence. These two types of businesses can be integrated and carried through heterogeneous operating system hybrid virtualization, jointly building motion intelligence systems. Through integrated carrying, while reducing hardware devices and reducing costs, it can also reduce power consumption and heat, extending equipment service life.

4.3.4 Virtualized Industrial Control Orchestration Technology

Through virtualization transformation, traditional PLC hardware devices become virtualized industrial control services decoupled from hardware. Flexible deployment of control services is needed in cloud-edge-end systems, so unified orchestration scheduling of virtualized industrial control services is required.

Virtualized industrial control orchestration scheduling supports deploying virtualized industrial control services in container or virtual machine modes to various general-purpose devices on the cloud-edge-end, such as 5G industrial gateways, 5G industrial base stations (BBU), 5G industrial UPF, and MEC. The orchestration system mainly consists of virtualized industrial control services, orchestration management platform, and target devices. Virtualized industrial control services provide service description files, providing information such as hardware and software resource requirements and communication methods of services. The orchestration management platform stores virtualized industrial control services and, according to business needs, deploys services to target devices. At the same time, target devices communicate with the management platform through the network and monitor the operational status of services on target devices. Target devices run virtualized industrial control services by providing virtualization environments.

In typical scenarios, cloud-side deploys production control systems, enterprise informatization management systems, etc. Edge-side mainly deploys master PLCs,

responsible for docking with cloud-side systems, generating control instructions in C2C mode and issuing them to slave PLCs deployed on the end-side. End-side slave PLCs are mainly responsible for C2IO communication, receiving control instructions from edge-side master PLCs, and controlling on-site IO devices. In terms of business, edge-side master PLCs are responsible for control businesses with industrial control cycles above 30ms, while end-side slave PLCs are responsible for control businesses with industrial control cycles below 30ms.

4.4 New Intelligence

With the rapid development of artificial intelligence technology, technological breakthroughs represented by large models have depicted a new vision for AI application implementation. China Mobile Chairman Yang Jie pointed out that in the future, AI will evolve towards the systematic integration of "Four Major Intelligences": computing intelligence, sensing intelligence, cognitive intelligence, and motion intelligence, accelerating implementation in vertical fields and key scenarios, forging a strong engine for new quality productive forces development. Accelerating the deep integration of artificial intelligence and manufacturing, comprehensively empowering new industrialization, has extremely important significance for China's development of new quality productive forces, establishment of a modern industrial system, and achievement of high-quality development. The "Four Major Intelligences" will empower all-wireless industrial control in four aspects: 1) Computing intelligence technologies represented by computing-in-memory will further reduce computing costs, achieving efficient, sustainable green computing. 2) New sensing intelligence technologies represented by passive sensing and wireless sensing can broaden sensing boundaries, empowering new industrialization applications. 3) Cognitive intelligence technologies represented by edge-side large models will mine industrial data, provide cognitive decision-making, transform production methods, and effectively improve production efficiency. 4) At the same time, technologies such as embodied intelligence and physical intelligence will break the boundaries between artificial intelligence and the physical world, changing AI from an observer of manufacturing to a participant, empowering intelligence throughout the production and control process.

In recent years, traditional small models have been widely applied in the industrial field, such as intelligent sorting, environmental monitoring, defect detection, etc., accumulating many capabilities and scenarios, laying a good foundation for industrial intelligent

development. However, industrial field needs are numerous and fragmented. Small models have problems such as poor generalization, long development cycles, high innovation costs, and high operation and maintenance complexity, restricting industrial intelligent development. General artificial intelligence large models (hereinafter referred to as "large models") integrate functions such as intelligent sensing, intelligent analysis, intelligent decision-making, and intelligent execution, comprehensively empowering various industrial processes such as R&D design, production manufacturing, operation management, and product service. Companies represented by Microsoft and OpenAI have formed extensive cooperation with industrial field partners, applying ChatGPT-based large model services to empower key links such as R&D design, code generation, equipment management, intelligent customer service, and industrial robots, forming many intelligent products.

However, the application and development of industrial large models still face four major challenges: insufficient computing power, high difficulty in algorithm optimization, low data quality and insufficient quantity, and high costs. With the development of new computing technologies represented by computing-in-memory, through innovations in devices, computing paradigms, and architectures, the computing power and energy efficiency levels of edge-side devices will continue to improve, promoting the development of new-type intelligence on the edge side. Facing the new requirements for deployment flexibility, cost control, and field-level intelligence capabilities proposed by intelligent production processes, future all-wireless industrial control systems will form new intelligence capabilities centered on edge-side private large models, with small models and cloud-side large models as supplements. Edge-side large models have characteristics such as local deployment, offline operation, high-performance computing, and controllable costs. In terms of empowering all-wireless industrial control systems, edge-side large models, by providing core capabilities such as multi-computing architecture compatibility, small-data fine-tuning, multi-modal data processing, and edge-side flexible deployment, help real-time analysis of industrial field data, effectively reducing data transmission latency, reducing risks of data leakage and attacks, improving system response speed, while reducing computing energy consumption and improving energy utilization efficiency, providing real-time and accurate decision-making basis for all-wireless industrial control systems.

4.4.1 Field-Level Intelligence Technology

Various links of industrial production have placed refined and differentiated requirements on intelligent capabilities. The process of industrial intelligence needs to comprehensively consider costs, deployment and maintenance difficulties, and actual scenario needs. Field-level intelligence technology refers to a technical system applied at industrial sites that integrates advanced data processing, automated control, and machine learning functions to achieve intelligent, efficient, and flexible production processes. In modern industrial production environments, based on field-level intelligence technology, real-time collection, processing, and analysis of production data can be achieved, providing valuable decision support and automated control of production processes for enterprises.

Currently, intelligent capabilities such as detection and recognition based on artificial intelligence small models and machine learning algorithms (such as image segmentation, object detection, behavior recognition, etc.) have achieved intelligent detection and control at single links and specific scenarios, which can not only reduce errors and instability caused by manual operations but also reduce labor costs and improve production efficiency and quality. However, because the production site environment is complex and changeable, intelligent systems need to have strong robustness and adaptability to ensure normal operation under various conditions. Secondly, data security and privacy protection are top priorities in industrial scenarios. Therefore, it is urgent to promote model construction and update technologies represented by few-shot learning and continuous learning to achieve flexible adaptation of models to environments. At the same time, tackle model lightweighting technologies such as model pruning, quantization, and knowledge distillation to reduce model deployment barriers and achieve ubiquitous intelligence. With continuous technological progress and expanding application scenarios, future field-level intelligent technologies will continue to improve, forming a situation of large-small model collaboration and general-specialist model collaboration, empowering intelligent all-wireless industrial control systems.

4.4.2 Industrial Large Model Technology

Basic large models, by significantly increasing the number of model parameters and optimizing their structural universality, can integrate and express knowledge from many fields and modalities, building an all-encompassing general model. Industrial large models, on the other hand, take the structure and knowledge of basic large models as

the foundation and further integrate specific industrial field data and expert wisdom to create application models with targeting, alignment with actual scenarios, and high specialization. Large model technology is still in the early stage in new industrialization, mainly applied in R&D design and operation management links. With technological maturity, it can rely on forward-looking design, efficient simulation, precise detection, and intelligent operation to promote the deep application of AI large model technology, empowering implementation in multiple scenarios. Addressing problems such as insufficient industry know-how reserves and low knowledge data quality faced by large model training, industrial upstream and downstream collaboration is needed to explore collaborative methods based on privacy learning, achieving more sufficient information sharing and collaboration on the basis of privacy protection, further tapping large model potential.

Industrial large models can provide powerful universality and low-cost operation and maintenance, while small models can achieve rapid iteration and lightweight deployment. In terms of costs and flexibility, large and small models are complementary rather than competitive relationships. The collaboration of large and small models can provide practical and feasible solutions for intelligent upgrading of industrial production. In terms of empowering all-wireless industrial control systems, edge-side large models, by providing core capabilities such as multi-computing architecture compatibility, small-data fine-tuning, multi-modal data processing, and edge-side flexible deployment, help real-time analysis of industrial field data, effectively reducing data transmission latency, reducing risks of data leakage and attacks, improving system response speed, while reducing computing energy consumption and improving energy utilization efficiency, providing real-time and accurate decision-making basis for all-wireless industrial control systems, helping improve industrial intelligence levels.

5. All-Wireless Industrial Control Application Practices and Exploration

5.1 All-Scene Applications of All-Wireless Industrial Control in Factories

With the continuous increase in the types and scale of smart factory application types empowered by information technology, the demand for all-factor, full-process, and full-business management in all-scenario applications of all-wireless industrial control factories is becoming increasingly urgent. The all-wireless industrial control system consolidates the basic capabilities of industrial site sensing, communication, control, and intelligence, builds system-level networking integration, wireless sensing, extreme communication, reliable control, and intelligent operation end-to-end all-wireless guarantee capabilities, achieving integrated supply of wireless services, supporting the differentiated needs of various applications, and achieving all-scenario deep empowerment of all-wireless industrial control factories.

5.1.1 Sensing Cases

(1) Industrial Equipment Energy Consumption Monitoring

Application Scenarios and Requirements

With the intensification of global energy shortage and environmental pollution, energy conservation and emission reduction have become important policy goals for governments of all countries. At present, China has issued multiple "dual carbon" related policies, requiring key energy-consuming enterprises to build energy consumption monitoring systems. Industrial enterprises face pressure to reduce carbon emissions and reduce environmental pollution. Building energy consumption online monitoring systems can help enterprises reduce pollutant discharge, ensure carbon emission compliance, and reduce environmental pollution. At the same time, energy consumption monitoring systems can real-time obtain equipment operation data, judge equipment work efficiency and health status through data analysis, discover faults in a timely manner and perform maintenance. Energy consumption monitoring can also help enterprises identify high-energy-consuming equipment and excessive energy consumption links, formulate energy-saving measures and management strategies, thereby reducing energy consumption, controlling costs, and improving profitability.

Solution Architecture and Application Effects

The equipment energy consumption monitoring system architecture includes perception layer, network layer, AI algorithm layer, and application layer. In the perception layer, energy consumption sensors collect core parameters such as current, voltage, and power factor, integrating environmental self-harvesting energy capability to achieve battery-free maintenance-free. In the network layer, based on all-wireless industrial control nodes, passive IoT communication methods are adopted to backhaul collected data, achieving low-power communication. In the AI algorithm layer, intelligent analysis is performed on monitoring parameters for refined energy consumption analysis and fault discrimination. Finally, in the application layer, visualized monitoring management is performed through operation and maintenance management platforms or apps.

By deploying passive industrial equipment energy consumption monitoring systems, achieving high-precision, refined underlying data collection, combined with AI algorithms, cloud computing and other technologies, it can provide energy-carbon analysis, environmental supervision, energy efficiency management, electricity safety, equipment maintenance and other capabilities for industrial enterprises:

1. "Dual Carbon" Energy Digitalization Solution (Supervision Need): Supported by multi-dimensional, multi-level precise data collection, combined with dynamic carbon emission factors, cloud-edge-end collaborative analysis of enterprise energy-carbon data, helping enterprises complete carbon footprint and carbon accounting applications.
2. Environmental Protection Electricity Supervision Solution (Supervision Need): By monitoring electricity data of environmental protection equipment, assisting environmental protection supervision departments in real-time supervision of pollutant-discharging enterprises, effectively improving supervision efficiency and reducing law enforcement difficulty, while also improving enterprise pollution discharge governance levels and equipment maintenance efficiency.
3. Smart Energy Efficiency Management Solution (Emission Reduction Need): Providing refined energy efficiency management means for energy-consuming units such as factories and parks, by collecting equipment energy consumption data, analyzing equipment operation status, combining AI algorithms to propose energy consumption adjustment and optimization strategies, achieving efficient energy utilization and improving economic benefits.

4. Electricity Safety Solution (Safety Need): Relying on IoT and AI algorithm technologies to identify electricity risks, compensating for the high false alarm rate problem of traditional electricity safety monitoring, providing warnings for risks such as short circuits, overloads, and fires, helping various industries in safe production.

5. Equipment Predictive Maintenance Solution (Operation and Maintenance Need): Collecting current waveforms of electricity-consuming equipment, combined with AI analysis, to accurately identify fault points and predict possible faults in advance. Achieving effects such as reducing downtime, reducing operation and maintenance costs, ensuring safe production, and extending equipment service life.

(2) Industrial Personnel Positioning

Application Scenarios and Requirements

In industrial environments, ensuring factory safe operation and improving space utilization is crucial. Industrial pipe galleries, flammable and explosive product processing plants, and dangerous goods workshops each face challenges. Industrial pipe galleries integrate multiple key pipelines such as industrial gas, chemical transportation, power supply, and control signal transmission. Current management methods still mainly rely on manual regular inspections. Due to complex pipe gallery environments with potential dangers such as oxygen deficiency, high temperature, toxic gases, and gas leaks, inspectors cannot accurately position themselves. Once danger occurs, the operation and maintenance center cannot provide timely rescue, easily causing personnel safety accidents. In factories processing flammable and explosive products, line-of-sight cameras are commonly used to position personnel. However, in unexpected situations such as fires and dust explosions, cameras may not work normally, making it impossible to accurately determine worker positions, affecting rescue timeliness and increasing rescue difficulty and personnel casualty risks. In dangerous goods workshops, strict control of personnel entry and exit is required, prohibiting unrelated personnel from entering.

Through industrial personnel positioning technology, it is possible to accurately identify whether unrelated personnel exist within the workshop and ensure operating personnel are at designated positions, reducing the probability of accidents. Introducing industrial

personnel positioning technology can effectively improve safety management levels in various scenarios, ensuring personnel safety and normal factory operation.

Solution Architecture and Application Effects

Traditional wireless sensing methods generally achieve positioning through bound tags, requiring target objects or people to carry sensing tags. In two-dimensional scenarios, traditional methods require simultaneously deploying 2-3 antennas to jointly determine target position. This method leads to a dramatic increase in system costs when deployed on a large scale, and installation and deployment processes are cumbersome. Especially in scenarios such as illegal intrusion monitoring, because targets do not carry sensing tags, traditional bound tracking methods lose effectiveness.

To address the above problems, China Mobile has innovatively proposed a wireless sensing-based solution. By deploying RFID tag arrays on pipe gallery walls and installing RFID-based all-wireless industrial control node equipment on pipe gallery ceilings, using the impact of personnel position changes on environmental RFID signals, using passive IoT CSI perception models to analyze phase and RSSI change trends, achieving fine-grained trajectory tracking of target spatial movement in an unbounded manner using RFID tags.

Currently, this solution has completed technical pilot testing at a pipe gallery in Beijing Tongzhou. By deploying all-wireless industrial control node equipment and passive sensing reference tags (RFID tags), it achieved low-cost precise personnel positioning, with positioning accuracy improved by 83%.

5.1.2 Communication Cases

(1) Unmanned Remote Control of Steel Plant Cranes

Application Scenarios and Requirements

As the main transportation equipment in steel plant production workshops, the safety and reliability of cranes are crucial, and their operational efficiency directly affects production capacity. Complex ground conditions bring many safety problems to equipment operation. Every year, varying degrees of accidents occur due to crane operation issues, causing damage to ground unit equipment and even personal safety issues. Therefore, wireless transformation of cranes is needed to provide a wireless

transmission network with low jitter, low packet loss, stable and reliable operation, solving safety and reliability problems caused by on-site personnel operation.

Solution Architecture and Application Effects

Based on the wireless network needs of crane transportation in steel manufacturing scenarios, an end-to-end deterministic transmission solution of all-wireless industrial control system was introduced, conducting automation transformation projects for 14 cranes at Anshan Metallurgical Hot Rolling Mill in Liaoning Province. By installing one 5G deterministic gateway on each crane to form the wireless client-side network, using the 5G deterministic gateway as the crane-side PLC slave station northbound communication node, crane PLCs, image scanners and other control equipment are connected to the gateway's standard Ethernet interface. The gateway simultaneously connects to ground dual-frequency networks through 5G dual modules, forming dual-path connections with the hot rolling plant electrical room, significantly reducing on-site wireless transmission packet loss rate, latency and jitter through multi-path redundant deterministic transmission functions. Additionally, by separating control tunnels from video tunnels, effectively ensuring priority configuration of control signals, and the large uplink transmission capability of 5G networks meets the large bandwidth requirements of video transmission services, ensuring stable operation of remote control services.

Based on the end-to-end deterministic transmission solution of all-wireless industrial control system, seamless switching of 5G dual-frequency networks during crane movement is achieved, guaranteeing stable and reliable transmission of control data. The system has been operating stably since deployment, significantly reducing crane operation failure rates and effectively helping enterprises reduce costs and increase efficiency.

(2) AGV Collaborative Transport

Application Scenarios and Requirements

Many large-sized goods require collaborative transport by multiple AGVs. AGV collaborative control strategies include swarm intelligence and leader-follower. In the swarm intelligence strategy, each AGV is an intelligent, autonomous subsystem, with multiple subsystems forming a distributed autonomous intelligent AGV system. In the leader-follower strategy, multiple AGVs adopt a coupled control scheme, setting one

AGV as the master vehicle for overall path planning and information processing, with the remaining vehicles as followers and information collection units, executing instructions issued by the master vehicle and gathering collected information to the master vehicle for unified processing. In AGV collaborative scenarios, information interaction between multiple AGVs is frequent, with extremely high requirements for communication real-time performance and determinism.

Solution Architecture and Application Effects

Based on the wireless network needs of AGV collaborative transport scenarios, an end-to-end deterministic transmission solution of all-wireless industrial control system was introduced at Zhejiang Huorui Technology. By integrating the gateway inside the AGV and deploying the deterministic controller on the robot control platform side, information interaction is performed simultaneously through 5G networks and Wi-Fi networks, ensuring stable transmission of information between AGVs, solving problems such as large information interaction latency between AGVs and large clock synchronization information errors in collaborative transport scenarios, improving the stability of the transport system.

5.1.3 Control Cases

(1) Battery Module Automated Assembly and Data Collection

Application Scenarios and Requirements

New energy power batteries are assembled from small battery modules. Through PLC-controlled robotic arms and screwdrivers, combined with visual positioning, battery module automated assembly sections can be built. Traditional PLCs generally work with data collection gateways to achieve process data collection and backhaul. The separation of control from data and communication capabilities leads to complex on-site hierarchy, many devices, and high costs.



Solution Architecture and Application Effects

By deploying a virtualized industrial control system on industrial gateways, providing "5G connection + on-site computing power + PLC industrial control" fusion capabilities on industrial gateways, achieving two-in-one of PLC and industrial gateways, with advantages such as simplified control hierarchy, reduced industrial control costs, core autonomous controllability, and support for flexible orchestration and expansion.

(2) Integrated Control of Compound Mobile Robots

Application Scenarios and Requirements

With the widespread use of AGVs/AMRs in industrial production, warehousing, logistics and other scenarios, compound mobile robots constructed by mounting robotic arms and other motion components on AGV/AMR bases have begun to appear and are being applied in scenarios such as production line intelligent inspection and production line auxiliary control. In traditional architecture, AGV/AMR controllers and robotic arm controllers are two independent systems. To complete specific actions, the scheduling platform needs to first issue control instructions to the AGV/AMR, then lock the AGV/AMR, and subsequently issue control instructions to the robotic arm to achieve specific actions. This separated architecture has problems such as low control efficiency and high scheduling costs.



Solution Architecture and Application Effects

By deploying a virtualized system on AGV/AMR controllers, achieving hybrid virtualization deployment of Linux and RTOS heterogeneous operating systems. Linux/ROS executes advanced algorithms such as SLAM, while RTOS executes robotic arm motion control algorithms. The two can communicate with each other through cross-VM communication mechanisms. Through virtualized industrial control achieving centralized control of AGV/AMR and robotic arms, reducing equipment complexity and reducing scheduling system scheduling difficulty.

5.1.4 Intelligence Cases

(1) Vision-Based Surface Defect Detection

Vision-based surface defect detection applications are relatively common in manufacturing. Using optical images to identify targets, quickly identifying minute and complex product defects on product surfaces through artificial intelligence small models and classifying them, such as detecting whether there are contaminants, surface damage, cracks, etc. on product surfaces. For defective products detected by the system, automatic reparability determination can be performed, and repair paths and methods are planned, then executed by equipment.

With the continuous improvement of PCB precision, integration, complexity and quantity, PCB defect detection has become an important part of the production process. At a certain factory, optical equipment is used to obtain images of PCB solder joint areas, extracting corresponding features and comparing them with standard features in the database, and using AI visual processing technology to determine the type of welding defects and mark them, achieving rapid and accurate automatic detection of welding

defects. This intelligent detection system based on visual sensors has advantages such as high time efficiency, simple structure, and strong anti-interference capability, with detection accuracy reaching over 95%, and has been widely applied on production lines.



(2) Field-Level Edge-Side Intelligence

As a frontier artificial intelligence technology, edge-side large models have core capabilities such as multi-computing architecture compatibility, small-data fine-tuning, multi-modal data processing, and edge-side flexible deployment, achieving low-cost, high computing efficiency, flexible deployment, and high privacy protection personalized local computing, helping improve industrial intelligence levels. With the development of artificial intelligence technology, equipment equipped with edge-side large models, such as robotic arms, inspection robots, robot dogs, humanoid robots, etc., will play increasingly important roles in industrial scenarios.

Embodied intelligent equipment equipped with edge-side large models can achieve flexible, rapid, and precise scheduling and collaboration at industrial sites. As intelligent capabilities sink to on-site equipment, data and decision-making tasks that originally needed to be processed in the cloud can be completed locally at industrial sites, improving equipment's ability to cope with differentiated needs. At the same time, the multi-modal data processing capability of large models can improve equipment's cognitive level of the environment. Facing new collaboration tasks, equipment can comprehensively analyze internal and external environmental factors, complete autonomous decision-making and achieve autonomous collaboration of multiple devices.

6. Outlook

New industrialization provides broad space and new opportunities for the development of industrial control systems, promoting the integrated coupling of all-wireless industrial control technology in sensing, communication, control, and intelligence. Its rapid development has important significance for fully realizing 5G value, ubiquitous sensing, open automation, and business intelligence:

First, expanding industrial network sensing capabilities, creating field-level integrated sensing and communication, achieving ubiquitous sensing. Facing problems such as numerous and complex production links, numerous production factors, frequent personnel flow at industrial sites, leading to difficult data sensing, insufficient management, and low production efficiency, based on wireless networking communication, building capabilities such as integrated sensing and passive sensing, creating field-level integrated sensing and communication, achieving low-cost ubiquitous sensing.

Second, fully leveraging 5G network value, building one-network multi-functionality, supporting diversified industrial applications. Facing 5G equipment and systems invested by factories in the early stage, creating 5G deterministic networks that integrate with emerging technologies and have good backward compatibility, avoiding additional costs and resource waste caused by technology updates, maximizing the protection of factory investments in 5G.

Third, upgrading industrial control open capabilities, breaking closed control ecosystems, achieving ICT/OT fusion. Traditional industrial automation systems adopt closed architectures and proprietary software and hardware, leading to difficulties in interconnection between systems, restricted information flow, and difficulty adapting to changes and needs in the production process. All-wireless industrial control systems achieve mixed deployment of IT/OT systems based on general software and hardware architectures, adopting object-oriented, reusable software development methods, achieving distributed deployment and dynamic orchestration of PLC applications, achieving data exchange and communication between different systems, promoting information sharing and collaborative work, helping improve industrial production flexibility, efficiency, and intelligence levels.

Fourth, optimizing industrial production processes, improving total factor productivity, achieving intelligent industrial production. Facing problems such as insufficient industrial production flexibility, low efficiency and quality levels, and fierce market competition, empowering industrial production core links with industrial large models as the intelligent foundation, supporting flexible production and process automation, thereby improving total factor productivity and quality levels, promoting industrial digital transformation and intelligent development.

Fifth, promoting energy conservation and emission reduction in the industrial field, creating low-carbon green industrial chains, achieving green industrial manufacturing. Under the background of new industrialization, industry is a key area for energy conservation and emission reduction. Creating green factories, green parks, and green industrial chains, and developing green low-carbon industries have become future trends.

With the continuous development of technology and industry, all-wireless industrial control technology is expected to deeply integrate with industrial applications, helping industrial enterprises achieve equipment transformation and upgrading, achieving high-quality improvement of productivity, truly achieving wireless, intelligent, and green production. China Mobile hopes to work with partners to carry out innovations in all-wireless industrial control technology, solutions, products, and applications, breaking technical barriers through means such as resource sharing and complementary advantages, forming consensus on the development vision of all-wireless industrial control systems improving total factor productivity, jointly promoting the formulation of all-wireless industrial control standards, accelerating the new industrialization process by building autonomous, innovation-leading new industrial technologies.

Abbreviations List

Abbreviation	English Full Name	Chinese Explanation
5G	5th Generation Mobile Communication Technology	Fifth Generation Mobile Communication Technology
AGV	Automated Guided Vehicle	Automated Guided Vehicle
AI	Artificial Intelligence	Artificial Intelligence
C2C	Controller to Controller	Controller to Controller
C2IO	Controller to IO	Controller to Input/Output
CSI	Channel State Information	Channel State Information
CT	Communication Technology	Communication Technology

DetNet	Deterministic Network	Deterministic Network
DN	Data Network	Data Network
I/O	Input/Output	Input/Output
IT	Information Technology	Information Technology
OT	Operational Technology	Operational Technology
PLC	Programmable Logic Controller	Programmable Logic Controller
RFID	Radio Frequency Identification	Radio Frequency Identification
TAN	Time Aware Network	Time Aware Network
TSC	Time Sensitive Communication	Time Sensitive Communication
TSN	Time Sensitive Network	Time Sensitive Network
UE	User Equipment	User Equipment
UPF	User Plane Function	User Plane Function
UWB	Ultra Wide Band	Ultra Wide Band Technology

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